Climate change impacts and uncertainties in flood risk management: Examples from the North Sea Region

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RAPPORT

Climate change impacts and uncertainties in flood risk management: Examples from the North Sea Region

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Climate change impacts and uncertainties in flood risk management: Examples from the North Sea Region

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Abstract: This report presents methods used for estimating the hydrological impacts of climate change and their uncertainties, the expected impacts on extreme flows in Norway, and in Sweden with particular reference to Lake Vänern, and examples of climate change impacts on river discharge and on agriculture in the Netherlands. Work considering changes in extreme precipitation is also reported, as are methods and strategies for communicating climate change impacts in flood management practice.

Key words: Climate change adaptation, hydrological projections, Flood Directive, flood hazard

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Preface

The Interreg IVB SAWA (Strategic Alliance for Water Management Actions) project (2008-2012) has been supported by EU Regional Development funds for the North Sea Region and has been managed by the Agency of Roads, Bridges and Water of the City of Hamburg, Germany. Partners from five countries in the North Sea region (Germany, Netherlands, Norway, Sweden, UK) have participated in three working groups related to Adaptive Flood Risk Management (WG1), Adaptive Measures (WG2), and Communication and Capacity Building (WG3). As part of the work of WG1, methods for estimating and communicating the potential impacts of climate change on processes contributing to flood hazard have been considered by a subset of project partners with expertise in this area. In particular, the Swedish Meteorological and Hydrological Institute (SMHI),the Norwegian Meteorological Institute (met.no) and the Waterboard Hunze en Aa's, the Province Flevoland, and the Waterboard Noorderzijlvest in The Netherlands have collaborated with NVE to produce the summary of methods, results and examples of current practice presented in this report. The report represents a transnational deliverable of the SAWA Adaptive Flood Management working group under the Phase 2 theme 'Climate change impacts and uncertainties'. Within NVE, the SAWA project has been coordinated by the Section for Areal Planning and Watercourse Safety in the Landslides and Floods Department. Work on the Phase 2 theme 'Climate change impacts and uncertainties' has been carried out by the Hydrological Modelling Section in NVE's Hydrology Department.

Oslo, January 2012

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Summary

Climate change will lead to changes in several factors which can impact flood hazard, including sea level rise, changes in precipitation patterns and depths, and increased temperatures which will alter patterns of evapotranspiration and snow storage. The local impact of these changes varies significantly between areas within the North Sea region, so analyses using regionally downscaled climate projections and further modelling are required to determine their effect on flood hazard. Numerous climate change projections based on different global and regional climate models are available from, for example, the EU FP6 ENSEMBLES project, and from earlier EU and regional projects. Due to differences between the various models, it is considered to be good practise to analyse impacts based on several climate models. The outcome of a climate impact analysis is therefore a range of projections, rather than a simple 'one-number' estimate. The spread in the projections can also be illustrated to give an indication of the level of agreement between the projections as a measure of their uncertainty.

Hydrological modelling based on climate projections has been used to distinguish regional patterns of projected change in the 200-year flood in Norway. Many areas will be subjected to more extreme flooding in the future, due to increases in rainfall-induced flooding. There are inland and northern areas of Norway, however, for which flood hazard is projected to decrease in the future, due to a decrease in the magnitude of the spring snowmelt flood. Similar patterns have been found in Sweden for the 100-year flood. In both cases, the differences between individual projections can be large. Consideration of the range of projections, however, suggests that the regional patterns of increase *vs.* decrease in flood magnitude are fairly robust. Work in Sweden has also focused specifically on changes in the inflow, including the design flood, to Lake Vänern and the impacts of these changes on corresponding lake levels. Although some scenarios indicate an increase and some a decrease in lake levels, the analysis indicates that changes in the lake regulation strategies would slightly mitigate the largest projected increases. Climate change effects on seasonal discharge in the large rivers Rhine and Meuse have also been studied based on four possible scenarios, and the results suggest higher winter flows and low summer flows in both river systems. Analyses of 30-minute and one-day duration precipitation have also been undertaken in Sweden for the central part of the Lake Vänern catchment and generally indicate rather large increases in the 10-year rainfall with these durations. Analyses of one-hour duration precipitation in Oslo also point towards an increase in the annual maximum values and in the most extreme values under a future climate.

Communication of climate change impacts on flood hazard is a necessary precursor for the development of adaptation strategies. In The Netherlands, flood managers are referred to KNMI's recommended scenarios for use in assessing the likely impacts of climate change. A current project is preparing interactive flood inundation maps which can be accessed by the public from a website. In Norway, regional guidance for taking account of climate change in some aspects of flood management has been developed and published, and these recommendations are now being implemented in conjunction with the country's flood hazard mapping project. In Sweden, there is currently a discussion as to how to best incorporate climate change impacts in flood hazard determination and mapping, and modelling tools to meet this need have been developed.

1 Introduction

The EU Flood Directive (2007/60/EC) states that consideration should be given to the possible effects of climate change on flood hazard in flood risk assessment and management (Ch.II, Art.4.2 and Ch.VIII, Art.14.4). This requirement assumes that the information necessary to make this assessment is available for the relevant types of floods in a given area. Although general results regarding expected changes in annual temperature and precipitation and in global sea level have been available for several years (*e.g*. IPCC, 2001; 2007), such results are usually unsuitable for direct application in flood risk management. This is due both to the lack of spatial detail in these projections and to the need for further analyses to interpret changes in variables relevant to flood hazards (*e.g*. regional changes in extreme precipitation, local changes in peak river discharges). As part of the EU Interreg IVB SAWA project, the Norwegian Water Resources and Energy Directorate (NVE), the Swedish Meteorological and Hydrological Institute (SMHI) and the Norwegian Meteorological Institute (met.no) have undertaken work quantifying expected changes in hydrological flooding and in extreme precipitation under a future climate for use in flood risk management. In addition, three SAWA partners from the Netherlands (Waterboard Hunze en Aa's, Provincie Flevoland, Waterboard Noorderzijlvest) have provided information as to how climate change impacts have been or will be taken into account in ongoing work in The Netherlands. This report summarises the methods and results from these studies and presents examples illustrating how results are being used in practice. A general overview of climate change and flood risk management in each of the five SAWA countries (Germany, the Netherlands, Norway, Sweden and the UK) was also previously presented at the SAWA Midterm Conference in Gothenburg (Lawrence and Graham, 2010) as a deliverable to SAWA Working Group 1.

This report is organised into sections which describe:

- Projected changes in climate and related factors which may impact flood hazard (Section 2);
- Methods for analysing likely changes in factors contributing to flooding, including ensemble methodology, hydrological modelling, flood frequency analysis, design flood estimation, and extreme value analysis of short-duration rainfall (Section 3);
- Climate projection data, including the global and regional climate model projections represented in the ensemble of models, and techniques for local adjustment of the data for use in local-scale modelling (Section 4);
- Results of climate impact analyses, including projected changes in flood magnitudes and seasonality and their uncertainties, expected changes in extreme precipitation at selected locations, and impacts on other water management issues (Section 5);
- Examples of methods and strategies for communicating the results of climate impact analyses related to flooding and water management (Section 6).

Each section is organised so as to highlight aspects of SAWA project work related to climate change and flood management in the three countries contributing to this report, *i.e.* Norway, Sweden and The Netherlands.

2 Projected changes in climate

Climate change projections for northern Europe (*e.g*. IPCC, 2007) indicate changes in both temperature and precipitation regimes in the future that, in some areas, will contribute to an increased hazard from hydrological flooding. In addition, the regional effects of global sea level rise and projected changes in patterns of storm surge will also have a significant effect on the likelihood and/or magnitude of flood inundation in many coastal regions. There are, however, significant variations between regions as to the impact of altered climatic regimes on flood hazard. In large parts of the Nordic region, for example, a decrease in the overall flood hazard is projected for many larger catchments, reflecting the projected decrease in the spring and early summer snowmelt floods which dominate peak flows in these catchments (*e.g*. Andréasson *et al.*, 2004; Roald *et al*., 2006; Veijalainen, *et al*., 2010). Simultaneously, an increase in the occurrence of extreme precipitation can increase the likelihood of floods in smaller catchments and in urban areas in the same region. Lake flooding can increase in areas currently dominated by snowmelt flooding due to changes in seasonal runoff volumes despite a projected reduction in the maximum daily inflow to the lake. Sea level rise will also have variable local effects throughout northern Europe due to regional differences in uplift resulting from isostasy as opposed to land subsidence. If one is to develop guidance for taking account of climate change in flood risk management, it is therefore necessary to conduct fairly detailed regional or local analyses.

