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Jarkko Okkonen

GROUNDWATER AND ITS RESPONSE TO CLIMATE VARIABILITY AND CHANGE IN COLD SNOW DOMINATED REGIONS IN FINLAND: METHODS AND ESTIMATIONS

UNIVERSITY OF OULU,
FACULTY OF TECHNOLOGY,
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Abstract

A conceptual framework was developed to assess how changes in temperature and precipitation affect sub-surface hydrology, groundwater recharge, groundwater quantity and quality. A conceptual and statistical approach was developed to predict groundwater level variations. Daily rainfall, snowmelt and evapotranspiration values were generated with a novel conceptual hydrological model developed in this study. These values were cross-correlated with observed groundwater levels to find representative time lags and significant correlations. A statistical model linking rainfall, snowmelt, evapotranspiration and groundwater level was then developed and validated. The model simulated seasonal variations in groundwater level very accurately. A sequential approach was developed to assess surface water-groundwater interactions. The simulated surface water level estimated with the WSFS model and recharge estimated with CoupModel were linked to the groundwater flow model MODFLOW. Groundwater, surface water and snow samples were collected to study the chemical composition of groundwater in an unconfined esker aquifer in Northern Finland. Concentrations of Ca^{2+}, Cl-, NO_3-N and SiO_2 and electrical conductivity were determined. Water quality in the main aquifer was found to be similar to that in the perched groundwater. Solute concentrations generally decreased during and immediately after snowmelt periods, indicating the importance of snowmelt input for groundwater quality. In the perched groundwater, NO_3-N concentration increased with elevated groundwater level, indicating a nitrogen source on the land surface. The Cl- concentration in groundwater decreased when the surface water level rose higher than groundwater level. According to simulation results for the A1B climate change scenario, groundwater recharge is projected to increase in winter months due to increased snowmelt and decreased soil frost depth. The spring snowmelt peak in late spring will decrease. This will reduce aquifer storage in early spring, increasing the vulnerability to summer droughts. It is projected that flow regimes between unconfined aquifers and surface water may change, affecting water quantity and possibly quality in groundwater systems.

Keywords: cold climate, conceptual framework, esker aquifer, geochemistry, numerical model, statistical model

Okkonen, Jarkko, Ilmaston vaihtelun ja muutoksen vaikutukset pohjaveteen kylmillä lumen peittämille alueilla Suomessa: menetelmien kehittäminen ja arviointi
Oulun yliopisto, Teknillinen tiedekunta, Prosessi- ja ympäristötekniikan osasto, PL 4300, 90014 Oulun yliopisto
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Tiivistelmä

Tässä työssä kehitettiin konseptuaalinen viitekehysmalli, jolla voidaan arvioida kuinka muutokset lämpötilassa ja sadannassa vaikuttavat hydrologiaan, pohjaveden muodostumiseen, pohjaveden määrään ja laatuun. Tässä työssä kehitettiin ja yhdistettiin konseptuaalinen ja tilastomatemaattinen regressiomalli, jolla voidaan simuloida pohjaveden pinnankorkeuden muutoksia. Konseptuaalisella mallilla laskettiin päivittäinen sadanta, lumen sulanta ja haihdunta. Havaitut pohjaveden pinnankorkeudet korreloitiin sadannan, lumen sulannan ja haihdunnan kanssa, jotta löydettiin merkitsevät korrelaatiot tyypillisillä viiveillä. Lopuksi tilastollinen regressiomalli, joka yhdistää sadannan, lumen sulannan, haihdunnan ja pohjaveden pinnankorkeuden, kalibroitiin ja validoitiin. Kehitetyllä mallilla onnistuttiin simuloimaan vuodenaikainen pohjaveden pinnankorkeus. Yhdensuuntainen mallinnusmenetelmä kehitettiin arvioimaan pinta- ja pohjaveden vuorovaikutusta. Menetelmässä pintaveden korkeus ja pohjaveden muodostuminen linkitettiin ajan suhteen muuttuvina reunaehtoina pohjavedenvirtauksen mallinnusohjelmaan MODFLOW. Simuloidut pintaveden pinnankorkeudet saatiin Suomen ympäristökeskuksen vesistömallijärjestelmästä ja pohjaveden muodostuminen simuloitiin 1D lämmön- ja aineensiirtomallilla, CoupModel. Pudasjärven Törrönkankaan pohjavesimuodostumasta, Pudasjärvestä, Kivarinjoesta ja lumesta kerättiin näytteet ja niistä määritettiin Ca^{2+}, Cl-, NO_3-N ja SiO_2 pitoisuudet sekä sähkönjohtavuus. Pitoisuudet pohja- ja salpavedessä olivat hyvin samanlaiset. Pitoisuudet yleisesti pienenivät, kun pohjaveden pinnankorkeus nousi etenkin keväisin lumien sulamisen jälkeen. Ainoastaan salpavedessä NO_3-N pitoisuus kasvoi, kun pohjaveden pinnankorkeus nousi. Tämä johtuu todennäköisesti salpaveden yläpuolella olevasta NO_3-N lähteestä. Cl- pitoisuus pohjavedessä pieneni, kun pintaveden korkeus nousi korkeammalle kuin pohjavesi. A1B ilmastoskenaariossa pohjaveden muodostumisen ennakoidaan lisääntyvän talvikuukausina. Tämä johtuu lumen sulannan lisääntymisestä ja roudan vähenemisestä. Keväinen lumen sulamisen huippu voi mahdollisesti pienentyä ja johtaa pohjavesivarojen pienentymiseen keväisin. A1B ilmastoskenaariossa pinta- ja pohjaveden vuorovaikutus voi myös muuttua ja siten vaikuttaa pohjaveden määrään ja mahdollisesti myös laatuun.

Asiasanat: geokemia, harju akviferi, konseptuaalinen viitekehysmalli, kylmä ilmasto, numeerinen malli, tilastollinen malli

To my beloved daughters

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I am in debt to Aarne Miettunen from the ELY Centre in North Ostrabothnia, who first introduced me to the field of groundwater hydrology, by hiring me in 2002 to work at ELY as a trainee and by putting me in charge of conducting a geophysical survey in the Ahmaskangas groundwater area. These investigations continued during 2003. In 2004 I did my graduate project on geophysical field studies in the Ahmaskangas groundwater area at the Department of Geophysics. The thought of being a research scientist crossed my mind then and later, when I was about to finish my second graduate project at the Department of Process and Environmental Engineering, Water Resources and Environmental Engineering Laboratory, in 2004. The topic was 'Groundwater flow model of the Ahmaskangas groundwater area'. However that project was extended into this PhD project. In 2004–2005 I really became involved in groundwater flow and transport modelling and groundwater hydrology at the University of Waterloo, Canada, and during my time there my PhD project really started to take shape. When I got back to Finland, in summer 2005, I started to work at the Water Resources and Environmental Engineering Laboratory.

I would like to express my gratitude to my supervisor, Prof. Bjørn Kløve at the Water Resources and Environmental Engineering Laboratory, for his advice and for helping me out to obtain funding support for this thesis project. Special thanks to him for hiring me as an assistant for the period of 2005–2006, when funding for this research was lacking. After completing my field work and data analyses in summer 2009, I moved on to work at the Geological Survey of Finland and to co-found and establish WRM Systems Oy, together with Jukka Happonen, but Bjørn encouraged me to finish this thesis. It gives me great pleasure to thank the staff and colleagues at the Water Resources and Environmental Engineering Laboratory and Geophysical Department at the University of Oulu for their helpfulness in the field work, practical matters and scientific issues. Cheers to Mikko Jyrkama at the University of Waterloo and his family. Without the grad-house experiments with Mikko and dinners with his family, the time my wife and I spent in Waterloo would have been much flatter. The pre-examiners of this thesis, Dr. Univ.-Doz. DI Dr. Hans Kupfersberger and Prof. Per-Erik Jansson are acknowledged for their revisions and valuable comments. I also thank Dr. Mary McAfee for revision of the language.

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List of symbols and abbreviations

FMI	Finnish Meteorological Institute
SYKE	Finnish Environmental Institute
EC	Electrical conductivity
P_{sn}	Snowmelt water
P_r	Rainfall
ET	Evapotranspiration
T	Temperature
t	Time
Δt	Time step
C	Regression coefficient
α	Regression coefficient
β	Regression coefficient
ε	Residual
R^2	Correlation coefficient
B	Bias
y'_i	Predicted groundwater level at time step i
y_i	Observed groundwater level at time step i
y_{mean}	Mean observed groundwater level
C_{xy}	Cross-correlogram
r_{xy}	Cross-correlation coefficient
σ_x	Standard deviations of the time series x
σ_y	Standard deviations of the time series y
WSFS	Watershed simulation and forecasting system
MAE	Mean absolute error
RMSE	Root mean square error
RCH	Recharge
FRCH	Focused recharge
HSD	Honestly significant difference
ANOVA	One-way analysis of variance
GW	Groundwater
Q_{in}	Surface runoff
C_s	Correction coefficient for snowfall
P_{tot}	Observed precipitation,
C_r	Correction coefficient for rainfall
F_r	Fraction of rainfall

F_s	Fraction of snowfall
M_d	Daily snowmelt
K_m	Degree day factor
T_a	Daily air temperature
T_m	Temperature at which snowmelt begins
F_d	Rate of freezing in the snowpack
K_f	Degree day freezing factor
T_f	Threshold temperature
e	Coefficient indicating the non-linear relationship between refreezing and temperature
WSP	Liquid water retention capacity of the snow pack
WIP	Liquid water of ice in the snow pack
SWE	Snow water equivalent
S	Soil water storage capacity
θ_f	Field capacity
θ_{wp}	Permanent wilting point
Z_r	Vertical extent of root zone
W_i	Water input

List of original articles

This thesis is based on four original publications, which are referred to in the text by their Roman numerals:

I Okkonen J, Jyrkama M & Kløve B (2010) A conceptual approach for assessing the impact of climate change on groundwater and related surface waters in cold regions (Finland). Hydrogeology Journal 18(2): 429–439.

II Okkonen J & Kløve B (2010) A conceptual and statistical approach for the analysis of climate impact on ground water table fluctuation patterns in cold conditions. Journal of Hydrology 388(1–2): 1–12.

III Okkonen J & Kløve B (2011) A sequential modelling approach to assess groundwater-surface water resources in a snow dominated region of Finland. Journal of Hydrology 411(1–2): 91–107.

IV Okkonen J & Kløve B (In Press) Assessment of temporal and spatial variation in chemical composition of groundwater in an unconfined esker aquifer in the cold temperate climate of Northern Finland. Cold Region Science and Technology.

The author's contribution to publications:

I: Designed the work together with Bjørn Kløve and Mikko Jyrkama, took responsibility for the framework development and wrote the paper. Bjørn Kløve and Mikko Jyrkama critically commented on the paper.

II–IV: Designed the work together with Bjørn Kløve, conducted the geophysical field studies, data analysis, model developments and simulations and wrote the papers. Bjørn Kløve critically commented on all the papers.

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1 Introduction

Groundwater is an important global source of fresh water, as it provides almost 40% of the world's potable water (Morris 2003). Groundwater usually requires less chemical treatment owing to its good quality and it is better protected against pollution than surface waters. Increasing groundwater extraction and the call for sustainable water management are creating an urgent need to clarify the impact of factors such as climate change that may affect groundwater resources globally. The impacts of climate change on groundwater will vary between regions, with some parts of the world experiencing more droughts and other parts experiencing an increase in groundwater recharge, improving its potential (IPCC 2007).

In recent years, there has been great interest in studying the impact of climate change on groundwater systems (Green *et al.* 2011). The focus has been on estimating changes in key climate drivers (temperature and precipitation) of groundwater recharge and groundwater levels. The impacts of extreme conditions, such as droughts, have been estimated (Kirschen 2002) but less attention has been paid to the indirect hydrological impacts of changes in e.g. land cover (Lambrakis & Kallergis 2001) and water demand (e.g. for irrigation; Rosenzweig *et al.* 2004). In addition, little research has been done on unconfined aquifers, especially on their interaction with surface water bodies (Bobba *et al.* 2000; Malcom & Soulsby 2000; Yusoff *et al.* 2002; Scibek *et al.* 2007; Rautio & Korkka-Niemi 2011; Korkka-Niemi *et al.* 2011), or on the impacts of climate change on these compared with the impacts on deeper aquifers (Loáiciga *et al.* 2000; Younger *et al.* 2002; Brouyère *et al.* 2004).

In Finland, nearly 60% of municipal water supply is groundwater and its usage is expected to increase in the future (Finnish Environmental Institute 2011). Most aquifers used for water supply in Finland are glaciofluvial deposits, i.e. eskers or ice-marginal end moraines (Mälkki 1999). In Finland, seasonal variations in groundwater levels and quality are common (Soveri *et al.* 2001; Hatakka & Väisänen 2007) and snow cover and soil frost play important roles in the hydrological cycle (Lunardini 1981; Kuusisto 1984; Williams & Smith 1989). In snow-dominated regions, snow cover usually hinders groundwater recharge in winter, while snowmelt water replenishes aquifers in spring (Kuusisto 1984; Rutulis 1989; Van der Kamp & Maathuis 1991). Because of the direct contact between the groundwater and the ground surface, unconfined aquifers, especially surficial and shallow aquifers, will be particularly sensitive to changes in climate conditions (Winter 1999; Healy & Cook 2002; Sophocleus 2002; Dingman 2002;

Lee *et al.* 2006). It is projected that in snow-dominated regions, warmer winters will cause snowmelt and groundwater recharge (Jyrkama & Sykes 2007; Sutinen *et al.* 2007) and runoff will occur over longer periods and earlier in the year (Veijalainen 2008). Changes in recharge and runoff pattern may eventually change groundwater and surface water levels and alter the interaction between groundwater and surface water.

