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Climate Change Impacts on Hydropower in the Nordic countries

State of the art and discussion of principles

Report by the CWE Hydrological Models group

NVE SMHI SYKE Norwegian Meteorological Institute met.no Hydrological Service National Energy Authority

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Sten Bergström
Johan Andréasson
Stein Beldring
Bengt Carlsson
L. Phil Graham
Jóna Finndís Jónsdóttir
Kolbjørn Engeland
Merja A. Turunen
Bertel Vehviläinen
Eirik J. Førland

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E-mail: cwe@os.is – Web site: http://www.os.is/cwe

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Sten Bergström [d], Johan Andréasson [d], Stein Beldring [c], Bengt Carlsson [d], L. Phil Graham [d], Jóna Finndís Jónsdóttir[a], Kolbjørn Engeland [c], Merja A. Turunen [b], Bertel Vehviläinen [b] and Eirik J. Førland [e]	Sten Bergström
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Participating institutes:

[a] Hydrological Service, National Energy Authority, Iceland
[b] Finnish Environment Institute
[c] Norwegian Water Resources and Energy Directorate
[d] Swedish Meteorological and Hydrological Institute
[e] Norwegian Meteorological Institute

Abstract:

The research project "Climate, Water and Energy" (CWE) is a joint Nordic effort focusing on climate impact assessments in the energy sector. The project is subdivided into the following four thematic groups: Climate Scenarios, Glaciers, Hydrological Models, and Long Time Series. This report is the first deliverable from the group on Hydrological Models, which focuses on climate change impacts to hydropower. The authors include representatives from Finland, Iceland, Norway and Sweden that are actively working with assessing hydrological impacts from climate change. The report briefly summarises the present knowledge of methods for hydrological interpretation of climate change, presents existing results from Nordic studies on climate change and hydropower production, and compares different strategies for conducting hydrological impacts assessment simulations. The intention of this work is to serve as common background for further co-operation within the Nordic countries on assessing climate change impacts on hydropower systems and production.

CONTENTS

1 INTRODUCTION

The research project "Climate, Water and Energy" (CWE) is a joint Nordic effort focusing on climate impact assessments in the energy sector. The project is subdivided into four thematic groups, namely Climate Scenarios, Glaciers, Hydrological Models, and Long Time Series. The work within the group on Hydrological Models is related to climate change impacts on hydropower. Its work plan can be summarised in the following 7 points:

1. Assessment of present level of knowledge of methods for hydrological interpretation of global warming internationally and in the Nordic countries.
2. Summary of existing results from Nordic studies on climate change and hydropower production.
3. Comparison of different strategies for production of hydrological impacts assessment simulations.
4. Comparison of different hydrological models for production of hydrological impacts assessment simulations.
5. Discussion of uncertainties generated in the production chain from emission scenarios to impacts on hydropower production.
6. Production of new results based on the New Nordic Climate Scenario (NNCS) created by CWEs climate group. This work has to rely upon results from projects adjacent to CWE.
7. Recommendations for future work concerning strategies and models for production of hydrological impacts assessment simulations scenarios for the hydropower industry.

At the first meeting of the group held at Røros, in August 2002, it was decided to concentrate on points 1-3 in 2002 and to report on this work at the end of the year. The present report is thus the first delivery from the group on Hydrological Models, addressing points 1-3 in the work plan. It has been elaborated by a group of representatives from Finland, Iceland, Norway and Sweden as reflected in the list of authors. The intention is that this report shall serve as common background for the further work on points 4-7 of the work plan of the subgroup on Hydrological Models of CWE.

2 PRESENT KNOWLEDGE OF METHODS FOR HYDROLOGICAL INTERPRETATION OF GLOBAL WARMING INTERNATIONALLY AND IN THE NORDIC COUNTRIES

There are large differences in the available resources for research in the field of climate change impacts on hydrological systems and water resources throughout the world. This is illustrated by the fact that there are very few references from developing countries. Most studies have been done in countries that have national centres for climate change modelling, either on the global scale, or regional downscaling of global climate models.

2.1 Climate scenarios

Climate scenarios are created at different levels of detail and with different assumptions regarding the future development of society and corresponding emissions of greenhouse gases. This is typically done with the help of global climate models (GCMs). Currently, there exist a number of GCMs available to supply hydrological modellers with climate scenarios. The horizontal resolution of GCMs is typically 200-300 km, which is too coarse to represent many climatic features on a regional scale. Therefore, in most cases, some kind of downscaling of the scenarios is done before the signal is transferred to the hydrological models. There are also examples where direct GCM output has been used, or simply corrected for elevation biases in order to better represent the regional climate (Wilby et al., 1999). Another way of representing the future climate is through sensitivity analysis, that is, given a certain change in temperature and precipitation what are the impacts on hydrological systems? This method is sometimes referred to as "best-guess" or hypothetical scenarios (Panagoulia and Dimou, 1997). A further example of estimation of future climate is found in a study of climate change impacts in Taiwan; there, trends in the observed climate were extrapolated to create a climate scenario (Yu et al., 2002).

2.2 Hydrological models

A number of different hydrological models have been used in the field of climate change impacts and hydrological response in a changed climate. Most studies have been done on the catchment scale, which covers a large variation in basin sizes, but there have also been studies on the continental and even the global scale (Arnell, 1998; Lehner et al., 2001). Daily conceptual rainfall-runoff models have often been applied to climate change impact studies. The HBV-model is the most common such hydrological model used in the Nordic countries. It has also been used by research groups in several other countries, including Latvia, Germany, The Netherlands, China and Taiwan (Booij, 2002; Butina and Balint, 1997; Menzel and Bürger, 2002; Menzel et al., 2002; Yu et al., 2002). Examples of other models used are the IRMB model (Gellens and Roulin, 1998), the CLASSIC model (Reynard et al., 2001), the ARC/EGMO model (Müller-Wohlfeil et al., 2000) and the HSPF model (Middelkoop et al., 2001). More simple monthly water balance models have also been used and in these cases the primary interest is often changes in the seasonal pattern of runoff (Conway et al., 1996; Panagoulia and Dimou, 1997).

A common distinction in hydrological modelling is the one between physically based and conceptual models. As the conceptual models are more empirical, it has been argued that this category should be less suitable for climate change impact studies. Nevertheless it seems that this type of model is used in most applications so far. One reason could be that they have proved to be robust in many different climates and that they are easy to apply. Another could be that most of the questions of non-stationarity of the hydrological processes, for example changes in evapotranspiration, are handled by the climate models and then transferred to the hydrological model.

2.3 Interfacing climate models and hydrological models

The most common method to transfer the signal of climate change from climate models to hydrological models is the "delta change" approach (Kaczmarek et al., 1996; Lemmelä and Helenius, 1998; Lettenmaier et al., 1999; Sælthun et al., 1998 and 1999; Vehviläinen and Huttunen, 1997; Conway et al., 1996; Gellens and Roudin, 1998; Hamlet and Lettenmaier, 1999; Hay et al., 2000; Loukas et al., 2002; Middelkoop et al., 2001; Miles et al., 2000; Neff et al., 2000; Reynard et al., 2001). This approach considers only the difference between climate model control simulations (present climate) and their respective scenario simulations and adds this to an observed database. A disadvantage of this method is that in its simplest version it does not alter the number of rainy days in the scenario climate, nor does it affect the frequency of extreme events. However, Reynard et al., (2001) tried three different ways to apply the delta-change to the observed database; i) the standard way with monthly average change, ii) delta change applied as an increase in rainy days and iii) delta change applied to rainy days above a certain threshold. They found that the climate change impacts were smaller with the delta change applied as an increase in rainy days and that the difference between the common delta change and the threshold delta change was almost indistinguishable.

The lack of consideration to changes in extreme events with the delta change approach makes it best suited for studying the effect of changes in the mean catchment response of a changed climate, such as changes in the seasonal runoff pattern. However, according to Jones and Reid (2001), "Two extremes of precipitation rate, drought and deluge, are likely to have greater immediate impact on our environment and human systems than any likely small change in the mean rainfall amount." This highlights the importance of also including changes in the extremes into the hydrological impact studies. Roy et al., (2001) made a frequency analysis of 24 hour summer-autumn precipitation in today's climate (GCM control run) and in a future climate (GCM scenario run). From the frequency analysis, 24 hour rainfall hyetographs corresponding to 20 and 100-year return periods were determined and used to study the effect on summer and autumn flooding. This illustrates one way that climate scenarios can also be used to study the effects of changing extremes.

3 EXISTING RESULTS FROM NORDIC STUDIES ON CLIMATE CHANGE AND HYDROPOWER PRODUCTION

The Nordic research program on Climate Change and Energy Production, CCEP, is the most comprehensive joint Nordic study on climate change impacts on hydropower carried out so far. The main objective of CCEP was to analyse the effects of climate change on runoff and the resulting impacts on the Nordic hydroelectric power production.

CCEP was carried out in co-operation between the Nordic hydrological services and the Nordic hydroelectric power industry with funding from the Nordic Council of Ministers and participating institutions. The program ran for the period 1991 -1996 and the final report "Climate change impacts on runoff and hydropower in the Nordic countries" was published by the Nordic Council of Ministers, Copenhagen, in 1998 (Sælthun et al., 1998). The final report addressed the following topics: Climate change scenarios, historical variations, runoff simulation, power production simulations, effects on electricity consumption, floods and dam safety. More country specific details on CCEP results follow below.

In addition to CCEP there have been a number of national efforts in the different Nordic countries. The most important ones are summarised below country by country.

3.1 Finland

In Finland about 20% of electricity is produced by hydropower. Possible future changes in hydrological systems in Finland are therefore important for the nation's production of electricity. In most of the climate scenario simulations made thus far in Finland, total runoff increases slightly (0-10%) and the yearly distribution of water becomes more favourable to water power production. Winter discharges increase and spring floods decrease, which means less spillage at hydropower plants. In the future, longer summers with higher total evaporation over the summer period may cause some water shortage and decrease hydropower production.