2.1 Norway

In Norway, the average temperature is expected to increase in all seasons throughout the country, and the average annual temperature will increase by between 2.3 and 4.6 °C by the end of the century with the largest increases occurring during the winter months. The average annual precipitation is also expected to increase by 5 to 30%, although there are large differences between seasons and between regions in Norway (Hansen-Bauer, *et al*., 2009). The largest increases in precipitation are expected during the autumn and winter months at most locations. In addition, days with heavy precipitation will increase in frequency, and the intensity of 1-day precipitation is expected to increase. These changes in temperature and precipitation regimes will, in turn, impact the magnitude and, in some cases, the seasonality of peak runoff and floods throughout the country. Due to the significant role of catchment storage (*e.g*. lakes, snow, soil and groundwater) in altering the timing between precipitation and runoff, there is not a simple one-to-one relationship between projected changes in precipitation and corresponding changes in runoff. Hydrological modelling based on locally-adjusted climate scenario data is required to assess the impact that changes in precipitation and temperature will have on land surface processes, such as stream flow generation leading to floods.

Hydrological projections for changes in runoff and peak flows in Norway under a future 2071-2100 climate have been previously reported by NVE (Beldring *et al*., 2006; Roald, *et al*., 2006) based on the regional climate scenarios available at the time. Percentage changes in flood statistics have been evaluated for 23 catchments (Roald *et al.*, 2006) using three regional climate scenarios from the RegClim project (Bjørge *et al*., 2000).

Those results indicate both wide-ranging responses to climate change in the individual catchments and considerable differences between projections from different climate scenarios. However, it is generally concluded that large snowmelt floods will be less common under a future climate, and that annual snowmelt floods will occur earlier in the year. A trend towards an earlier spring snowmelt is already apparent in patterns of discharge in some Nordic catchments (Wilson, *et al.*, 2010). Beldring *et al.* (2006) also evaluated the percentage change in the mean annual flood and the 50-year flood in four catchments. Those results indicate moderate decreases in flood magnitude for the inland catchment (Nybergsund in Trysil) and the northernmost catchment (Masi in Alta), while moderate increases are projected for the southern coastal catchment (Flaksvatn in Tovdal) and moderate to large increases are expected in the western catchment (Viksvatn in Gaular).

The previous work by NVE on changes in flood statistics under a future climate is based on a limited number of catchments and their spatial distribution is not particularly uniform over Norway, with only three catchments representing the area north from Trøndelag and no catchments in south-eastern Norway in the region around Oslo. Additionally, a newer generation of higher resolution regional climate scenarios are now available from the EU FP6 Ensembles Project (van der Linden and Mitchell, 2009). These come from updated climate models and methods for linking global and regional climate models. Therefore, to generate a set of hydrological projections that can contribute to an adaptation strategy for managing expected climate change impacts on floods throughout Norway, further work was undertaken within the SAWA project. The work is based on the most up-to-date climate scenario data available and also considers a denser and more uniform selection of catchments for hydrological modelling to take account of regional variations. The methods used and results of that work are reported in detail in Lawrence and Hisdal (2011), in addition to the highlights presented in this report.

In addition to projections for changes in precipitation and in hydrological flooding, expected changes in sea level and in storm surge have also been estimated for coastal communities in Norway (Vasskog, *et al.*, 2009). The impact of sea level rise is variable along the Norwegian coastal due to regional differences in isostatic uplift relative to the increases in sea level. By the end of the 21st century, however, local sea level rise of 40 to 70 cm are projected along the Norwegian coast. The magnitude of the 100-year storm surge is also projected to increase due to an increase in storm activity and intensity (Lowe and Gregory, 2005) in the North Sea region.

2.2 Sweden

Sweden is expected to experience greater warming than the global average (SOU, 2007:60, 2007). By the 2020s, mean annual temperatures are expected to be some 2°C higher than for the period 1961-1990. By the 2050s, this could reach 2-3°C and by the 2080s 3-5°C. Regional downscaling projections have consistently shown a stronger increase in wintertime temperatures compared to summertime temperatures in northern Sweden (*e.g*. Giorgio *et al*., 1992; Jones *et al*., 1997; Christensen *et al*., 2001; Déqué *et al.*, 2007; Graham *et al.*, 2008). Consequently, most of this warming will take place in the winter, slightly less during the spring and the autumn, and the least during the summer. By the 2080s winter warming could reach as high as 5-6°C in southern Sweden and 6-7°C in northern Sweden, for example.

Precipitation in Sweden could increase by as much as 50% during winter months already by the 2020s, although this varies with the projections used (SOU 2007:60, 2007). In some places, this increase could be as much as 100% by the 2080s. For future summers, regional climate change simulations show increases in precipitation for northern Sweden and decreases for southern Sweden. The transition zone between increase and decrease generally falls in mid Sweden (Kjellström and Ruosteenoja, 2007). The summertime decrease in precipitation in southern Sweden could be approximately 20-30%. However, not all climate model projections show a summer decrease for southern Sweden. An increase in the number of days with heavy precipitation is also expected for the winter season. Furthermore, independent of whether mean changes increase or decrease, an increase in the most intensive precipitation is expected (Kjellström and Ruosteenoja, 2007).

Climate change projections have been translated into hydrological projections for Sweden with the help of hydrological modelling. Studies to date indicate that mean runoff will increase across most of the country under future climate conditions. This is particularly true for western and northern parts of the country. With respect to extreme events, analysis of 100-year floods shows increases in magnitude for south-western and north-western parts of the country. This also indicates that floods with a 100-year magnitude for the present climate will become more frequent in these areas under a future climate (SOU 2007:60, 2007). In other areas of Sweden, the magnitude of 100-year floods could decrease, as snowmelt floods decrease. As analyses of this type evolve with information from new climate projections, efforts made during the SAWA project have enhanced the development and understanding of these projected impacts. These are reported in more detail in the following sections of this report.

Statistical properties of extreme short-term (sub-hourly) rainfall are used particularly in the design of storm water sewers and other urban hydrological structures, such as overflows and retention ponds. An expected consequence of climate change is a general increase in the highest short-term intensities, which implies an increased frequency of urban flooding and increased volumes of storm water that overflow untreated to recipients. As urban hydrological structures generally have a renewal rate of 50-100 years, climate change impact assessment is crucial.

Regional sea level rise, *e.g.* in the Baltic Sea and the North Sea, is expected to be 10-20 cm greater than the global average (IPCC, 2007; SOU 2007:60, 2007). In the Baltic Sea region, this increase is countered by rises in land levels, but is boosted by the fact that westerly winds are expected to increase in frequency. In simulations by SMHI of how sea levels in the Baltic change by the end of the 21st century under various scenarios for global sea levels, levels along Sweden's coastline increase by as much as 80 cm in the southern Baltic, while along the northern Baltic rises in land and sea levels cancel each other out. Extremes of high water are expected to increase by more than the average water level (SOU 2007:60, 2007).

Low-pressure movements and winds are also of great significance to sea levels and the risk of flooding and erosion along the coasts. With an increased dominance of westerly winds, the maximum high-water levels in the Baltic Sea will rise substantially. For example, the maximum high-water level in Karlskrona in southern Sweden today is one metre above the present-day mean water level. At the end of the century, it is estimated to be two metres above the present-day level.

2.3 The Netherlands

The climate change scenarios currently used for adaptation planning in the Netherlands (KNMI, 2009a,b) indicate an increase in the average winter temperature of 0.9 to 2.3°C and in the average summer temperature of 0.9 to 2.8°C by the year 2050. The average winter rainfall is expected to increase by 4 to 14%, and changes of between -19% and +6% are projected for summer precipitation. The 10-day duration rainfall with a 10-year return period is projected to increase in both the winter and summer seasons (by up to 27% in the summer), and extreme precipitation is expected to increase by 10 to 30% by 2050. These changes will increase the risk of inundation from pluvial and fluvial flooding throughout the country. In addition, an absolute rise in sea level of between 15 and 35 cm by 2050, together with regional land subsidence, point towards an increased risk of marine flooding in the future.

3 Methods for analysing impacts

3.1 Ensemble methodology

Work within the SAWA project by NVE and SMHI has focused on developing projections for changes in hydrological flooding under a future climate in Norway and Sweden, respectively. To assess climate change impacts on hydrological flooding, a modelling scheme comprised of a series of linked models is required, as illustrated in Figure 3.1.

