A conceptual approach for assessing the impact of climate change on groundwater and related surface waters in cold regions (Finland)

Jarkko Okkonen · Mikko Jyrkama · Bjørn Kløve

Abstract A literature review of the impacts of anticipated climate change on unconfined aquifers is presented, along with a conceptual framework for evaluating the complex responses of surface and subsurface hydrology to climate variables in cold regions. The framework offers a way to conceptualize how changes in one component of the system may impact another by delineating the relationships among climate drivers, hydrological responses, and groundwater responses in a straight-forward manner. The model is elaborated in the context of shallow unconfined aquifers in the boreal environment of Finland. In cold conditions, climate change is expected to reduce snow cover and soil frost and increase winter floods. The annual surface water level maximum will occur earlier in spring, and water levels will decrease in summer due to higher evapotranspiration rates. The maximum recharge and groundwater level are expected to occur earlier in the year. Lower groundwater levels are expected in summer due to higher evapotranspiration rates. The flow regimes between shallow unconfined aquifers and surface water may change, affecting water quantity and quality in the surface and groundwater systems.

Keywords Climate change · Esker · Groundwater/surface-water relations · Boreal environment · Finland

Received: 10 December 2008 / Accepted: 8 September 2009

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Introduction

Projected future climate-change scenarios suggest that global average surface air temperature will increase by 1.4 to 5.8°C by the end of the 21st century. Precipitation is projected to increase especially in the mid and high latitudes. In these areas, wider year-to-year variations of precipitation together with extreme events are likely, while snow and ice-cover extent will continue to decrease (IPCC 2007). The effects of global warming on water resources, and especially on groundwater, will depend on the groundwater system, its geographical location, and changes in hydrological variables (Alley 2001; Sophocleous 2004; Huntington 2006). Expected consequences of global warming include lower water tables and decreased groundwater discharge, which may in turn reduce stream base flows and lake water levels. These effects will be intensified if water abstraction is increased to meet a growing demand for water.

The implications of anticipated climate change are difficult to measure and quantify not only at the global scale but also at regional and local levels. Numerical simulation models provide the most effective way to estimate the quantity and quality of water exchange between aquifers and surface-water bodies and thereby to quantify the impact of groundwater abstraction (i.e., pumping) and climate change on groundwater systems. Recent studies have demonstrated that hydrological changes and climate change impacts on groundwater can be evaluated with both statistical tools (e.g., McCuen 2003; Chen et al. 2002) and complex distributed models (e.g., Bouraoui et al. 1999; Rosenberg et al. 1999; Loáiciga et al. 2000; Malcom and Soulsby 2000; York et al. 2002; Yusoff et al. 2002; Croley and Luukkonen 2003; Loáiciga 2003; Brouyère et al. 2004; Allen et al. 2004; Hanson and Dettinger 2005; Scibek and Allen 2006a; Scibek and Allen 2006b; Scibek et al. 2007; Jyrkama and Sykes 2007).

Quantifying the impacts of changing evaporation, precipitation, and temperature on water-table variations has been the main focus of earlier research. The effects on groundwater of extreme conditions, such as droughts, have also been estimated (e.g., Kirschen 2002). Less attention has been given to the indirect hydrological effects of changes in land cover (Lambrakis and Kallergis 2001) and water demand (e.g., for irrigation Rosenzweig et al. 2004). Moreover, very little research has been done

DOI 10.1007/s10040-009-0529-9

on shallow, unconfined aquifers, particularly on their interaction with surface-water bodies (Bobba et al. 2000; Malcom and Soulsby 2000; Yusoff et al. 2002; Scibek et al. 2007), and on the impacts of climate change on them as compared to the impacts on deeper aquifers (Loáiciga et al. 2000; Younger et al. 2002; Brouyère et al. 2004).

The coupling of numerical sub-models to groundwater models continues to be a challenge. Conceptual models or frameworks can be used as an alternative to demonstrate several factors that need to be considered in integrated modeling that links climate to hydrology. Conceptual frameworks are also useful for water managers, and are recommended in European Commission guidelines (CIS 2003). The guidelines state that regular improvements to conceptual frameworks should be made, but no details are given on how to develop them. In this paper, there is a short review of previous studies of climate-change impacts on unconfined aquifers. Because surface waters are typically connected to shallow groundwater deposits, stream- and lake-aquifer interactions are also discussed. Such interactions are a key uncertainty in the implementation of the European Union Groundwater Directive and need close attention (EC 2006) in conceptual frameworks. This paper develops a conceptual framework for evaluating the potential impacts of climate change (temperature and precipitation) in cold regions, showing how they will affect the various components of the near-surface hydrological regime (e.g., snow cover, soil frost, evapotranspiration, runoff), surface-water bodies, and groundwater. Both quantity and quality aspects of groundwater are considered. The model development follows the 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. This three-step procedure is adopted in the discussion below with respect to cold regions and unconfined aquifers, and with northern Finland providing a specific case study.

Climate change impacts on unconfined groundwater systems: a review

In unconfined aquifers, water table fluctuation is dependent on the recharge and discharge, permeability, storage capacity, and water withdrawal (Todd 1980). Unconfined aquifers, especially surficial and shallow ones, are at high risk from surface contamination, and they are particularly sensitive to changes in climatic conditions (Winter et al. 1998; Sophocleous 2002; Dingman 2002; Lee et al. 2006). In the following, the impacts of climate change on recharge and interaction between groundwater and surface water are considered.