Previous studies in snow-dominated regions in Finland have pointed out the cumulative effect of extra-regional, regional and site-specific effects (Korkka-Niemi 2001) and seasonal trends in groundwater quality (Soveri *et al.* 2001; Hatakka & Väisänen 2007). However, there has been relatively little research into temporal variations in the response of groundwater quality to snowmelt and rainfall, which may give an indication of groundwater recharge periods, the spatial variability of the recharge (Cherry 2000), potential surface water-groundwater interactions (Rautio & Korkka-Niemi 2011) and groundwater flow paths in the aquifer. The water quality in different units may also vary depending on the mineralogy and groundwater residence time within the aquifer (Kortelainen & Karhu 2009). Seasonal changes in groundwater solute concentrations may indicate the sensitivity of the groundwater to any action that occurs on the land surface. Such knowledge is important in assessing aquifer vulnerability to pollution and climate change and in developing good monitoring strategies.

The impacts of hydrological changes and variability on groundwater can be estimated with statistical tools (Chen *et al.* 2002; McCuen 2003) and complex distributed numerical models (Scibek & Allen 2006a; Scibek & Allen 2006b; Scibek *et al.* 2007; Jyrkama & Sykes 2007). Statistical methods can be useful in areas where more physically-based models would be difficult to implement, e.g. due to the lack of detailed information on hydrogeological parameters. Previous studies have shown the ability of autoregressive models (Viswanathan 1984; Bierkens *et al.* 2001; Knotters & Bierkens 2001) and an empirical statistical model developed by Chen *et al.* (2002) to predict groundwater levels by climate variables. However, recent models do not account for snowmelt in assessment of aquifer recharge.

Numerical simulation models provide a very effective way to estimate the quantity and quality of groundwater and surface water interaction and to quantify the impact of climate change and variability on groundwater systems. Groundwater and surface water interactions can be simulated through application of physically-based models, such as HydroGeoSphere (Therrien *et al.* 2007), MIKE-SHE (DHI 2007), GSFLOW (Markstrom *et al.* 2008) and ParFlow (Maxwell *et al.* 2009).These models allow two-way feedback between surface water and groundwater. However, physically-based models require a large amount of data to simulate and calibrate watershed models. The lack of freeze and thaw sub-models and components to account for water infiltration through partially frozen soil make it difficult for these physically-based models to simulate the timing of recharge, minimum and maximum groundwater levels, surface runoff and water levels in lakes and rivers in cold, snow-dominated regions. Without these important components in the models, the interaction between groundwater and surface water is difficult to assess. One alternative approach is to assess the boundary conditions, which for unconfined esker aquifers can be variations in groundwater recharge and surface water level, and link these variations in surface water and recharge into the groundwater flow model. If the variation in adjacent surface water level is not affected by the groundwater discharge, two-way coupling between lakes, rivers and seas is not necessary (Ataie-Ashtiani *et al.* 1999) and estimated boundary conditions can be linked to the groundwater model in a one-way manner. Seasonal variations in surface water levels (lakes, rivers and seas) and recharge can then be imported as time variant boundary conditions in groundwater flow models (Ataie-Ashtiani *et al.* 1999).

Conceptual models or frameworks can also be used to demonstrate several factors that need to be considered in an integrated modelling system that links climate to hydrology. In addition, conceptual frameworks are useful for water managers, and are recommended in European Commission guidelines (CIS 2003). The guidelines state that regular improvements should be made to conceptual frameworks, but details on how to develop them are not given.

1.1 Objectives

The overall objective of this work was to develop approaches to assess the impacts of climate variability and change on groundwater levels and groundwater-surface water interactions and to study temporal and spatial variations in groundwater chemistry in unconfined esker aquifers in a cold, snow-dominated region of Finland. Specific objectives were to:

- Develop and apply a conceptual framework for evaluating the potential impacts of climate change on various components of the near-surface hydrological regime, surface water bodies and groundwater. Quantity and quality aspects of groundwater were both considered. The key objective was to determine how changes in key climate variables, i.e. temperature and precipitation, propagate through a near-surface hydrological regime and eventually affect groundwater levels and possibly groundwater quality. An additional objective was to find an easy-to-use framework to assist water professionals in their understanding of the impact of climate change on groundwater resources, and to facilitate the development of numerical models by identifying linkages between the different parameters affecting groundwater systems. The following research question was formulated: Can a conceptual framework be developed as an alternative tool to more complex statistical and numerical approaches in the assessment of climate change effects on groundwater quantity and quality?

- Develop and apply a conceptual and statistical approach for the analysis of climate impact on groundwater fluctuation patterns in cold conditions. The following research questions were formulated: Does a snowmelt component improve a model that uses precipitation and temperature alone? Can a statistical model predict the groundwater level variation for areas where hydrogeological data for more complex distributed models are lacking?
- Develop and apply a sequential approach to simulate surface water-groundwater interactions in order to study the impact of climate variability on groundwater hydrology in cold conditions in northern Finland. A key objective was to better predict the role of soil frost on recharge and groundwater level. (III)
- Study the temporal and spatial variability in groundwater and surface water hydrogeochemistry in a seasonally snow-covered unconfined esker aquifer (Pudasjärvi) in northern Finland. The concentrations of Ca^{2+}, Cl^{-}, NO_3-N and SiO_2 and electrical conductivity were determined in a number of water samples. These chemical constituents represent the weathering of the mineral soil (Ca^{2+}, SiO_2) and possible sources of pollution (Cl^{-}, NO_3-N). SiO_2 has also been used as an indicator of groundwater age (Burns *et al.* 2003). Monthly groundwater and surface water samples were collected over a one-year period. The following research questions were formulated: To what extent does the groundwater solution vary with time and space within the aquifer? Can groundwater and surface water interaction be determined by analysing Ca^{2+}, Cl^{-}, NO_3-N and SiO_2 concentrations and electrical conductivity?

2 Description of study sites

The two unconfined esker aquifers studied are located in northern Finland (Ruukki) and central Finland (Pudasjärvi). The groundwater area for the Ruukki aquifer (Fig. 2) is not affected by anthropogenic impacts other than the drainage ditches in the discharge zone of the aquifer. The Pudasjärvi aquifer (Fig. 3) is threatened by anthropogenic and surface water intrusion and groundwater has been pumped out for domestic use by the municipal authority.

2.1 Unconfined eskers in Finland (I, II, III, IV)

Eskers are typically well-sorted gravel and sand deposits. Hydraulically uniform strata may extend more than tens of kilometres and groundwater flows in longitudinal directions from higher to lower groundwater level. The groundwater flow gradient is typically low and flow velocity and permeability high (Mälkki 1979). The groundwater level usually lies 2 to 4 m below the surface, but can be as deep as 30 m in some regions of southern Finland. In northern Finland, unconfined esker aquifers are often located next to surface water bodies, i.e. lakes, ponds, rivers and wetlands.

The climate conditions prevailing in different parts of Finland result in groundwater level fluctuation patterns that can be divided into four distinct types, as shown in Fig. 1 (Mäkinen 2003). In regions II to IV, annual maxima occur in the spring due to snowmelt and at the end of the year due to increased precipitation and lower evapotranspiration. Annual minima occur in the summer and late winter. In northern Finland (region I), the groundwater level fluctuation pattern shows a single minimum and a single maximum, the minimum occurring immediately prior to snowmelt and the maximum immediately following spring snowmelt. In esker aquifers, the groundwater chemistry may also change over time and usually responds to precipitation and snowmelt events (Soveri *et al.* 2001), with concentration minima occurring in spring and autumn and concentration maxima in winter and summer. As shown in Fig. 1, the groundwater level declines from its maximum at a near-constant rate, until it reaches the annual minimum. The distinctive pattern in the north is mainly due to the colder temperatures in autumn, which allow a stable snow cover to develop, and the lower precipitation (Karlsson 1986; Silander *et al.* 2006).

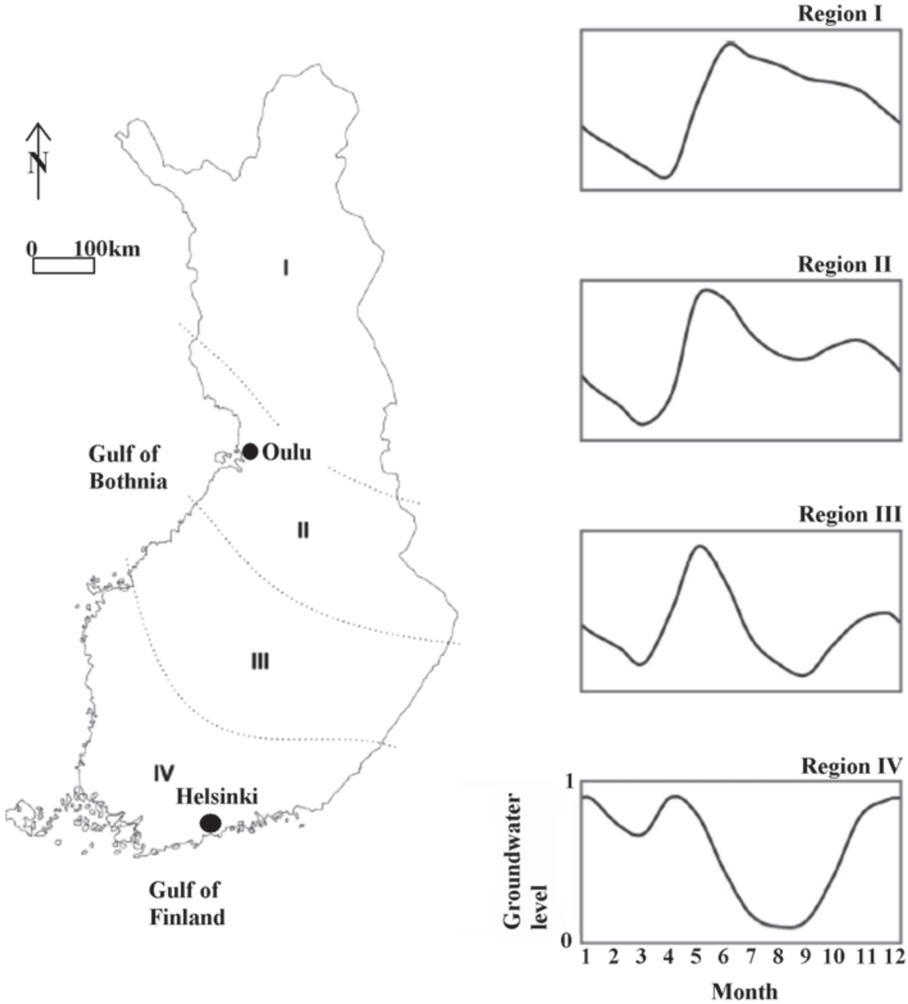

Fig. 1. Current groundwater fluctuations in northern (region I), central (regions II, III) and southern Finland (region IV) (modified with permission from Mäkinen *et al.* 2008) (Paper I). Reprinted with permission from Springer.

2.2 Ruukki groundwater area (II)

In the Ruukki groundwater area, the aquifer consist mainly of coarse sand with minor amounts of silt in discharge zones. The aquifer discharges water to the surrounding wetlands through ditches in north-east and south-west parts of the discharge area. The vegetation is a mixture of reindeer moss (*Cladonia rangiferina*), lingonberry (*Vaccinium vitis-idaea*) and Scots pine (*Pinus sylvestris*). The surface area of the aquifer is 2.77 km^2, and the groundwater elevation is 80–86 m above sea level, and 2–3 m below the ground surface. The area is not affected by anthropogenic impacts other than the drainage ditches in the discharge zone of the aquifer. Drainage in the discharge area commenced in 1980 (Tirronen 1983) and continued until 1999 (Soveri *et al.* 2001). There are 12 observation wells (P1–P12, see Fig. 2) and biweekly measurements of groundwater levels were made in 11 of these wells (P1–P11), between 1975 and 2006, and daily measurements were made in one well (P12) between 1990 and 1999.

The Finnish meteorological institute (FMI) provided daily temperature and precipitation data for the period 1975–2006 from the automatic weather station that is located 17 km north-east of the aquifer. The Finnish environmental institute (SYKE) provided snow water equivalent data for the period 2005–2007. The snow water equivalents were measured at the forested area 6 km south-west of the aquifer.

