Modelling and statistical analysis of catchment water balance and discharge in Finland in 1951–2099 using transient climate scenarios

Noora Veijalainen, Johanna Korhonen, Bertel Vehviläinen and Harri Koivusalo

ABSTRACT

In this study climate change impacts on water balance components were estimated from transient climate scenarios for 1951–2099 in Finland. The future changes in evapotranspiration and discharge in annual and seasonal scales as well as annual mean high and low flows were projected for four catchments in different parts of Finland. The assessment was carried out using temperature and precipitation series simulated by four regional climate models (RCMs) as input to a conceptual hydrological model. The daily data from RCMs was bias corrected with the quantile–quantile mapping method and statistical properties of the simulated discharges were analysed to detect trends over time. Without bias correction the simulated discharges in the control period did not match the observed discharges, but the fit was improved considerably after bias correction. The results showed that seasonal changes, most importantly increase in winter runoff, were clearly visible and consistent in different climate scenarios and catchments. Individual scenarios also produced changes in annual mean, high and low flows, but without consistency in scenarios. The use of bias corrected RCM data as input to the hydrological model enables transient simulations, but the simulation results aggregate considerable uncertainties from the climate modelling, bias correction and the hydrological model.

Key words | bias correction, climate change, hydrological modelling, transient climate scenarios, trend analysis

INTRODUCTION

Climate change impacts on runoff and flooding are traditionally examined by comparison of the model results for future time periods against the results for past control periods (e.g. Arnell 1999; Schneiderman et al. 2010). The meteorological conditions within these future or historical periods are generally assumed to be stationary, i.e. the meteorological variables show no trends during the periods. However, the increasing availability of transient simulations from RCMs with different driving global climate models (GCMs) may change this approach. The daily results from the RCMs can be used as input to hydrological models in order to simulate water balance components over long transient time series until 2099. The statistical properties of the produced time series can be analysed for detecting trends and significant changes of the variables. Transient hydrological scenarios have hitherto been analysed in only a few earlier studies (e.g. Minville et al. 2010).

Korhonen & Kuusisto (2010) used the Mann–Kendall test to detect trends in observed discharges and water levels in Finland until 2004. No statistically significant changes in mean annual flow were found in general, but there were clear trends in seasonal streamflow series. Winter and spring mean monthly discharges had increased in most of the observation sites. The timing of the spring peak had
become earlier in more than one-third of the sites, although the magnitude of spring high flow had not changed.

Studies of the occurrence of trends in runoff regime reveal considerable differences between the Nordic countries (Hisdal et al. 1995, 2004, 2007; Roald 1998; Lindström & Bergström 2004). Mean annual discharge has increased in some regions in Denmark and Sweden. Positive trends are also found occasionally in Norway and Finland depending on the studied time period (Hisdal et al. 2004). In the period 1941–2002, statistically significant increasing trends were found in Finland, probably because the first year of the period (1941) was the driest ever observed in many sites (Hyvärinen 2003). In Iceland, annual values of discharge do not show clear trends (Jónsdóttir et al. 2006). In Karelia, northwest Russia, the river runoff decreased during the 20th century (Filatov et al. 2005), whereas in the Baltic countries increases in winter and annual discharges were observed (Reihan et al. 2007; Klavins & Rodinov 2008). Trend analyses of long time series of large Western and Central European rivers showed no significant trends in mean annual runoff, but revealed a cyclic occurrence of dry and wet periods (Pekárová et al. 2003). In North America statistically significant increases in streamflow were observed in rivers in the Great Lakes Basin (McBean & Motiee 2008), and a shift to earlier spring floods was observed in some rivers in Canada (Cunderlik & Ouarda 2009).

A variety of transient RCM results across Europe has recently become available through the ENSEMBLES project (Hewitt 2005; van der Linden & Mitchell 2009). The ENSEMBLES scenarios cover the years 1951–2050 or 1951–2099/2100 and thus enable transient simulation of climate change impacts on the processes driven by meteorological conditions (Hewitt 2005). The increases in horizontal resolution and improvements in the physical content and parameterisation of both RCMs and GCMs have to some extent improved the model reproduction of historical meteorological observations (Boberg et al. 2010). However, there are still systematic biases in RCM results (Jacob et al. 2007; Lind & Kjellström 2009). Many of the biases are inherited from the GCMs used as boundary conditions, but in some cases the RCM itself even enhances the biases, as shown by Kjellström & Lind (2009).

Methods for downscaling climate model results to local scales that are appropriate for use in off-line hydrological modelling at catchment scales have been extensively studied (see, for example, the review by Fowler et al. 2007). Several studies have compared different statistical and dynamical downscaling methods (Wood et al. 2004; Diaz-Nieto & Wilby 2005; Salathé 2005; Fowler et al. 2007; Graham et al. 2007; Lenderink et al. 2007; Beldring et al. 2008; van Pelt et al. 2009; Seguí et al. 2010). Along with the increasing number of available RCM scenarios, the use of these dynamically downscaled scenarios as direct input to the hydrological model has become more common (e.g. Graham et al. 2007; Lenderink et al. 2007; Beldring et al. 2008). Compared to the previously common delta change approach, the use of dynamically downscaled data from RCMs has the advantage of representing not only the changes in mean values of the climatic variables, but also the changes in their variability (Graham et al. 2007). This makes the dynamical downscaling more attractive, especially when extremes such as extreme precipitation, floods and droughts are of interest, since in these cases the variability is usually more important than averages (Katz & Brown 1992). However, the hydrological simulations are sensitive to systematic biases in the RCM results, particularly in regions where seasonal snowpack causes a time shift in runoff generation from one season to another (Wood et al. 2004). Hydrological simulations must be able to reproduce the historical conditions in order to be reliable and to produce plausible future projections (Wood et al. 2004). In most cases a bias correction on a monthly time scale is needed to match the modelled and observed hydrological conditions (Fowler & Kilsby 2007). Several bias correction methods have been proposed and to some extent compared (Wood et al. 2004; Diaz-Nieto & Wilby 2005; Graham et al. 2007; Lenderink et al. 2007; Beldring et al. 2008). The choice of the bias correction method influences the results, especially in the simulation of extremes (Graham et al. 2007; Fowler et al. 2007). Fowler et al. (2007) noted that different climatic conditions may require different downscaling methods, and that the suitability of the downscaling method needs to be individually assessed.