Groundwater recharge

Groundwater recharge is the water that arrives at the water table and increases the groundwater storage. Recharge is affected by parameters both on the land surface and in the vadoze zone. A portion of the precipitation water (either rain or snow) is first intercepted by the vegetation canopy. Depending on the precipitation intensity, temperature, and ground surface cover, water reaching the ground surface may then flow overland directly into streams and ditches, be stored in water bodies or the snowpack (if present), or infiltrate into the soil. The infiltrated water percolates downwards through the vegetative root zone where a portion of it may be taken up by plant roots and subsequently transpired through the vegetation canopy or evaporated from the ground surface. The remaining water percolates deeper into the soil column, eventually becoming groundwater recharge when it crosses the water table into the saturated zone.

Water levels in unconfined aquifers are susceptible to changes in key climate variables (Healy and Cook 2002; de Vries and Simmers 2002). In early work, Vaccaro (1992) investigated the sensitivity of recharge to past climate and climate change scenarios in the northwestern United States and found that the year-to-year variations in recharge were under irrigations less than in predevelopment conditions. Similar trends and cycles were observed between precipitation and recharge and temperature and recharge. The amount of recharge was found to be more dependent on total precipitation than on temperature. However, the correlation between temperature and recharge increased from predevelopment conditions to irrigation conditions due to the increase in evapotranspiration that accompanies irrigation. Under projected climate-change scenarios, the annual recharge was expected to decrease as the combined results of increase in summer temperature and decrease in winter precipitation.

In an investigation of changes in recharge under condition of doubled atmospheric CO_2 concentration in a watershed in France, Bouraoui et al. (1999) found that while increase in atmospheric CO_2 would greatly increase evaporation owing to higher temperatures, the impact on rainfall would be marginal. As a result of the increased evaporation, recharge would decrease. Rosenberg et al. (1999) studied the impact of climate variability on recharge in the central United States and concluded that recharge will decrease as a result of increased temperatures: even if precipitation increases, the excess water will be lost in increased evapotranspiration. Eckhardt and Ulbrich (2003) estimated changes in recharge in central Europe for different rainfall and temperature scenarios, concluding that winter recharge will likely increase owing to an increase in winter rainfall, while summer recharge will decrease as a result of reduced precipitation and higher temperatures. Looking at climate change impacts on a carbonate aquifer in southern Manitoba, Canada, Chen et al. (2004) showed that in a shallow portion of this upper aquifer, temperature would have a greater impact on recharge than would precipitation. They also concluded that a reduction in winter and spring precipitation would reduce the net recharge in a temperate climate. Scibek and Allen (2006a) conducted groundwater-modeling studies in a highly permeable aquifer in British Columbia in western

Canada and found that only minor changes in recharge would be expected due to climate change. The greatest increase in recharge was spring and early summer as a result of the increased intensity of rainfall events. A study by Jyrkama and Sykes (2007) on the effects of climate variability on groundwater recharge in southern Ontario, Canada, in turn, indicated that the overall recharge may increase with a shift from cold to temperate climate, and further the spring melt period may occur earlier in the year and reduce the ground frost allowing more water to infiltrate.

Groundwater and surface water interaction

Groundwater and surface water interaction occurs in almost every landscape, by subsurface flow through unsaturated or saturated soils. In karst, chalk, or fractured terrain, the groundwater flow takes place through fractures or solution channels (Sophocleous 2002). Both the magnitude and the direction of the flow between surface water bodies and aquifers may be controlled by climate variability. Rain and snowmelt water may increase overland flow, which then increases water storage in surface-water bodies. This changes the gradient between the surface water and groundwater, and may even reverse the flow direction between them. Flow reversal due to transient focused recharge was found to be common in Crystal Lake in northern Wisconsin, USA: during wet periods, the groundwater discharged to the lake, but the reverse was the case during dry periods (Anderson and Cheng 1993). Similar changes in flow direction due to climate variations have also been widely reported by others (e.g., Sacks et al. 1992; Doss 1993; Phillips and Shedlock 1993; Wurster et al. 2003; Rodríguez-Rodríguez et al. 2006).

Changes in precipitation and temperature and their impact on groundwater levels, flow directions, and river base flows have been studied through the use of numerical models. In a modeling study by Cooper et al. (1996), climate-change impacts on a Triassic sandstone aquifer and chalk aquifer in the UK found that 4% increase in evapotranspiration and 4% increase in precipitation would increase recharge of the Triassic sandstone aquifer by 2% and decrease that of the chalk aquifer by the same amount. The river base flow did not markedly change annually or seasonally in the Triassic sandstone aquifer, but was reduced up to 15% in autumn in the chalk aquifer. A modeled 4% increase in precipitation and 30% and 29% increases in evapotranspiration in the Triassic sandstone aquifer and the chalk aquifer, respectively, decreased the recharge by 13% and 21%. In the Triassic sandstone aquifer, the amount of base flow was over the year uniformly reduced by 12%. In the chalk aquifer, the timing and the amount of the maximum base flow did not change much but the minimum base flow occurred 2–4 weeks later in the autumn and was reduced by 55%.

Increasing temperature was also found to play a significant role in an unconfined aquifer–river interaction in the northeastern United States. Kirschen (2002) showed that a large enhancement of the actual evapotranspiration (AET) would lower the water table and further reduce the river low flows. In drought scenarios, the seasonal timing of the water-table fluctuation would not change significantly; however, a large increase in the AET would significantly reduce water availability to the aquifer. The worst-case scenario suggested a significant water loss to headwater streams and marked lowering of the water table. Even a minor increase in the AET would reduce flows to streams and lower the water levels.