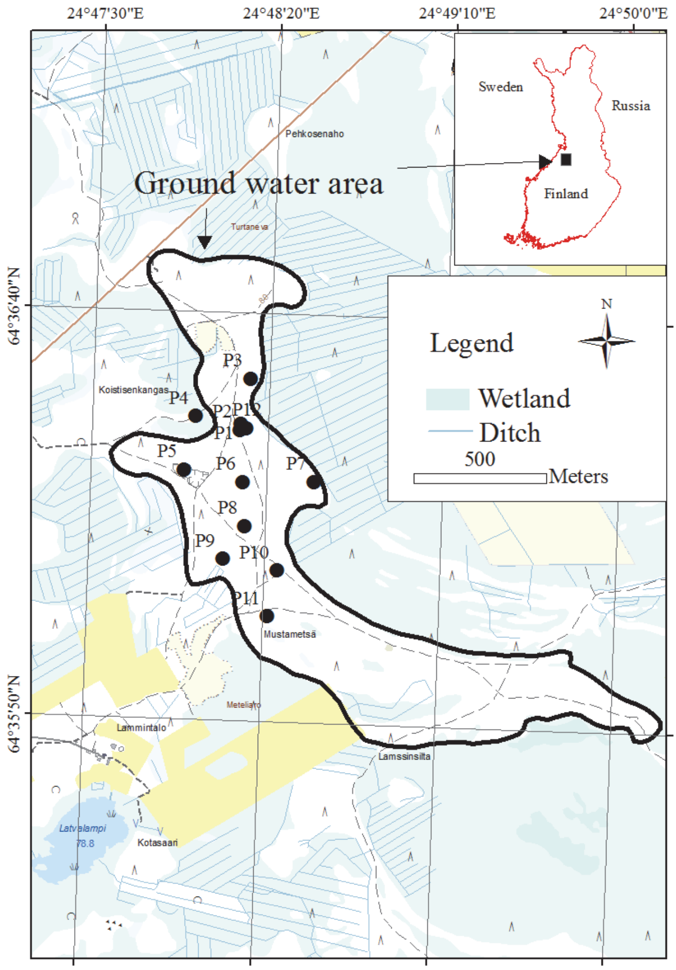

Fig. 2. Study site and water level observation wells P1–P12. The groundwater area consists of coarse sand and the discharge area of coarse sand and silt (Paper II). Reprinted with permission from Elsevier.

2.3 Pudasjärvi aquifer (III, IV)

The Pudasjärvi aquifer forms part of the 10 000 km^2 Iijoki (river Ii) watershed (Fig. 3). Since 1981, the groundwater in Pudasjärvi has been pumped out for domestic use by the municipal authority, at an average pumping rate of 750 m^3/d. Seasonal variations in the water level of Lake Pudasjärvi and in the groundwater level were observed every year between 1981 and 2000. Because surface water intrusion is likely to occur during and just after the spring snowmelt period, when the surface water elevation reaches the groundwater elevation, pumping of groundwater is halted in May and June. The Pudasjärvi aquifer is surrounded by the lakes Kivarijärvi and Pudasjärvi and the river Kivarijoki. The catchment of Lake Pudasjärvi is 8424 km^2, while that of Lake Kivarijärvi and the river Kivarijoki is 316 km^2.

In the Pudasjärvi aquifer five different hydrogeological units were delimited based on the geophysical studies and boreholes by PSV- Maa ja Vesi (1996, 2001, 2002 and 2003). The Pudasjärvi aquifer is part of the Yli-Iin-Hossan interlobate complex, a glaciofluvial formation (esker) deposited between two ice lobes during the ice retreat (PSV- Maa ja Vesi 2001). The middle part of the aquifer consists of gravel, which is bordered by glacial till and sands. These sands vary from coarse to very fine and layer thickness varies from 1 to 20 m. The bedrock is nearly flat, varying between 94 and 96 m above sea level, and the ground surface varies between 110 and 135 m above sea level. The observed groundwater level varies between 108 and 109 m above sea level. In the northern part of the aquifer (Obs4, Obs5, Obs7 and Obs13), there is a silt layer that creates a perched watertable 6 m higher than the rest of the aquifer (114–116 m above sea level). The vegetation is a mixture of reindeer lichen (*Cladonia rangiferina*), lingonberry (*Vaccinium vitis-idaea*) and Scots pine (*Pinus sylvestris*). The surface area of the aquifer is 4.5 km^2.

In the Pudasjärvi aquifer, the potential anthropogenic factors affecting groundwater quality are a gravel pit, an airport, roads, oil tanks, industries, farming, an abattoir and a landfill site (PSV- Maa ja Vesi 2001) (Fig. 3). The airport is located in the north-west part of the aquifer and is only used in summertime. The main road cuts the aquifer at 1.6 km length and the de-icing salt that is used to prevent ice on this road poses a risk to groundwater by increasing the Cl^- and Na concentrations (PSV- Maa ja Vesi 2001). The main industries operating near the pumping well are also considered a risk factor (PSV- Maa ja Vesi 2002).

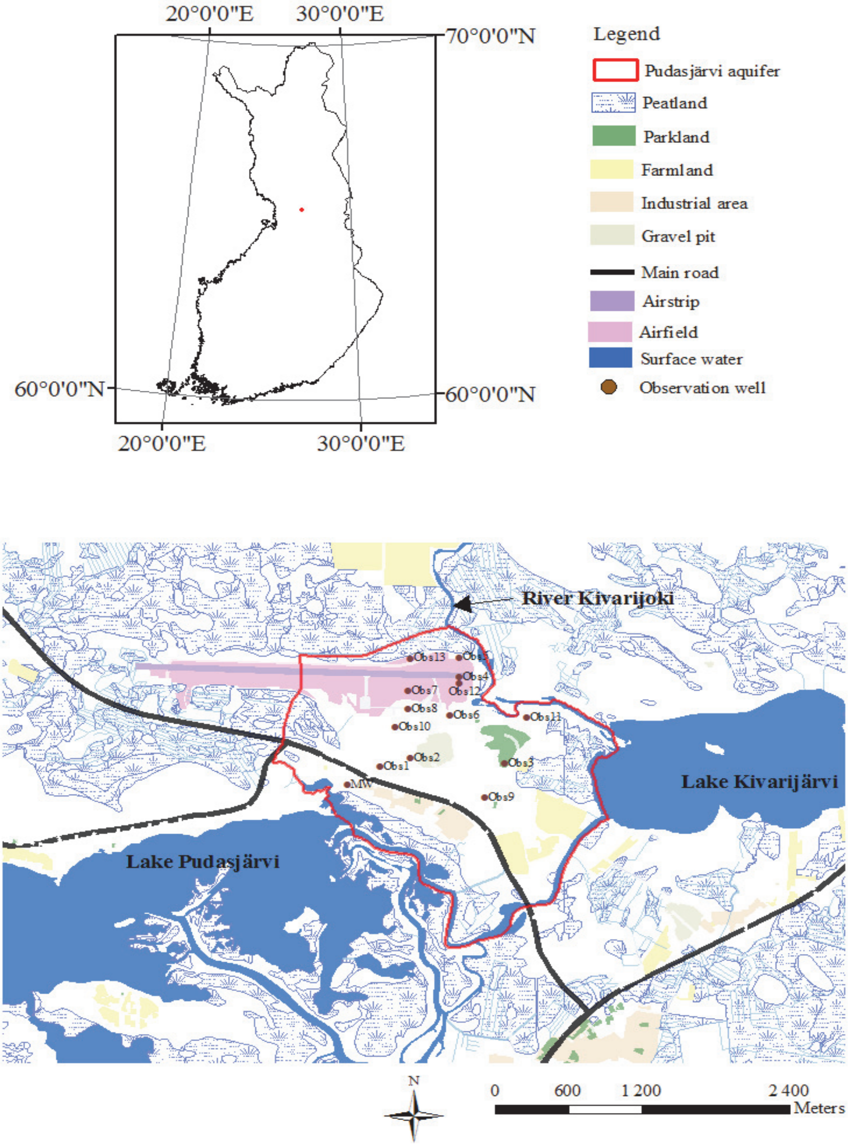

Fig. 3. Pudasjärvi aquifer. MW refers to Municipality Well (pumping well).

3 Methods and analyses

The methods used and analyses performed in this thesis are described briefly in this section. Full descriptions can be found in Papers I–IV. This work started with a simple conceptual approach, followed by the development of a statistical and more complex numerical model in order to estimate the impacts of precipitation and temperature on groundwater quantity. In addition, over a one-year period, monthly groundwater samples were collected in order to assess the impact of climate variability on groundwater quality. The relationship between the modelling approaches and water sampling are presented in Fig. 4.

The conceptual framework was used to provide an easy-to-comprehend assessment of changes in precipitation and temperature and their influence on hydrology and groundwater resources and to facilitate the development of numerical and statistical modelling by identifying linkages between precipitation, temperature, rainfall, snowmelt water, soil frost, runoff, recharge and water quantity and quality (Fig. 4). The statistical model was used to provide a simple approach to predict groundwater level variations in areas where no detailed hydrogeological information is available. This approach assumes that the variation in groundwater level in an aquifer follows the variation in rainfall, snowmelt and evapotranspiration with a time delay depending on the properties of the aquifer. The model was tested for a case study area in central Finland. The test included studies of model fit and prediction of groundwater level variations. A more complex distributed hydrological modelling approach was used to assess groundwater levels and groundwater-surface water interactions in a changing climate. The approach included recharge simulations with a coupled water and heat transport model (CoupModel; Jansson & Karlberg 2004) that can be used to simulate the role of soil frost on recharge rates. The results of the recharge model were then imported to the groundwater flow model as a Neumann type boundary condition. The surrounding surface water levels were estimated by SYKE using a surface water model (WSFS; Vehviläinen 2007) and these results were imported to the groundwater flow model as Dirichlet-type boundary conditions. Monthly groundwater and surface water samples were collected over a one-year period. The time series obtained were then studied to differentiate groundwater recharge periods by examining variations in groundwater level and the impacts of precipitation and snowmelt water on variations in solute concentrations in groundwater and surface water.

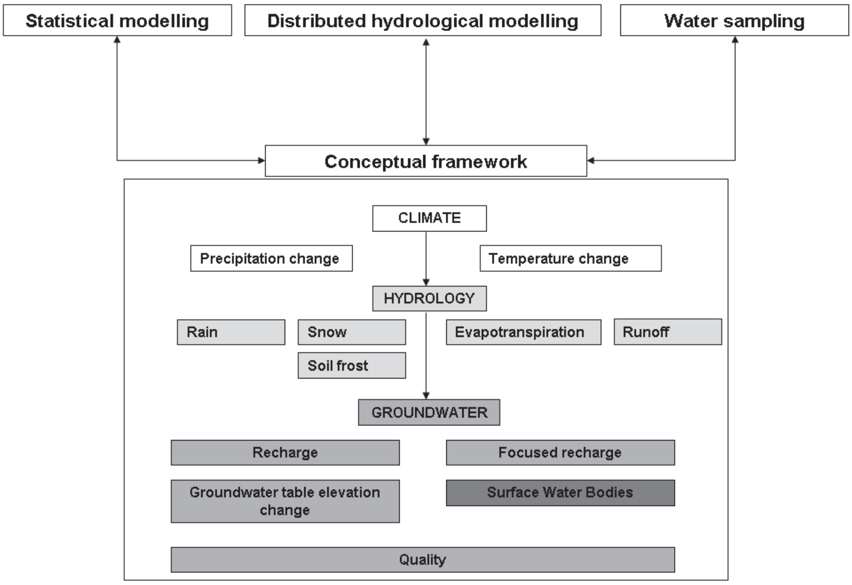

Fig. 4. Relationship between modelling, water sampling and conceptual framework.

3.1 Water sampling and analysis

Monthly groundwater and surface water samples were collected during the period 2006–2007 from Lake Pudasjärvi, the Kivarijoki river and wells Obs1, Obs2, Obs3 and Obs4. On 21 August 2006, the spatial variation was studied more carefully by taking samples from 14 wells across the study site (Table 1). Snow samples were also collected for chemical analysis close to wells Obs1, Obs3 and Obs4. At the accredited laboratory of the Regional Environmental Centre, NO_3-N, Ca^{2+}, Cl^- and SiO_2 were analysed.

The Finnish meteorological institute (FMI) provided daily temperature and precipitation data for the period 3 January 2006–23 January 2007. The precipitation water samples were recorded by FMI during the period 1 April 2006–31 December 2006 at the Oulanka weather station, located 150 km to the north-east of the Pudasjärvi aquifer. The concentrations of Ca^{2+}, Cl^- and NO_3-N in precipitation water were analysed and monthly time series were provided by FMI. The Finnish environmental institute (SYKE) provided snow water equivalent data for the period 3 April 2006–31 May 2007.

Table 1. Observation wells, well data, number of samples and sampling period for the Pudasjärvi aquifer. NO_3-N, Ca^{2+}, Cl^- and SiO_2 were analysed in every sample. EC was analysed in every sample except those from Lake Pudasjärvi, the river Kivarijoki and snow (Paper IV). Reprinted with permission from Elsevier.

Observation well	Thickness of the vadose zone [m]	Sampling depth below the ground surface [m]	Well screen below the ground surface [m]	Material between the ground surface and sampling depth [%]				Gravel mixed with fines	Number of samples	Time period (dd-mm/yyyy)
				Gravel	Sand	Fine sand	Silt			
MW	3	12	10–15	35	65				12	3.4.2006–31.5.2007
Obs1	2.85	4	3–5	47	53				12	3.4.2006–31.5.2007
Obs2	10	11	10–12		30			70	12	3.4.2006–31.5.2007
Obs3	3.35	4.5	3.5–5.5			100			12	3.4.2006–31.5.2007
Obs4 (perched watertable)	6.5	7.5	6.5–8.5		100				10	30.6.2006–31.5.2007
Obs5 (perched watertable)	7	7–9	7–9		100				1	21.8.2006
Obs6	14	15	14–16		100				1	21.8.2006
Obs7 (perched watertable)	4.5	5.5	4.5–6.5			100			1	21.8.2006
Obs8	10	11	10–12		30	70			1	21.8.2006
Obs9	6	7	6–8			100			1	21.8.2006
Obs10	6	7	6–8		100				1	21.8.2006
Obs11	5.2	6.2	5–7			100			1	21.8.2006
Obs12	11.18	12	11–13		50	45	5		1	21.8.2006
Obs13 (perched watertable)	3.62	4	3.5–5.5		100				1	21.8.2006
Lake Pudasjärvi									12	3.4.2006–31.5.2007
River Kivarijoki									12	3.4.2006–31.5.2007
Snow									1	3.4.2006

3.2 Modelling, calibration, validation and sensitivity analysis

This section briefly summarises the model calibration and validation processes and the sensitivity analysis, which are described in detail in Papers II and III.