Climate change impacts the entire water cycle from precipitation to evaporation, snow accumulation, snowmelt, runoff, and soil and ground water fluxes. In order to understand changes in runoff generation it is important to explore the other components of the water cycle as well. Changes in
water balance components simulated by the hydrological model, and reflection of these changes against the corresponding variables from a climate model, can offer insight into the functioning of the models and their reliability.

The objective was to use transient climate scenarios in order to simulate climate change impacts on water balance components and river discharge in four catchments in different parts of Finland and to analyse the statistical properties of the simulated discharge series. Trends in long transient simulations were examined and compared to the observed trends. RCM-simulated temperature and precipitation series from four scenarios were bias corrected with the quantile-quantile mapping method (Déqué 2007; Seguí et al. 2010) and used as input to a conceptual hydrological model. The simulated hydrology was validated against observations from the period 1961 to 2000. Transient simulations from 1951 to 2099 were produced and the trends in annual and seasonal discharge and high and low flow series were analysed.

Study area

Finland is situated in the transitional zone between maritime and continental climates. The air temperature gradient from north to south is strong, especially during winter (Figure 1(b)), which affects the accumulation and melt patterns of snow. In southern Finland the air temperatures in winter often fluctuate close to 0 °C, which makes the snow processes sensitive to small changes in temperature.

Finland can be divided into three hydrological regions (Figure 1(a), Hyvärinen & Puupponen 1986; Korhonen & Kuusisto 2010): the northern rivers, the lake area, and the coastal rivers. In the large northern rivers the seasonality is strong and a large part of annual runoff as well as all the major floods are produced by the spring snowmelt. In the small- and medium-sized rivers in the coastal areas with only few lakes, both flood and drought periods are common and, especially in the southern coastal zone, floods can occur at any time of the year. In the large watersheds in the lake area the large storage volume of numerous lakes modulates seasonal discharge variations (Korhonen & Kuusisto 2010).

In this study we focus on four watersheds in different parts of Finland: Juutuanjoki, Nilakka, Kitusjärvi and Hypöistenkoski (Figure 1(a)). The following criteria were used to select the sites: (1) each site represents a different type of area in Finland, (2) the watershed areas did not include regulated lakes, (3) river discharge observations

![Figure 1](http://iwaponline.com/jwcc/article-pdf/3/1/55/375300/55.pdf)
from 1951 onwards were available, and (4) the watershed was independent of other selected areas and was included in a study by Korhonen & Kuusisto (2010), thus enabling comparisons against their results. The watersheds represent the three main hydrological regions in Finland (Figure 1(a)) with different hydrological regimes and water balance; the snow-dominated northern rivers (Juutuanjoki), the lake region (Nilakka and Kitusjärvi, larger and smaller lake) and the small coastal rivers (Hypöistenkoski).

All the sites had discharge observation for at least 62 years starting from the year 1948. The catchment area of the sites is between 350 km² (Hypöistenkoski, d in Figure 1(a)) and 5,160 km² (Juutuanjoki, a in Figure 1(a)) and the lake percentage varies from 0% (Hypöistenkoski, d in Figure 1(a)) to 18% (Nilakka, b in Figure 1(a)). The characteristics of the study areas are presented in Table 1.

Korhonen & Kuusisto (2010) analysed long-term trends in mean annual (calendar year) discharge, high flow, low flow, timing of the peak flow, and mean monthly discharge, as well as mean seasonal (winter/DFJ, spring/MAM, summer/JJA, autumn/SON) discharge at several discharge sites. Only a few significant trends in these variables were found at the sites included in this study.

At the northernmost site, Juutuanjoki, no overall changes in discharges during the period 1921–2004 were detected. However, the timing of the spring peak had become earlier and the mean January discharge decreased. At Nilakka lake outlet, in the central part of the country, statistically significant changes were not found for the observation period 1896–2004, except that the April mean discharge increased over this period of 109 years. Another lake outlet in central Finland, Kitusjärvi, did not show any statistically significant changes for the time period 1911–2004. The southern river site, Hypöistenkoski, showed an increase in some winter/spring and summer month mean discharges (February and March, June and July) in 1948–2004.

**METHODS**

Figure 2 shows the schematic representation of the study methodology, which includes the following steps: compilation of climate scenarios from RCMs, implementation of the bias correction for each RCM daily dataset, hydrological modelling and statistical analysis. These steps are described in more detail in the following sections.

**Climate scenarios**

The four climate scenarios used in this study were obtained from the ENSEMBLES data archive (Hewitt 2005; van der Linden & Mitchell 2009). Daily air temperature and precipitation series from the RCMs were obtained from a 0.25 degree grid over Finland. The four scenarios are from four RCMs with three driving GCMs (Table 2) and were produced using the A1B emission scenario (IPCC 2000). From the UKMO-HadCM3 GCM there are two versions with different permuted parameter sets (Collins et al. 2005): the standard version (mean sensitivity) and the low sensitivity version, which produces lower increase in temperature by the end of the twenty-first century (Table 2). Use of scenarios from several GCMs is recommended (e.g. Christensen &

<table>
<thead>
<tr>
<th>Letter in map</th>
<th>Study site, river</th>
<th>Type (hydrological region, lake/river)</th>
<th>Discharge observations since</th>
<th>Catchment area (km²)</th>
<th>Lake percentage (%)</th>
<th>MQ 1961–2000 (m³/s)</th>
<th>Average max snow water equivalent 1961–2000 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Saukkoniva Juutuanjoki</td>
<td>Northern, river</td>
<td>1921</td>
<td>5,160</td>
<td>5</td>
<td>58</td>
<td>182</td>
</tr>
<tr>
<td>b</td>
<td>Nilakka</td>
<td>Lake area, lake outflow</td>
<td>1896</td>
<td>2,157</td>
<td>18</td>
<td>20</td>
<td>134</td>
</tr>
<tr>
<td>c</td>
<td>Kitusjärvi</td>
<td>Lake area, lake outflow</td>
<td>1911</td>
<td>550</td>
<td>10</td>
<td>5.6</td>
<td>135</td>
</tr>
<tr>
<td>d</td>
<td>Hypöistenkoski Aurajoki</td>
<td>Coastal area, river</td>
<td>1948</td>
<td>350</td>
<td>0</td>
<td>3.5</td>
<td>97</td>
</tr>
</tbody>
</table>
Christensen 2007; Prudhomme & Davies 2009), since the results from different GCMs can vary markedly. Prudhomme & Davies (2009) suggested that even three GCMs can provide a reasonable envelope of variability. Only one emission scenario (A1B) was used, since this is the emission scenario available in the ENSEMBLES data archive. In Finland, scenarios with higher greenhouse gas emissions (e.g. A2) would lead to larger increases in projected temperature and precipitation, especially during winter (Ruosteenoja 2007), and thus larger changes in the water balance components and discharges, while the opposite would be true for emission scenarios with lower emissions (e.g. B1). Previous studies reveal that the differences between emission scenarios with the same climate model are often smaller than differences between climate models with the same emission scenario (Prudhomme & Davies 2009; Veijalainen et al. 2010).