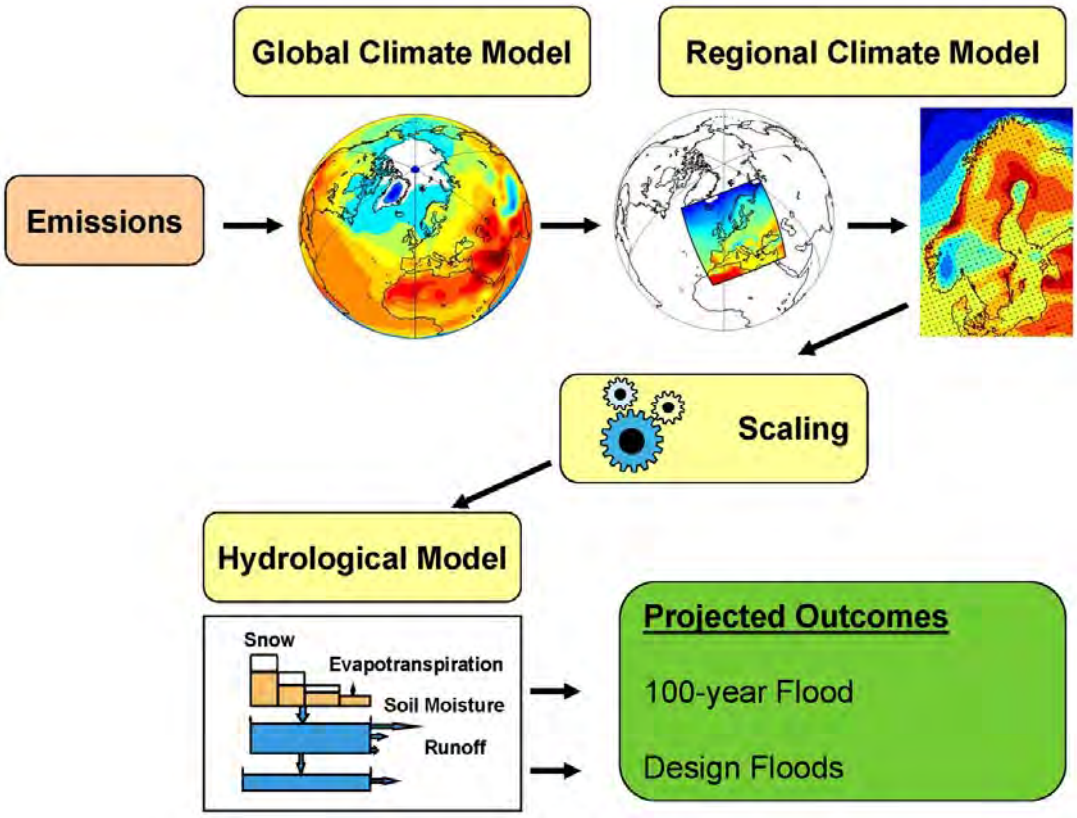


Figure 3.1 **Coupling between global and regional climate models, adjustment (scaling) procedures and hydrological models for use in climate impact studies.**

Climate change analyses are based on simulations derived from large-scale Global Climate Models (GCMs) which model atmospheric, and in some cases, linked oceanic processes, both for historical and future periods. For modelling future periods, the GCMs are run under 'SRES' emissions scenarios representing various alternatives as to how society and technology will develop through the 21st century and the impacts this will have on greenhouse gas emissions (Nakićenović *et al.*, 2000). The assumed CO_2 emissions for different future scenarios and the resulting CO_2 concentrations are illustrated in Figure 3.2. Note that differences in the resulting CO_2 concentrations only become apparent from about 2050. For this reason, climate change impact analyses for near future periods are often only based on one emission scenario, *e.g.* A1B. By the end of the 21st century, there are considerable differences between the scenarios, and the B2, A1B and A2 scenarios are generally taken to represent low, medium and high CO_2 concentrations, respectively. Due to uncertainty with respect to how society and technology will develop in the future, results derived from alternative emission scenarios are often used in climate impact analyses, so that the full range of possible outcomes is taken into account. It is also worth noting, however, that recent comparisons of CO_2 emissions with the SRES scenarios indicate that as of 2009 the growth rate in emissions since 2000 exceeded that projected by the most fossil fuel intensive SRES scenario (A1F1 – Stippled red line in Figure 3.2) (McMullen and Jabbour, 2009).

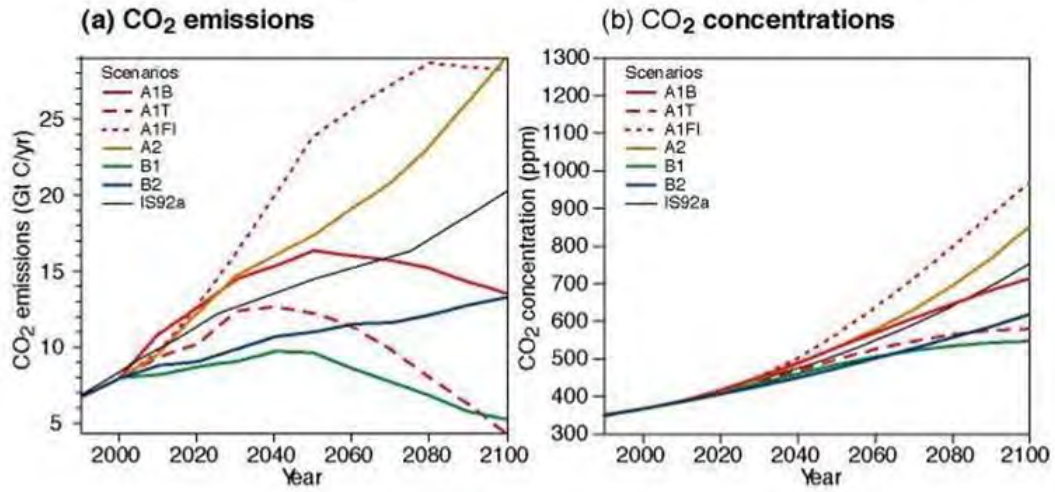


Figure 3.2 **Scenario development for assumed CO_2 emissions (a), and resulting CO_2-concentrations (b) according to different SRES scenarios (modified from Nakićenović *et al.*, 2000).**

The output from the GCM model runs must be dynamically downscaled to a higher resolution grid (*e.g.* 25 x 25 or 55 x 55 km) using Regional Climate Models (RCMs) before they are suitable for regional scale impact analyses. Different GCMs and RCMs often produce dissimilar results at regional scales, due to differences in how certain physical processes are represented in the climate models, and in the methods and the variables used in coupling the RCMs to GCM output. Therefore, for climate impact analyses, it is considered to be good practice to use climate data derived from several models and model combinations and to evaluate the range of results, rather than to limit consideration to a single GCM/RCM combination. This use of multiple models or methods to generate a spectrum of results based on a large number of simulations is sometimes referred to as 'Ensemble' modelling.

Following the dynamical downscaling of projections using RCMs, analyses of changes in extreme rainfall are often undertaken at this point in the modelling chain (Figure 3.1). Local-scale analyses of rainfall, however, also require further adjustment to better match local observations. For use in catchment-based analyses (such as are required to evaluate changes in hydrological flood frequency), the local adjustment of precipitation and temperature output series from RCMs prior to their use in hydrological models is absolutely necessary. These techniques correct one or more of the statistical moments (*e.g.* mean, standard deviation) of the monthly modelled data to better match local observations during a historical period, and may also adjust the total number of rainy days. There are different methods for achieving this correction or 'scaling', and these methods are each based on assumptions as to how the statistical moments will change in future periods. Consequently, the alternative methods can also lead to differing results when the adjusted input data are used in hydrological modelling or other local analyses. In some applications of ensemble modelling (*e.g.* that used by Norway for hydrological flooding), different scaling methods are also sampled by the model ensemble.

Locally-adjusted data (precipitation and temperature series) derived from the climate models are used as input data to a hydrological model so that changes in patterns of streamflow or in, for example, the design flood can be determined. In order to assess changes in floods of a given return period (*e.g.* the 100-year flood), the modelled stream

flow series must be further analysed using flood frequency analysis. Hydrological modelling and flood frequency analysis are both methods which rely on the adjustment of parameters to obtain a best fit to a data set (*e.g*. observed discharge data in the case of hydrological model calibration, and the annual maximum series in the case of flood frequency analysis). However, models rarely provide a perfect fit to the data. In addition, model parameters calibrated based on observations are not necessarily the most suitable for modelling future conditions (for which observations are not available). Consequently, hydrological models are associated with parameter uncertainty. Previous climate impact analyses in four Norwegian catchments have indicated that in some cases, this uncertainty can be as large as the differences between the climate projections used (Lawrence and Haddeland, 2011). For this reason, the ensemble methodology applied by NVE has also included multiple hydrological model parameter sets. Uncertainty in the flood frequency estimation procedure has also been considered by NVE for a subset of the projections published by NVE (Lawrence, 2010; Lawrence and Hisdal, 2011).