3.1.1 Projects in Finland

There have been three major studies concerning climate change and hydropower production in Finland. The first one was the Nordic program CCEP. The second one, the Finnish Research Program on Climate Change SILMU was initiated in 1990 and the work was carried out during 1991-1995 (SILMU 1996). SILMU was funded from the Finnish Academy of Sciences. The main goal of this multidisciplinary program was to increase the knowledge of climate change, its causes, mechanisms and consequences. Since there were eighty individual research projects in SILMU, there were also seven universities and eleven research institutions involved. The results of the hydrological part were reported by Vehviläinen and Huttunen (1997) and the effects on the hydropower production by Forsius et al. (1996).

A more recent project, ILMAVA (ILMAVA 2002), was carried out in 2002 as part of the CLIMTECH program. The project was done as a co-operation with the Finnish Meteorological Institute and the Finnish Environment Institute as partners, and Fortum Engineering Ltd as a sub-contractor. The project was partially funded from the Finnish National Technology Agency (TEKES) and the Finnish Energy Industries Federation (Finergy). The aim of ILMAVA was to produce basic information on the climate effect upon the energy sector in Finland by using the newest information and model results on climate change in northern Europe.

There are also other notable studies on hydrological effects of climate change in Finland. Research on dam safety issues and especially the evaluation of the changes in design floods due to climate change are currently ongoing in Finland. Reports are not yet available except for the report of the possible changes of maximum precipitation by Tuomenvirta et al. (2001).

3.1.2 Methodology used in Finland

Climate scenarios

The scenarios applied in climate change studies in Finland have all used the same meteorological data baseline 1961-1990. The CCEP research program used a climate change scenario, which was based on statistically downscaled information from four different General Circulation Models (IPCC 1992). Also the SILMU scenarios were based on an intercomparison study of GCM simulation results (Räisänen 1994). In the ILMAVA project two scenarios of the HadCM3 climate model (Hadley Centre, UK) were used as climate change approximations. The changes in temperature and precipitation were produced using the SRES emission scenarios A2 and B2 (ILMAVA 2002; Nakićenović et al. 2000).

The differences in climate scenarios are compared in Table 1. The biggest uncertainties in predicting the climate in Finland are related to the limited ability of the global models to describe the natural variation of weather and regional distribution of the climate change.

Hydrological modelling

All the runoff simulations were calculated using the watershed models of the Finnish Environment Institute. The watershed models are conceptual models used for operational forecasting (Vehviläinen 1994). The models are based on a conceptual distributed runoff model, which is a Finnish version of the original HBV-model (Bergström 1976), and water balance model for lakes, a river routing model (Muskingum) and flood area models. The input variables to the models are daily precipitation and temperature. Potential evaporation (Class A pan) is calculated by a temperature, precipitation and season dependent model. The evaluated terms are runoff, evapotranspiration, lake evaporation, water equivalent of snow, soil moisture, groundwater storage, discharge and water level.

Table 1. *Average changes in temperature and precipitation per decade in different studies in Finland.*

	Temperature		**Precipitation**	
	Annual change per decade	Seasonal changes per decade	Annual change per decade	Seasonal changes per decade
CCEP	+ 0.4 – 0.45 °C	Winter: + 0.6 °C Summer: + 0.3 °C	+ 1.5 %	Winter: + 2 % Summer: + 1 %
SILMU Central scenario (1 x CO2)	+ 0.4 °C	Winter: + 0.6 °C Spring: + 0.4 °C Summer: + 0.3 °C Autumn: + 0.4 °C	+ 1 %	Winter: + 2 % Spring: + 0.5 % Summer: + 1 % Autumn: + 1 %
ILMAVA HadCM3-A2	+ 0.4 °C	Winter: + 0.6 °C Spring: + 0.3 °C Summer: + 0.3 °C Autumn: + 0.4 °C	+ 1.2 %	Winter: + 2 % Spring: + 0.3 % Summer: + 1.3 % Autumn: + 1 %
ILMAVA HadCM3-B2	+ 0.3 °C	Winter: + 0.4 °C Spring: + 0.2 °C Summer: + 0.2 °C Autumn: + 0.3 °C	+ 1.5 %	Winter: + 0.7 % Spring: + 1 % Summer: + 3 % Autumn: + 1.3 %

3.1.3 Finnish test basins

The drainage basins (Figure 1) were selected in order to estimate the climate change effects throughout the country. In the CCEP project sub-catchments from southern (Kokemäenjoki) and northern Finland (Vuoksi, Oulujoki, Kemijoki) were used to calculate the changes in hydrological variables. In the SILMU project the drainage basins were chosen mostly from the same main watersheds but partly from different areas. The main difference was that instead of Oulujoki, larger parts of Vuoksi and Kokemäenjoki were used. In the ILMAVA the catchments (Kemijoki, Oulujoki and Vuoksi) producing most of the hydropower were chosen for the simulation.

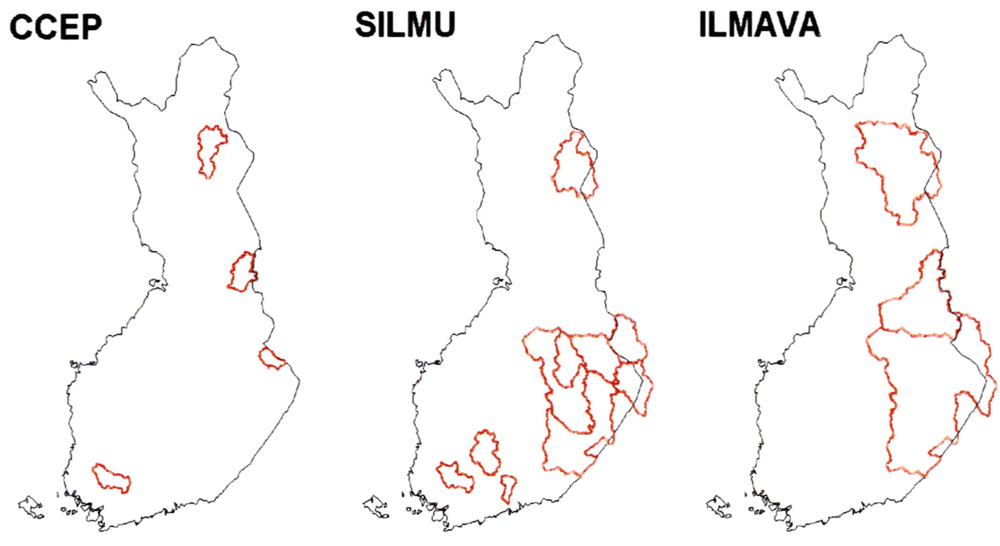


Figure 1. *The drainage basins used in different research projects on climate change and hydrological impacts in Finland.*

3.1.4 Main results from Finnish studies

In general the main result of the recent ILMAVA project was similar to the results of the CCEP and the SILMU projects. The climate change will strongly effect the seasonal distribution of runoff and other water balance terms. As the temperature increases the snow cover diminishes or almost vanishes in southern Finland and its duration will be shortened. Frequent thawing periods result in increased occurrence of winter floods and decreased spring floods. Summers will become drier due to the longer summer season and thus increased total evapotranspiration and lake evaporation.

The greatest differences between the annual results of these studies were obtained in the changes of runoff. In the CCEP project the annual runoff of the Kemihaara sub-basin at Kemijoki drainage basin was found to increase 2% in 30 years whereas in the SILMU project no essential changes at the annual level were found. In the ILMAVA however, the runoff was estimated to increase by 5 – 8%. In the Oulujoki drainage basin the CCEP project reported that there will be almost no change in runoff. In the ILMAVA project the increase in runoff was found to be 2 – 7%. In the Vuoksi drainage basin the corresponding figures varied between -1 – +4% (CCEP), -2% (SILMU) and 0 – 8% (ILMAVA). These differences were due to the differences of climate scenarios, especially in precipitation. Also it was found that evapotranspiration and lake evaporation affected the results considerably.

In the SILMU project it was also found that the change in maximum flood in a large lake rich catchment depends strongly on the location of the site in the lake route (Figure 2). In upper basins of large watersheds and basins without lakes the maximum discharges will decrease by 20-60% due to smaller spring floods. However, the maximum inflows to the central lakes in large watersheds with long lake routes will increase by 3-17%, because the snowmelt and precipitation accumulate into the central lakes during winter when no evaporation takes place.

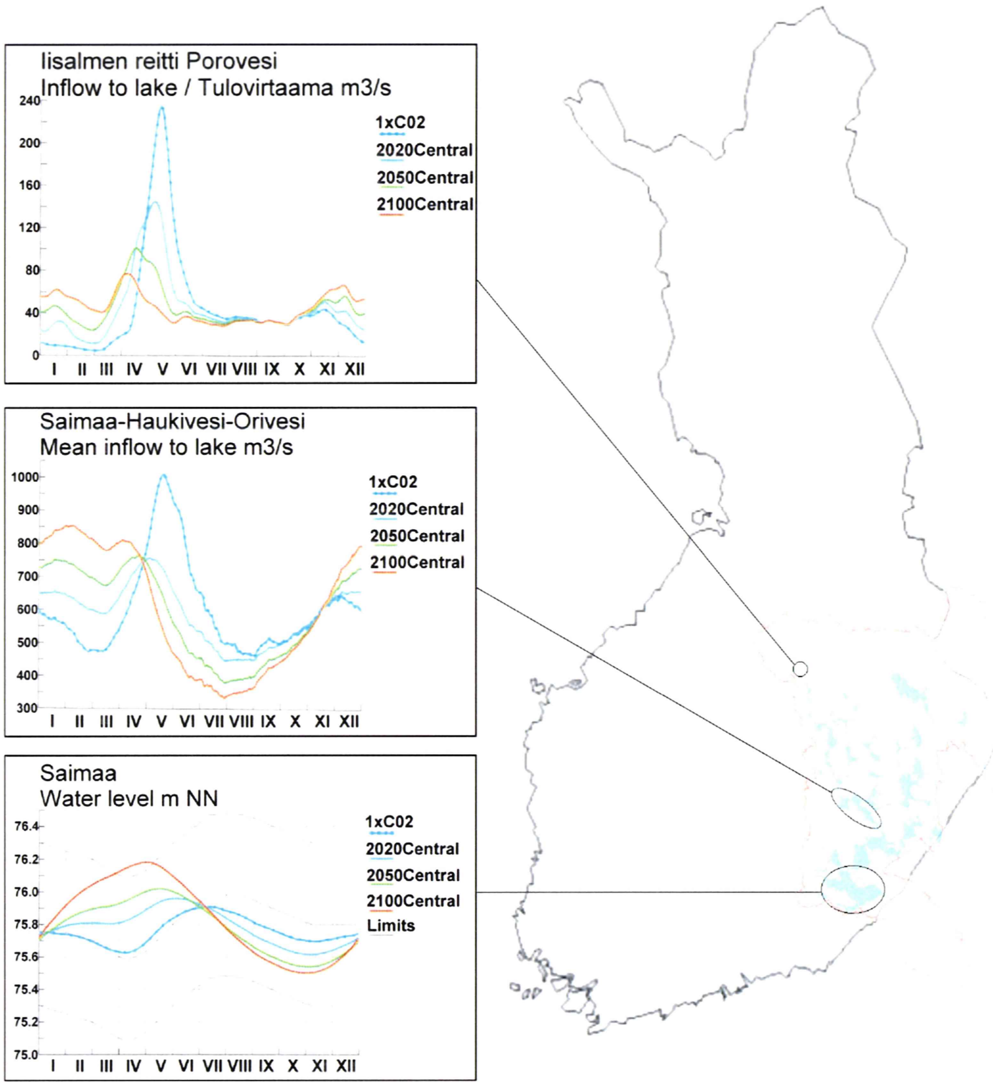


Figure 2. *The change in maximum flood depends on the location of the area in the watershed.*