3.2.1 Statistical modelling (II)

In the Ruukki groundwater area, a regressive model was proposed to predict groundwater level variation. The model is based on a statistical empirical model proposed by Chen *et al.* (2002) (eq.1) but is more detailed, taking better account of physical characters such as daily, seasonal and yearly snowmelt water (P_{sn}), rainfall (P_r) and evapotranspiration (ET) (see Fig. 5). The model proposed by Chen *et al.* (2002) is of the form:

$$H(x, t, \Delta t) = C + \alpha 1 P_1(t - \Delta t) + \alpha 2 P_s(t - \Delta t) + \alpha 3 P_{sv}(t - \Delta t) + \beta T(t - \Delta t), \quad (1)$$

where C, α_i, β are coefficients to be determined, t (t = 1,…,N) is time, Δt (Δt = 1,…,N) is time delay, P_1, P_s, and P_{sv} are long-term precipitation, short-term precipitation and seasonal precipitation, respectively, and T is temperature. The time of maximum correlation ($t - \Delta t$) is found by cross-correlating precipitation or temperature and groundwater level using equations 5 and 6 below (Chen *et al.* 2002). The equation developed is:

$$H(z, t, \Delta t) = c + \alpha 1 P_{sn}(t - \Delta t) + \alpha 2 P_r(t - \Delta t) + \alpha 3 ET(t - \Delta t) + \varepsilon(t), \quad (2)$$

where c, α_1, α_2, α_3 are the coefficients to be evaluated, and ε is the residual. In addition, we used dynamic coefficients c, α_1, α_2 and α_3 that vary annually in a dynamic model simulation. In the recharge zone, the time lag between the groundwater level response to snowmelt water, rainfall and evapotranspiration depends on the vertical distance *z* between the ground surface and the groundwater level, and on hydrogeological conditions in the vadose zone (Zaradny 1993).

The inputs for the model (eq. 2) are snowmelt water, rainfall and evapotranspiration, which were estimated using the water balance model presented in Fig. 5. The inputs are daily precipitation and temperature, while the outputs are daily rainfall, snowmelt, evapotranspiration and snow water equivalent. The derivations of snowmelt water (P_{sn}), rainfall (P_r) and evapotranspiration (ET) are presented in Appendix A. The groundwater levels predicted with eq. (1) and eq. (2) are compared. Here, the statistical model was calibrated with data from the period 1975–1989 and validated with the data from the period 1990–2006. The quality of the model calibration was measured on a monthly time step using the Nash-Sutcliffe efficiency (R^2, eq. 3) and bias in mm (B, eq. 4).

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{N} \left(y_i - y_i^{'} \right)^2}{\sum_{i=1}^{N} \left(y_i - y_{mean} \right)^2} \right), \tag{3}$$

$$B = \sum_{i=1}^{N} \left(y_i^{'} - y_i \right), \tag{4}$$

where y_i is the observed groundwater level at time step i, $y_i^{'}$ is the predicted groundwater level at time step i, y_{mean} is the mean observed groundwater level, and N is the number of data points.

Cross-correlation analysis

The relative importance of climate and hydrological variables for groundwater level was estimated by cross-correlation analysis:

$$C_{xy}(k) = \frac{1}{n} \sum_{t=1}^{n-k} \left(x_t - \overline{x} \right) \left(y_{t+k} - \overline{y} \right), \tag{5}$$

$$r_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x \sigma_y}, \tag{6}$$

where $C_{xy}(k)$ is the cross-correlogram, $r_{xy}(k)$ is the cross-correlation coefficient with time lag k, and σ_x and σ_y are the standard deviations of the time series x and y. The significance level of correlations at 95% confidence level was set as greater than the standard error $\sim 2/(N)^{0.5}$ (Diggle 1990), where n is the number of data points. Daily rainfall, evapotranspiration, snowmelt, temperature and the groundwater level during the period 1975–2006 were cross-correlated to identify time lags and significant correlations. In a more detailed analysis, the daily time series for the period 1990–1999 was subdivided into periods of 1 to 12 months to identify seasonal differences in groundwater level variation.

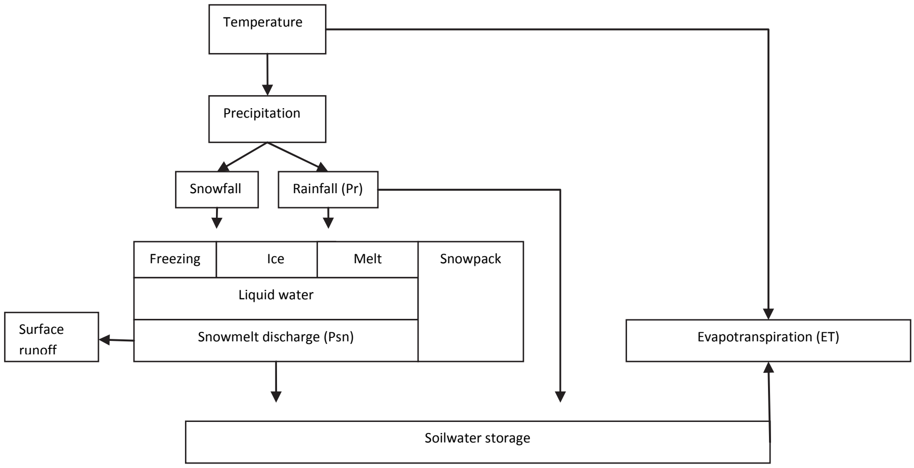

Fig. 5. Schematic conceptualisation of the near surface hydrology (Paper II). Reprinted with permission from Elsevier.

3.2.2 Distributed hydrological modelling (III)

The modelling approach used in the Pudasjärvi groundwater systems is schematically presented in Fig. 6. The intention was to link three models: The Watershed Simulation and Forecasting System (WSFS model; Vehviläinen 2007), a 1-D coupled heat and mass transfer model for soil-plant-atmosphere systems (CoupModel; Jansson & Karlberg 2004), and a groundwater flow model (MODFLOW; Harbaugh 1990) in order to assess seasonal variations in groundwater-surface water interactions. The water level in Lake Pudasjärvi, Lake Kivarinjärvi and the river Kivarinjoki and recharge rates were imported to MODFLOW as time variant boundary conditions in a sequential manner.

The inputs for the WSFS model are precipitation and temperature. In the present case, the precipitation and temperature data were estimated for the whole watershed using area-weighted averages. The precipitation was corrected for surface elevation and solid and liquid precipitation and gauge errors. The outputs from the WSFS model in this study were temperature, precipitation and water levels in lakes and rivers.

The inputs used for CoupModel were precipitation and temperature values simulated by the WSFS model. The outputs of CoupModel in this study were snowmelt, soil frost, evapotranspiration and groundwater recharge rate.

The WSFS model is a Finnish version of the Swedish HBV. It is a lumped conceptual model that accounts for precipitation, snow, soil, lake and river routing. The inputs for the WSFS model are precipitation and temperature. The outputs from the WSFS model in this study were temperature, precipitation and water levels in lakes and rivers. The disadvantage of the WSFS model is that it does not account for freezing of rivers and lakes and the effect of frozen soil, and may hence over- or under-predict the water levels in rivers, lakes and groundwater. The WSFS model does not explicitly take into account hydraulic conductivity and the thickness of the vadose zone, which are important for aquifer recharge (Scibek & Allen 2006a). Therefore in estimation of groundwater recharge a more sophisticated model is required, such as CoupModel (Jansson & Karlberg 2004).

The physically-based hydrological model CoupModel was used to estimate temporal and spatial changes in groundwater recharge (Fig. 6). Current and projected climate conditions were estimated. The advantage of CoupModel over previously used recharge methods (Scibek & Allen 2006a, Jyrkama & Sykes 2007) is that it accounts for water flow through partially frozen soil, which can be important in accounting for the timing of groundwater recharge. Recent studies in Finland suggest that water can infiltrate through a frozen soil and increase aquifer recharge (Sutinen *et al.* 2007). The groundwater recharge was estimated for eight different zones and zones RCH1 and RCH2 were used to investigate the impacts of soil frost on recharge.

Changes in aquifer storage and flow direction were studied using MODFLOW. Simulated groundwater levels were compared against the Pudasjärvi water level to investigate head difference at each time step and hence surface water-groundwater interaction. Monthly and daily time steps were used in the simulations. The sequential approach was chosen for the following reasons: Groundwater discharge from the Pudasjärvi aquifer was expected to be insignificant in terms of total inflow to Lakes Pudasjärvi and Kivarijärvi and the river Kivarijoki. The groundwater discharge rate from the Pudasjärvi aquifer was assumed to be an insignificant factor in the surface water balances. To justify this, modelled runoff to lakes and rivers was thus compared with modelled groundwater discharge rate from the Pudasjärvi aquifer. However, temporal changes in the water levels in Lake Pudasjärvi, the river Kivarijoki and Lake

Kivarijärvi may affect groundwater discharge rates from the Pudasjärvi aquifer and hence the temporal variations in surface water levels are needed at boundaries in the aquifer.

The groundwater flow model was calibrated using 17 observation wells (Fig. 7). Both steady state and transient calibrations were performed. The groundwater model was also validated using the observations from Obs14. The calibrated groundwater flow model was run with simulated surface water levels and with observed surface water levels. This was done to investigate the sensitivity of the groundwater model to variations in boundary conditions along surface waters. The correlations between observed and simulated groundwater levels (R^2), standard deviation, groundwater discharge and focused recharge rates were compared in the situation when MODFLOW was run with the observed surface water level. A model bias, mean absolute error (MAE) and root mean square error (RMSE) were also estimated as follows (McCuen 2003):

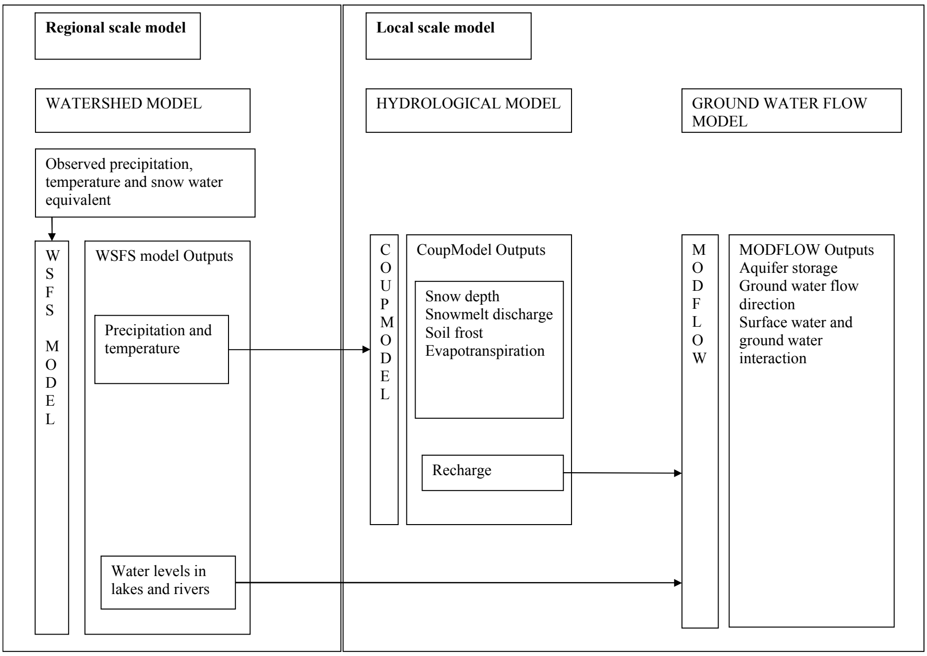

Fig. 6. Methodology used for estimating aquifer storage, flow patterns and surface water-groundwater interactions for cold regions where surface water bodies are intimately connected to groundwater in relatively large watersheds.

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(y_i - f_i), \tag{7}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_i - f_i\right|, \tag{8}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - f_i)^2}, \tag{9}$$

where y is the predicted value and f is the observed value.

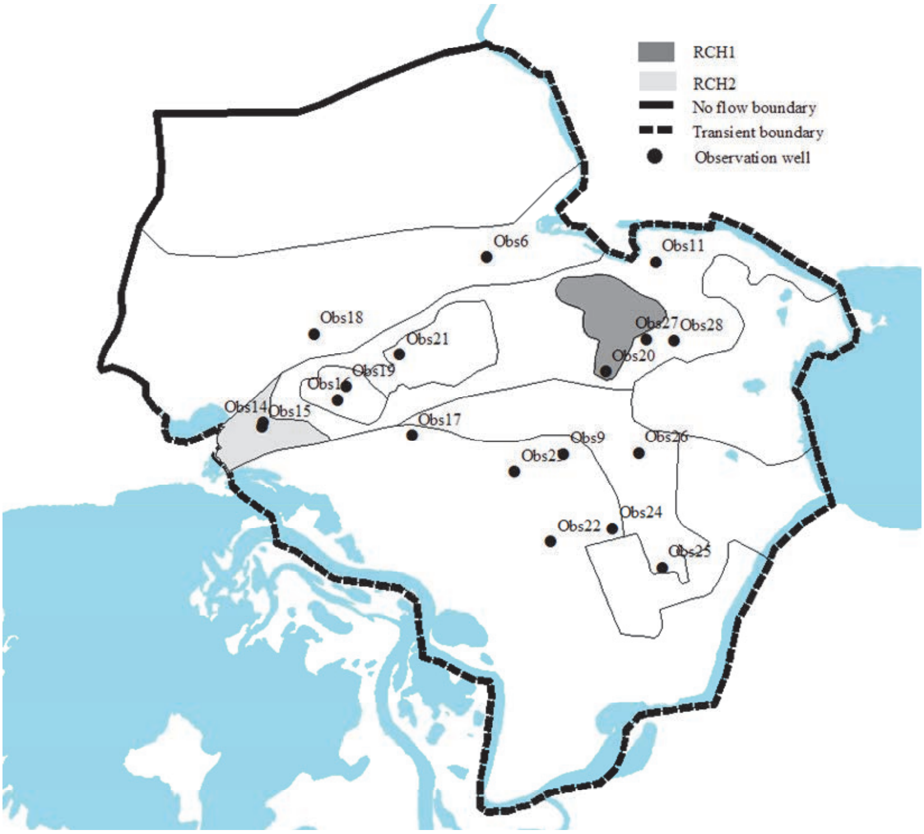

Fig. 7. Recharge zones and observation wells.