3.2 Hydrological modelling

Hydrological simulations for both Norway and Sweden were carried out with the HBV hydrological model which is best characterised as a semi-distributed conceptual model (Bergström, 1995). Like many hydrological models of its genre, the HBV model is composed of subroutines for snow accumulation and melt, soil moisture accounting, surface and subsurface flow pathways and river routing. Variations of the HBV model are now standard tools for runoff simulations in Sweden, Norway and Finland, and the model has also been applied in more than 50 countries outside the Nordic region. Climate input variables to the HBV model are normally daily values of precipitation and air temperature. In some versions, an estimate of potential evapotranspiration can also be input to the model, and in other versions evapotranspiration is estimated from the input temperature using a simple index temperature model. A version of the model with an hourly time resolution is also available. The model has been applied at a wide range of scales, from small research basins of less than 1 km^2 up to a continental scale.

3.2.1 Norway

For the hydrological modelling undertaken by NVE, the 'Nordic' version of the HBV hydrological model (Sælthun, 1996) was calibrated and validated for 115 catchments as described in Lawrence, *et al*. (2009). The spatial distribution of catchments is illustrated in Figure 3.3. Catchment area varies from approximately 3 km^2 to 15,500 km^2, with a median value of 190 km^2. Thus, smaller catchments are fairly well represented in the modelling. The HBV model was calibrated and validated for each catchment using observed daily average discharge at the catchment outlet. The model simulations are based on 1 x 1 km gridded historical daily precipitation and temperature data for the period 1961-2008. The hydrological modelling used a daily time step, reflecting the temporal resolution of the input precipitation and temperature data. Thus, the modelled runoff values represent daily average values, rather than instantaneous peak values.

The period 1972-1995 was used for model calibration and the remaining years for model validation for most of the catchments. Model calibration was accomplished using PEST parameter estimation routines (see Lawrence, *et al*., 2009 for further details), and 150

different best fit model parameter sets were calibrated for each catchment. The best 25 parameter sets were selected for each catchment for further use, such that for individual catchments the Nash-Sutcliffe criterion which assesses the model fit (Nash and Sutcliffe, 1970) varies by no more than 2%. The volumetric bias was also used as a secondary calibration criterion during model calibration. The Nash-Sutcliffe values for the fitted models for the catchments indicate good to excellent model fits in most areas (Figure 3.3). The best model fits (> 0.85) tend to be associated with larger catchments in regions where the annual flow regime is dominated by peak flows in the spring and early summer derived from snowmelt. Poorer model fits are often obtained in western and coastal regions where steep topography and large local gradients in rainfall contribute to a higher degree of model uncertainty. Hydrological simulations for future climatic conditions were undertaken using the 25 best fit parameter sets for each catchment together with input data from climate projections, details of which are described in Section 4.1.

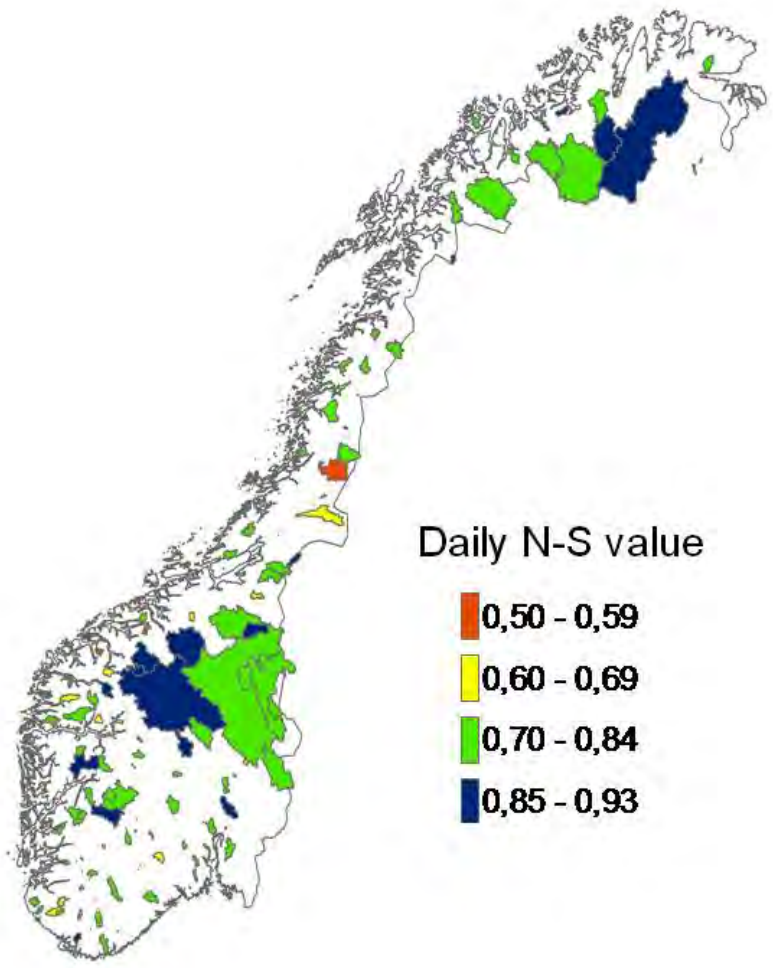


Figure 3.3 **Location of the 115 catchments used for HBV model calibration in Norway, with the catchment boundaries indicated. The value for the Nash-Sutcliffe criterion based on daily discharge values is indicated by colour.**

3.2.2 Sweden

For the hydrological modelling undertaken by SMHI, the standard "Swedish" version of the model was used (Lindström *et al.,* 1997). For determining changes in the 100-year flood, a nationwide application that covers all of Sweden using 1001 sub-basins was used. Sub-basins for this application are on average about 450 km^2. For work involving detailed modelling of the Lake Vänern drainage basin, the HBV model setup used is the current operational forecast model that SMHI developed for the Vattenfall hydropower company to optimise regulation of Lake Vänern. For the nationwide study, an optimised regional calibration routine was applied to obtain the best possible performance. For Lake Vänern, the automatic calibration routine was applied in a more detailed fashion. Both calibrations were based on the best available observations during 1961-2008 for calibration and validation. The calibration was based both on performance according to the Nash-Sutcliffe efficiency criterion (Nash and Sutcliffe, 1970) and on volume error. Precipitation and temperature observations were optimally interpolated to a 4 x 4 km grid that covers all of Sweden (Johansson, 2000; Johansson and Chen, 2003) for use as input to the hydrological model. Daily potential evapotranspiration was calculated using the simple temperature-index method described in Lindström *et al.* (1997).

3.2.3 The Netherlands

Water systems in The Netherlands are very modified by human intervention and are often managed by structures such as weirs and dikes, thus differing significantly from those in the Nordic region. Therefore, a combination of hydrological and hydraulic models is needed to give a good picture of the potential impacts of climate change on these water systems. Climate impact studies at the national level have been undertaken for the main water system (principal rivers and the sea) by national research institutes (*e.g.* Deltares) and have mainly focused on flood risk due to dike failure as the most important flood risk. For the larger rivers, the studies have resulted in a plan to make more space available for water storage during flood inundation. Details of the regional wet infrastructure are held by the 25 regional Water Authorities (waterschappen), and for this reason regional Water Authorities execute climate impact studies on regional water systems. These studies were completed in 2005 and resulted in plans which will be updated again in 2013.

3.3 Flood frequency analysis

To estimate the probability of a peak flow of a given magnitude or, conversely, to assess the magnitude of a flow with a given probability, flood frequency methods must be applied. In Norway, flood frequency analysis is undertaken to provide estimates for flood hazard mapping, for which the 200-year flood is used, representing a flood magnitude with a 0.5% likelihood of occurrence in any given year. For dam safety, the 500 and 1000-year floods are considered, depending on the safety class of the dam, and these represent floods with likelihoods of 0.2% and 0.1%, respectively. In Sweden, the 100-year flood and a specific Swedish 'worst case' design flood are estimated in conjunction with flood hazard analysis and for dam safety. In both countries, rainfall-runoff

modelling methods are used for assessing the 'design' flood. This corresponds to an extreme event with a very long return period, and is described in Section 3.4.