In some cases, changes in river flows may have a higher impact on water level fluctuation than changes in temperature and precipitation. For example, in a modeling study of Allen et al. (2004), climate-change impacts on an aquifer–river system in a semiarid area of British Columbia, Canada found that under extreme conditions (low temperature/high precipitation and high temperature/low precipitation scenarios), high recharge would result in an average 0.05-m increase in the water table levels throughout the aquifer, while low recharge would result in an average 0.025-m decrease. The river stage elevation was examined for higher-than-peak flow levels (i.e., flood) and lower-than-base flow levels (low base flow situations, i.e., droughts). The higher-than-peak flow cases, representing 20% and 50% increases in the river stage, would result in 2.72-m and 3.45-m average increases in the water table levels, respectively. The lower-than-base flow cases, consisting of 20% and 50% reduction in river stage, would result in average 0.48-m and 2.10-m declines in the water table levels, respectively. A subsequent study by Scibek et al. (2007) in the same area used climate shifts derived from a global climate model to predict changes in stream discharge and groundwater recharge separately. The resulting changes were used to alter the boundary conditions of a transient groundwater flow model. The results were generally consistent with those of Allen et al. (2004) but focused on the transient impacts on groundwater storage rather than on mean annual changes.

Methodology: conceptual framework

The reviewed literature shows the impacts of climate variability (i.e., changes in temperature and precipitation) on near-surface hydrology (i.e., snow, soil frost, evapotranspiration, runoff), on surface-water levels and ultimately on groundwater. The impacts of climate change on groundwater, groundwater–surface water interaction, and groundwater quantity and quality are still difficult to assess, and especially in cold regions, where considerable changes in rainfall/snowfall distribution, snow depths, and soil frost are expected. The responses to future climate change will differ from region to region. A conceptual framework offers a way to conceptualize how changes in one component of the system can impact another by delineating the relationships among climate drivers, hydrological responses, and groundwater responses.

In the following section, a conceptual framework is developed for assessing the impacts of future climate

DOI 10.1007/s10040-009-0529-9

change (precipitation and temperature) on hydrology and groundwater in cold regions in northern Finland. Equations (1–6) were used to estimate changes in recharge, runoff, surface-water level, groundwater level, and groundwater quality, and the results are charted in the conceptual framework presented in Fig. 1 to show the impacts propagating through the system. The term *focused recharge* refers to surface water intrusion into an aquifer and *ET* refers to evapotranspiration. The arrows added in Fig. 1 show the predicted impacts of climate change on hydrology and groundwater resources in the case area.

The climate conditions for temperature and precipitation are based on the A2 emission scenario, which assumes high emissions (Nakićenović et al. 2000). In Finland, temperature is projected to increase by 2.9–4°C and precipitation by 7–21% by 2050 (Jylhä et al. 2004). The projections for temperature and precipitation were derived from six different atmospheric-ocean general circulation models. Details of the projected changes in temperature and precipitation and of the methodology can be found in Jylhä et al. (2004). On the basis of the conceptual framework, the overall impact of climate change on hydrology and groundwater can be predicted simply from the anticipated changes in temperature and precipitation (Fig. 1).

$$Recharge = Rain + Snow + Soil\ frost - ET \tag{1}$$

$$Runoff = Rain - ET + Snow - Soil\ frost \tag{2}$$

$$Surface\ water\ level = Runoff + Groundwater\ level \tag{3}$$

$$\begin{aligned} Groundwater\ level = {} & Surface\ water\ level + Recharge \\ & + Focused\ recharge \end{aligned} \tag{4}$$

$$\begin{aligned} Focused\ recharge = {} & Groundwater\ level \\ & - Surface\ water\ level \end{aligned} \tag{5}$$