3.2.3 Conceptual framework (I)

A conceptual framework for assessing the potential impacts of climate change (temperature and precipitation) in cold, snow-dominated regions was developed. The framework shows how changes in temperature and precipitation affect the different components of the near-surface hydrological regime (e.g. snow cover, soil frost, evapotranspiration, runoff), surface water bodies and finally groundwater quantity and quality. Model development was based on a three-step procedure: 1) Review of state of the art and baseline; 2) development of a conceptual framework for the specific case and the particular hydrogeological situation; and 3) prediction of future changes for local conditions. This stepwise procedure is in agreement with CIS guidelines (CIS 2003).

Equations (10)–(15) were used to estimate changes in recharge, runoff, surface water level, groundwater level and groundwater quality, and the results are presented in the conceptual framework in Fig. 8. The term 'focused recharge' refers to surface water intrusion into an aquifer and ET refers to evapotranspiration. The arrows added in Fig. 8 show the predicted impacts of climate change on hydrology and groundwater resources in northern Finland.

$$\text{Recharge} = \text{Rain} + \text{Snow} + \text{Soil frost} - \text{ET} \quad (10)$$

$$\text{Runoff} = \text{Rain} - \text{ET} + \text{Snow} - \text{Soil frost} \quad (11)$$

$$\text{Surface water level} = \text{Runoff} + \text{Groundwater level} \quad (12)$$

$$\text{Groundwater level} = \text{Surface water level} + \text{Recharge} + \text{Focused recharge} \quad (13)$$

$$\text{Focused recharge} = \text{Groundwater level} - \text{Surface water level} \quad (14)$$

$$\text{Groundwater quality} = \text{Recharge} - \text{Focused recharge.} \quad (15)$$

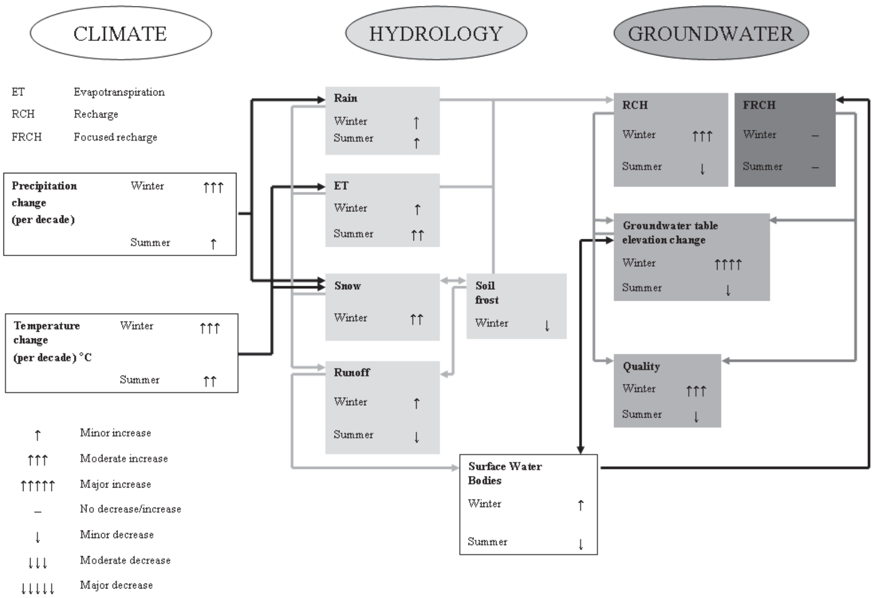

Fig. 8. Conceptual framework for assessing the impacts of climate change on hydrology and groundwater in cold regions in northern Finland where surface water bodies are present. (Paper I). Reprinted with permission from Springer.

3.2.4 Other methods

Biplots, correlations between variables and one-way analysis of variance (ANOVA) (Helsel & Hirsch 2002) followed by Tukey's multiple-comparison post-hoc test (Tukey Honestly Significant Difference, HSD) were used to examine the groundwater samples. Matlab 7.4.0 was used to perform these analyses.

4 Simulated scenarios

The development of the conceptual framework and the WSFS model and CoupModel simulations were carried out without uncertainty analysis. Thus the results only provide a general overview of potential changes in groundwater response to projected scenarios in this study. Climate scenarios are an additional source of uncertainty, as has been found in previous studies (e.g. Minville *et al.* 2008; Steele-Dunne *et al.* 2008). In the present study, the delta approach was used to project changes in temperature and precipitation. The delta approach ignores possible changes in precipitation variability and intensification of extreme events and this limitation may not give adequate results in terms of surface water level variations, which are highly dependent on short-term precipitation events (Veijalainen *et al.* 2010). However, the surface water level rises in Finland are mainly due to snowmelt and not short-term precipitation events, and therefore the delta approach can give acceptable results (Veijalainen *et al.* 2010).

4.1 Projections for temperature and precipitation

The temperature and precipitation were modified to correspond to projected changes in temperature and precipitation in Finland under IPCC emissions scenarios A2 (I, II) and A1B (III). The delta method was used to modify observed temperature and precipitation records.

A2 emissions scenario (I, II)

The A2 emissions scenario was chosen because it produces high emissions (Nakićenović *et al.* 2000). The projections for precipitation and temperature were derived from six different atmospheric-ocean general circulation models. Details of the projected changes in precipitation and temperature along with the methodology can be found in Jylhä *et al.* (2004). Table 2 shows the projected changes in temperature and precipitation for Finland in the coming 30-year period.

Table 2. Projected changes in temperature (T) and precipitation (P) in Finland during the period 2010–2039 under the A2 climate change scenario.

	2010–2039	
	T[°C]	P [%]
Dec–Feb	2.2	9
Mar–May	2.1	6
Jun–Aug	1.2	4
Sep–Nov	1.8	6

A1B emissions scenario (III)

The emissions scenario A1B assumes very rapid economic growth; a global population that reaches 9 billion in 2050 and then gradually declines; the rapid spread of new and efficient technologies; a converging world income and way of life between regions and extensive social and cultural interactions world-wide; and a balanced emphasis on all energy sources (IPCC 2007). The A1B emissions output data used were based on the average of 19 general circulation models obtained from the Finnish Meteorological Institute (Ruosteenoja *et al.* 2005). Table 3 presents the projected changes in temperature and precipitation in Finland under this scenario up to the end of the century.

Table 3. Changes in temperature (T) and precipitation (P) in Finland during the period 2010–2099 under the A1B climate change scenario.

	2010–39		2040–69		2070–99	
	T [°C]	P [%]	T [°C]	P [%]	T [°C]	P [%]
Jan	2.4	4	4.9	15	6.8	28
Feb	2.2	10	4.5	18	6.4	29
Mar	1.8	7	3.8	15	5.2	20
Apr	1.4	7	2.8	9	3.9	17
May	1.3	5	2.5	8	3.7	11
Jun	1.2	4	2.4	12	3.3	15
Jul	1.1	3	2.3	8	3.0	10
Aug	1.1	5	2.1	11	2.9	10
Sep	1.1	4	2.2	10	3.2	12
Oct	1.3	3	2.6	11	3.6	14
Nov	2.2	8	4.2	18	5.7	27
Dec	2.2	8	4.7	18	6.7	28

4.2 Statistical modelling (II)

In the Ruukki groundwater area, the water balance model (Appendix A) was used to estimate rainfall, snowmelt water and evapotranspiration, which were cross-correlated with groundwater level to identify time lags and significant correlations during the period 1975–2006. The climate data for the period 1975–2006 were then modified to get projections under the A2 emissions scenario.

4.3 Hydrological distributed modelling (III)

Four steps were used in the Pudasjärvi groundwater simulations. A constant pumping rate of 750 m^3/d was used under in steps 2, 3 and 4 below. Daily time steps were used in the 1, 4 simulations and monthly time steps in the 2, 3 simulations.

1. The groundwater recharge for zones RCH1 and RCH2 was first examined with the options ‘influence of soil frost’ and ‘no influence of soil frost’. The modelled recharge rates were then compared with observed groundwater level in Obs14 and Obs20. The impacts of climate change on recharge, snowmelt, depth of soil frost and evapotranspiration under emissions scenario A1B were also estimated. The influence of soil frost on recharge was used in projections.
2. The simulated groundwater discharge was compared with simulated surface runoff estimated using the WSFS model.
3. The simulated groundwater and surface water levels were compared during the periods 2010–2039, 2040–2069 and 2070–2099.
4. Hot/dry (year 1988) and cold/wet (year 1981) scenarios were examined during the periods 2010–2039, 2040–2069 and 2070–2099.

4.4 Conceptual framework (I)

The projected changes in temperature and precipitation were based on the A2 emissions scenario. On the basis of the conceptual framework and using equations (10)–(15), the overall impact of climate change on hydrology and groundwater was projected simply from the changes in temperature and precipitation.

4.5 Calibration and validation

4.5.1 Statistical model (II)

Cross-correlation analysis

The significance level of the daily cross-correlation analysis was 0.03. The maximum correlation coefficient between rainfall and groundwater level was 0.57 and the time lag 15–25 days. The maximum correlation coefficient between evapotranspiration and groundwater level was 0.38, and the time lag was 20–40 days. The maximum correlation coefficient between temperature and groundwater level was 0.36, and the time lag was 20–40 days. The maximum correlation coefficient between snowmelt and groundwater level was 0.45, with a time lag of 50–60 days.

The timing and amplitude of groundwater level variation in spring were mainly coupled to snowmelt water, but heavy rainfall just after snowmelt shifted the maximum groundwater level toward summer. As expected, the timing of the summer groundwater minimum mainly depended on the amount and distribution of rainfall and less on the evapotranspiration rate. In autumn, snowmelt events shifted the timing of the autumn maximum toward winter and slightly increased the magnitude of that maximum.

In the calibration period 1975–1990, the correlation coefficient (R^2) between predicted and observed groundwater level increased from $R^2 = 0.24$ to $R^2 = 0.76$ using eq. (1) and (2), respectively. The correlation between predicted and observed groundwater levels was highest using the dynamic model ($R^2 = 0.98$). During the validation period 1990–2006, the correlation between predicted and observed groundwater levels was 0.10, 0.59 and 0.98 with eqs. (1), (2) and the dynamic model, respectively. The bias increased from the calibration to validation period. Intensive peatland drainage in the discharge zone could have affected the validation results. The dynamic model showed good agreement in both the calibration and validation period. The model bias may also be related to empirical parameters in the model, which may vary from one hydrological year to the next (Li *et al.* 2008). However, it was found to be important to include the snowmelt component in multiple linear regression models in snow-dominated regions in prediction of seasonal groundwater level fluctuation.

4.5.2 Hydrological distributed model (III)

In the steady state simulations, the simulated and observed groundwater levels were within the range −0.65 to 0.4 m. The bias was 0.07, MAE was 0.18 and RMSE was 0.24. When the surface water level was changed from observed to simulated, the range of simulated and observed groundwater levels, bias, MAE and RMSE remained unchanged.

The transient simulation showed larger errors between observed and simulated groundwater level than the steady state simulation (Fig. 9). When surface water level was changed from observed to simulated, the groundwater level in Obs14 was over-predicted (see black line in Fig. 9). This indicates that near Lake Pudasjärvi, the groundwater level reflects variations in water level in the lake.

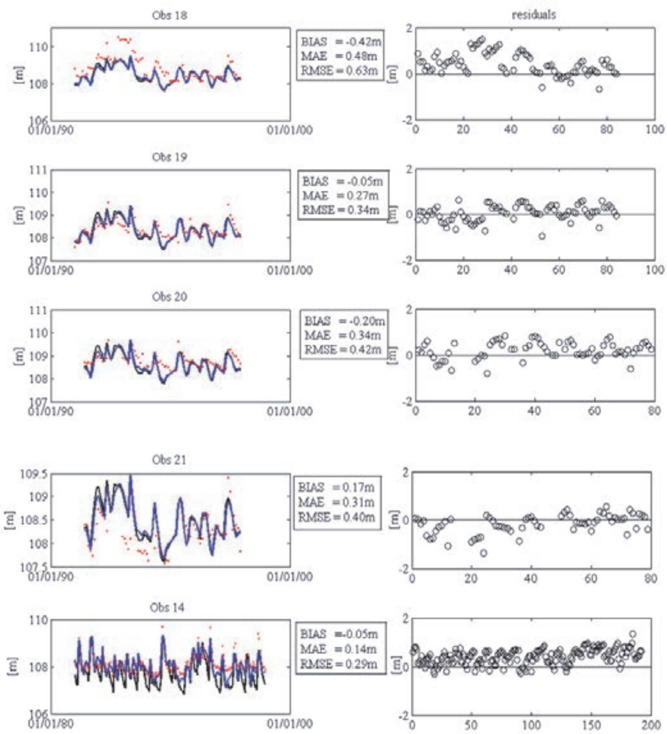

Fig. 9. Monthly simulated groundwater levels and residuals, when simulated (black line) and observed (blue line) surface water levels were used as boundary conditions, and observed groundwater level in Obs 18, 19, 20, 21 and 14 (red dots). Obs 18, 19, 20

and 21 were used in transient calibration and Obs 14 was used to validate the groundwater flow model. Residuals are only presented when simulated surface water level variation was used as the boundary condition (Paper III). Reprinted with permission from Elsevier.