Several studies evaluate the performance of different RCMs in Europe or in Finland (Jylhä et al. 2004; Jacob et al. 2007; Lind & Kjellström 2009; Boberg et al. 2010). In recent years the performance of RCMs has improved due to the increase in resolution and improvements in model configuration of both GCMs and RCMs (Boberg et al. 2010), but especially seasonal biases still remain (Jacob et al. 2007; Lind & Kjellström 2009). Some RCMs show a warm winter bias over Scandinavia (Jacob et al. 2007) and the Baltic Sea drainage basin (Lind & Kjellström 2009). Approximately 20% systematic wet bias was found in the RCM RCA3 in the Baltic Sea drainage basin that includes most of Finland (Lind & Kjellström 2009). The interannual precipitation variability simulated by the RCMs was found to be in rather good agreement with observations (Jacob et al. 2007). Boberg et al. (2010) found mainly good agreement with the observed and RCM-simulated precipitation probability density functions (PDFs). Three RCM and GCM combinations (REMO-E, HadRM-H and HIRHAM, Table 2) that were included in both this study and in the study by Boberg et al. (2010) were among the best performing RCM and GCM combinations in Scandinavia.

In the four study sites the projected increase in temperature during the twenty-first century according to the four RCMs is between 0.35 and 0.59 °C per decade (Table 2) and the temperature increases are higher in winter than in summer. Precipitation increase is between 1.0 and 2.5% per decade.

Table 2 | Climate scenarios used in the study and their projected changes per decade in the study sites by 2099

<table>
<thead>
<tr>
<th>GCM</th>
<th>RCM</th>
<th>Emission scenario</th>
<th>Abbreviation</th>
<th>T change (°C/decade)</th>
<th>P change (%)/decade</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECHAM5/MPI-OM</td>
<td>REMO-E</td>
<td>A1B</td>
<td>REMO-E</td>
<td>0.47</td>
<td>1.0</td>
</tr>
<tr>
<td>UKMO-HadCM3 (low sensitivity)</td>
<td>RCA3-H</td>
<td>A1B</td>
<td>RCA3-H</td>
<td>0.35</td>
<td>2.5</td>
</tr>
<tr>
<td>UKMO-HadCM3 (mean sensitivity)</td>
<td>HadRM-H</td>
<td>A1B</td>
<td>HadRM-H</td>
<td>0.59</td>
<td>1.8</td>
</tr>
<tr>
<td>ARPEGE(CNRM-C3)</td>
<td>HIRHAM</td>
<td>A1B</td>
<td>HIRHAM-A</td>
<td>0.38</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Daily RCM data and bias correction

The daily air temperature and precipitation simulated by the RCMs were used as input to the hydrological model after the time series were first corrected for systematic biases found in the simulation of the historical periods. The bias correction method chosen in this study was the quantile-quantile mapping (Wood et al. 2004; Boé et al. 2007; Déqué 2007; Seguí et al. 2010).

Different bias correction methods have been proposed and used in previous studies, although some studies used the RCM data without any bias correction (Arnell 2005; Dankers & Feyen 2008). The simplest method is to use a seasonal or monthly correction factor to match the mean of the RCM data to the observed mean values (Graham et al. 2007; Lenderink et al. 2007), but this procedure easily leaves large biases in the distribution of the values. Other methods used for the bias correction were introduced by Leander & Buishand (2007), who corrected both mean and variance of temperature and precipitation and by Hay et al. (2002), Piani et al. (2010) and Yang et al. (2010), who assumed precipitation to be gamma distributed and corrected the parameters of this distribution.

The plan in this study was to use a relatively simple but effective bias correction method that reproduces the observed hydrological fluxes in the control period for all the four climate scenarios. As the tails of the distribution often play the most important role in hydrological applications, the methods having variable bias correction in different parts of the distribution are most suitable (Déqué 2007). Hydrological simulations are sensitive to biases in air temperature and precipitation, especially when seasonal snowpack temporarily stores precipitation from one season to another (Wood et al. 2004). Therefore, nearly all local biases must be removed from the climate inputs (Wood et al. 2004).

The bias correction method adopted in this study is the quantile-quantile mapping, which was recently used in several studies (Wood et al. 2004; Boé et al. 2007; Déqué 2007; Seguí et al. 2010). In this method the simulated distributions (in practice the cumulative density functions (CDFs)) of air temperature and precipitation are corrected to match their observed distributions. A correction function with differences between the simulated and observed CDFs is made up for all 99 percentiles and a linear interpolation is performed between the percentiles. Outside the 99% range the value of the closest quantile is used.

The measured and simulated meteorological variables were made comparable in the following way. The catchment area in the hydrological model was subdivided into sub-catchment areas, and areal values of the observed meteorological variables for these sub-catchments were calculated from the four closest observation sites for the period 1961–2000. Correction factors for rain and snow were used to account for the differences in precipitation gauging errors for liquid and solid precipitation. These areal values were then used to compute average observed meteorological variables for 0.25 degree grid cells corresponding to the RCM grids. The observed values were finally compared to the RCM-simulated values and corrections were calculated in the resolution of the RCMs in a 0.25 degree grid on a daily level. The areal values used as input for the watershed model were calculated on the basis of the corrected RCM-simulated temperature and precipitation values of the four closest grid cells for each sub-catchment. The control period used to calculate the correction function was 1961–2000. The bias in the model distribution depends on the season (Boé et al. 2007) and therefore the bias correction was carried out separately for different times of year. To avoid problems in the transition between seasons, the corrections were calculated for each month as a three-month moving average (Leander & Buishand 2007). The same bias corrections estimated for 1961–2000 were applied to the entire period 1951–2099. The assumption is that the correction function remains constant with time (Seguí et al. 2010).