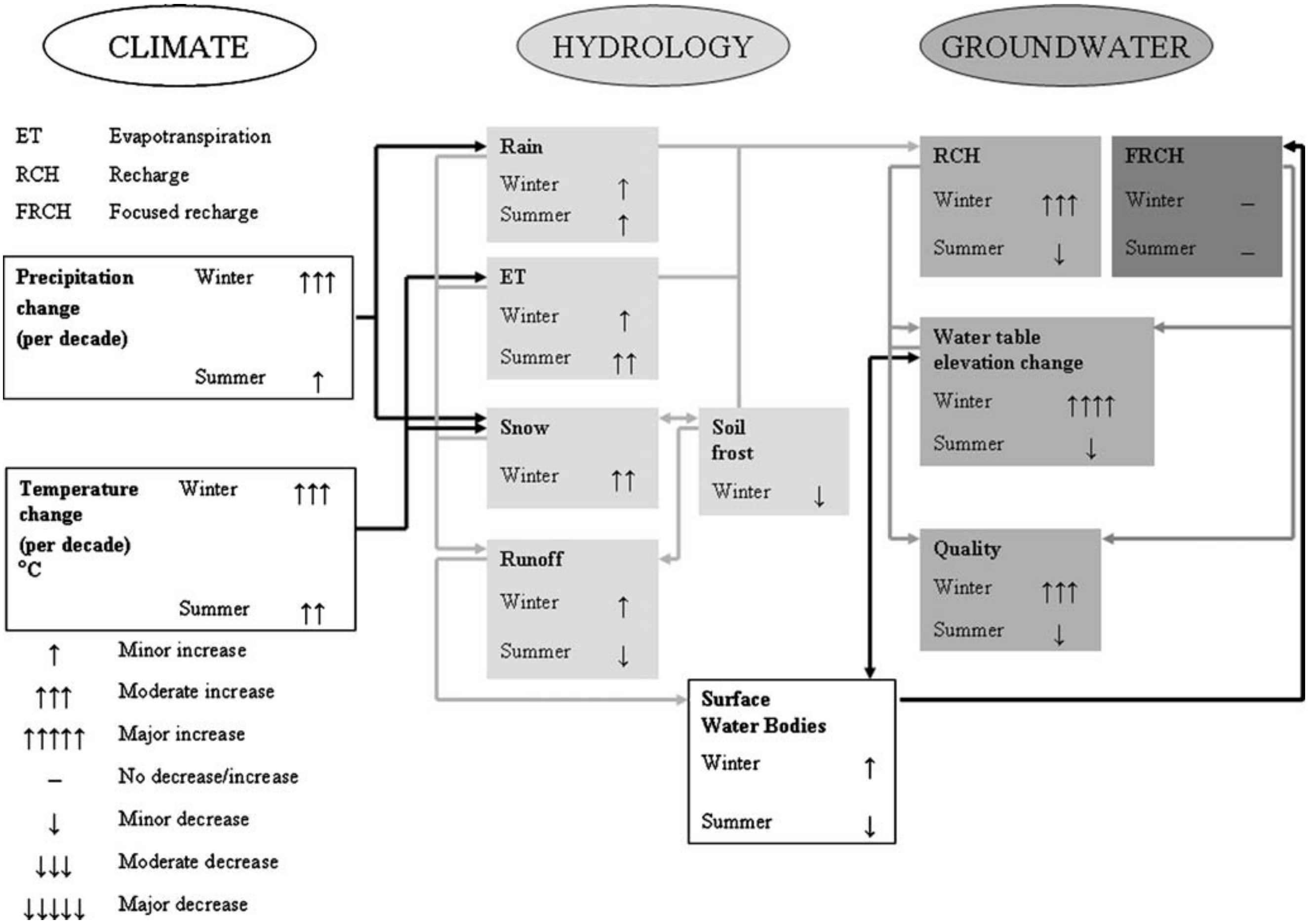


Fig. 1 Conceptual framework for assessing the impacts of climate change on hydrology and groundwater in cold regions in northern Finland where surface water bodies are present

$$\textit{Groundwater quality} = \textit{Recharge} - \textit{Focused recharge} \tag{6}$$

Description of case study area: unconfined eskers in northern Finland

Most aquifers used for water supply in Finland are glaciofluvial deposits, i.e., eskers. Eskers are typically well-sorted gravel and sand deposits. Hydraulically uniform strata may extend more than tens of kilometers and groundwater flows in longitudinal directions from higher to lower groundwater level. The gradient typically varies between 0.001 and 0.006, flow velocity between 6.0×10^{-7} and 1.2×10^{-3} m/s and permeability between 0.1×10^{-2} and 44×10^{-2} m/s (Mälkki 1979). The water table usually lies 2–4 m below the ground surface, but as much as 30 m in some regions in southern Finland. In northern Finland, unconfined esker aquifers are often hydraulically connected to surface water bodies, i.e., lakes, ponds, rivers, and wetlands (Fig. 2).

There are 54 groundwater stations located in different parts of Finland that have been operating since 1974 to monitor groundwater level variation. The climatic conditions prevailing in different parts of Finland result in water-table fluctuation patterns that can be divided into four distinct types as shown in Fig. 3 (Mäkinen 2003). To be able to compare the seasonal variation of the groundwater level in different regions, the observed groundwater levels were standardized to a range of values from 0 to 1. In regions II to IV, annual maximums occur in the spring due to snowmelt, and at the end of the year due to increased precipitation and lower evapotranspiration. Annual minimums are reached in the summer and late winter. In northern Finland (region I), the water-table fluctuation pattern shows a single minimum and a single maximum, the minimum occurring immediately prior to the snowmelt and the maximum immediately following the spring snowmelt. As shown in Fig. 3, the water table declines from the 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).

Northern Finland is classified as having a mid-boreal climate, typically with a permanent snow cover from November to April. Precipitation is highest in summer (June-July-August) and lowest in spring (March-April-May). Snow accumulates from November to April and melts between April and May. The end day of the snowmelt usually occurs in mid-May. The maximum snow water equivalent is usually observed in mid-March. Soil frost starts to accumulate in October and usually has disappeared by mid-May.