The over- and under-prediction in simulated groundwater levels can be explained by factors such as recharge estimation and conceptual errors at the modelled site (van Roosmalen *et al.* 2007; Hill & Tiedeman 2007). Since the recharge is difficult to measure directly, numerical methods are greatly used in estimation of recharge. The Pudasjärvi groundwater flow model did not perfectly capture the variation in groundwater level (Fig. 9). In Obs18, the recharge was probably under-predicted during the period 1991–1993, causing too low simulated groundwater level. The over-prediction of recharge in summer 1994 and 1995 most likely caused the under-prediction in groundwater level in Obs 21.

There are many factors that affect and increase the uncertainty in estimation of recharge, e.g. land cover, soil type and the depth of the vadose zone (Jyrkama & Sykes 2007; Scibek *et al.* 2007). In cold, snow-dominated regions with seasonal soil frost, snowfall-rainfall distribution, soil frost and the impact of soil frost on hydraulic conductivity increase the uncertainty of estimated recharge (Stähli *et al.* 1999). The lack of reliable methods in estimation of recharge increases the uncertainty and model errors in simulations of groundwater level. Over-prediction and under-prediction can be explained by many factors that affect recharge, such as local soil conditions and plant dynamics. Errors can be related to empirical parameters in the models, which may vary from one hydrological year to the next (Li *et al.* 2008). For example, surface runoff (Q_{in}) estimated using the WSFS model was much higher than groundwater discharge estimated using MODFLOW (Fig. 10). The one-way coupling between the surface water and groundwater simulation can therefore be justified.

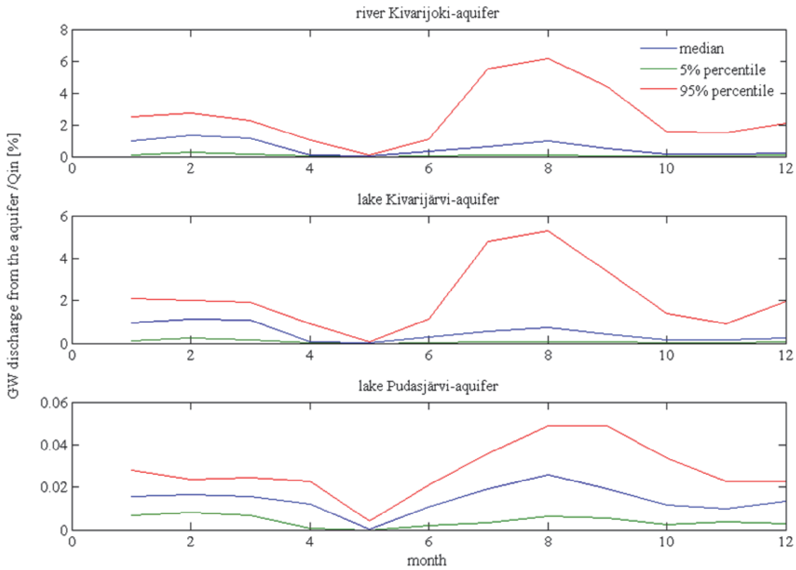

Fig. 10. Modelled monthly median with 5% and 95% percentiles of relationship (as a percentage) between groundwater discharge, estimated using MODFLOW, and surface water runoff (Q_{in}) to lakes and river, estimated using the WSFS model during the period 1971–2000.

5 Results and discussion

Different methods were used in different study areas to examine the impact of soil frost on groundwater recharge, solute concentration in groundwater and surface water, the impact of climate variability and change on groundwater recharge, surface water groundwater interaction and solute concentration. Section 5 summarises the main results obtained and presents overall findings. Full detailed findings from the individual studies can be found in Papers I–IV.

5.1 Impact of soil frost on groundwater recharge (III)

The simulated spring and summer recharge was higher than autumn and winter recharge (Fig. 11). Overland flow only occurred with the option 'influence of soil frost' and was simulated during the spring melt period. This was due to soil frost preventing infiltration. The onset of recharge was simulated in April in zones RCH1 and RCH2. In RCH1 the mean monthly sum of recharge in May and June was higher with the option 'no influence of soil frost' than with the option 'infiltration with the influence of soil frost'. In April it was the same for both options. The recharge decreased from June to December. Similar results were obtained from zone RCH 2. These findings are in agreement with recent studies in Finland suggesting that snowmelt infiltration in sandy soils increases the soil moisture content below the partially frozen soil and increases aquifer recharge (Sutinen *et al.* 2007). The infiltration of snowmelt water into partially frozen soil has also been observed in a sub-alpine tree environment in Canada (Leenders & Woo 2002) and in sandy soils in central Sweden (Stähli *et al.* 1999). The groundwater level in Obs 14 was higher than the surface water level in every month except May. The decrease in groundwater level in summer was due to discharge through the drainage system (surface water bodies).

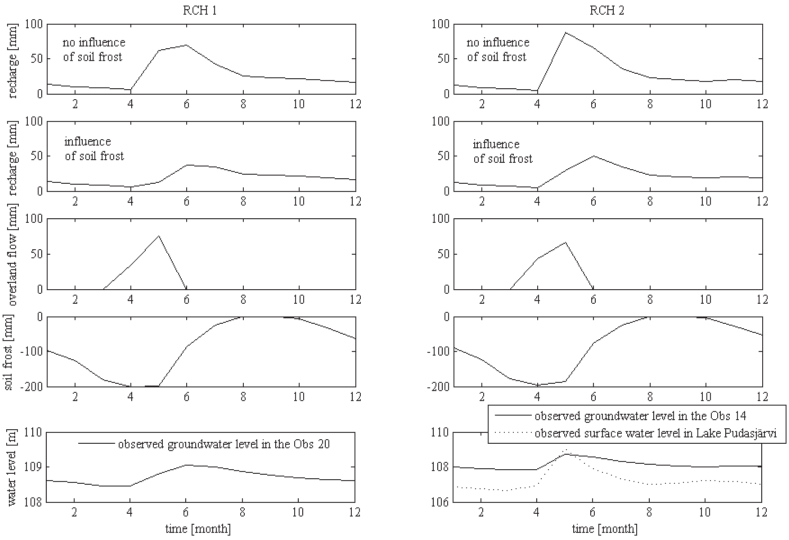

Fig. 11. Simulated mean monthly groundwater recharge in the Pudasjärvi aquifer with two different infiltration options in recharge zones (a) RCH1 and (b) RCH2, observed mean monthly groundwater levels in wells (a) Obs20 and (b) Obs14, and observed mean monthly surface water level in Lake Pudasjärvi (b). Overland flow only occurred with the option 'influence of soil frost' (Paper III). Reprinted with permission from Elsevier.

5.2 Temporal and spatial variability in groundwater chemistry in the Pudasjärvi aquifer (IV)

The mean concentrations of solutes in groundwater differed slightly from those previously found for Finnish esker aquifers (Table 4). The solute concentrations are close to those found by Soveri *et al.* (2001) but lower than those reported by Backman *et al.* (1999). The nitrate concentration was lower than the EU quality standard of <50 mg/l (EC 2006). The Cl^- concentration in the Pudasjärvi groundwater is typical for inland aquifers located in areas experiencing the impact of relict sea water deposits (Korkka-Niemi 2001). The low Ca^{2+} concentration was probably due to few calcium compounds being present in the geological deposits. There was also a high correlation between Ca^{2+} and Cl^- ($r = 0.64$), which can be due to atmospheric deposition (Korkka-Niemi 2001).

Table 4. Mean concentrations of NO_3-N, Ca^{2+}, Cl^- and SiO_2 in groundwater in Pudasjärvi compared with values reported by Soveri *et al.* (2001) and Backman *et al.* (1999) and concentrations in snow and precipitation.

	Pudasjärvi	Soveri *et al.* 2001	Backman *et al.* 1999	Snow (Pudasjärvi)	Precipitation (Oulanka)
NO_3-N [mg/l]	0.28	0.093	4.1	0.24	0.18
Ca^{2+} [mg/l]	2.73	4.54	10.6	0.20	0.05
Cl^- [mg/l]	3.15	2.46	9.13	0.90	0.18
SiO_2 [mg/l]	10.27	10.6	13	<0.1	Not analysed

Temporal variations in solute concentrations in surface water and groundwater (Fig. 12) and variations in group means of solute concentrations across the study site were observed (Fig. 15). At Obs1, solute concentrations varied slightly with time, which can be due to coarse material permitting high hydraulic conductivity. At Obs2, solute concentrations showed moderate variations with time, which can be due to the greater depth of the vadose zone, 10 m at this point (Mälkki 1999; Soveri *et al.* 2001). At Obs2 and Obs3, low NO_3-N concentrations were observed during high groundwater periods and high NO_3-N concentrations were observed during low groundwater periods. The decrease in NO_3-N concentration with elevated groundwater is probably due to oxygen-rich water infiltrating into soil as a consequence of precipitation and snowmelt (Korkka-Niemi 2001). Decreases in solute concentrations in spring 2007 were due to prior precipitation and snowmelt, as indicated by a decrease in SWE (Fig. 14) in December 2006 and early January 2007 infiltrating to the groundwater and lowering the concentrations.

The variations in solute concentrations were similar in the perched groundwater (Obs4) to those in the actual groundwater, with the exception of NO_3-N concentration. At Obs4, the NO_3-N concentration increased with elevated groundwater level. This is most likely due to an NO_3-N source at the airport increasing the NO_3-N concentration in the vadose zone, as also noted by PSV-Maa ja Vesi (2003). As a consequence of infiltration, any pollution source on the land surface or in the vadose zone may impair groundwater quality (Gooddy *et al.* 2001; Johnson *et al.* 2001; Korkka-Niemi 2001; Bloomfield *et al.* 2006; Sugita & Nakane 2007). Stable isotopes of N and O could be used to identify the sources of nitrate and assess the likelihood of denitrification naturally lowering the nitrate concentration (Appelo & Postma 2005).

The mean SiO_2 concentration varied the least and NO_3-N concentration the most. The water quality at MW differed from the other observation locations, most notably for Cl^- concentration. This can be due to de-icing salt from the road crossing the aquifer. The Cl^- concentration decreased when the groundwater level rose above 108.5 m and the water level in the Lake Pudasjärvi rose higher than the groundwater level (Fig. 13), indicating surface water intrusion into the aquifer. The surface water-groundwater interaction could be studied in more detail by e.g. analysing isotopes of O and H, as suggested by Rautio and Korkka-Niemi (2011). The higher Ca^{2+} concentration indicates stronger weathering of the mineral soil at MW and the low temporal variations can be explained by the coarse gravel material and the greater sampling depth below the groundwater than in the other observation wells.

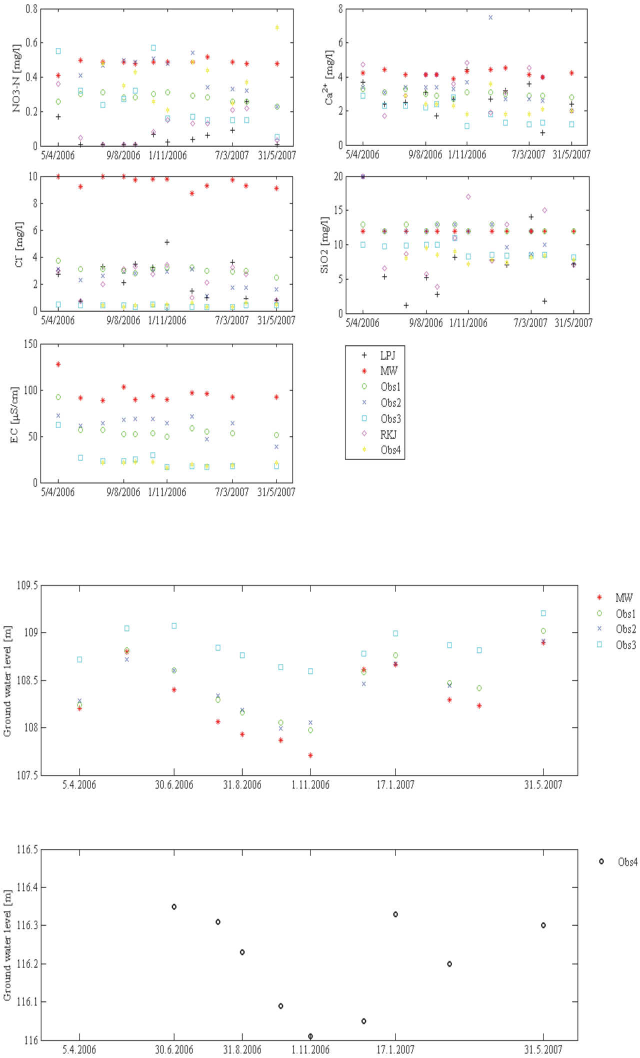

Fig. 12. NO_3-N, Ca^{2+}, Cl^- and SiO_2 concentration and EC of the groundwater, Lake Pudasjärvi (LPJ) and the river Kivarijoki (RKJ) and groundwater levels during the period 3.4.2006–31.5.2007 (Paper IV). Reprinted with permission from Elsevier.