To analyse changes in the magnitude of a flow of a given return period (*e.g*. the 100- or 200-year flood), flood frequency analysis is applied to the annual maximum series for the periods of interest (Figure 3.4). The percentage change in flood magnitude is then estimated as the difference between the two curves divided by the flood magnitude for a reference period (*e.g*. 1961-1990 in Figure 3.4). There are several extreme value distributions that can be used for this analysis (Coles, 2001). The two-parameter Gumbel distribution was used by both NVE and SMHI to model the annual maximum series for the work presented in the report. This distribution was chosen for the analysis due to the limited length of the data series (*i.e*. 30 values of the annual maximum for a 30-year time period) which makes the fitting of a three-parameter distribution very uncertain. The Gumbel distribution has also been widely applied, including in other recent studies of climate change impacts on floods in Europe (*e.g*. Dankers and Feyen, 2008; Veijalainen *et al*., 2010).

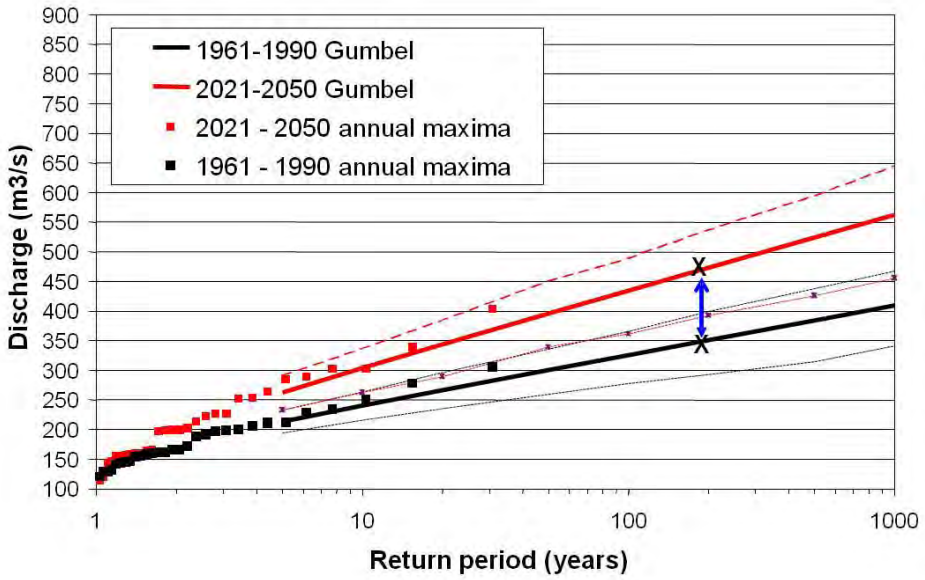


Figure 3.4 **Example flood frequency analysis of annual maximum series from simulated data for a reference (1961-1990) and a (2071-2100) future period, based on the two-parameter Gumbel distribution. The 10th and 90th percentile confidence bounds are indicated to illustrate the uncertainty in the estimated discharge of a given return period. The blue arrow indicates the difference in the estimated magnitude of the discharge with a 200-year return period for the reference vs. the future period. This quantity is used to estimate the percentage change in the 200-year flood.**

In an attempt to illustrate the non-stationary character of the projections, flood frequency analysis was carried using stepwise 30-year time slices over the entire coming century for hydrological basins in Sweden. This was done by performing flood frequency calculations for a 30-year moving window which was incrementally progressed over the period 1963-2100. Beginning in 1992, the magnitude of the 100-year flood was estimated for the preceding 30 year period (*e.g*. 1963-1992). This was compared with the estimate for the period 1962-1991, and a percentage change was calculated. For each successive year, a new flood frequency analysis was calculated (*e.g*. 1964-1993 for 1993, 1965-1994 for 1994, *etc*.) In this way, trends in how the 100-year floods develop as the changing climate develops can be plotted and examined.

3.4 Design flood estimation

In addition to estimating floods of given return periods (*e.g*. 100-year or 1000-year floods) using statistical flood frequency analysis, both Norway and Sweden use rainfall-runoff modelling methods to estimate extreme floods, *e.g.* the 'design' flood. Design flood estimation is important in dam safety and, more generally, in the analysis of inflows to lakes and corresponding lake levels. Design floods are flows with a very long return period, although the actual length of the return period represented is difficult to precisely estimate. SMHI has estimated that their method for design flood analyses corresponds to a flood with approximately a 10,000 year return period (Norstedt *et al.*, 1992). The method used in Norway tends to produce higher values of discharge than those used in Sweden, suggesting an even longer return period.

The rainfall-runoff method for extreme flood estimation used by NVE applies an event-based rainfall-runoff model using synthetic rainfall input data representing an estimated PMP (probable maximum precipitation) sequence for a given area. The PMP is calculated by met.no (Norwegian Meteorological Institute) based on extrapolation of the rainfall with a 5-year return period following the methods outlined in Førland and Kristoffersen (1989) and Førland (1992). This sequence is used in a simple three-parameter rainfall-runoff model, PQRUT. A snowmelt contribution can also be added to the precipitation sequence, for locations and seasons where this is relevant. Saturation conditions for the catchment can also be adjusted. To estimate the PMF (probable maximum flood), the maximum possible rate of snowmelt for a particular region is used, based on the maximum observed temperature and snow cover/snow depth for the season of interest. The catchment is also assumed to be fully saturated throughout the precipitation sequence. Taken together, the input data and the assumptions used in the model represent the worst possible conditions that can be experienced in that catchment. For the hydrological modelling, a very simple model is used, as design flood estimates are often required for small catchments in data poor areas of Norway, precluding the possibility of calibrating a full HBV hydrological model. Further details of the model, methods and their application can be found in NVE (2011) and in Wilson, *et al*. (2011). These are also currently being reviewed by NVE in conjunction with Norway's participation in the EU COST Action ES 0901 – Flood frequency estimation procedures in Europe, in which methods used in different countries for flood estimation are being compared for a set of test catchments.

Sweden also has a specific method for estimating its own "maximum probable flood," that was developed primarily for use in evaluating safety at the numerous dams in the country (Swedenergy *et al.*, 2007; Norstedt *et al.*, 1992; Flödeskommittén, 1990). The underlying presumption with the Swedish approach is that the river systems are very complex with many reservoirs, and critical floods are generated by an interaction between snowmelt and heavy rainfall. This approach identifies a series of the worse possible combination of meteorological and hydrological conditions in a given drainage basin to come up with a very extreme, yet plausible event that would lead to maximum inflows, referred to as the "Swedish Design Flood." The primary factors considered are soil moisture conditions, snow storage and an extreme sequence of precipitation and

temperature. Extensive hydrological modelling using the HBV hydrological model is required to complete the analysis, as various combinations of factors are tested in the model. The original basis for this approach was detailed analysis of long periods of meteorological observations to develop well-defined, pragmatic guidelines that can be applied throughout Sweden.

As the methods used by both Sweden and Norway are based on observed data, the question as to how to incorporate the effect of climate change into the variables and assumptions used is very relevant. Recent efforts have analysed this in detail, both in Sweden and in Norway, whereby the basic assumptions that go into deriving these extreme floods are adjusted by relevant variables that will change as climate changes. For the Swedish method, temperature and precipitation input series are the main variables in question, and much work has gone into developing an appropriate method for this in the required hydrological modelling. (Andréasson *et al.*, 2009, 2011). In the case of the Norwegian method, the focus has been on changes in the PMP (probable maximum precipitation), and the Norwegian Meteorological Institute (met.no) has estimated this for a subset of the climate scenarios used by NVE (Table 4.1) for use by NVE. Likely changes in the snowmelt contribution in individual catchments are, however, currently under investigation. Comparisons using a full HBV hydrological model, as compared with the simpler PQRUT model, to address this issue have been made in several catchments, including the Norwegian/Swedish transboundary Trysil/Klärälven catchment. The results of this comparison are briefly discussed in the Results section of this report.

The Swedish design flood method was also used by SMHI to evaluate the potential effects of climate change on extreme floods, and the results of this analysis for Lake Vänern are summarised in the Results section of this report. For the Norwegian/Swedish transboundary catchment Trysil/Klärälven, a comparison of the Swedish calculations with NVE's estimates for a 100-year flood and for the design flood has also been made and is reported in Bergström *et al.* (2012). Key details from that work are also reported in the Results section.

3.5 Extreme value analyses of short-term rainfall

In the current procedure at SMHI, the Gumbel distribution is used to model annual maxima, in a similar manner to the flood frequency analysis described above (Section 3.3 and Figure 3.4). The analysis is normally applied to 30-year time series of 30-min precipitation from single RCM grid boxes. For each year in the series, annual maxima of durations ranging from 30 min to 24 hours are identified using a sliding window. The Gumbel fit to these maxima is generally very good (Figure 3.5). By performing the procedure for one reference and one future period, the future change corresponding to a certain duration and a certain return period may be estimated in a similar manner to that illustrated in Figure 3.4.