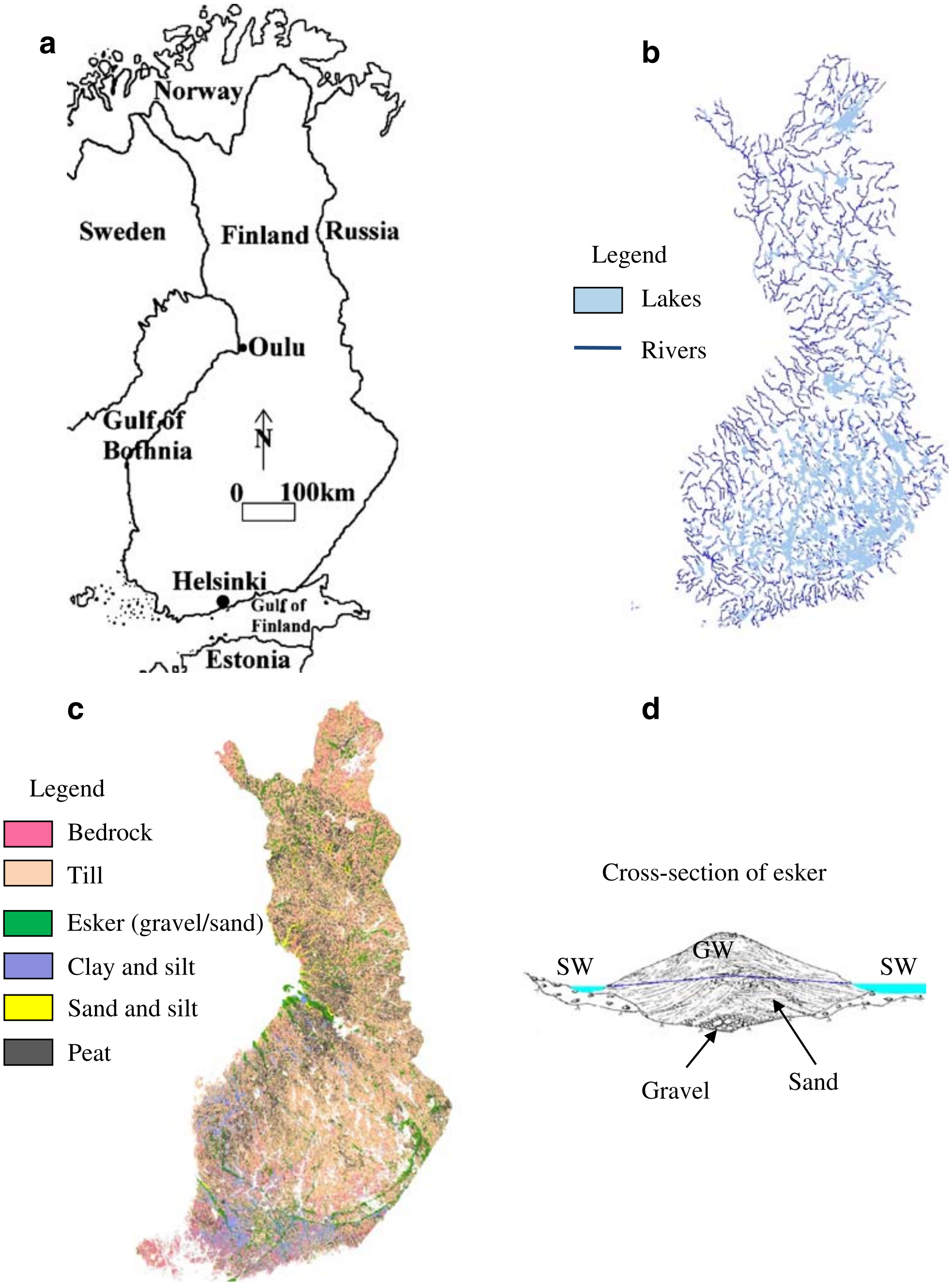
Previous studies on climate variability in Finland have suggested that in the 20th century the mean annual temperature increased by 0.7°C while the mean annual precipitation has not shown any obvious trend in the past 100 years (Jylhä et al. 2004). Seasonal trend analysis suggested that summer temperature increased by 0.7°C and spring temperature by 1.4°C. No significant trends in temperature were observed in autumn and winter (Jylhä et al. 2004). Snow depth as snow water equivalent has increased slightly in northern Finland since 1946 due to an increase in winter precipitation as snow (Solantie 2001; Rasmus 2005). No clear trends in evapotranspiration, soil frost, runoff, groundwater, and surface waters have been observed in northern Finland (Hyvärinen 2003). It is nevertheless expected that global warming will change the distribution of winter rainfall/snowfall, the snow cover period and depths, date of snowmelt, amount and duration of soil frost, and evapotranspiration rates; surface and groundwater levels may change and affect the interaction between surface water bodies and groundwater (Silander et al. 2006). In areas where surface water intrusion is harmful for groundwater quality, there would likely be an impact on groundwater usage.

Effects of climate change on evapotranspiration, rain and snow, soil frost and groundwater

According to predicted climate change scenarios for Finland, precipitation will increase on average by 5–40%, and average temperatures by 2–7°C by 2099 (Jylhä et al. 2004). In the A2 emission scenario by 2050, winter precipitation will increase 20% and summer precipitation 7% as compared to the present climate. Temperature is predicted to increase by 4.6°C in winter and 2.1°C in summer. Increase in temperature is expected to enhance evapotranspiration in summer and could lead to an increase in soil moisture deficit up to 30% as compared to the present climate (Ruosteenoja et al. 2005). The length of dry periods could increase by 2 months due to a shift in onset and the later end of summer (Silander et al. 2006). 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 of the minimum groundwater level toward autumn due to increase in the 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 the groundwater recharge and water levels. The expected impacts of temperature on evapotranspiration and groundwater recharge and water levels are conceptualized in Fig. 1. Evapotranspiration affects the groundwater levels by decreasing the amount of recharge.