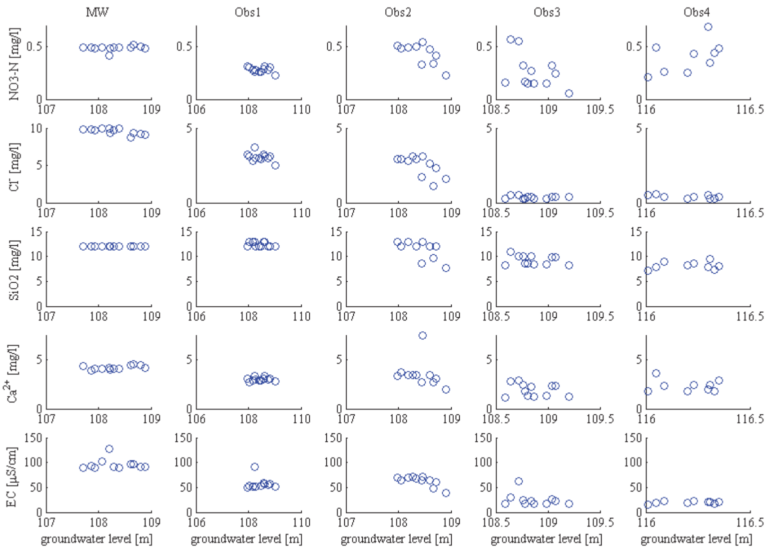

Fig. 13. Scatter plots between groundwater level and NO_3-N, Cl^-, SiO_2 and Ca^{2+} concentration, and between groundwater level and EC in wells MW, Obs1, Obs2, Obs3 and Obs4 (Paper IV). Reprinted with permission from Elsevier.

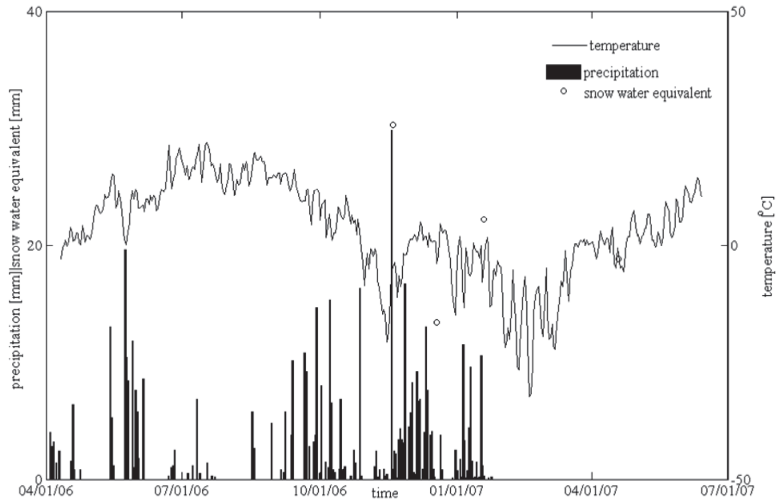

Fig. 14. Daily precipitation, temperature (FMI 2010) and snow water equivalent measured at the Pudasjärvi aquifer (OIVA 2009) (Paper IV). Reprinted with permission from Elsevier.

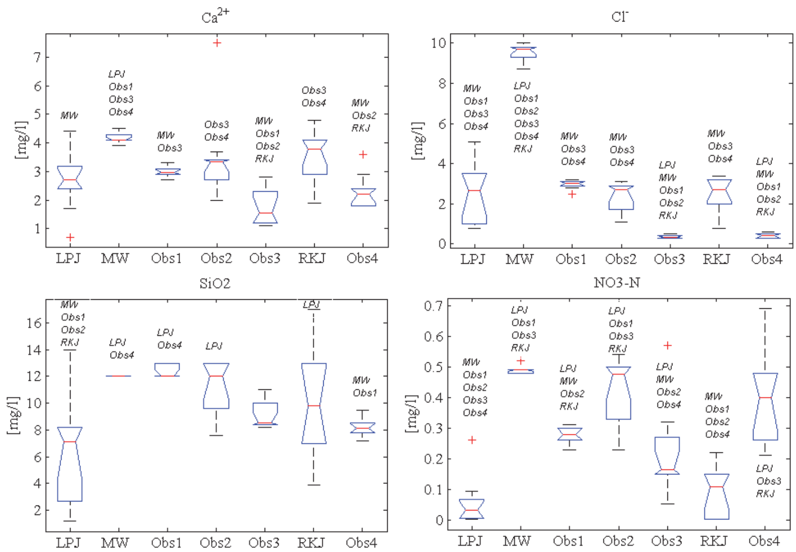

Fig. 15. Box plots of Ca^{2+}, Cl^{-}, SiO_2 and NO_3-N concentrations. Cursive text indicates the statistical difference between observation points (Paper IV). Reprinted with permission from Elsevier.

5.3 Impact of climate change on groundwater recharge (I, II, III)

In the conceptualisation of the impact of temperature, precipitation, evapotranspiration and soil frost on groundwater level presented in Fig. 8, precipitation occurs in the form of snow or rain depending on the temperature. Both rain and snowmelt water influence the groundwater system by increasing recharge and evapotranspiration influences the groundwater system by decreasing recharge. A decrease in soil frost and an increase in snowmelt and rainfall would potentially increase the winter recharge and groundwater levels in northern Finland. According to the A2 and A1B emissions scenarios, winter and summer precipitation will increase compared with the current climate (IPCC 2007). Figure 16 shows the simulated impact of climate change on groundwater recharge. Only the A1B climate change scenario was considered.

Temperature is projected to increase more in winter than in summer. Increased temperature is projected to enhance evapotranspiration in summer and could lead to an increase in soil moisture deficit compared with the current climate, while the length of dry periods could increase due to a shift in onset and later end of summer. An increase in the length of dry periods and the soil moisture deficit could lead to lower minimum groundwater levels in summer. The duration of the low groundwater period may increase along with a shift in onset of summer and a shift in the minimum groundwater level toward autumn due to increased soil moisture deficit (Mäkinen *et al.* 2008). Higher temperatures will potentially increase direct evaporation from surface water bodies and the ground surface, enhance transpiration through the vegetation canopy and so decrease groundwater recharge and water levels.

It is expected that along with a warmer climate, winter rainfall will increase and snow accumulation decrease. Changes in snowmelt are likely to have significant impacts on groundwater recharge, and snowmelt water may also have a disproportionately large influence on recharge compared with rain (Earman *et al.* 2006). For northern Finland it is projected that during the next three decades, the increase in winter precipitation will fall as snow, enhancing snow depth, but thereafter the amount of rainfall will increase and snow depth will decrease until the end of the 21st century. The period of snow cover is also projected to contract until the end of the century. Higher temperatures in autumn will delay the beginning of snow accumulation, while higher temperatures in spring will advance the onset of snowmelt (Jylhä *et al.* 2008).Reduced snow depth owing to higher winter temperature may reduce soil frost. The snow depth in northern Finland is projected to decrease and soil frost would then decrease (Venäläinen *et al.* 2001). Despite the decrease in protective snow cover, the depth of soil frost would decrease rather than increase because of the higher winter temperatures. Frost days are projected to be fewer and the frost season will contract as a result of the rise in daily winter minimum air temperature (Jylhä *et al.* 2008). A decrease in the depth of soil frost and an increase in winter rainfall and snowmelt will potentially enhance groundwater recharge.

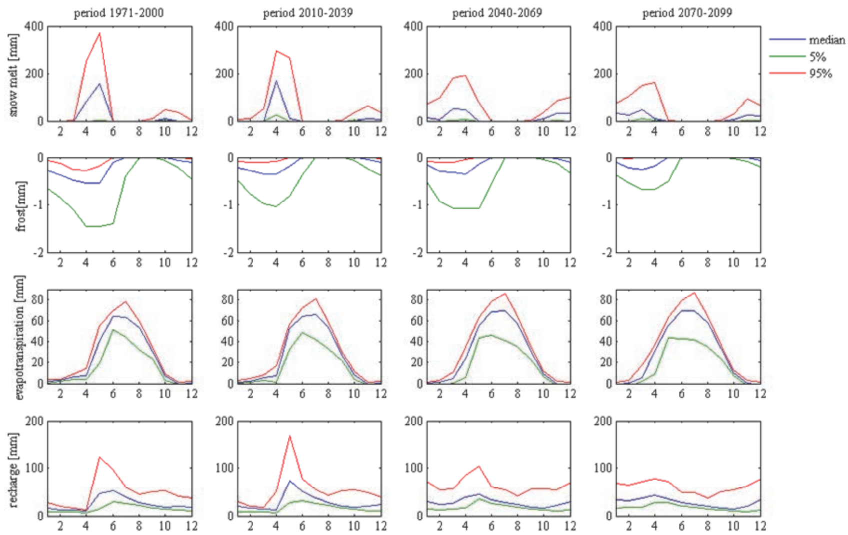

Fig. 16. Modelled monthly median with 5% and 95% percentiles of snowmelt discharge, depth of soil frost, evapotranspiration and groundwater recharge during the periods 1971–2000, 2010–2039, 2040–2069 and 2070–2099 (Paper III). Reprinted with permission from Elsevier.

5.4 Impact of climate change on groundwater-surface water exchange (I, III)

The linkages between precipitation, evapotranspiration (ET), runoff, snow cover, soil frost, surface water level, focused recharge and groundwater level are illustrated in Fig. 8. In areas where the groundwater is connected to the surface water, the groundwater level and groundwater discharge are affected by the position of the surface water level. In northern Finland, it is projected that the seasonal distribution of runoff will change (Veijalainen *et al.* 2008). Then at the end of the 21st century, winter runoff and flooding are projected to increase due to an increase in snowmelt and rain, and spring flooding is projected to decrease. At the Pudasjärvi study site during the next three decades, the surface water level may rise higher than the groundwater level in the pumping cell in all months except January, August and September (Fig. 17). During the period 2040–2069, surface water may rise higher than the groundwater level in almost every month. Flow reversals are also possible in autumn and spring. During the period 2070–2099, the occurrence of surface water intrusion will be highest in autumn and winter and lowest in spring and summer. In the hot/dry scenario for the period 2010–2039, a groundwater minimum will only be observed in the summer and will be lower than the present minimum (Fig. 18). The groundwater maximum is projected to occur earlier in the year, but remain fairly constant. The focused recharge is projected to increase in February and peak in April and May and from August to November. The groundwater is projected to discharge to the surface water from May to June. During the period 2040–2069, surface water infiltration may increase from January to March and from August to December and the groundwater is projected to discharge to surface water from April to June. During the period 2070–2099, groundwater levels may be higher than surface water levels from January to July and surface water infiltration is projected to increase from August to December (Fig. 18). The cold/wet scenario studies indicate that the most dominant snowmelt event in late spring is projected to disappear and snow is projected to melt in winter months too. The groundwater minimum values are projected to increase and the seasonality to decrease (Fig. 18). The projections indicate that during the next three decades, surface water infiltration may increase in April–May and November–December and decrease in other months. During the periods 2040–2069 and 2070–2099, surface water levels will vary widely and flow reversals may occur more frequently.

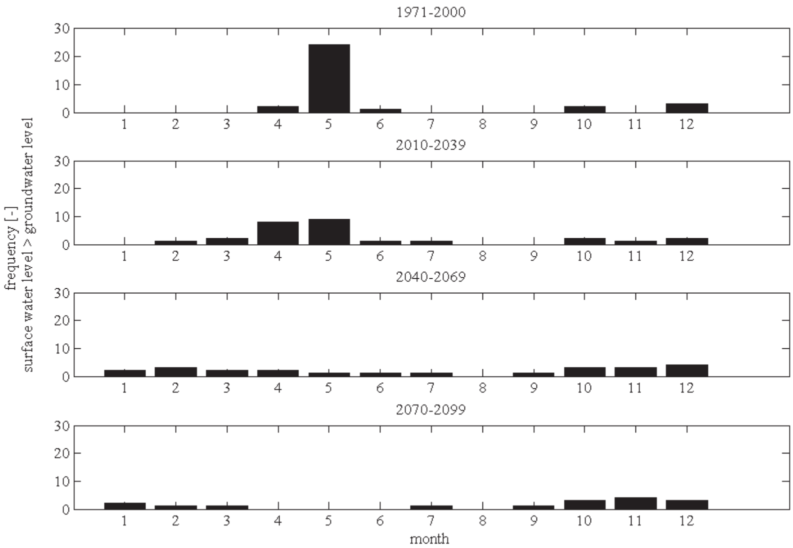

Fig. 17. Frequency with which simulated surface water level in Lake Pudasjärvi is higher than simulated groundwater level in the cell of the pumping well (MW see Fig. 3).