Hydrological modelling

The simulations were performed with the Watershed Simulation and Forecasting System (WSFS) developed and operated at the Finnish Environment Institute (Vehviläinen et al. 2005). The WSFS is used in Finland for operational hydrological and flood forecasting, flood warnings and research purposes (www.environment.fi/waterforecast/). The main part of the WSFS is a conceptual soil moisture accounting routine of the type of the HBV-model (Bergström 1976). HBV is the most commonly used rainfall-runoff model type in Scandinavia (e.g. Vehviläinen & Huttunen 1997; Andréasson et al. 2004; Beldring et al. 2008) and its
derivatives have widely been used for estimating climate change impacts on hydrology (e.g. Andréasson et al. 2004; Steele-Dunne et al. 2008; van Pelt et al. 2009).

The WSFS is semi-distributed as it divides the watersheds into small lumped sub-catchments (−40–500 km²) with their own parameters and water balance simulation. The WSFS was calibrated against observations of snow water equivalent, water level and discharge from 1986 to 2009. Only one optimal parameter set for each catchment was used in the modelling.

Potential evapotranspiration from the climate models was not used since it was not available from all the models in the ENSEMBLES data archive. The potential evapotranspiration was calculated in the WSFS with empirical equations as a function of air temperature, precipitation and date (Vehviläinen et al. 2005). The empirical equations have been calibrated with Class A pan evaporation measurements. This simple method was assumed to be sufficient for the purposes of producing the hydrological scenarios, although the method does not consider all the factors affecting evapotranspiration in changing climate. The uncertainties associated with this assumption are discussed below in the section Uncertainty.

Statistical analysis methods

Trend analysis was applied to detect changes in annual mean discharges (calendar year), monthly mean and seasonal mean discharges (winter (DJF), spring (MAM), summer (JJA), autumn (SON)), and annual maximum and minimum flows. The significance of the trends was tested with a non-parametric Mann–Kendall trend test using 5% as the risk level. Trend magnitude was calculated using a non-parametric linear Sen’s slope estimator (Sen 1968). The result of the Mann–Kendall test depends strongly on the autocorrelation. When there is a positive autocorrelation in the time series, the test rejects the null hypothesis more often than without autocorrelation (von Storch & Navarra 1993). Autocorrelation from the time series was removed if it was statistically significant (p < 0.05) by using the pre-whitening method of Wang & Swail (2001). The trend significance was tested for the pre-whitened data set.

RESULTS

Validation for temperature and precipitation

The quantile–quantile mapping bias correction removed most of the bias in temperature and precipitation (Table 3). The average bias of the uncorrected temperature, −2.2 to +0.9°C, was removed almost completely and the precipitation bias, which was +10 to +33% before correction, was reduced to −3% compared to observed precipitation. The difference between standard deviation of observed and RCM-simulated values was improved considerably for temperature, but for precipitation the standard deviation of the corrected values was slightly underestimated. The remaining difference between observed and simulated precipitation series was partly caused by the difference in the most extreme precipitation values. The last percentile of precipitation was corrected only on the basis of the difference between the observed and simulated 99 percentile values. As the highest 1% of precipitation can include approximately 10–15% of the three month precipitation sum, a difference in this percentile affects the average values. The role of the extreme precipitation values became most visible in the smallest catchment on the coast (Hypöistenkoski), where the difference between mean observed and simulated in precipitation was greatest and where precipitation extremes were greater than in other catchments.

Figure 3 shows the distribution of biases with four uncorrected climate scenarios in one study site during summer and winter. The biases were different in different seasons, models and in different parts of the distribution. In most scenarios the greatest temperature biases were in the lowest winter temperatures. After the bias correction the biases were close to zero.

The simulation of snow improved when the bias corrected RCM temperature and precipitation were used as
input of the hydrological model compared to when the uncorrected RCM temperature and precipitation were used (Table 3). Without bias correction the average maximum snow water equivalent for the study sites was overestimated by 34–70% compared with the values simulated with WSFS using the observed temperature and precipitation series. With the bias correction the differences were much smaller, from −26 to +1%. The correction of precipitation caused greater reduction in bias than the correction of air temperature.

Validation of simulated discharges

The ability of the hydrological model to reproduce the observed discharges when the observed air temperature and precipitation were used as input was assessed based on the Nash–Sutcliffe efficiency criterion $R^2$ (Nash & Sutcliffe 1970), which was on average 0.82 and varied from 0.67 to 0.89 in the study sites for the control period 1961–2000. For the calibration period 1986–2009 the Nash–Sutcliffe efficiency criteria $R^2$ was on average 0.83 (0.61–0.92) and for the validation period 1961–1985 0.81 (0.71–0.89). The volume error was on average −4% and varied between −10 and +0%.

Table 4 shows a comparison between the mean annual discharge, annual high flow and annual low flow that are produced from observations, simulated with observed meteorological variables as input, and simulated with bias corrected RCM input data. The mean annual discharge simulated using the bias corrected RCM input was 2–3% smaller than the corresponding discharge simulated with observed input. The mean discharge simulated with the observed input was approximately 5% lower than the observed mean discharge. The mean annual high flows simulated with the bias corrected RCM input were on average 8% lower (−27 to +14%) than the observed values. The hydrological model tends to underestimate the mean annual minimum discharge with both observed and RCM-based temperature and precipitation. The results with the RCM data, however, correspond well to the results produced with the observed temperature and precipitation input. In Hypöistenkoski, the poor measurement accuracy during low flows is likely to contribute to the differences between observed and modelled values. The differences were partly caused by the structural and parameter uncertainty of the hydrological model and partly by the underestimation of the bias corrected precipitations compared to observations (Table 3). In addition, the small scale
extreme precipitation events and the high flows caused by them may have been underestimated due to the spatial scale of the RCMs on the two study sites with small catchment areas (Kitusjärvi and Hypöistenkoski).

Without bias correction the mean annual discharge was overestimated by 15–63% with different scenarios. The correction of precipitation removed most of the biases, but the bias correction of temperature was important to match the timing of the spring runoff peak and the magnitude of winter runoff with the observed values (Figure 4). As shown in Figure 4, the bias correction improved the simulated discharge markedly, although some differences remained between the observations and the values simulated with the bias corrected RCM input.

The mean annual discharge from the bias corrected simulations did not differ from the observations when tested with Student’s t-test at 5% confidence level. However, there were some significant differences in the seasonal mean...
discharges: the simulated winter discharge of river Juutuanjoki differed from observed discharge in all hydrological model simulations, both with observed and bias corrected RCM input, and the spring discharge did not match the observations with the input from the HadRM-H scenario. In Hypöistenkoski the summer discharge differed from observations in all scenarios and spring discharge in the RCA3-H scenario. In Nilakka the summer discharge differed from observations in the RCA3-H scenario.