It is expected that along with a warmer climate, winter rainfall would increase and snow accumulation would decrease. Changes in the snowmelt are likely to have a significant impact on the groundwater recharge. Recent studies in the southwestern United States suggest that snowmelt may contribute 40–70% of groundwater recharge even when only 25–50% of the precipitation

Fig. 2 **a** Study site in Finland. **b** Major rivers and lakes in Finland. **c** General hydrogeological map of Finland. **d** Cross section of a typical esker aquifer. *GW* represents groundwater, *SW* indicates surface water (Finnish environmental institute, source: groundwater database HERTTA)



falls as snow (Earman et al. 2006). In other words, snowmelt water may have a disproportionately large influence on recharge as compared to rain. In Finland, it is expected that winter precipitation may increase by up to 55% relative to that of 1971–2000 mainly because of increased convection to northern Europe. An increase in winter temperatures would potentially increase the amount of rainfall and snowmelt. For northern Finland it is expected that during the next three decades, the increase in winter precipitation will fall as snow enhancing the snow depth but thereafter the amount of rainfall will increase and the snow depth will decrease until the end of the 21st century. The period of snow cover is also expected to contract until the end of the century. Higher temperatures in autumn will delay the beginning of snow accumulation and in spring advance the snowmelt (Jylhä et al. 2008). The impact of precipitation on groundwater level is conceptualized in Fig. 1. 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.

Reduced snow depths consequent upon higher winter temperature may reduce the soil frost (Venäläinen et al. 2001). Frost penetration in Finland depends on depths of the snow cover. With snow depth of 30 cm or more, the soil temperature seldom decreases below –1.5°C (Sutinen

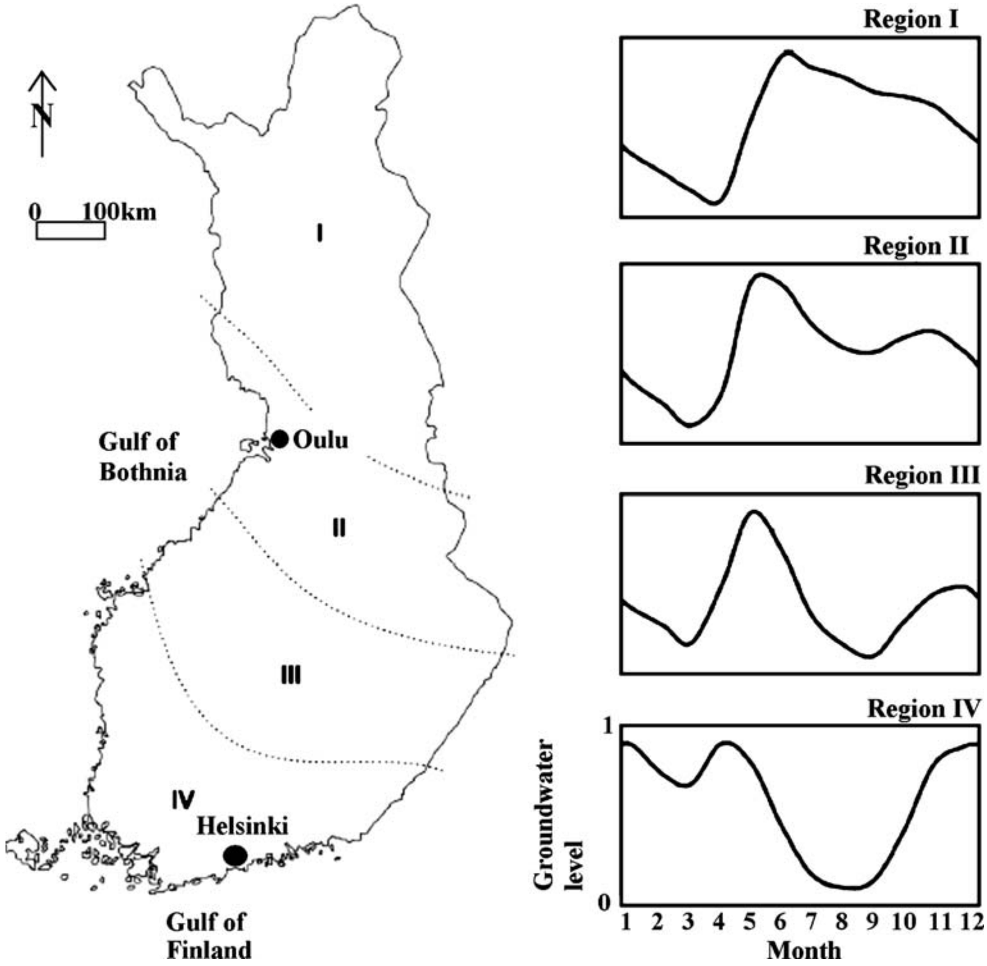


Fig. 3 Present groundwater fluctuations in Finland. Region I refers to north Finland, regions II and III refer to central Finland and region IV refers to south Finland (modified with permission Mäkinen et al. 2008)

et al. 2007). The snow depth in northern Finland is expected to decrease from 60–70 cm to 30–40 cm and soil frost would then decrease from 60–70 cm to 10–15 cm (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 expected 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 the groundwater recharge and water levels in a temperate climate.

Recent studies in Finland suggest that in a mild climate, snowmelt infiltration in sandy soils increases the soil moisture content below the partially frozen soil and may increase aquifer recharge (Sutinen et al. 2007). In agreement with this, the infiltration of snowmelt water into the partially frozen soil has been found in the subalpine tree environment in Canada (Leenders and Woo 2002), in agricultural soil of Minnesota (Baker and Spaans 1997), and in sandy soils in central Sweden (Stähli et al. 1999). Contrary to this, however, Earman et al. (2006) have conjectured that with milder winters, aquifer recharge in the mountainous southwestern United States would decrease because the reduced snowfall and increased rainfall would result in heavier runoff and decreased infiltration from a thinner snow pack and more rapidly melting snow pack. In areas of steep topography, the ratio of runoff to infiltration depends not only on the soil properties and slope but also on climate periods. A snowmelt period of long duration may enhance the groundwater recharge whereas a short intensive snowmelt period could have the opposite effects. Earman et al. (2006) based their conclusions on isotope compositions and did not consult detailed information on soil, soil frost, or measurements other than stable isotopes of O and H of rain and snow. Arguably, isotopes do not unequivocally explain the complex processes of snowmelt infiltration during milder winter climate. Runoff, in general, is expected to decrease and infiltration to increase as the result of a decrease in soil frost and an increase in snowmelt (Ekhardt and Ulbrich 2003; Jyrkama and Sykes 2007).