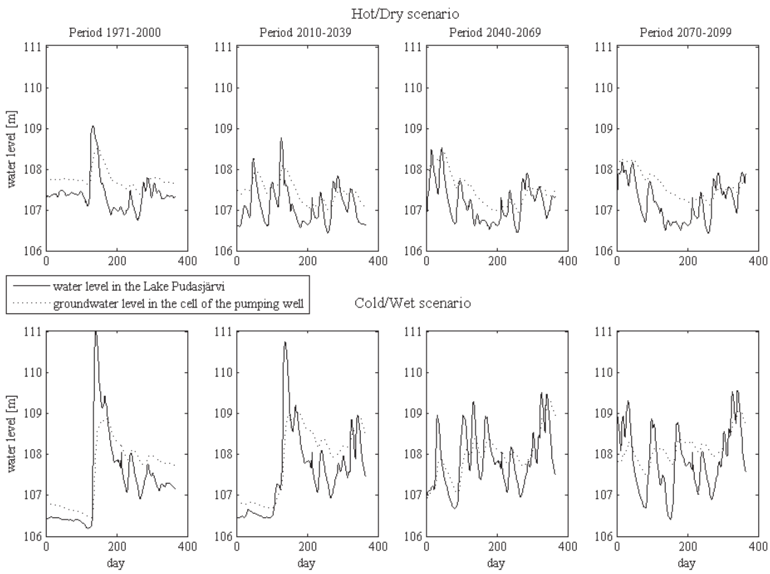

Fig. 18. Modelled groundwater level in the cell of the pumping well and surface water level in Lake Pudasjärvi in a hot/dry scenario (year 1988) and cold/wet scenario (year

1981). The year 1988, with annual accumulated precipitation of 499 mm and mean annual temperature of 1.5 °C, is the representative year for hot/dry conditions in the current period; levels for other periods were modelled by adding the predicted precipitation and temperatures under climate change to the 1988 values. The year 1981, with annual accumulated precipitation of 771 mm and mean annual temperature of 0.6 °C, is the representative year for cold/wet conditions in the current period; levels for other periods were modelled by adding the predicted precipitation and temperatures under climate change to the 1981 values (Paper III). Reprinted with permission from Elsevier.

5.5 Groundwater quality and climate (I, IV)

The projected impacts of precipitation and temperature on groundwater quality are shown in Fig. 8. Changes in the amount and distribution of groundwater recharge and focused recharge may affect groundwater quality. Seasonal changes in groundwater quality are typical in northern regions. Concentration maxima usually occur in summer and late autumn due to an increase in evapotranspiration rates. The concentration minimum usually occurs after spring snowmelt as a result of the infiltrating oxygen-rich water (Soveri *et al.* 2001). Climate variability and future climate change may also affect groundwater quality in the vadose zone (Gurdak *et al.* 2007). Recent studies of chalk aquifers in the UK (Gooddy *et al.* 2001; Johnson *et al.* 2001; Bloomfield *et al.* 2006) and laboratory experiments (Sugita & Nakane 2007) showed that increased recharge can increase solute leaching, capture pesticides and other pollutants in the unsaturated zone and reduce groundwater quality. For example, in the Pudasjärvi aquifer the NO_3-N concentration increased in the perched groundwater with rising groundwater level. Unconfined esker aquifers may be at risk of contamination by bacteria due to winter and spring floods (Silander *et al.* 2006). In the Pudasjärvi aquifer, the solute concentration in summer decreased when groundwater level declined. An increase in concentration is possible during dry periods due to a decrease in dissolved oxygen in groundwater (Silander *et al.* 2006). The amount and the seasonal changes in recharge are site-specific and affect the groundwater chemistry in different ways. In agricultural areas, the seasonal changes in the recharge due to a warmer climate might accentuate the seasonal variation in pesticide concentration in groundwater, and an increase in storm events might increase the maximum concentration of pesticides (Bloomfield *et al.* 2006).

Recharge, the interaction between groundwater and surface water under a temperate climate, is not well understood for northern Finland, especially for winter conditions. It is projected that the increase in winter snowmelt and rainfall events may change the solute concentration in groundwater. In the Pudasjärvi aquifer, the solute concentration changed with temperature and precipitation changes: during the mild climate events (temperatures > 0 °C) in 2006 and 2007, low temperature initiated snowmelt, which decreased solute concentrations in groundwater. Thus snowmelt during mid-winter may not only increase aquifer recharge in snow-dominated regions, as previously reported by Sutinen *et al.* (2007), but may also affect solute concentrations in groundwater. If anticipated global warming changes the amount of recharge water during winter periods, it also poses a risk of changing groundwater quality. The impacts may not be negative if oxygen-rich water replenishes the aquifer, improving the groundwater quality. However, the impact of climate change on groundwater chemistry is still difficult to quantify and needs to be much better studied.

6 Conclusions

The impact of climate variability on groundwater quantity can be determined by a simple conceptual approach or by more rigorous statistical and numerical models. This study showed that a well-developed conceptual approach can be used as an alternative to statistical and numerical models. It also identified the factors that need to be considered in integrated modelling linking climate to groundwater. In addition, the study showed that the conceptual approach can be used for interpreting the propagation of changes from one system to other. This is an important practical matter for converting the results of e.g. more complex statistical and numerical models into an easily comprehensible framework.

The statistical approach developed in this study links rainfall, snowmelt and evapotranspiration to groundwater fluctuation. This new approach produced better predictions of groundwater level variations than previous statistical approaches using temperature and precipitation alone. The analyses demonstrated the importance of accounting for snow accumulation and snowmelt, which are important factors for groundwater level fluctuations in unconfined aquifers found in cold, snow-dominated regions. A particularly important finding was that intra-annual groundwater level can be simulated without detailed hydrologeological information, which is rarely available, when precipitation, temperature and groundwater levels are known. The model can easily be extended to take into account e.g. groundwater pumping and its effect on groundwater level.

A distributed hydrological approach was developed in order to estimate the impacts of climate variability on groundwater storage and groundwater-surface water interaction. This approach revealed the importance of soil frost in estimation of groundwater recharge and storage in cold, snow-dominated regions. The approach also resulted in good predictions of seasonal groundwater level variations. The results showed that one-way coupling can be justified in areas where groundwater plays a minor role in the water balance in surrounding discharge areas and variation in groundwater level does not affect recharge rates. This is an important finding, because detailed information on hydrogeological parameters is only needed from the aquifer of interest, which may be a small fraction of the watershed. Surface water level variation and groundwater recharge can thus be independently estimated from the groundwater flow model and imported as a boundary condition to groundwater flow model, as shown in this study.

Solute concentration varied seasonally and showed a clear spatial variation within the aquifer. Solute concentrations and electrical conductivity generally decreased during and immediately after the spring snowmelt periods and after rainfall events in autumn and increased during summer. In addition, during the unseasonably warm period in some winters studied ($T > 0$ °C) the solute concentration decreased. This is an important finding because it shows that solute concentration can be sensitive to future warming when snowmelt is projected to increase in winter. The water levels between the groundwater and surface water reversed during the snowmelt period and Cl^- concentration in groundwater decreased, indicating surface water infiltration into the aquifer.

Simulations of future A1B and A2 climate scenarios indicated less soil frost and an increase in snowmelt, winter precipitation and winter recharge. Greater mean annual recharge will result in greater water potential of aquifers. The simulations also showed that recharge areas can be vulnerable to changes in climate. Decreases in the amplitude of variation in surface water and groundwater levels are also projected, together with shifts in peak surface water and groundwater levels to earlier in the year. These changes can potentially also affect surface water-groundwater interactions: intra-annual surface water intrusion can become more irregular as the intra-annual surface water level approaches the groundwater level. In warmer climate conditions, surface water infiltration to aquifers may occur more often during wet periods than during dry periods. These findings shows that groundwater in cold, snow-dominated regions can be highly sensitive to changes in near surface hydrology, recharge and surface water bodies surrounding an aquifer.

Future groundwater studies in cold, snow-dominated regions need to focus on recharge processes and surface water-groundwater interactions in more detail. The effects of snow cover, snowmelt water and ice in seasonally frozen ground on hydraulic conductivity should be thoroughly studied, as these factors play an important role in winter recharge, surface runoff and water level responses in groundwater and surface water in general. Changes in water quantity may also affect water quality. The linkages between water quantity and quality need to be better explored. The uncertainty related to different climate scenarios should also be addressed in more detail, in particular with respect to predicted groundwater response to climate change, but also with respect to different development cycles within the construction of a conceptual model such as that developed here. The delta approach chosen for use here, which is based on averaging time series of temperature and precipitation derived from global circulation model scenarios, should be analysed and compared with use of regional circulation models in combination with statistical downscaling for a number of scenarios.

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Appendix A

A water balance model was used to estimate the input parameters to eq. 2, i.e. daily snowmelt (Psn), rainfall (Pr) and evapotranspiration (ET) during the periods 1975–2006, 2010–2039. The input parameters for the water balance model were daily precipitation and temperature and the model outputs were daily snowmelt, rainfall, and evapotranspiration and snow water equivalents.

The portion of precipitation falling as rainfall and snowfall was calculated as (Vehviläinen 1992):

$$\text{Snowfall} = C_s F_s P_{tot}, \tag{A.1}$$

$$\text{Rainfall} = C_r F_r P_{tot}, \tag{A.2}$$

where P_{tot} is observed precipitation, C_s is a correction coefficient for snowfall and C_r is a correction coefficient for rainfall. F_r and F_s are fraction of rainfall and snowfall, respectively, and were calculated as follows (Vehviläinen 1992):

$$F_r = \begin{cases} 0 & \text{if } T < T_{min} \\ \dfrac{T - T_{min}}{T_{max} - T_{min}} & \text{if } T_{min} \le T \le T_{max}, \\ 1 & \text{if } T > T_{max} \end{cases} \tag{A.3}$$

$$F_s = 1 - F_r, \tag{A.4}$$

The daily snowmelt M_d was calculated with a degree day model (Kuusisto 1984). Refreezing of the snow pack was also taken into account. Snow cover and freezing were calculated as follows (Vehviläinen 1992):

$$M_d = \begin{cases} K_m \ (T_a - T_m) & \text{if } T_a > T_m \\ 0 & \textit{otherwise} \end{cases}, \tag{A.5}$$

$$F_d = \begin{cases} K_f (T_f - T_a)^e & \textit{if } T_a > T_f \\ 0 & \textit{otherwise} \end{cases}, \tag{A.6}$$

where M_d is the daily snowmelt depth and K_m is the degree day factor. T_a is the daily air temperature and T_m is the temperature at which the snow begins melt. F_d is the rate of freezing in the snow pack, and K_f is the degree day freezing factor, T_f is the threshold temperature for freezing, and *e* is the coefficient indicating the non-linear relationship between refreezing and temperature (Bengtsson 1982). The liquid water retention capacity of snow pack (WSP) controls the water yield from the snow pack. When the maximum liquid water retention capacity of the snow pack (WSP_{max}) is surpassed, the melt water can leave the snow pack (Kuusisto, 1984). WSP was related to liquid water of ice in the snow pack (WIP) as follows (Vehviläinen 1992):

$$WSP_{max} = R*WIP \tag{A.7}$$

where R is a retention parameter. Mass balance of the snow pack was calculated as follows:

$$dWSP/dt = P_r + M_d + F_d,\ WSP \leqslant WSP_{max}, \tag{A.8}$$

$$dWIP/dt = P_s - M_d + F_d, \tag{A.9}$$

$$SWE = WSP + WIP, \tag{A.10}$$

where SWE is the snow water equivalent. The soil water storage S was calculated after Alley (1984) to estimate the evapotranspiration (ET). The method needs an estimation of maximum soil water storage capacity S_{max} and an initial value for soil water storage capacity for continuous calculations. In this study, the initial soil water storage capacity was assumed to be S_{max}. The calculation started in autumn and it was therefore reasonable to assume that the soil had reached its maximum soil water storage capacity. The potential evapotranspiration (PET) was calculated by a temperature-based method after Hamon (1963) where only the daily temperature and day length were needed. The field capacity θ_f and the permanent wilting point θ_{wp} used in this study were taken from the literature (Korkka-Niemi & Salonen 1996; Allen *et al.* 1998; Mälkki 1999). The vertical extent of rootzone Z_r in pine forest was assumed to be 300 mm (Helmisaari *et al.* 2007). The maximum soil water storage capacity and the water input, i.e. the water available for infiltration, W, for the i^{th} day were estimated as follows (Dingman 2002).

$$S_{max} = \theta_f - \theta_{wp}, \tag{A.11}$$

$$W_i = P_{r,i} + P_{sn,i}, \tag{A.12}$$

If $W_i > PET_i$, evapotranspiration was estimated as follows:

$$ET_i = PET_i, \tag{A.13}$$

The soil water storage was estimated as follows:

$$S_i = \min[(W_i - PET_i) + S_{i-1}),\ S_{max}], \tag{A.14}$$

where min[…] indicates the smallest of the quantities within the brackets.
If $W_i < PET_i$, evapotranspiration is estimated as follows:

$$ET_i = W_i + S_{i-1} - S_i, \quad (A.15)$$

where the decrease in soil water storage is estimated as follows:

$$S_{i-1} - S_i = S_{i-1} \times (1 - \exp[-(PET_i - W_i)/S_{max}]). \quad (A.16)$$

Model calibration

The model was calibrated with observed snow water equivalent for the period 2005–2007 using the sum of squared errors method. The threshold temperatures T_{min}, T_m, T_f and the exponent *e* were set to constant in order to reduce the calibration parameters. The calibration parameters were T_{max}, C_s, C_r, K_m, K_f and R and they were constrained between values found in the literature (Male & Gray 1981; Kuusisto 1984; Vehviläinen 1992; Førland *et al.* 1996). The R^2 between observed and simulated snow water equivalents was 0.94.

Original publications

I Okkonen J, Jyrkama M & Kløve B (2010) A conceptual approach for assessing the impact of climate change on groundwater and related surface waters in cold regions (Finland). Hydrogeology Journal 18(2): 429–439.

II Okkonen J & Kløve B (2010) A conceptual and statistical approach for the analysis of climate impact on ground water table fluctuation patterns in cold conditions. Journal of Hydrology 388(1–2): 1–12.

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