The results of the projects indicate that climate change is advantageous for hydropower production in Finland due to the seasonal distribution changes and increased runoff. Both in the CCEP and SILMU projects the hydropower production simulations were carried out by Imatran Voima Oy (Kuivalainen et al. 1996; Forsius et al. 1996). In the CCEP the predictions show a 4% increase in hydropower production in the 30-year simulation period. In the SILMU project the increase was estimated to be 2%. In the ILMAVA project the hydropower simulations were carried out by Fortum Engineering Ltd. According to the results the average power produced by hydropower plants will increase by 7% (HadCM3-A2) and 11% (HadCM3-B2). The increase in hydropower production is higher in northern Finland.

3.2 Iceland

The impacts of climate change on glaciers are probably the most important factor for the hydrology of many watersheds in Iceland (Umhverfisráðuneytið, 2000). Also most of the hydropower industry in Iceland depends on glacier fed rivers. Therefore a lot of effort has been and will be directed at understanding the response of Icelandic glaciers to climate change.

3.2.1 Projects in Iceland

Until recently the Nordic research program CCEP was the only research project that had studied directly the impacts of climate change on energy production in Iceland. However, in light of the recent IPCC Climate Change Assessment (IPCC 2001a, 2001b, 2001c) and recent progress made in meteorological and hydrological modelling, the CHIN network initiated this Climate, Water and Energy (CWE) research project that will continue the work done earlier on a Nordic level. In conjunction with the CWE project there has been established a research project in Iceland (VVO) that will study the impacts of climate change on hydropower in more detail for Iceland.

The Iceland contribution to the CCEP consisted of the work of Kristinn Einarsson at the Hydrological Service of the NEA who led the hydrological watershed modelling and Tómas Jóhannesson at the Icelandic Meteorological Office who led the glacier mass balance modelling.

The ongoing Icelandic research project VVO was initiated at the Hydrological Service of the National Energy Authority (NEA) and the National Power Company of Iceland (Landsvirkjun) with funding from the State Energy Fund (Orkusjóður), Landsvirkjun and participants. The project was started in 2002 and will extend until the end of 2003 with possible continuation if funding will be available. The research team consists of scientists from the Hydrological Service at the NEA, Icelandic Meteorological Office, Science Institute at the University of Iceland and Vatnaskil Consulting Engineers. Some references concerning the project include Ólafsson and Rögnvaldsson (2002), Rögnvaldsson and Ólafsson (2002) and Sigurðsson et. al. (2002).

3.2.2 Methodology used in Iceland

Climate scenarios

The CCEP project used a climate scenario built on information from GCM runs as well as statistically derived downscaled information. The climate change scenario was applied for two timescales, +30 years and +100 years. For Iceland the changes in mean surface air temperature, were mean annual (0.30), winter (0.35) and summer (0.25) values, in °C per decade from a 1961–1990 baseline. The scenario for precipitation increase in Iceland gave accumulated annual (1.5), winter (1.75) and summer (1.25) values, in per cent per decade from a 1961–1990 baseline.

Hydrological modelling

The HBV runoff model was used in the CCEP study. In Iceland a MBT glacier mass balance model was used alongside with the HBV model to constrain the calibration parameters in the HBV model (Einarsson and Jóhannesson, 1994). For scenarios involving climate change, decades into the future, a dynamic glacier model was coupled to the mass balance model and run for the glaciated parts of the Icelandic watersheds, rendering new extent and elevation distribution for use in the HBV model (Jóhannesson, 1997).

In the Icelandic VVO project a scenario is created with the MM5 numerical simulation model. The model simulates the meteorological parameters on a grid with 8 km horizontal resolution. This simulation output will then be used as an input for glacier and watershed modelling. The hydrological models that will be used in the study will be the coupled NAM2/AQUA3D model developed at Vatnaskil, the HBV model and hopefully some other distributed hydrological models such as the grid-based hydrological catchment model WaSIM-ETH. Downscaling experiments have been done with the MM5 model in order to determine the optimal configuration for climatological downscaling studies of precipitation in Iceland (Rögnvaldsson and Ólafsson 2002) and simulation for the period 1992 – 2002 has been completed.

3.2.3 Icelandic test basins

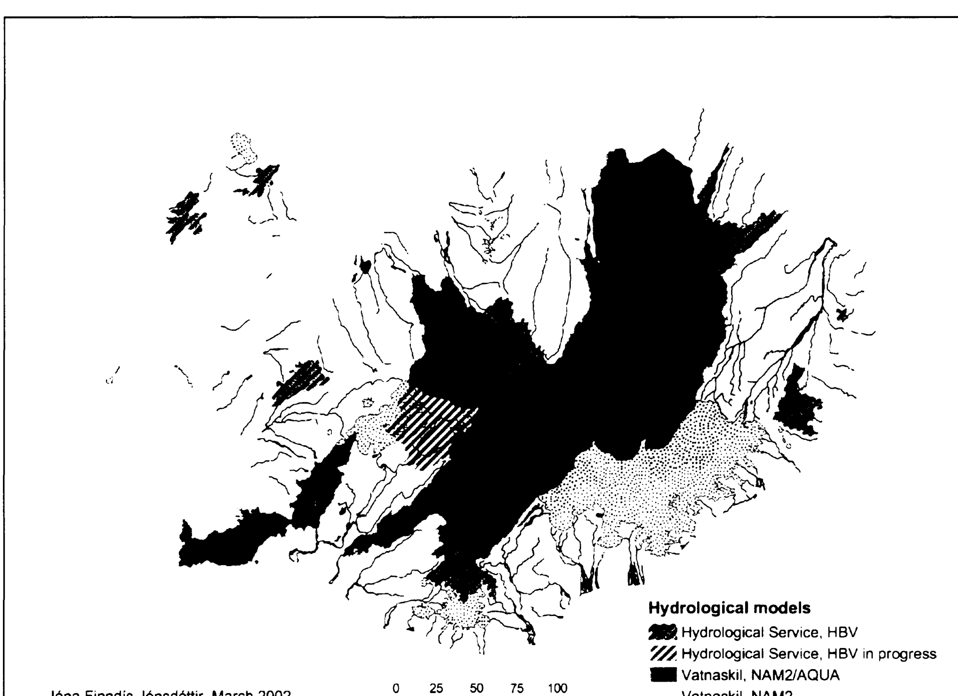


Figure 3. *Watersheds in Iceland modelled by conceptual hydrological models, dotted areas represent glaciers*

In the CCEP project the test basins in Iceland were the watersheds of three glacier fed rivers, Blanda at Guðlaugsstaðir, Austari Jökulsá at Skatastaðir and Jökulsá in Fljótsdalur at Hóll. For the ongoing VVO project the test basins have not been selected except for the Þjórsá -Tungnaá area that is the area that at present supplies about 64% of the electric power in Iceland. Other test basins will be selected from the collection of basins that have earlier been modelled to some extent. Figure 3 shows the watersheds in Iceland, which have been modelled with either the NAM2/AQUA3D or the HBV model.

3.2.4 Main results from Icelandic studies

The main results of the CCEP research was that in Iceland climatic change has great influence on glaciers and affects the power industry most clearly through the glacier fed rivers. The discharge of rivers in Iceland will increase with increased precipitation and (temporarily) increased glacier melt. The greatest increase on a time scale of the next 150 to 200 years will therefore be in glacier fed rivers. The value of mean discharge in many Icelandic rivers will probably increase 5 - 20% in the next 30 years. The seasonal variations in discharge and floods will change and glaciers will retreat. (Umhverfisráðuneytið, 2000).

Since the Icelandic power industry is isolated from the mainland of Europe there can neither be export of energy in good water years nor import in bad ones. Even though the melting of glaciers in the next decades will temporarily increase the runoff, it remains to be calculated how much of the increase the power industry can harness and how the seasonal variation may influence the system. (Sælthun et al. 1998). Figure 4 shows the calculated influence of climate change on glacier runoff from the Hofsjökull glacier.