Changes in runoff

Figure 5 shows the annual predicted changes in the water balance components in the study sites during the twenty-first century. Precipitation increased in all sites and scenarios except for one scenario (HIRH-A) in Hypöistenkoski in southern Finland. Potential evapotranspiration (PET) and actual evapotranspiration (ET) increased with all the scenarios. Increases in ET were smaller than in PET, because decreasing soil moisture (not shown) in summer limits the increase of ET. Soil moisture (not shown) starts to decrease earlier in the summer due to earlier snowmelt and the moisture reaches a lower level during summer and early autumn as a result of the increasing length of the growing season. A similar pattern is found in ground water levels (not shown), which decrease to deeper levels during longer growing seasons. The ground water level during winter increases when the length of the snow-cover period decreases. Because of the increased ET the changes in runoff were smaller than the changes in precipitation; the average increase in runoff was 61 mm (18%) in river Juutuanjoki in northern Finland, and 31–44 mm (10–14%) in the sites in southern and central Finland. Even though only four climate scenarios were considered, the range of

Table 4 | Comparison of the observed and simulated mean annual discharge (MQ), mean annual maximum discharge (MHQ) and mean annual minimum discharge (MNQ) in the control period 1961–2000. Simulated values were calculated with observed temperature and precipitation (Obs T & P) or bias corrected RCM temperature and precipitation from four climate scenarios (see Table 2) as input to the hydrological model

<table>
<thead>
<tr>
<th></th>
<th>(a) Juutuanjoki (m³/s)</th>
<th>(b) Nilakka (m³/s)</th>
<th>(c) Kitusjärvi (m³/s)</th>
<th>(d) Hypöistenkoski (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Obs MQ 1961–2000</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sim MQ 1961–2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obs T &amp; P</td>
<td>52.5</td>
<td>19.2</td>
<td>5.49</td>
<td>3.50</td>
</tr>
<tr>
<td>RCM REMO-E</td>
<td>50.9</td>
<td>19.4</td>
<td>5.59</td>
<td>3.12</td>
</tr>
<tr>
<td>RCM RCA3-H</td>
<td>51.8</td>
<td>19.0</td>
<td>5.54</td>
<td>3.11</td>
</tr>
<tr>
<td>RCM HadRM-H</td>
<td>51.7</td>
<td>19.0</td>
<td>5.54</td>
<td>3.11</td>
</tr>
<tr>
<td>RCM HIRH-A</td>
<td>52.3</td>
<td>19.1</td>
<td>5.54</td>
<td>3.16</td>
</tr>
<tr>
<td><strong>Obs MHQ 1961–2000</strong></td>
<td>339</td>
<td>39.7</td>
<td>20.3</td>
<td>52.2</td>
</tr>
<tr>
<td>Sim MHQ 1961–2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obs T &amp; P</td>
<td>326</td>
<td>37.2</td>
<td>20.9</td>
<td>47.8</td>
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<td>16.4</td>
<td>38.2</td>
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<td>342</td>
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<td>18.5</td>
<td>39.2</td>
</tr>
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<td>37.4</td>
<td>20.7</td>
<td>45.3</td>
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<td>10.5</td>
<td>1.52</td>
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</tr>
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<td></td>
<td></td>
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<tr>
<td>Obs T &amp; P</td>
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<td>10.2</td>
<td>1.21</td>
<td>0.02</td>
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<tr>
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<td>9.43</td>
<td>1.08</td>
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<td>9.72</td>
<td>1.18</td>
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</table>
precipitation and runoff change was wide. Change in runoff ranged from $-18$ to $+46\%$ and the range of change was the widest in Hypöistenkoski in southern Finland, where the range of precipitation change was also widest. Most of the average runoff increase in the three other sites, excluding Juutuanjoki, already occurred during 2001–2030 and remained on average almost unchanged during the rest of the century.

In addition to the changes in mean annual discharges, there were also changes in the seasonal values (Figure 6). In all watersheds the simulated mean winter discharge increased (26–144% by 2061–2099 compared to 1961–2000) and the spring discharge peak caused by snowmelt occurred earlier (11–39 days). In the southernmost watershed Hypöistenkoski (d), the mean spring discharge decreased clearly (36–63%), whereas in the more northern sites Nilakka and Juutuanjoki spring (MAM) discharges increased (37–158%), due to snowmelt runoff occurring earlier during the spring rather than in the summer months.
For the same reason the summer runoff of these northern sites decreased (5–53%), whereas in Hypöistenkoski there were changes in both directions in summer (−64 to +144%) depending on the scenario.

Statistical analysis of transient scenarios for trends in annual and seasonal mean discharge revealed statistically significant seasonal trends, but also differences in the results between sites and scenarios (Table 5, Figure 7). Trends became most visible when the longest period (1951–2099) was analysed. There were statistically significant trends in mean annual discharge in 1951–2099, with seven out of 16 scenarios. One scenario, the RCA3-H scenario, which had the largest increases in precipitation, produced increases in all four sites. With the other scenarios there were only two increases in the mean annual discharge, in river Juutuanjoki with the HadRM-H and HIRH-A scenarios and one decrease in Hypöistenkoski with the HIRH-A scenario. River Juutuanjoki is therefore the only site where the majority of the

(Figure 6).
scenarios (three out of four) produced a significant increase in mean annual discharge. This result is explained by the greater increase in precipitation in HadRM-H and HIRH-A scenarios in northern Finland (18–35% by the end of the century) than in other parts of Finland (–2 to 19%).

The clearest trend was the increase of winter discharge, which was statistically significant in all the sites and all the scenarios in 1951–2099 (Table 5, Figure 8). Summer discharge decreased in all sites with at least three scenarios, but with the wet RCA3-H scenario there was an increase in Hypöistenkoski. Spring discharge increased with all scenarios in Juutuanjoki and Nilakka. This is because the spring snowmelt season currently lasts in these sites until early summer in June (Figure 6), but in the future the snowmelt season shifts earlier and occurs mainly during the spring months from March to May. In Juutuanjoki the late timing of snowmelt is due to its northern location, whereas in Nilakka large lakes cause delay in the discharge. In Hypöistenkoski the spring discharge decreased as less snow accumulated during winter and spring snowmelt decreased.
During autumn the scenarios produced inconsistent results as both increased and decreased discharges were simulated in three of the four sites. Juutuanjoki showed increasing autumn discharges with all scenarios, while in the other sites one scenario (RCA3-H) produced a positive trend and the other scenarios showed either no significant change or a negative trend.