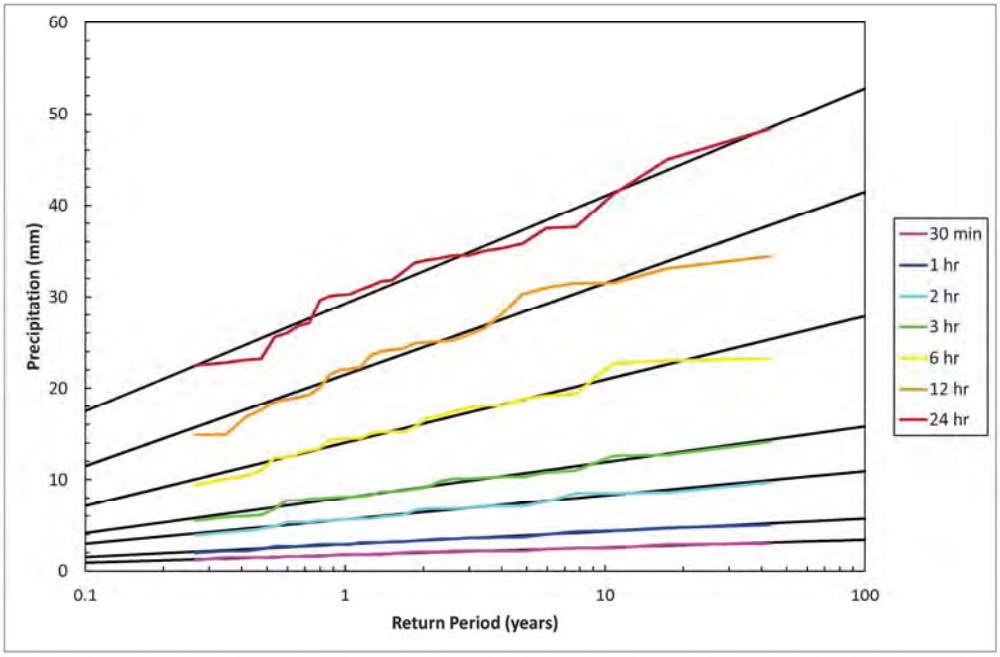


Figure 3.5 **Example of Gumbel fit (straight black lines) to RCM-simulated annual rainfall maxima of durations between 30 min and 24 hours (coloured lines) in the Vänern region during a 30-year period.**

The Norwegian Meteorological Institute (met.no) has been calculating Intensity-Duration-Frequency (IDF) values from a network of recording gauges with a temporal resolution of up to 1 minute. As in Sweden, the Gumbel distribution is used to model annual return period values. The IDF-analysis is normally applied to optimal data series, and return periods are estimated for durations of 1 minute and longer. Some of the available observed series begin in the 1960s, allowing analyses of trends in extreme short-term precipitation for the last 45 years (Mamen & Iden, 2010). By performing IDF-analyses for present and future periods, projected changes corresponding to different durations and return periods may be estimated from available RCM data using the method illustrated in Figure 3.4. However, current RCM modelling of intense heavy convective precipitation can be improved, and met.no is presently implementing fine-scale models with a spatial resolution of a few kilometers which will better represent these very localised, extreme rainfall events for use in further analyses of the impact of climate change on extreme short-term rainfall.

4 Climate projections for impact analyses

4.1 Sources of RCM data

Both Norway and Sweden have used precipitation and temperature data from a range of climate projections, including the most recently available projections from the EU FP6 ENSEMBLES Project (van der Linden and Mitchell, 2009). Most of these projections are from GCM model simulations based on the A1B SRES emission scenario representing 'medium' levels of CO_2 concentration by the end of the 21st century (Figure 3.2), and have been further downscaled using a range of RCMs. Additional projections from earlier projects have also been used by Norway and Sweden, so that differences between emissions scenarios (*e.g*. Fig. 3.2) by the end of the 21st century are also included in the model ensembles.

4.1.1 Norway

The climate change projections used by NVE for hydrological modelling and by met.no for rainfall analyses are listed in Table 4.1. Some of the RCM projections were generated in the RegClim (Regional Climate Development under Global Warming) project (Bjørge *et al*., 2000) in which they were dynamically downscaled to spatial resolutions of 55 km or 25 km by met.no using the HIRHAM regional climate model. The remaining scenarios come from the ENSEMBLES project and have a 25 x 25 km model grid cell resolution. The method used for local adjustment is also given in Table 4.1 and is discussed later in this section. For hydrological modelling, 13 climate projections were available for assessing changes between a 1961-1990 reference period and a 2021-2050 future period and 13 for the 2071-2100 future period. The 13 available projections differ somewhat, as only nine of the projections are common to both periods. The projections for 2071-2100 represent three SRES emissions scenarios, A2, A1B, and B2, which correspond to low, medium and high levels of greenhouse gas emissions, respectively (Fig. 3.2). Three of the projections also represent the same GCM/RCM combination with different methods applied to locally adjust the data. For analyses of extreme rainfall, seven of the first eight projections (*i.e*. those that were locally corrected using met.no's 'empirical adjustment' method) were used. The acronyms given for these are also used in the figures presenting results later in this report.

4.1.2 Sweden

The projections used for hydrological modelling and for rainfall analyses by SMHI are listed in Table 4.2. They are a combination of projections from the ENSEMBLES project together with other projections produced at SMHI. The B1, A1B and A2 SRES emission scenarios are represented in the model ensemble, and the spatial resolution of the RCMs is 12.5, 25 or 50 km. All are simulated over continuous periods beginning in 1961, and most of them extend to 2100, although four end in 2050. Both the ECHAM5 and HadCM3 projections include 'mini-ensembles' whereby the only difference in the GCM simulations are the initial conditions for the simulation.

Table 4.1 **Climate change projections used for analyses of changes in hydrological flooding and in extreme precipitation in Norway, indicating the Global Climate Model (GCM), the emission scenario used in the GCM run, and the Regional Climate Model (RCM) used for dynamic downscaling. The nation given represents the location of the institution which ran the RCM. (The origin of the GCMs is given in the description for Table 4.2 below.) Seven projections (the first eight listed, but excluding SMHIA1B) were used in the analysis of extreme precipitation, and all of the projections were used in the analysis of hydrological flooding, with the exception of the projection indicated with (*).**

Nation	GCM	Scenario	Domain/RCM (institution)	Resolution	Local adjustment	Future periods used
	HadAm3H	A2	RegClim/HIRHAM (met.no)	55 km	Empirical adjustment	2071-2100
	HadAm3H	B2	RegClim/HIRHAM (met.no)	55 km	Empirical adjustment	2071-2100
	ECHAM4	B2	RegClim/HIRHAM (met.no)	55 km	Empirical adjustment	2071-2100
	ECHAM4	B2	NorAciaNorClim/ HIRHAM (met.no)	25 km	Empirical adjustment	2071-2100
	BCM	A1B	Ensembles/RCA3 (SMHI)	25 km	Empirical adjustment	2021-2050 2071-2100
	HadCM3ref	A1B	Ensembles/HIRHAM (met.no)	25 km	Empirical adjustment	2021-2050
	ECHAM5	A1B	Ensembles/HIRHAM5 (DMI)	25 km	Empirical adjustment	2021-2050 2071-2100
	*ECHAM4/ OPYC3	IS92a	RegClim/HIRHAM (met.no)	25 km	Empirical adjustment	2021-2050
	BCM	A1B	Ensembles/RCA3 (SMHI)	25 km	Delta change	2021-2050
	HadCM3ref	A1B	Ensembles/HIRHAM (met.no)	25 km	Delta change	2021-2050
	ECHAM5	A1B	Ensembles/HIRHAM5 (DMI)	25 km	Delta change	2021-2050
	Arpege	A1B	Ensembles/HIRHAM5 (DMI)	25 km	Delta change	2021-2050 2071-2100
	HadCM3ref	A1B	Ensembles/HadRM (Hadley Centre)	25 km	Delta change	2021-2050 2071-2100
	HadCM3high	A1B	Ensembles/HadRM (Hadley Centre)	25 km	Delta change	2021-2050 2071-2100
	HadCM3low	A1B	Ensembles/HadRM (Hadley Centre)	25 km	Delta change	2021-2050 2071-2100
	ECHAM5	A1B	Ensembles/REMO (Max Planck Inst.)	25 km	Delta change	2021-2050 2071-2100
	ECHAM5	A1B	Ensembles/RCA3 (SMHI)	25 km	Delta change	2021-2050 2071-2100
	HadCM3low	A1B	Ensembles/RCA3 (SMHI)	25 km	Delta change	2021-2050 2071-2100