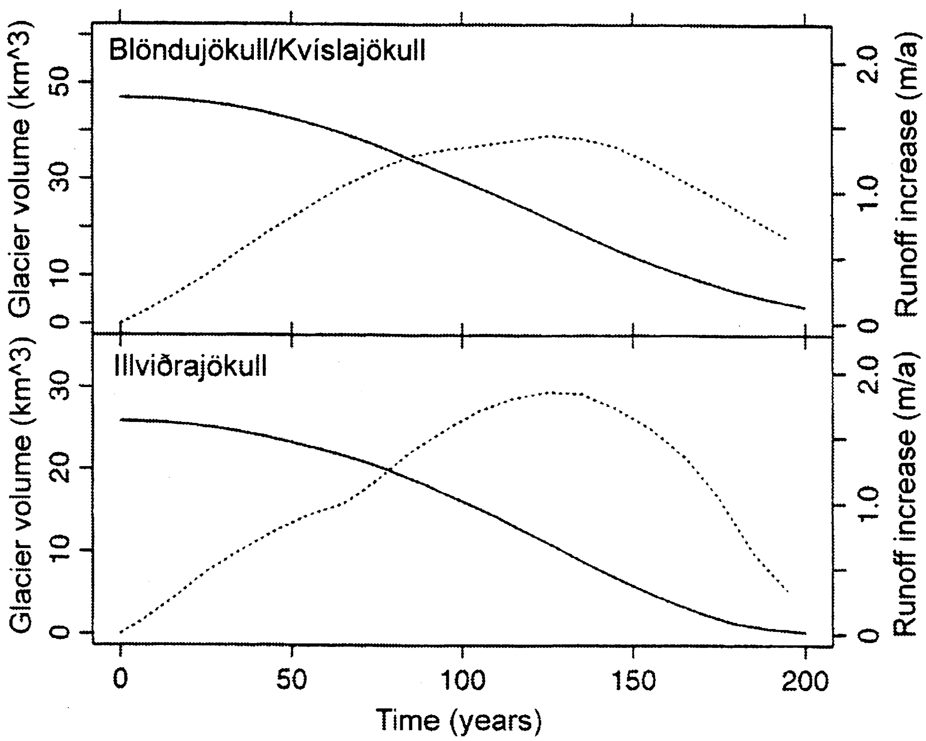


Figure 4. *Glacier volume as a function of time (solid curves) and predicted runoff increase from the area presently covered by the glaciers due to the reduction in the ice volume (dashed curves) for BlöndujökullKvislajökull (upper panel) and Illviðrajökull (lower panel). (Jóhannesson, T. 1997)*

3.3 Norway

Energy use in Norway is characterised by a very high use of electricity. No other IEA country comes close to the levels consumed per capita in Norway. The reasons are a high share of electricity intensive industry in Norway and the broad penetration of electric heating (Unander and Schipper, 2000). An increasing temperature will lead to a decreasing energy demand in Norway (Bye, 2002). As almost 100% of the Norwegian electricity is hydropower, climate changes are important for the future energy availability and demand in Norway

In addition to the Nordic research program CCEP, two national projects have investigated the topic climate change and hydropower production in Norway.

3.3.1 Projects in Norway

The national project "Climate change and water resources" (Sælthun et al., 1990) was a part of the Norwegian Interministerial Climate Change Policy Study and was funded by the Ministry of Oil and Energy. The work was carried out at the Norwegian Water Resources and Energy Directorate (NVE) with assistance from the Power Pool of Norway and the Norwegian Institute for Water Research (NIVA). The report addresses the following topics: runoff simulations, glaciers, water temperature and ice conditions, erosion and sediment transport, water quality, floods and flood damage, and hydropower production.

The national project "Climate change and energy production potential" (Roald et al., 2002; Skaugen et al., 2002; Skaugen and Tveito, 2002) was funded by the Norwegian Electricity Industry Association (EBL) and The Norwegian Research Council. The participating institutions were NVE and the Norwegian Meteorological Institute (met.no). The work was carried out for the period 2000-2002. The project addressed the following topics: historical long-time variations in climate and runoff, adjustment of dynamically downscaled temperature and precipitation data, runoff scenarios, energy production potential, changes in heating season, and changes in extreme rainfall.

3.3.2 Methodology used in Norway

Climate scenarios

Sælthun et al. (1990) used climate change scenarios based on the NCAR model (Washington and Meehl, 1989). No downscaling procedure was applied. Two climate scenarios were used: one based on what was considered the most probable changes of precipitation and temperature, and one based on high changes. These scenarios were interpolated to monthly values, and subsequently used to manipulate historical temperature and precipitation series from the period 1957-1988 into new series that were assumed to represent the future climate. The temperature of each day was increased by the differential values, and the precipitation was increased by percentages. This means that the variability of the temperature, and the coefficient of variation for precipitation for each month as well as the number of precipitation days were unaltered. Sælthun et al. (1998) presented a climate change scenario for the Nordic countries mainly based on statistically downscaled information from transient runs of the AOGCM at Max-Planck-Institut für Meteorologie in Hamburg (MPI) (Cubash et al., 1992). Information from three other transient AOGCM runs (NCAR, GFDL and HadCM) were also considered. The IPCC scenario SA90 (IPCC, 1990), a "business as usual" scenario, for the future emissions and concentration of greenhouse gases was utilised. The scenarios were presented in IPCC (1992). Historical data from the period 1961-1990 were manipulated in the same way as in Sælthun et al. (1990) to obtain future temperature and precipitation scenarios for 30 and 100 years ahead. These scenarios indicate a lower temperature increase and slightly lower precipitation increase compared to the scenarios in Sælthun et al. (1990).

Local and regional climate scenarios have been studied in the RegClim project since 1997. Information about this project is available at the Internet; http://www.nilu.no/regclim. One of the overall aims is to estimate probable changes in the regional climate in Northern Europe, bordering sea areas and major parts of the Arctic, given a global climate change.

The RegClim project has, up to now, worked mainly on the results from the global climate model of MPI with the AOGCM ECHAM4/OPYC3 with the GSDIO integration (Roeckner et al., 1999). In this integration, the concentration of greenhouse gases has been specified according to the IPCC IS92a scenario, with an annual 1% increase in CO2 from 1990, giving a near doubling in concentration in 2050. This integration describes the climate development from 1860 up to 2050. Both projected increase in greenhouse gases and direct and indirect effects of aerosols are accounted for as well as the change of the amount of ozone in the troposphere. The model gives a realistic description of the present climate in Norway and is therefore chosen as a basis for the downscaling of temperature and precipitation scenarios.

The results from ECHAM4/OPYC3 GSDIO have a resolution of about 300x300 km. In RegClim both empirically and dynamically based techniques were used to downscale the AOGCM results to local scale. Empirical downscaling techniques involve identification of empirical links between observed local climate elements, and large-scale atmospheric fields. These relations are then used to estimate local climate from the large-scale fields produced by global climate models. So far the empirical downscaling in RegClim has been performed at monthly basis (Hanssen-Bauer et al, 2000, 2001, Benestad, 2002). In addition to the results from the GSDIO simulation, empirical downscaling has been applied to 16 global scenarios. Figure 5 shows projected changes of precipitation in January at a selection of Norwegian weather stations for the period 2000-2050. Each scenario is downscaled with different predictor domains so that the figure represents 50 different estimates. In these downscalings, sea level pressure (SLP) is the only predictor, implying that the intensification of the hydrological cycle caused by increasing temperature is not included. Consequently the mean value of the scenarios is dubious, but the spread in scenarios illustrates the magnitude of uncertainty connected to precipitation scenarios.

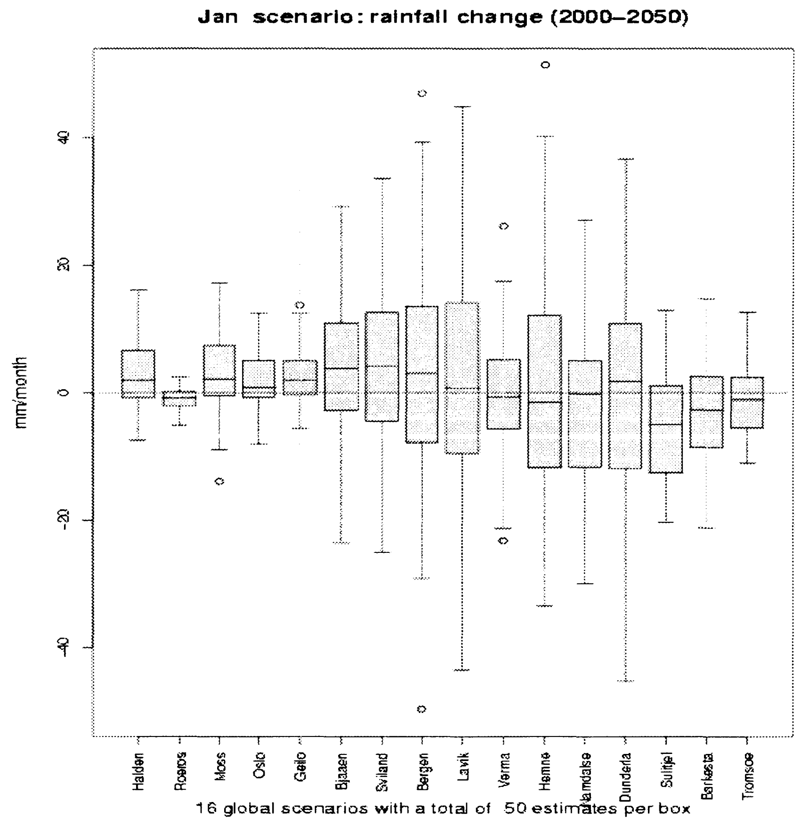


Figure 5. *Box and whisker plot representation of 50 precipitation change estimates for January for the period 2000-2050. The results are based on 16 different AOGCM scenarios (10 different models) using the SLP fields (Benestad, 2002).*

In dynamical downscaling, the results from a global climate model are used as input in a regional weather forecast model with finer resolution. In RegClim the regional model, HIRHAM, was run with a spatial resolution of 55x55 km and a 6 hourly time resolution, over an area that covers Northern Europe, the northern North Atlantic and parts of the Arctic. Both the present (1980-1999) and future climate (2030-2049) were dynamically downscaled from the GSDIO scenario (Bjørge et. al, 2000). For evaluation purposes, HIRHAM was also run with "perfect boundaries", applying observationally based re-analysed data from the ECMWF during the period 1979-1993 ("ERA-15 data") to define the boundary conditions. Comparison of results from this run and observations from Norwegian meteorological stations during the same period showed that although temperature and precipitation fields produced by HIRHAM are far more realistic than the fields produced by ECHAM4/OPYC3, the resolution is still too coarse to give values that are directly comparable to point observations. The annual temperature and precipitation difference between the period 2030-2049 and 1980-1999 are presented in Figure 6. The largest increase in temperature will occur in the north during winter (up to 3 °C). There will be smallest changes during summer. Precipitation will increase at the most at the west coast in autumn (up to 30%).