The snowmelt discharge during warm winter periods is likely to change the timing and possibly the quantity of groundwater recharge in northern regions. The relationship between soil frost and groundwater level is conceptualized in Fig. 1. Soil frost is dependent on many factors, such as temperature, snow accumulation, and the underlying geologic material, and therefore influences the

DOI 10.1007/s10040-009-0529-9

groundwater recharge in different ways. Percolation is highly dependent on the soil material, and gravelly soils, such as eskers, would be able to receive almost all the melt water (Gray et al. 2001); other soil types may resist infiltration and promote runoff instead. A decrease in the soil frost and an increase in snowmelt and rainfall would potentially increase the winter recharge and groundwater levels in northern Finland.

Effects of climate change on surface water–groundwater interaction

In areas where the groundwater is intimately 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 expected that the seasonal distribution of runoff will change (Veijalainen 2008). Then at the end of the 21st century, winter runoff and flooding are expected to increase due to an increase in the snowmelt and rain, and spring flooding is expected to decrease. Lake evaporation is expected to increase in summer, which may cause the surface water levels to decline as compared to the situation under present climate conditions (Silander et al. 2006). Changes in surface water levels may change the flow direction between the groundwater and surface water, and increases or decreases in the focused recharge are expected. In winter, flow reversals may become more frequent if the response of surface-water level is faster than that of the groundwater level to rainfall and snowmelt events. In summer, a lower surface-water level may lower the groundwater level, and this could impact ecosystems dependent upon groundwater.

The linkages between precipitation, evapotranspiration (ET), runoff, snow cover, soil frost, surface-water level, focused recharge, and groundwater level are shown in Fig. 1. The flow direction between groundwater and surface water depends on the water levels. An increase in snowmelt and rainfall may enhance the runoff and raise the surface water levels, shifting the spring maximum to earlier in the year (Veijalainen 2008). A rise in the surface water level may not change the flow direction between the surface water and the groundwater if the groundwater levels rise concurrently. However, there is a high risk that the surface water level rises faster and higher than groundwater level as a result of snowmelt and rain. Therefore, flooding and surface water intrusion may well increase in the future (Silander et al. 2006). Changes in the timing and the height of the surface and groundwater levels may affect the interaction between the surface water and groundwater in different ways and this needs to be studied in more detail.

Climate change and groundwater quality

Changes in the amount and distribution of groundwater recharge and focused recharge may affect the groundwater quality. Seasonal changes in groundwater quality are typical in northern regions. Concentration maximums usually occur in summer and late autumn due to the increase in evapotranspiration rates. The concentration minimum usually occurs after the spring melt as a result of the infiltrating oxygen-rich water (Soveri et al. 2001). Recent studies suggest that pesticide concentrations in the groundwater will increase after intense rainfall events (Gooddy et al. 2001; Johnson et al. 2001). Sugita and Nakane (2007) found that an increase in nitrate concentration also followed heavy rainfall events. An increase in the winter recharge and higher groundwater levels may increase solute leaching, capture pesticides, and other pollutants in the vadose zone and reduce the groundwater quality (Bloomfield et al. 2006). Shallow unconfined aquifers may be at risk to contamination from bacteria due to winter and spring floods; on the other hand, an increase in the winter recharge may contribute more oxygen-rich water to the groundwater system and improve the groundwater quality (Silander et al. 2006). The groundwater quality in summer may also change if groundwater levels fall. 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 impact on the groundwater quality in different ways. In agricultural areas, the seasonal changes in the recharge due to a warmer climate might accentuate the seasonal variation of 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 and the focused recharge under anticipated climate change are not well understood for northern Finland, especially for winter conditions. It is possible that greater winter runoff due to an increase in winter snowmelt and rainfall events will increase the surface-water level variation and change the surface water–groundwater interaction, thereby changing the focused recharge and groundwater quality. Changes in the focused recharge will also depend on the groundwater level response to the winter snowmelt and the rainfall and the runoff. If the interaction does not change or if it weakens from that of the present climate, the groundwater quality may improve as a result of increase in the recharge and oxygen-rich water from the snow cover. In summer, intensified lake-water evaporation may cause the surface water levels to decline and together with increase in evapotranspiration may cause groundwater levels to fall too. The expected impacts of precipitation and temperature on groundwater quality are shown in Fig. 1.

Discussion

Estimating groundwater recharge is the key issue in the assessment of climate-change impacts on groundwater resources. The reviewed literature suggests that changes in recharge are highly dependent upon both temperature and precipitation. Warmer temperatures, increased winter rainfall, and decreased depth of soil frost can be expected to allow more water to percolate into the ground, thereby increasing aquifer recharge. In southerly areas (as in central Europe) where the effects of snow cover and soil frost are not a major influence in groundwater recharge because the period of snow cover and soil frost is short, only changes in the amount of recharge are expected. Higher recharge rates in winter will lead to higher groundwater levels in winter. Recharge rates and groundwater levels in summer will depend on precipitation. In the case of highly permeable aquifers, heavy summer rainfalls will likely lead to more infiltration and higher groundwater levels. In areas with only light summer rain, however, an increase in summer temperatures and evapotranspiration may reduce groundwater recharge and water levels.