Table 4.2 **Climate change projections used in Sweden. The Nation indicates the nationality of the institute where the RCM simulations were performed. The origin of the GCMs is as follows: ECHAM5 - Max Planck Institute, Germany; ARPEGE – CNRM, France; HadCM3 - Hadley Centre, United Kindom; BCM – METNO, Norway; and CCSM3 - an American model that was run at SMHI, Sweden. ECHAM5 and HadCM3 produced numerous projections using different initial conditions; these are indicated by "()" in the GCM name.**

Nation	GCM	Scenario	RCM	Institute	Resolution	Period
	ECHAM4	A2	RCA3	SMHI	50 km	1961-2100
	ECHAM4	B2	RCA3	SMHI	50 km	1961-2100
	ECHAM5(1)	A1B	RCA3	SMHI	50 km	1961-2100
	ECHAM5(2)	A1B	RCA3	SMHI	50 km	1961-2100
	ECHAM5(3)	A1B	RCA3	SMHI	50 km	1961-2100
	ECHAM5(3)	A1B	RCA3	SMHI	25 km	1961-2100
	ECHAM5(3)	A1B	RCA3	SMHI	12.5 km	1961-2100
	ECHAM5(1)	B1	RCA3	SMHI	50 km	1961-2100
	CNRM	A1B	RCA3	SMHI	50 km	1961-2100
	CCSM3	A1B	RCA3	SMHI	50 km	1961-2100
	ARPEGE	A1B	Aladin	CNRM	25 km	1961-2050
	ECHAM5(3)	A1B	RACMO	KNMI	25 km	1961-2100
	ECHAM5(3)	A1B	REMO	MPI	25 km	1961-2100
	ECHAM5(3)	A2	RCA3	C4I	25 km	1961-2050
	HadCM3(Q0)	A1B	HadRM3	HC	25 km	1961-2100
	HadCM3(Q16)	A1B	RCA3	C4I	25 km	1961-2100
	BCM	A1B	HIRHAM	METNO	25 km	1961-2050
	HadCM3(Q0)	A1B	HIRHAM	METNO	25 km	1961-2050
	ECHAM5(3)	A1B	HIRHAM	DMI	25 km	1961-2100

4.1.3 The Netherlands

In 2000, the Dutch Meteorological Institute (KNMI) interpreted the IPCC report available at that time to produce three differing projections for climate change effects in the Netherlands, and these projections were used in water management studies. Four new projections were developed in 2006 (Figure 4.1) to include the latest results published by the IPCC (2007) and to cover 80% of the range of GCM projections. The four KNMI'06 scenarios differ in the degree of global temperature rise and whether or not there is a significant change in atmospheric circulation patterns in the region (van de Hurk, 2006). An update of these four projections has recently been published by KNMI (2009a). Currently, new model results from, for example the ENSEMBLES project, are being evaluated to determine the most suitable controlling variables for the new KNMI projections that are expected to become available in 2013.

The temperature rise in the G/G+ projections in Figure 4.1 represents a 'low' B1 emission scenario (Figure 3.2), while the W/W+ projections correspond to the high A1FI emission scenario. The G+/W+ scenarios are based on the assumption that regional circulation patterns will change under a future climate (with more frequent easterly winds during summer), as is projected by some, but not all, of the RCM simulations considered. The G/W scenarios assume that this change will not occur. Therefore, rather than considering a large number of GCM/RCM combinations for climate impact analyses, available climate models have been interpreted by KNMI to develop these four projections. Changes in, for example, seasonal temperature, average rainfall, rainy days, extreme precipitation, wind velocity and sea level are specified for each of the four options. These estimated changes are then in turn applied by water managers in climate change impact analyses.

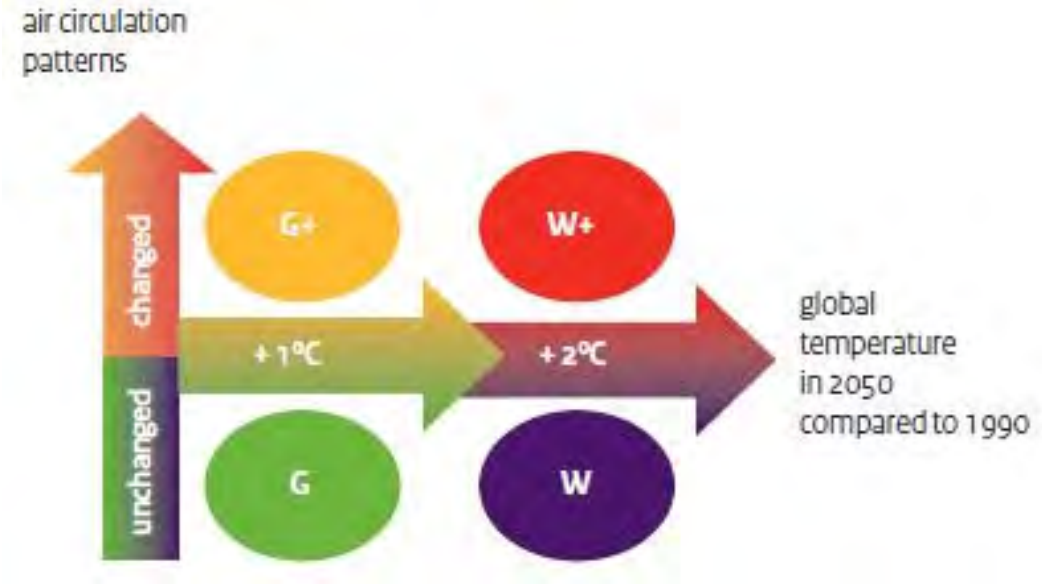


Figure 4.1 **The four climate change projections developed by KNMI for use in The Netherlands.**

4.2 Adjustment of simulated regional climate data

4.2.1 Norway

The RCM data for daily precipitation and temperature described in Table 4.1 were further adjusted from the RCM grid cell resolution (*i.e.* either 25 km or 55 km) to a 1 x 1 km grid covering the whole of Norway for use in hydrological modelling. Two methods were used for the adjustment: the widely applied "delta change" method (Reynard *et al.*, 2001) and an empirical adjustment method developed by met.no (Engen-Skaugen, 2007). The delta change method uses estimates of monthly changes in precipitation and temperature derived by comparing monthly values between a reference and a future period. These 'change factors' are then applied to observed data with the precipitation factor calculated as a percentage change and the temperature factor as an change in °C. A smoothing routine is used to eliminate sharp, abrupt changes between days at the beginning and end of each month. This method is simple to implement and has been widely applied in climate impact research. The advantage of this technique is that it is applied directly to the gridded, historical dataset and thus preserves all of the statistical moments of the local data for the period of observation. However, important changes, for example in the standard deviation of precipitation values between historical and future periods, are not transferred from the climate model output to the locally adjusted data with this method.

The empirical adjustment method, on the other hand, works directly with RCM data for both the historical and future periods. The mean and standard deviation of the RCM data for the historical period are corrected relative to gridded, observed data. A further adjustment is applied to RCM output for future scenario periods, based on residuals representing the variability in daily precipitation and temperature. The method transfers changes in monthly mean values and in the monthly standard deviation, which is its primary advantage over the delta change method. The primary disadvantage is that only the mean and standard deviation are used for the correction relative to observed data. Higher statistical moments (*e.g.* skewness) or extreme values better represented by other statistical distributions (*e.g.* gamma distribution for rainfall) are not necessarily corrected. It is anticipated that the two methods for the local adjustment of RCM data will give differing results, which may be significant in the analysis of changes in floods, and this is supported by previous comparisons for Norwegian catchments (*e.g.* Beldring *et al.*, 2008). At this point in time, there is insufficient evidence to justify the choice of one method over the other for use in analyses of future flooding, and this is a topic of ongoing research. Therefore, scenarios adjusted using both of these methods have been included in the ensemble of models used by NVE (*i.e.* Table 4.1).