The trends were also analysed for 1951–2050 and for 1961–2004, the latter corresponding to the time period used to analyse trends from the observed discharge series (Korhonen & Kuusisto 2010). In 1951–2050 the trends were similar to the longer time series, but as could be expected there was a lower number of significant trends. In Kitusjärvi and Nilakka the HIRH-A scenario gave an increase in mean annual discharge in 1951–1950, whereas no trend appeared in the longer time series with this scenario (Figures 7(h) and (l)).

There were only a few significant trends in 1961–2004 and they were mostly found in the southern sites. Kitusjärvi showed an increase in the mean annual discharge with two scenarios and Hypöistenkoski with one scenario. The trends in seasonal discharges were equally rare. In observed discharges of 1961–2004, there were statistically significant trends only in the winter discharge in Hypöistenkoski (Korhonen & Kuusisto 2010).

Lag-1 autocorrelations for all scenarios in 1951–2099 were tested and the following significant autocorrelations were found. In Juutuanjoki, minimum, winter and spring flows were autocorrelated with a one year lag in every scenario. In Nilakka, mean annual, spring and summer flows were autocorrelated in three scenarios. In Kitusjärvi, autocorrelation existed in winter flows in all scenarios and in summer flows in three out of the four scenarios. In Hypöistenkoski, winter and spring flows were autocorrelated in each scenario.

<table>
<thead>
<tr>
<th>1 Juutuanjoki</th>
<th>2 Nilakka</th>
<th>3 Kitusjärvi</th>
<th>4 Hypöistenkoski</th>
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</thead>
<tbody>
<tr>
<td><strong>1951–2099</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean annual discharge (%)</td>
<td>+75</td>
<td>+25</td>
<td>+25</td>
</tr>
<tr>
<td>Mean seasonal discharge</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Winter (%)</td>
<td>+100</td>
<td>+100</td>
<td>+100</td>
</tr>
<tr>
<td>Spring (%)</td>
<td>+100</td>
<td>+100</td>
<td>+25</td>
</tr>
<tr>
<td>Summer (%)</td>
<td>−100</td>
<td>−75</td>
<td>−75</td>
</tr>
<tr>
<td>Autumn (%)</td>
<td>+100</td>
<td>−75/+25</td>
<td>+25/−25</td>
</tr>
<tr>
<td><strong>1951–2050</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean annual discharge (%)</td>
<td>+50</td>
<td>+50</td>
<td>+50</td>
</tr>
<tr>
<td>Mean seasonal discharge</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Winter (%)</td>
<td>+100</td>
<td>+75</td>
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</tr>
<tr>
<td>Spring (%)</td>
<td>+100</td>
<td>+100</td>
<td>0</td>
</tr>
<tr>
<td>Summer (%)</td>
<td>−50</td>
<td>−25</td>
<td>−25</td>
</tr>
<tr>
<td>Autumn (%)</td>
<td>+25</td>
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<td>+25</td>
</tr>
<tr>
<td><strong>1961–2004</strong></td>
<td></td>
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<tr>
<td>Mean annual discharge (%)</td>
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<td>0</td>
<td>+50</td>
</tr>
<tr>
<td>Mean seasonal discharge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter (%)</td>
<td>0</td>
<td>0</td>
<td>+25</td>
</tr>
<tr>
<td>Spring (%)</td>
<td>0</td>
<td>+50</td>
<td>+25</td>
</tr>
<tr>
<td>Summer (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Autumn (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Autumn flows were least autocorrelated compared to other variables in all sites and scenarios. Eliminating the autocorrelation effect (pre-whitening) did not change the trend results in any case. For shorter time period simulations (1961–2004) no autocorrelations of lag-1 were found in general.

In addition to serial autocorrelation, the correlations for the scenario data of 1951–2099 with all variables between different study sites were examined. It is obvious that the two closest lake outlet sites (Kitusjärvi and Nilakka) had strong correlations ($r > 0.5$) in all scenarios and all variables. Kitusjärvi and Hypöistenkoski had a rather strong correlation in most scenarios and most variables. The northernmost site, Juutuanjoki, did not generally correlate with the other sites.
Changes in high and low flows

Statistical analysis of trends in annual maximum high flows in 1951–2099 showed significant trends in half of the scenarios and no change in the other half (Table 6, Figure 9). The stimulated maximum discharges in Nilakka increased with two scenarios, caused by the increase of autumn and winter floods. In the other three sites the significant trends were decreasing and were related to the decreases in spring snowmelt floods. Hypöistenkoski was the only site where the majority of scenarios (three out of four) produced significant trends. In 1951–2050 the trends were in the same direction as in 1951–2099, but only a quarter of the scenarios produced significant changes.
During 1951–2099 the annual minimum discharge increased in Juutuanjoki with all scenarios, because of an increase in winter discharge (Table 6). In Nilakka, three out of four scenarios showed no trend and one scenario a decreasing trend, whereas in Kitusjärvi there were both increases and decreases in the minimum discharge. In Hypöistenkoski, this analysis could not be performed because the modelled minimum discharges were too low (less than 0.1 m³/s) for analysis with the program used.

## DISCUSSION

The RCM-simulated precipitation and air temperature contain systematic biases (e.g. Jacob et al. 2007), which are not uniform throughout the range of the precipitation and temperature distribution (Figure 3, Déqué 2007). For example, the REMO-E model has a large warm bias in cold temperatures in winter, but hardly any bias in the warmest winter temperatures. Correction of only mean monthly or seasonal values to match the observed mean (e.g. Fowler & Kilsby 2007; Graham et al. 2007; Lenderink et al. 2007) imparts bias to the different percentiles of the distribution of a meteorological variable. Since climate model biases vary between different models, a bias correction developed for one RCM and GCM may not function properly for another RCM and GCM.

Salathé (2005) compared results of simple bias correction of mean monthly values of three GCMs and noted that one GCM performed well with this simple correction whereas the other two models yielded results that differed from observed hydrology. Salathé concluded that the application of a simple local scaling exposes the capacity of the model to simulate the current conditions. In this study, the simpler bias correction methods were not adopted because the simulated discharge differed unacceptably from the observed discharge, at least with some scenarios and sites. The biases in different models are so different that the simple methods do not function in all the scenarios and sites (Figure 3). To remove the biases in the distribution of temperature and precipitation (Déqué 2007) a more complicated bias correction, in this case quantile–quantile mapping, was needed. The use of several models in climate change impact studies is also strongly recommended (e.g. Prudhomme & Davies 2009) and therefore there is a trade-off between the number of scenarios producing acceptable results and the simplicity of the bias correction method.