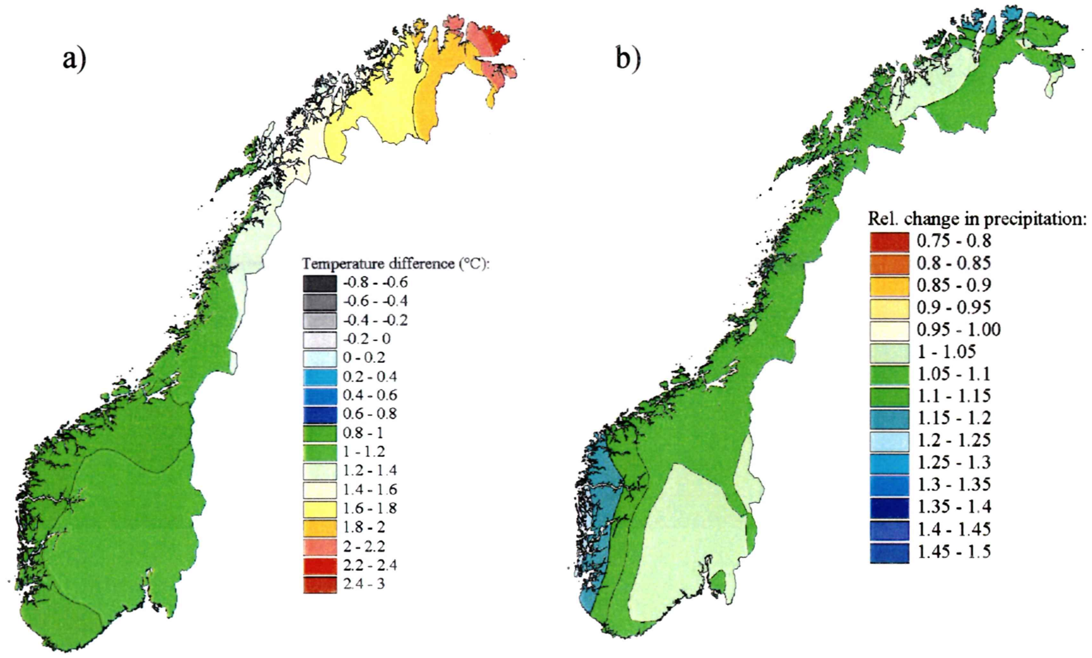


Figure 6. *Annual a) temperature change and b) precipitation ratio between the periods 2030-2049 and 1980-1999.*

Studies of potential hydrological change depend on meteorological input with fine resolution both in space and time. The available empirically downscaled climate scenarios have a coarse time scale, while the dynamically downscaled scenario has a too coarse spatial resolution for many impact studies. The dynamically downscaled results from the ECHAM4/OPYC3 GSDIO simulation were therefore adjusted in order to make them comparable to site observations (Skaugen et al. 2003). The adjusted climate scenarios were utilised by Roald et al. (2002).

Hydrological modelling

In all the three Norwegian studies (Roald et al., 2002, Sælthun et al., 1998 and Sælthun et al., 1990) the runoff simulations were calculated by the HBV model. The model includes a snow distribution within each elevation zone and a degree-day glacier mass balance model. The effect of evapotranspiration is important for calculating the future water balance. Sælthun et al. (1990) therefore developed a routine where evapotranspiration is proportional to temperature above freezing, by a seasonally varying coefficient. The same evapotranspiration routine was included in the two following studies. Sælthun (1996) added an interception routine, and this version was used both in Sælthun et al. (1998) and Roald et al. (2002). Roald et al. (2002) used also the Gridded Water Balance (GWB) model (Beldring et al., 2002) to calculate future changes in the water balance for the whole of Norway. The GWB model is based on the HBV model described by Sælthun et al. (1998). In all three studies other possible physical changes in the basins (e.g. vegetation cover and glaciated areas) were ignored.

3.3.3 Norwegian test basins

Figure 7 shows the test basins for the three studies. In Sælthun et al. (1990) 7 basins were used, in Sælthun et al. (1998) 10 basins, and in Roald et al. (2002) 42 basins. These basins are geographically distributed all over Norway and represent different hydrological regimes.

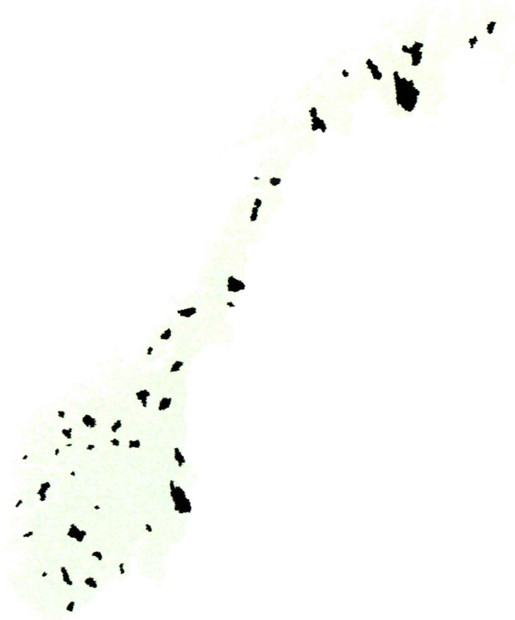


Figure 7. *Catchments used in climate change studies in Norway.*

3.3.4 Main results from Norwegian studies

Annual water balance

Sælthun et al. (1990) concluded that changes in annual runoff are controlled by the evapotranspiration and the precipitation. Correct modelling of evapotranspiration was therefore considered important when it comes to estimating the future water balance (Fossdal and Sælthun, 1993). The annual evapotranspiration increase was 40-55 mm in mountainous areas, 45-100 mm in medium areas and 50 to 110 mm in lowland areas. The most probable climate change scenario resulted in an increase in annual runoff in mountainous areas with more than 750 mm. In lowland and forested inland basins, annual runoff was expected to decrease in response to increased evapotranspiration. The high (wettest) scenario resulted in increased runoff all over Norway, and up to 15% on the west coast. Sælthun et al. (1998) drew similar conclusions. Evapotranspiration was expected to increase due to increased summer temperature and longer snow free periods. The results showed that evapotranspiration will increase between 100 and 200 mm over 100 years, and precipitation will increase between 15 and 20 % for the same period. An evapotranspiration increase of 100 mm will counterbalance the precipitation increase where the present precipitation is less than 700 mm. The annual runoff will therefore increase in western areas and be reduced on the more continental areas.

Results from Roald et al. (2002) are shown in Figure 8. Runoff is expected to increase almost all over Norway, following the same pattern as the increase in precipitation.

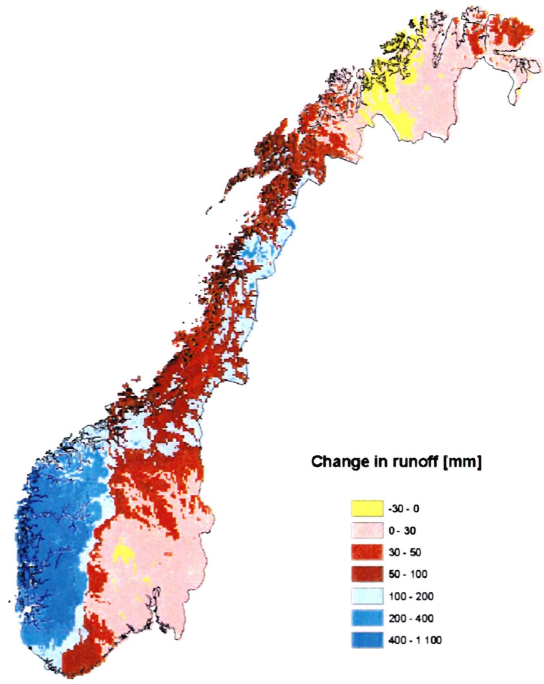


Figure 8. *Changes in runoff for the scenario period 2030 - 2050 compared to the control period 1980 - 2000 calculated by the GWB model (Roald et al., 2002).*

Seasonal variations in runoff

The scenarios in Sælthun et al. (1990) and Sælthun et al. (1998) showed a drastic change in the seasonal distribution of runoff. Winter runoff increases, spring floods are reduced in magnitude and occur earlier, and summer runoff decreases. The changes are mostly controlled by temperature, which is important for snow cover formation and snow melt processes. The seasonal distribution will not change much in the coastal regions that do not have stable snow cover today. The most drastic changes will take place in the lower elevation bands of regions that now have a stable snow cover during winter. Sælthun et al. (1998) showed that seasonal changes are noticeable in the 30 year scenarios and are for most basins dramatic after 100 years. The stations analysed by Roald et al. (2002) only partly coincide with the stations used by Sælthun et al. (1998). Some of the catchments are regulated, and others requires downscaled series from more climate stations than could be provided for. Roald et al. (2002) showed that summer runoff will decrease due to increased evapotranspiration. Autumn runoff will increase, especially at the west coast, due to the large increase of precipitation at this time of the year. Changes in seasonal distribution due to changes in snow cover are important in the lower elevation bands along the coast.

Floods

The first two studies showed that floods will be more frequent in autumn and winter and that spring floods will be reduced in magnitude. The flood risk in large continental basins will decrease whereas the risk will increase in smaller basins. The scenarios do not account for an increased variability in precipitation. Possible effects of more extreme rain or changes in the general circulation are therefore ignored. Skaugen et al. (2002) used downscaled precipitation fields from the HIRHAM model. They found that extreme precipitation will increase, especially along the coast.

Glaciers

Sælthun et al. (1990) concluded that melting of the glaciers will increase and the summer discharge in glacier basins will therefore increase. Most of the glaciers will have a negative mass balance, resulting in reduced volume. When the glacierised areas are significantly reduced, the long-term effect will be reduced summer runoff in basins which have glaciers today. But high altitude glaciers in maritime climates with high precipitation might keep their volume and even grow.

In Roald et al. (2002) simulation with the MBT (Mass Balance of Temperate Glaciers) model, which is an HBV-type glacier mass balance model, suggested that both winter and summer balances will increase in a future climate, which increases the net balance by 0.1 m to 1.0 m water equivalent. The effect on runoff continues to be negative as the glacier accumulates water as ice and thus reduces runoff, as opposed to a state of equilibrium. The scenario reduction in a changed climate equals 700 mm for the Nigardsbre catchment, which is 80 mm higher than the average reduction for the control period 1980-1999.