In cold regions where the period of snow cover and soil frost is long, typically from November until May, a shift in the overall amount and timing of recharge is expected. The rise in winter temperature will increasingly change the form of precipitation from snow to rain and reduce the soil frost, significantly increase winter recharge rates, shift the spring melt period to earlier in the year, and may also decrease the snowmelt peak. Changes in recharge will eventually lower the amplitude of fluctuations in the water table and the minimum and maximum water levels. In northern Finland (regions I and II), the water-table fluctuation pattern may in the future resemble the current patterns in central or in southern Finland, with higher risks of summer low water-table levels (Mäkinen et al. 2008). In cold regions, soil frost and snow cover will play an important role in variations of groundwater quantity and possibly also quality (Silander et al. 2006), and these should be investigated in more detail as part of groundwater resource studies in cold regions.

In some aquifers, water-level fluctuations may be more susceptible to changes in surface-water bodies than to recharge. The interaction between surface water and groundwater is sensitive to climate variability, particularly temperature changes, which influence the interaction between surface water and groundwater particularly during the base flow period when groundwater discharge dominates. In cold regions, warmer winters are expected to decrease (Jyrkama and Sykes 2007) or increase (Earman et al. 2006) surface runoff. A decrease in the surface runoff is expected in regions of highly permeable soil where topography is flat, but an increase in surface runoff along with a thinner snow pack and an intensive snowmelt period are expected in mountainous regions where topography is steep. In northern Finland, a decrease in the amplitude of surface water level but an increase in the fluctuations is expected. Surface water level maximums will occur earlier in the year, and water levels will fall in summer because of higher evapotranspiration rates (Veijalainen et al. 2008). In areas where the interaction between surface water and groundwater is sensitive to variations in precipitation and temperature, a detailed analysis should be carried out to fully understand the impacts of key climate variables on surface-water levels and groundwater levels. Changes occurring in one of the systems may lead to changes in surface water–groundwater interaction as well. An increase in surface-water intrusion from wetlands, for example, may increase not only the organic matter content in the underlying aquifers but also iron and manganese concentrations owing to the lack of dissolved oxygen (Carter et al. 2005; Silander et al. 2006).

In cultivated land or in land-use areas where an increase in the groundwater recharge and higher groundwater levels are expected, the groundwater quality may deteriorate owing to an increase in pesticides or solute leaching. In eskers where no human impacts other than groundwater abstraction occur, mild winter weather will allow the replenishment of aquifers through recharge and increase oxygen-rich water from the snow cover and enhance the groundwater quality. In summer, rising temperature will increase evapotranspiration, which will lead to a decrease in recharge and lower water levels. This will not only reduce the groundwater quantity but may alter the quality as well due to a shortage of dissolved oxygen (Silander et al. 2006). Higher evapotranspiration in summer will decrease water levels in surface water bodies; however, this will not necessarily change the flow direction between the surface water and groundwater system because the groundwater levels are depressed at the same time.

The conceptual framework presented in this study provides only a first step in the assessment of climate change impacts on the groundwater resources in northern Finland. The impact of predicted climate change on groundwater were not estimated on the basis of numerical modeling, but rather were deduced from information accumulated in previous studies in similar environments in other countries. Although numerical modeling should eventually be performed to avoid conjecture, the presented conceptual framework will still greatly assist water professionals in their understanding of the impact of climate change on groundwater resources. The framework developed not only provides an easy-to-comprehend assessment of changes in precipitation and temperature and their influence on hydrology and groundwater resources but also facilitates the development of numerical modeling by identifying linkages between the different parameters impacting groundwater systems.

Conclusions

A conceptual framework for evaluating the potential impact of climate change on the various components of the near-surface hydrologic regime and groundwater system was developed in this paper. Three steps were followed in development of the framework: (1) Review the state of the art, (2) conceptualize the particular hydrogeological case, and (3) use a case framework to study the local conditions. The effectiveness of this methodology was demonstrated by applying it to northern Finland. The results show how an increase in winter precipitation and decrease in soil frost can be expected to enhance recharge, leading to a rise in groundwater levels in winter. Warmer temperatures in summer, in turn, will increase evapotranspiration and may lead to a decrease in recharge and lower water levels.

In the boreal environment, reduced snow cover and soil frost due to global warming can be expected to have a substantial impact on the timing of minimums and maximums in the water-table fluctuation pattern. Increased snowmelt and decreased frost may contribute oxygen-rich water, resulting in improved water quality. Changes in water-table elevations and surface-water levels may shift flow directions, leading to alterations in water quantity and quality: reduced groundwater discharge from aquifers is a threat to surface-water bodies, while flooding and surface-water intrusion, from wetlands, for example, may increase the organic matter content in aquifers, thereby impairing groundwater quality. Thus in areas where surface water bodies are dynamically connected to the groundwater system, a detailed analysis should be conducted to properly quantify the relationship between the two systems.

Acknowledgments This research was financed by Oulun Vesi Oy, Pudasjärven Vesiosuuskunta, Maa- ja Vesitekniikan Tuki r.y., K.H. Renlundin säätiö, Vesi- ja viemärilaitosyhdistys r.y., Koneen Säätiö, and the EC 7th framework project GENESIS (226536).

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