In many previous studies (e.g. Leander & Buishand 2007), more emphasis has been given to the correction of precipitation since it is the primary cause of floods in many regions. In regions where snow accumulation and melting have an important role in the water balance and where winter temperatures typically fluctuate close to 0 °C, the maximum temperatures during winter and spring largely control runoff generation of these seasons (Hay et al. 2002). Thus, even relatively small persistent temperature biases in the upper quantiles of the temperature range strongly affect snow accumulation. In these areas correction of air
temperature becomes as important for correct simulation of runoff seasonality and floods as the correction of precipitation (Hay et al. 2002; Wood et al. 2004).

The overestimation of the annual mean discharge and high flows simulated with uncorrected RCM input is mainly due to the systematic overestimation of precipitation by 10–33% compared with the observed values (Table 3).

After bias correction, some differences still remained between the seasonal simulated and observed discharges. The differences are explained by the combined influence of several factors, such as the performance of the hydrological model, the remaining biases in the autocorrelations and spatial patterns of precipitation and temperature, the correction of extreme 1% in the precipitation distribution, the
spatial scale of the RCM precipitations, the corrections in grid form and the interpolation from grids to areal values. In some cases there can even be problems with observations. For example, the rating curve used to calculate discharge from the observed water level in Hypöistenkoski does not continue below 0.1 m³/s and as a result the measurement accuracy of the low flows poor. Rating curve extrapolation also causes uncertainty in the flood discharge estimation. Wood et al. (2004) used the same methodology for bias correction of GCM and RCM data and found that the independent correction of temperature and precipitation failed to correct the more subtle differences between climate model simulated and observed climate. There is still a need for further development and evaluation of the bias correction method, and this work will continue in future studies.

The results concerning future runoff dynamics are in line with previous findings from climate change impact studies in Finland and other Nordic countries (Veijalainen & Huttunen 1997; Andréasson et al. 2004; Beldring et al. 2006, 2008; Graham et al. 2007; Schneiderman et al. 2010). The main message is the same in all these studies performed with variable methods and models: winter discharges increase and spring snowmelt flow peaks occur earlier. This also corresponds to the trends found in observed time series (Hisdal et al. 2007; Korhonen & Kuusisto 2010). An increase in autumn runoff and decrease in summer runoff were also reported by Andréasson et al. (2004), Graham et al. (2007) and Beldring et al. (2008). Annual mean runoff is projected to increase in northern Sweden, whereas different scenarios produce both increases and decreases in southern Sweden (Andréasson et al. 2004), which corresponds well to the changes in runoff in this study (Figure 5). Results using the delta change approach in Finland (Veijalainen et al. 2010) produced qualitatively similar changes to the hydrographs shown in Figure 6. A study in Canada using transient bias corrected RCM input to a hydrological model showed a positive trend in annual and seasonal hydropower production by 2099, which was closely related to the future increase in discharge (Minville et al. 2010).

Veijalainen & Huttunen (1997) estimated changes in water balance components in ten watersheds in Finland by 2100 with an earlier version of the WSFS model. Their results showed a similar change in evapotranspiration to that found in this study, but since the climate scenario used had smaller increases in precipitation, the increases in annual runoff were smaller than in Figure 5. As both studies used the same evapotranspiration formula, the similarities are to be expected. Changes in potential evapotranspiration and evaporation by 2071–2100 in Mustajoki (a small river in southern Finland) included in a study by Schneiderman et al. (2010) were similar to the results of this study (Figure 5) with greater increases (10–35%) and variability in potential evapotranspiration than in evaporation (5–15% increases). The changes in streamflow (2–45%) in Mustajoki predicted by Schneiderman et al. (2010) were also rather similar to the values found in this study (−18 to +46%).

Although the return periods of the floods are quite different, the changes in annual high flows in the four study sites are similar to changes in 100 year floods estimated with the delta change approach for 67 sites, including the catchments of the current study (Veijalainen et al. 2010). In both studies the floods remained unchanged or decreased in most sites except for the large lakes (Nilakka), where the floods remained unchanged or increased.

Uncertainty

The assumptions and methods adopted in this study affect the results. Climate scenarios are a major source of uncertainty and the use of even four different scenarios produces a wide range of uncertainty in the output hydrological variables. Previous studies report the GCMs as the largest or one of the largest sources of uncertainty (e.g. Minville et al. 2008; Steele-Dunne et al. 2008; Prudhomme & Davies 2009). Four climate scenarios from four RCMs with three driving GCMs were used in the study to enable quantification of the uncertainties caused by the climate models to some extent. Different scenarios provide a wide range of results, clearly emphasising the problems that appear when relying on results from a single model. The use of several climate scenarios from different GCMs is strongly recommended (Prudhomme & Davies 2009). All the RCMs use the same emission scenario (A1B) and therefore the uncertainties arising from the emission scenario cannot be assessed.

Bias correction of the RCM data adds another source of uncertainty to the modelling process (van Pelt et al. 2009).
and may mask deficiencies in the climate model performance (Salathé 2005). The validity of the assumption that biases of the control period still remain in future projections cannot be assessed (Hay et al. 2002; Boé et al. 2007; van Pelt et al. 2009). The method of bias correction used for the daily RCM data affects the results of changes in discharge (Steele-Dunne et al. 2008; van Pelt et al. 2009). Comparisons between different downscaling and bias correction methods have shown that the methods especially affect the extreme discharge values, as well as the mean values (Beldring et al. 2008; van Pelt et al. 2009; Seguí et al. 2010). The impact of the bias correction on uncertainty in the projections will be greater the poorer the climate model performance is in the control period (Yang et al. 2010). However, Seguí et al. (2010) noted that generally the uncertainty related to downscaling and bias correction is lower than the uncertainty related to emission scenarios and climate modelling.

The quantile–quantile mapping is an entirely empirical bias correction method which has no physical basis. Limitations of the quantile–quantile mapping method are that it does not correct the spatial pattern or the temporal properties, i.e. the autocorrelation properties of the variables, and that it corrects each variable independently, even though they are correlated (Déqué 2007; Seguí et al. 2010). The method is also rather weak in correcting the most extreme precipitations, since it offers a constant bulk correction for the most influential top 1% of the observed precipitation distribution. For extreme precipitation the use of gamma distribution (Yang et al. 2010) or double gamma distribution (Yang et al. 2010) may provide better results.