Hydropower production and reservoir management

Sælthun et al. (1990) concluded that the hydropower production in Norway will increase by 2-3% due to increased inflow and reduction in reservoir spill. The seasonal distribution of runoff may more closely match that of energy consumption, thereby increasing the firm power yield. There is less need for reservoir capacity to provide seasonal regulation and therefore an increased capacity available for year-to-year carry over. The increased winter runoff and the reduced spring flood allow the regulation dams to be used more efficiently for flood dampening and increased energy production. Sælthun et al. (1998) indicated an increase in hydropower production by about 4% in 30 years, and about one third of this increase might be explained by the changed seasonality of runoff. The changed seasonal distribution of runoff will change the use of reservoirs. The water level during summer and autumns might be lower and in late winter might be higher.

3.4 Sweden

About half of the electricity in Sweden is produced by hydropower, therefore impacts of climate change on this sector have been under discussion for some time. During the last 15 years interest has grown due to unusually high production of hydropower due to higher than average precipitation. The issue of dam safety has also come more into focus after some severe flooding events.

3.4.1 Projects in Sweden

Climate change studies began at SMHI in the early 1990s (Alexandersson and Dahlström, 1992). Parallel to this were some studies of the influence of climate change on runoff due to assumed temperature changes (e.g. Carlsson and Sanner, 1994). Hydrological modelling of the impacts of climate change on hydropower started with the Swedish participation in the Nordic research program CCEP, where SMHI made a comprehensive study of evapotranspiration effects (Lindström et. al., 1994). Since 1997 simulations of the impacts of climate change on hydrology in Sweden have mainly been produced within the Swedish Regional Climate Modelling Programme (SWECLIM).

SWECLIM simulation results of climate change impacts on runoff in Sweden are described by Bergström et al. (2000), Bergström et al. (2001) and Gardelin et al. (2002b). Further studies addressed issues related to hydropower production (Carlsson et al., 2001; Gardelin et al., 2002) and flooding (Andréasson et al., 2002). Graham et al. (2001a) and Graham et al. (2001b) describe hydrological impacts on the entire Baltic Sea drainage basin from climate change scenarios.

3.4.2 Methodology used in Sweden

Climate scenarios

The climate change impact studies within SWECLIM are based on a combination of global climate models (GCMs), a regional climate model and a hydrological runoff model. Most simulations produced to date were based on two different GCMs, the HadCM2 from the Hadley Centre of the UK Meteorological Office (UKMO) and the ECHAM4/OPYC3 of the Max Planck Institute for Meteorology. These were downscaled with the Rossby Centre Regional Atmospheric Model (RCA) developed at SMHI. This is a modified version of the international HIRLAM meteorological forecast model.

In late 2002 new simulations based on the SRES emission scenarios A2 and B2 (Nakićenović et al. 2000) were available from UKMO HadCM3/AM3 and ECHAM4/OPYC3. These have been downscaled with the coupled RCAO regional climate model, which consists of the RCA model coupled with the Rossby Centre 3D Oceanographic Model, RCO. The RCAO system is described by Döscher et al. (2002). An example of changes in temperature and precipitation from RCAO driven with HadCM3/AM3 boundary conditions is shown in Figure 9. Impacts on runoff from these new simulations are currently being analysed.

In addition to dynamical downscaling produced by regional climate models, statistical downscaling and direct application of GCM results have also been tested in hydrological impacts models within SWECLIM.

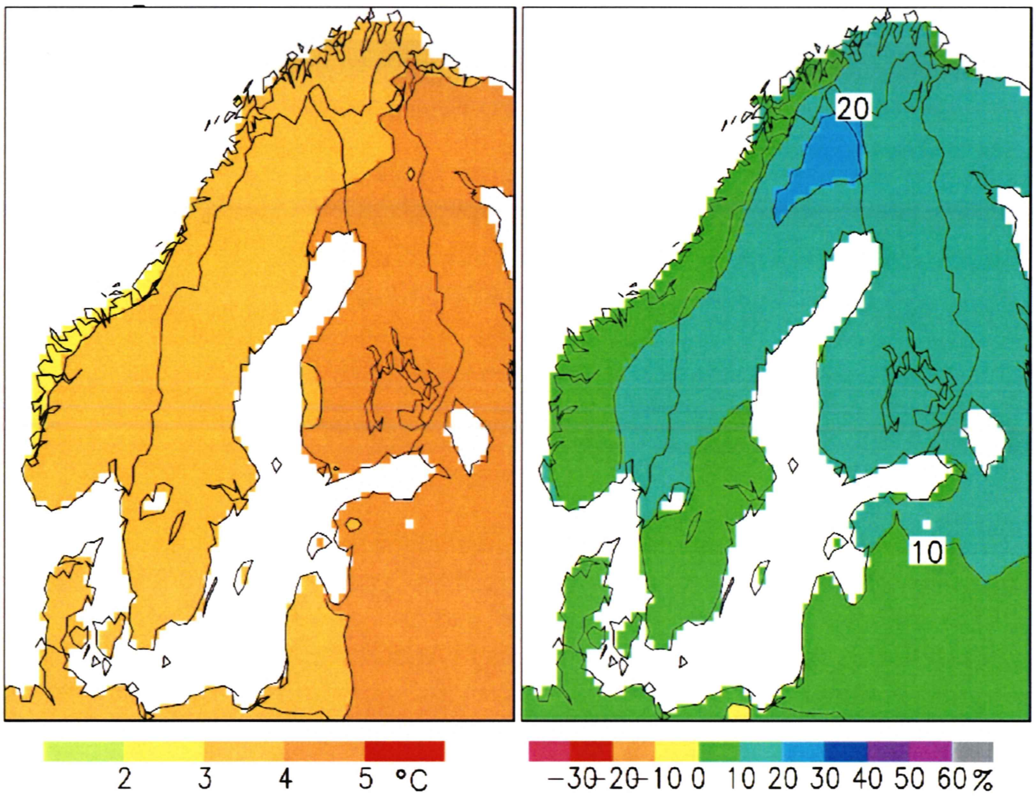


Figure 9. *Changes in temperature (°C) and precipitation (%) from RCAO driven with HadCM3/AM3 boundary conditions for SRES scenario A2. These simulations were produced in autumn, 2002.*

Hydrological modelling

The Swedish studies of climate change impacts on runoff have used the HBV hydrological model in offline simulations (Bergström et al., 2001; Graham et al., 2001b). Particular effort has been placed on the development of the evapotranspiration processes and on the interface to transfer climate change information from the regional climate model to the hydrological model. New impacts simulations have been successively produced as new regional climate model results have been made available from the Rossby Centre during the period 1997-2002.

Differences in meteorological variables between present climate simulations and future climate scenario simulations are processed in the interface before use in the hydrological model. Direct use of meteorological output from regional climate models has not been considered applicable, as bias in both temperature and precipitation are still considerable in most climate models. As hydrological models are particularly sensitive to the seasonal distribution of precipitation, such biases strongly affect hydrological simulations. The indirect use of the meteorological changes, however, introduces its own uncertainties and biases to the analysis process. This is discussed further under strategies below.

3.4.3 Swedish test basins

Six test basins, representative for different climate and hydrological regimes in Sweden, were initially chosen for runoff impacts analysis within SWECLIM. Later, they were supplemented with another two basins, River Luleälven representing a highly regulated basin and Lake Vänern, a basin where serious flooding occurred in 2000. Simulations addressing soil frost and groundwater dynamics were also made in a third basin, Svartberget experimental forest in Vindeln in northern Sweden. On a larger scale, impacts to the entire Baltic Sea drainage basin have also been assessed.

3.4.4 Main results from Swedish studies

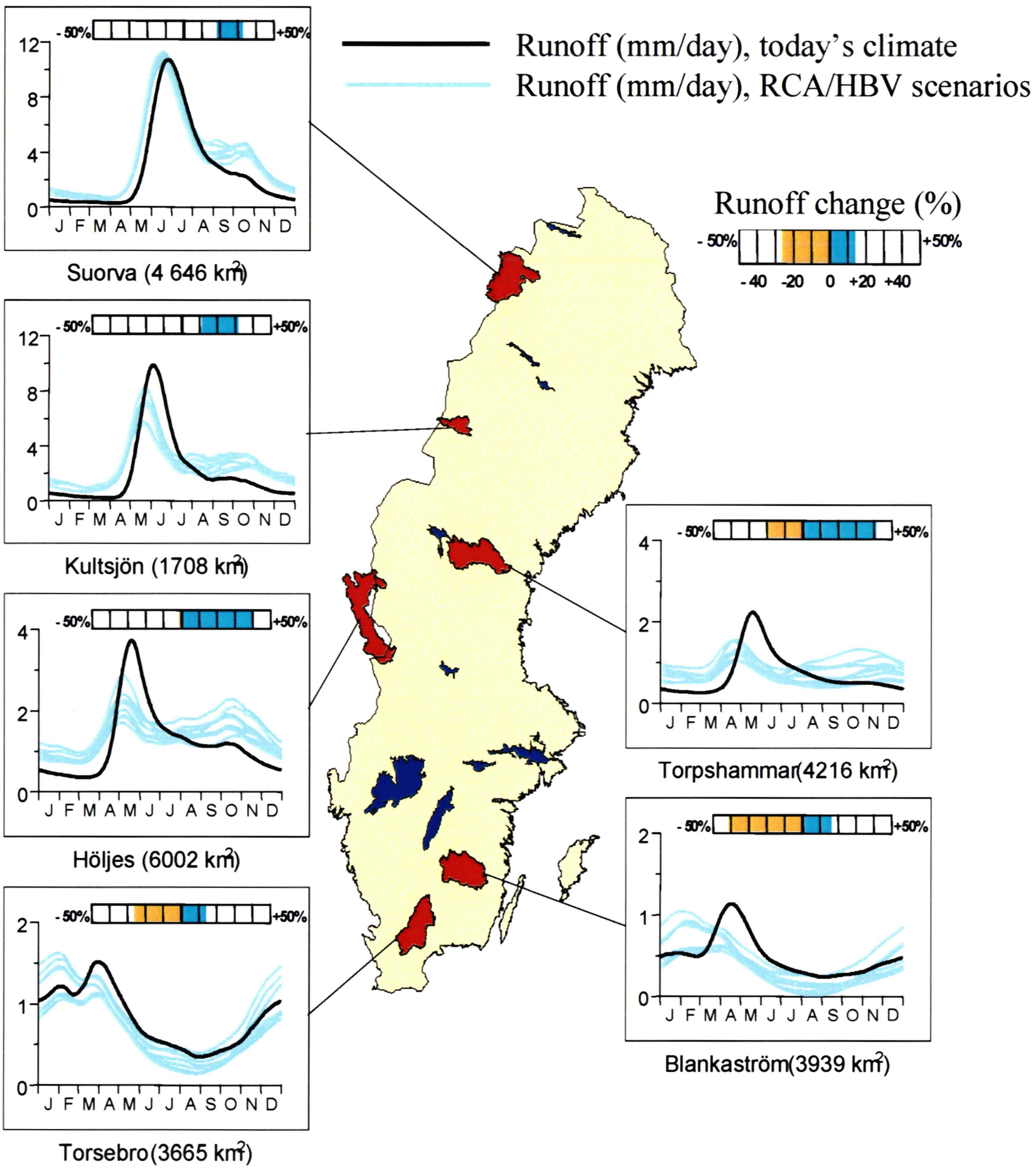
The use of two different GCMs for external boundary forcing, two different horizontal resolutions of the RCA model, 88 km (RCA88) and 44 km (RCA44), and two methods for calculating evapotranspiration in the HBV model (HBV-a and HBV-b) resulted in an ensemble of eight different hydrological impacts simulations. Figure 10 summarises these simulations for the six test basins. The results were analysed with respect to average conditions and with respect to extreme values.

The curves in the figure illustrate the effects of the climate change scenarios on the seasonal variation of runoff. A general tendency in northern Sweden, is the shift in the runoff regime towards decreasing spring flows and increasing flows during autumn and winter. Only in the northernmost basin will the magnitude of runoff in spring be nearly unchanged since snow accumulation will not be significantly affected in this region. The timing of snowmelt will however be affected in all the northern basins. A rather drastic decrease in spring flows can be noticed in southern Sweden, while results for the other seasons diverge. The range of the ensemble results illustrate to some degree the range of uncertainties in the impact studies.

Frequency analyses of extreme values are summarised in Table 2. They show a decreasing frequency of spring floods (approximately between 10-50%) in all basins except for in the northernmost one (Gardelin et al., 2002a). The frequency of floods during the rest of the year generally increases in the four northern basins. The largest increases (up to approximately 90%) are found in the HBV-b simulations based on RCA44-H. Even though the analyses show diverging results for southern Sweden, the frequency of summer and autumn floods generally decrease in most scenarios for this region. In general, the return period for today's 100-year spring flood far exceeds 100 years under scenario conditions (the Suorva basin excluded). The return period for floods during the rest of the year generally decreases in the four northern basins and increases in the southern basins.

The shift in northern Sweden from spring floods towards increased floods during the rest of the year can be critical for reservoirs and dams in regulated rivers. Reservoirs are often low in spring but autumn and winter floods may occur when reservoirs are full and without capacity for flow dampening.

Impacts of climate change on river runoff and hydropower production has been studied in more detail in River Luleälven, which is one of the most developed rivers in Sweden. Combining the scenarios and the present day close relationship between hydropower production and runoff leads to a projection of possible hydropower production in the future. The increased runoff according to the scenarios will thus give potentially up to 40% higher hydropower production. How much this will be in reality is however unclear, as the production systems probably will change during the time horizon of the scenarios.



	RCA88-H	RCA88-E	RCA44-H	RCA44-E
Temperature (°C)	+3.2	+3.5	+3.7	+3.8
Precipitation (%)	+13	+7	+18	+8

Figure 10. *Calculated 30-year average daily runoff in six test basins in Sweden for today's climate and eight different climate change impact simulations. The table shows annual averages of changes in air temperatures and precipitation over Sweden according to the scenarios.*

Table 2. *Changes in 100-year floods and return periods for six test basins in Sweden. Scenarios based on two different GCMs (H=HadCM2; E=ECHAM4), two different resolutions in the RCA model and two versions of the HBV model.*

		Change in 100-year flood (%)				Return period of today's 100-year flood under scenario conditions			
		RCA88		RCA44		RCA88		RCA44	
		HBV-a	HBV-b	HBV-a	HBV-b	HBV-a	HBV-b	HBV-a	HBV-b
Spring (January-July):									
1. Suorva	H	0	0	+2	+2	100	100	80	80
	E	-1	-1	+1	+5	110	110	90	60
2. Kultsjön	H	-28	-25	-20	-17	>1000	>1000	710	500
	E	-24	-22	-15	-12	>1000	870	400	300
3. Torpshammar	H	-44	-37	-47	-37	>1000	>1000	>1000	>1000
	E	-51	-46	-43	-36	>1000	>1000	>1000	>1000
4. Höljes	H	-48	-44	-42	-36	>1000	>1000	>1000	>1000
	E	-46	-43	-43	-31	>1000	>1000	>1000	>1000
5. Blankaström	H	-51	-35	-49	-28	>1000	>1000	>1000	>1000
	E	-46	-32	-48	-36	>1000	>1000	>1000	>1000
6. Torsebro	H	-21	-7	-29	-10	700	170	>1000	230
	E	-20	-8	-27	-13	640	190	>1000	320
Summer and autumn (August-December):									
1. Suorva	H	+31	+36	+45	+49	20	10	10	10
	E	+27	+32	+23	+42	20	20	30	10
2. Kultsjön	H	+36	+48	+44	+56	20	10	10	5
	E	+13	+28	+17	+31	50	20	40	20
3. Torpshammar	H	+58	+82	+41	+88	10	5	20	5
	E	-12	+7	0	+41	240	70	100	10
4. Höljes	H	+27	+40	+50	+92	30	20	10	5
	E	+21	+35	+29	+74	30	20	20	5
5. Blankaström	H	-33	-5	-11	+21	>1000	140	240	30
	E	-22	-2	-27	0	550	110	>1000	100
6. Torsebro	H	-23	-8	-21	+1	600	170	570	90
	E	-24	-12	-27	-10	670	230	>1000	210

4 STRATEGIES FOR PRODUCTION OF HYDROLOGICAL IMPACTS ASSESSMENT

There are many links in the analysis chain that leads to the assessment of anthropogenic climate change on hydrological systems. Starting with international consensus on different greenhouse gas emissions scenarios, simulations of climate change are produced by GCMs. Introducing results from these simulations into hydrological models then produces assessments of impacts to hydrological systems. However, the transfer of the signal of climate change from the GCMs to the hydrological models is not direct.

The primary input variables used in hydrological modelling are temperature and precipitation. Most water balance models depend upon these two variables, together with different methods for calculating potential evapotranspiration, to solve the water balance and simulate river flow. Although GCMs can do a reasonable job at modelling large-scale temperature fluctuations, accurate representation of precipitation is much more difficult. The typical horizontal resolution of GCMs (200-300 km) tends to greatly smooth out the geographical features of the earth's surface. An intermediate step to increase the resolution of GCM results over limited regions of the globe is the use of regional climate models (RCMs), which typically have horizontal resolutions of 50 km or less. This "dynamical downscaling" can greatly influence where precipitation falls as orographic influence from mountains and highlands becomes more prominent (Rummukainen et al., 2001).

Statistical downscaling methods can also be used to improve regional representation from GCMs. With them, statistically inferred relationships between long time series (e.g. sea level pressure, temperature) and GCM control (i.e. present climate) simulation results are applied to GCM scenario simulations to obtain regionally oriented future climate results. This assumes that regional weather is a function of large-scale circulation patterns and that these relationships are valid also in a changed climate (Müller-Wohlfeil et al., 2000). Although statistical methods for downscaling are quicker and require little resources (e.g. no supercomputers needed), they provide much less detail than RCMs.

Direct use of either GCM or RCM simulations in hydrological impact models is uncommon. This is mostly due to the combination of biases in seasonal precipitation from these simulations and the inherent sensitivity of hydrological systems (and models) to precipitation. Past experiments have shown that direct input of precipitation from control simulations into hydrological models leads to incorrect representation of the present-day hydrological regime (Graham and Jacob, 2000). Knowing this, hydrological modellers hesitate to directly input scenario simulation results in their models, as they know even less about the validity of the future climate.

To date, the most common strategy for transferring the signal of climate change from climate models to hydrological impacts models is shown by the schematic in Figure 11. The delta change approach occurs in the hydrological interface of this analysis chain. In addition to temperature and precipitation, additional variables, such as evapotranspiration can be transferred via a delta change type of interface.

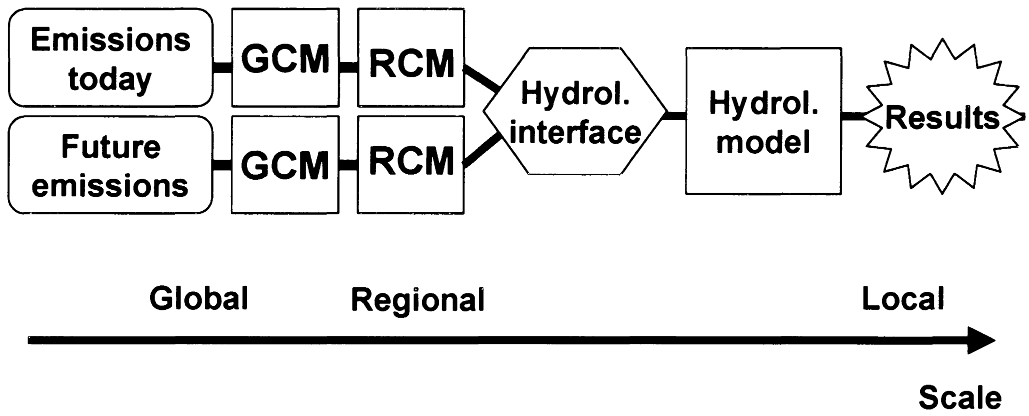


Figure 11. *The analysis chain for assessment of hydrological impacts from climate change.*

There are shortcomings in the delta change approach. One is that changes in the timing and frequency of extreme weather events from the climate models are difficult to represent. The extreme events in the baseline climate are often simply adjusted upward or downward according to the scenario changes applied. Another is that the delta change interface between the climate model and the hydrological model is a type of filter that tends to smooth out information. The amount of smoothing that occurs depends a great deal on how the analysis of changes is performed and what information is included in the transfer from climate model to hydrological model. For instance, if wintertime temperature increases are more prominent at extreme low temperatures and less prominent for temperatures around zero, use of an average change results in an overestimation of snowmelt in the future climate.