The calculations were performed with only one conceptual hydrological model and one calibrated set of parameters for each catchment. Thus the modelling uncertainty was not estimated and the parameters were assumed to be unchanged over time. The reliability of the conceptual hydrological model is diminished by the fact that in the climate change simulation it was used beyond the conditions on which it was calibrated and validated (Seibert 2005). Previous studies indicate that the hydrological modelling uncertainty can be an important, although not generally the greatest, source of uncertainty (Steele-Dunne et al. 2008; Prudhomme & Davies 2009; Lawrence & Haddeland 2011). Lawrence & Haddeland (2011) found that the HBV hydrological model parameter uncertainty contributed significantly to the overall spread of the model results, especially in rain-dominated areas in Norway.

The evapotranspiration routine used in the hydrological model was simple and limited by the fact that it does not consider changes in many of the important factors affecting potential evapotranspiration such as cloudiness, air humidity, wind, vegetation cover, length of the growing season, change in the stomatal resistance, and change in transpiration of plants caused by increase of CO2 concentrations (Wigley & Jones 1985; Betts et al. 2007). However, the future changes of these factors and their combined effect on evapotranspiration are uncertain (Beldring et al. 2008). For example, cloudiness, humidity and wind are variables that are usually not simulated reliably by climate models (IPCC 2007), and the climate change impact on plants and transpiration is even more unknown (Boorman & Sefton 1997). Some studies have suggested that ignoring the potential decrease of transpiration due to plant responses to increasing CO2 concentrations can lead to underestimation of future increase in runoff and overestimation of its decrease (Betts et al. 2007). In snow-affected regions such as Finland, the decrease of soil moisture during summer due to earlier snowmelt and higher evapotranspiration in spring causes an increase in evaporative resistance and thus a negative feedback from warming to evapotranspiration (Barnett et al. 2005). This feedback, combined with the moderately low evapotranspiration rates in Finland, cause the changes in precipitation to have a larger influence in the changes in average and high flows than the changes in evapotranspiration. However, low flows can be affected by even low differences in evapotranspiration and thus low flow results need to be interpreted with care.

Another issue not addressed in this study is the impact of land use and vegetation change on the results. Finland is predominately forested (72% of land area) and includes many peatland areas. Change of forest to agricultural land and large scale drainage of peatland areas have altered the hydrological conditions during the twentieth century (Seuna 1981; Koivusalo et al. 2008; Korhonen & Kuusisto 2010). In the future, land use change and change of forest into a different type of forest may occur in response to global warming to an extent that is reflected in the runoff generation processes. Reynard et al. (2001) found that
moderate changes in land use produced only a small difference in the response to climate change compared to unchanged land use, and that dramatic changes in land use were needed to produce large shifts in flow duration and flood frequency curves. The conceptual hydrological model used here is not really suitable to address these land use change issues, as parameter values cannot be directly attributed to physical catchment characteristics. In addition, scenarios of land use or vegetation changes extending to the end of the twenty-first century are not available for Finland.

As the long chain of modelling contains uncertainties in every step, most of which were not sampled in this study, the cumulative uncertainties in the end become very large (Menzel et al. 2006). Therefore, care is needed in the interpretation of the results and further studies of the impact of bias correction method and model parameters on uncertainty propagation should be carried out.

CONCLUSIONS

Despite some considerable recent advances in climate models and downscaling methods, the direct results from the RCMs, which are used to dynamically downscale the GCM results to smaller scale, still contain large biases (Jacob et al. 2007; Lind & Kjellström 2009). The direct use of these data as input to hydrological models leads to considerable misrepresentation of current discharge levels in catchments and potentially misleading interpretations of climate change impacts on hydrology in Finland. Precipitation is overestimated in all scenarios, and air temperature biases, especially in winter and spring, cause clear differences in the seasonality of runoff generation. The bias correction is necessary to reproduce the key statistical properties of the observed hydrology in the control period. The plan was to use a relatively simple bias correction, but one that provides satisfactory results when compared with observed discharges in annual and seasonal scale. Therefore, a more complex bias correction method of quantile–quantile mapping (Déqué 2007; Seguí et al. 2010) was used. In this method not only the mean, but the entire distribution was corrected to match observed air temperature and precipitation percentiles. The quantile–quantile bias correction markedly improved the fit of the discharges simulated with the hydrological model to the observed discharges in the control period 1961–2000. However, bias correction adds a new source of uncertainty to the results (van Pelt et al. 2009) and the validity of the correction in future is unknown (Hay et al. 2002; Boé et al. 2007; van Pelt et al. 2009). The RCM data should be improved in the future in order to enable direct use of the data without bias correction as input to the hydrological model. Until then, more attention should be paid to bias correction methods and their effects on the results.

The results show that climate change has significant seasonal impacts on hydrology in Finland, but that differences between scenarios remain considerable. The annual mean discharge does not change statistically significantly with most scenarios, except in the northernmost study site Juutuanjoki where three out of four scenarios showed an increasing trend. The most consistent result was the positive trend in winter discharge, which occurred in all sites and scenarios. Other seasonal trends, such as increase in spring discharge in the more northern sites and decrease in the southernmost site in spring discharge, were also found with all four scenarios. The clearest trends were those related to increase of temperature rather than changes in precipitation. The corresponding finding has been reported in earlier studies of observed discharges (Hisdal et al. 2007; Korhonen & Kuusisto 2010). This outcome is understandable as the projected increases in temperature are more consistent among the climate models than changes in precipitation (Barnett et al. 2005), and projected precipitation changes are in relative terms more uncertain than those of air temperature when compared to natural variability (Räisänen & Ruokolainen 2006).

The results demonstrate the need for examining several climate scenarios, since a single scenario can lead to misleading predictions of the future discharge changes. Four scenarios from three GCMs provide a reasonable range of results and enable the estimation of consistency of the results from different models, although even more scenarios would be beneficial.

Transient climate scenarios enable different types of analysis, compared to the more traditional analysis of future and control period time slices. The transient projections can offer a more realistic view of climate change, since changes in reality are expected to be gradual over time. With the
number of available transient climate scenarios increasing and their quality hopefully improving, they have potential for future use. More realistic projections in variance of meteorological variables can offer improvement for flood analysis and enable the use of non-stationary flood frequency analysis (Cox et al. 2002). The considerable uncertainties involved in this kind of analysis should, however, be considered.

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