Further shortcomings and uncertainties exist throughout the analysis chain. A highlight of some of them follows below.

4.1 Emission scenarios

Future emissions of greenhouse gases into the atmosphere are uncertain but there is little doubt that these will keep on increasing for a long period to come. This uncertainty is dealt with by global modellers by use of different emission scenarios as driving forces for the GCMs. The most current emissions scenarios are from the SRES storylines for future development (Nakićenović et al. 2000).

4.2 Global climate models

Even though the results from most GCMs indicate a warmer global climate due to an enhanced greenhouse effect, regional differences are great. This is particularly true for scenarios of future regional precipitation, which is the most important variable for hydrological impacts analysis. The uncertainty is most often addressed by the use of different GCMs from different research institutes.

4.3 Regional downscaling

Regional downscaling is the process whereby the course resolution in the GCM is transferred to a regional scale. This is a necessary process for any hydrological impacts study as the size of a river basin is often much smaller than that of a grid cell in a GCM. As mentioned above, two fundamentally different downscaling methods dominate, *dynamical* and *statistical*. The uncertainty in the downscaling process is generated both by the choice of approach and, in the case of the dynamical method, the choice of model, its parameterisation and its spatial and horizontal resolution. Statistical methods are heavily dependent on available observations, which introduce their own uncertainties dependent on measurement accuracy and network density, among others. Figure 12 indicates how the choice of downscaling strategy can affect simulations of hydrological impacts assessment for three basins in Sweden. In this case the dynamical and the statistical methods have been supplemented by the use of output from GCMs without any downscaling. Two global models have been used (the climate forcing is in this case the same for the global and statistical downscaling, but slightly different for the dynamical downscaling).

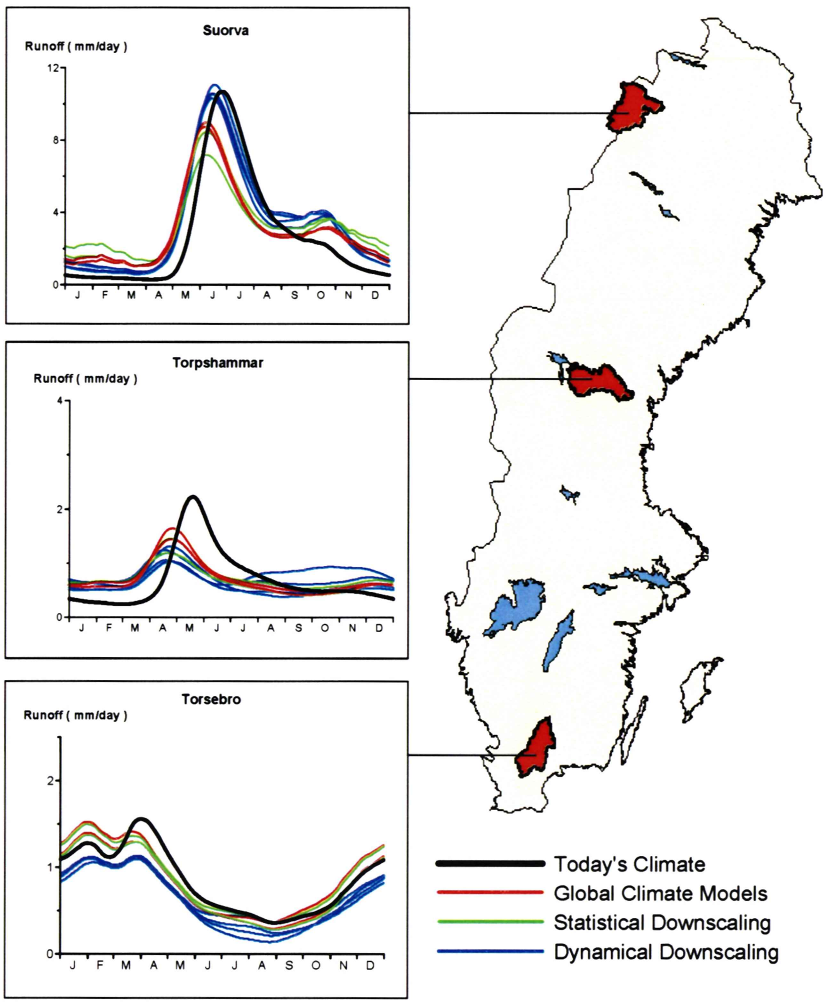


Figure 12. *Climate change impacts to runoff for three basins in Sweden based on output from two global climate models, statistical downscaling and dynamical downscaling.*

4.4 The hydrological model

Hydrological models developed for flood forecasting or other purposes are normally used in studies of climate change on hydrology. Uncertainty is generated in their calibration. One can never be certain that an optimal parameter calibration that holds both for the present and future climates is obtained. Just because a model may perform well for the present climate is no guarantee that it will accurately represent the future climate. Modelling evapotranspiration is another source of uncertainty; different methods give different results. One way of addressing these issues is to use more than one hydrological model or different approaches in its representation of critical processes.

4.5 Data analysis and baseline problems

Once the simulation of runoff records for the new climate is ready there are a few additional problems to consider. One is the uncertainty in any frequency analysis of extremes, a well known source of frustration to any hydrologist. Another is the baseline problem. The latter is very much in focus in Scandinavia today due to extraordinary hydropower production in recent years. The question posed is simple: To which reference climate do we impose climate change?

4.6 Discussion

It is quite obvious that there are many factors that introduce uncertainty in the production of hydrological impacts assessment even though the future climate seems to be the most uncertain one. What is then to be done about the problem of transferring the climate change signal to hydrological impact models? The ideal solution would be for the climate models to reach a level of development where their results could be used directly without any transfer mechanisms where information is lost or filtered. It may be some time before this is achieved, if ever. However, substantial progress has been made in the land parameterisation schemes of climate models over recent years and representation of runoff processes is now starting to get the attention that it deserves. This means that the hydrological components of these models are starting to behave more as a hydrologist would like and less as the error correction function that they so often were in earlier climate models. Still, this does not mean that the models will provide the correct hydrological outputs; problems with precipitation remain.

Even though the current state-of-the-art in analysing climate change impacts on hydropower is still offline hydrological models using the delta change approach, we need not limit ourselves to this approach. Why not explore many different options; only then can one gain an understanding for how wide the band of uncertainty is. Different approaches to assessing the hydrological impacts from climate change scenarios are summarised in Figure 13. These approaches range from direct output of an RCM with river routing procedures included in the climate model (Graham, 2002) to statistical downscaling. For the AGCM case, delta change occurs in two places along the analysis chain. AGCM here refers to the atmospheric part of a coupled GCM at higher resolution, where the global ocean modelling is replaced by the change in SSTs (delta change) from the coupled GCM. Studies of this type are currently ongoing in a major EU project (PRUDENCE, 2002).

The choice of strategy for the interface between a climate model and a hydrological application is crucial in the light of recent concern about changes in extreme precipitation in a future climate. It can be questioned whether the delta-change approach can be modified to capture this realistically and with proper conservation of statistical properties. This is one of the issues that need to be addressed in the next phase of CWE.

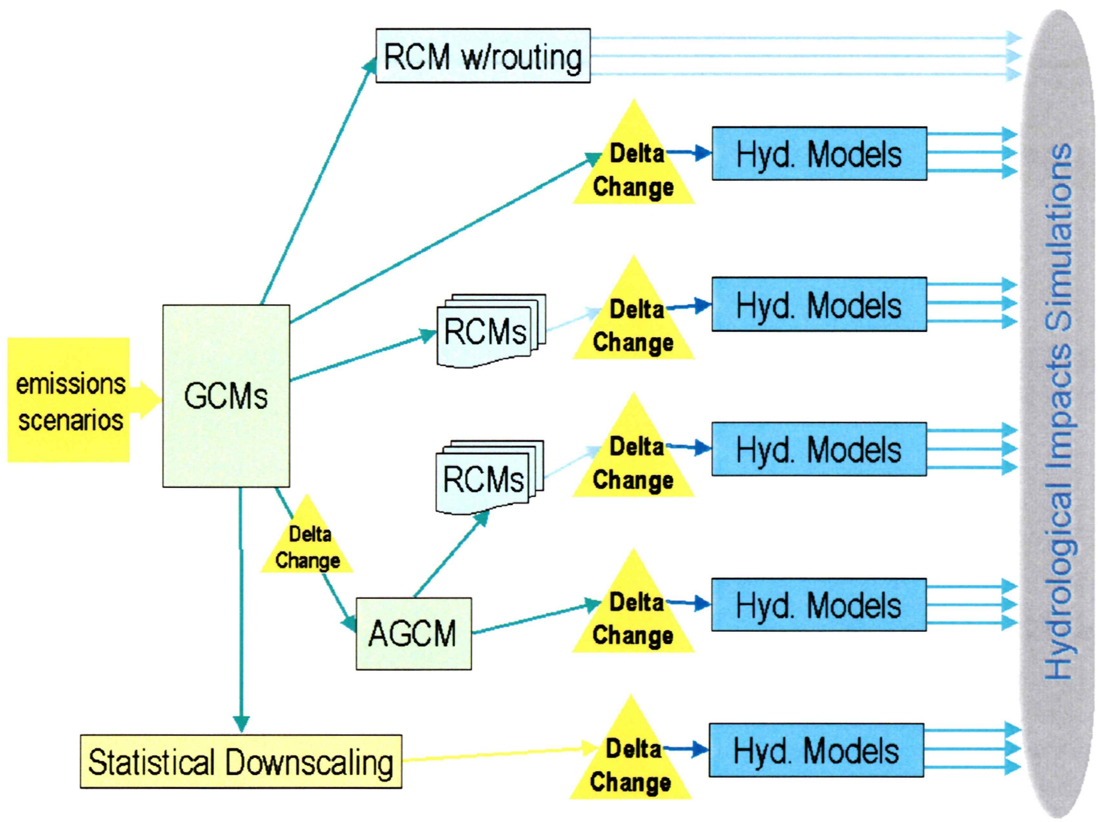


Figure 13. *Alternative approaches to assessing hydrological impacts from climate change scenarios.*

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