4.2.2 Sweden

For use in Sweden, the daily RCM data for precipitation and temperature were further adjusted to a 4 x 4 km grid covering all drainage basins in the country using optimal interpolation (Johansson, 2000; Johansson and Chen, 2003). SMHI has also used the delta change approach in many previous studies (e.g. Andréasson *et al.*, 2004; Bergström *et al.*, 2001; Graham *et al.*, 2007b). More recently, however, bias correction techniques have been used instead. The latest technique developed at SMHI is the DBS method (Distribution Based Scaling; Yang *et al*, 2010). This approach scales climate model results relative to meteorological observations to remove systematic errors. The scaling

correction factors derived for the present climate are then applied to future climate results from the climate models, which makes them more appropriate for use in local-scale modelling.

Using such an approach preserves changes in both mean values as well as changes in variability from the climate models. The DBS method has some similarities with the empirical adjustment method applied in Norway in that regional climate model results are adjusted based on their correspondence with local historical data, and that changes in the statistical distribution under a future climate are also transferred. The approaches differ in the statistical properties that are used for the scaling. The DBS method includes a 'double gamma' distribution which allows for a more specific representation of extreme precipitation. In this approach, one gamma statistical distribution is used for the most frequent precipitation events and a separate gamma distribution is used for the most extreme events, *i.e.* those above the 95^{th} percentile.

Adjustment of temperature and precipitation from climate model projections with the DBS method was used to locally correct all of the projections listed in Table 4.2 . Studies where this approach has been used include Andréasson *et al*. (2011), Bergström *et al.* (2010), Graham *et al.* (2011) and Olsson *et al*. (2011a). Earlier scaling efforts by SMHI are reported in Graham *et al.* (2007a, 2007b). It is important to note that in presenting the results from such techniques, the future climate results from a particular climate model projection are compared to the present climate results from that projection, and not directly to meteorological observations. This maintains consistency in the application, and is also one of the differences between these methods and the delta change method. The role of observations in this regard is to determine the scaling correction factors for the present climate, which are derived individually for each respective climate projection. The method thus assumes that the statistical properties of the corrected climate data provide a good match with those characterising the observed local station data.

An example of the adjustment that occurs with the DBS method is shown for temperature, the number of rainy days and rainfall intensity in Fig. 4.1. The figure demonstrates how the DBS method corrects the raw outputs from a climate model to better represent the observed climate during a control period. Particularly noticeable is the correction for the number of rainy days in the climate model, which are typically overrepresented in such models. Similar changes in the number of rainy days are observed in the application of the empirical adjustment method in Norway and are reported in Engen-Skaugen (2007).

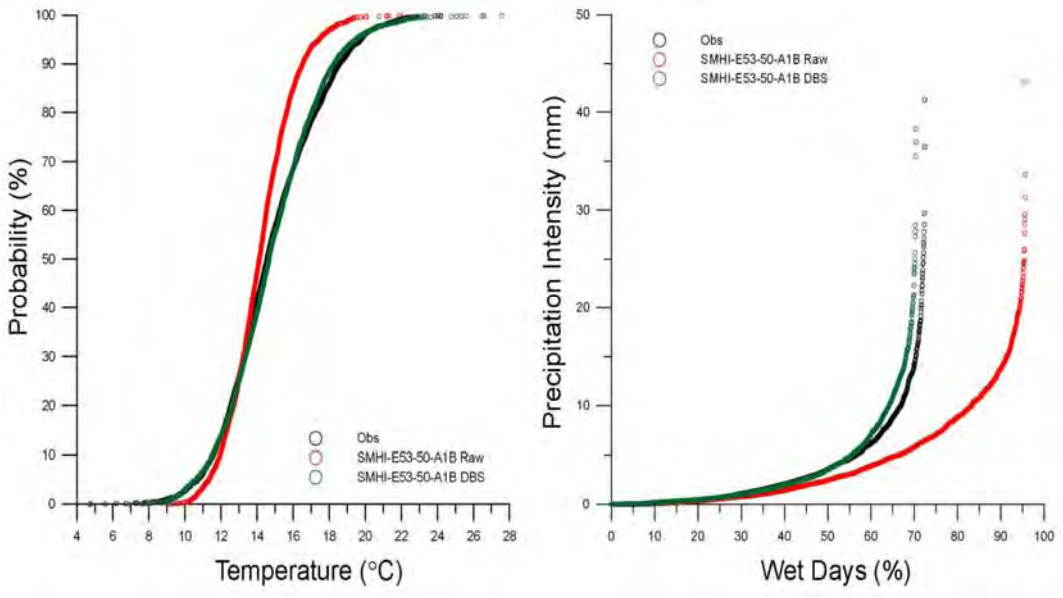


Figure 4.2 **Comparison of raw outputs from a climate model (red) with DBS-adjusted values (green) and observations (black). Mean daily temperature is shown on the left and the number of days with different rainfall intensities is shown on the right.**

4.2.3 The Netherlands

As the Netherlands has an area of only approximately 200 x 300 km, the climate models used for the KNMI'06 climate projections are too coarse (50 x 50 km) to determine regional differences in climate change impact within the country in sufficient detail. Accordingly, methods for downscaling to develop more detailed models are currently being tested by KNMI which will make it possible to generate information about regional differences. An example is given in Figure 4.3, which illustrates precipitation results from the regional climate model RACMO at 2 different grid resolutions (KNMI 2009a).

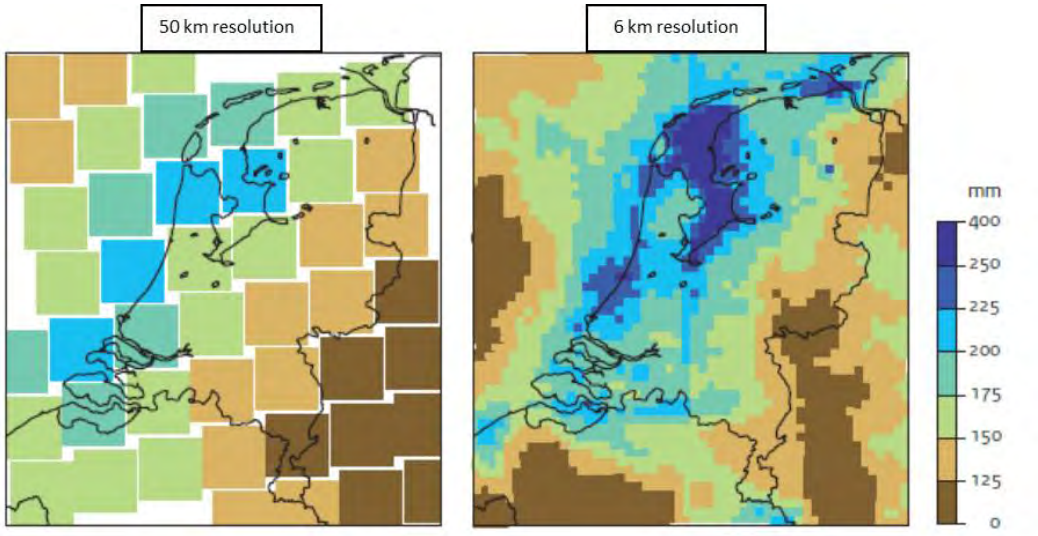


Figure 4.3 **Comparison of precipitation fields from the RACMO regional climate model at two different grid resolutions (KNMI, 2009a).**

5 Results of climate impact analyses

The data and methods described in Sections 3 and 4 have been used to assess changes in processes and variables relevant to flooding so that these results can be applied in flood hazard mapping and flood risk management. This section focuses on work undertaken as part of the SAWA project on changes in flood discharges and in extreme rainfall for Norway and Sweden. Changes in inflow to and lake levels in Lake Vänern have also been estimated by SMHI as part of the SAWA project and are reported here. The Trysil/Klärälven catchment lies upstream of Lake Vänern, and a comparison of the projections for changes in flooding developed by NVE and by SMHI for this area has been made and is also briefly reviewed here. In all of these applications, the use of the ensemble modelling approach described in Section 3.1 has enabled the quantification of some of the uncertainties in the projections and this is also described for each application, using various methods. A brief summary of various work undertaken in The Netherlands which has made use of the climate scenarios described in Section 4.1.3 is also given in this section.

5.1 Norway – Projected changes in 200-year flows

As part of the SAWA project, NVE has undertaken a study quantifying expected climate change effects on flood discharges throughout Norway for further use in flood hazard mapping and flood management. This work is fully described in Lawrence and Hisdal (2011), and a few key results are reproduced here. For the study, the models and methods described in Sections 3 and 4 were used for simulating daily runoff for a reference period (1961-1990) and two future periods (2021-2050 and 2071-2100) for the 115 unregulated catchments illustrated in Fig. 3.3. The modelling ensemble for each catchment for each future time period is comprised of 325 simulations, reflecting input data from 13 sets of adjusted RCM output (Table 4.1) and simulation with 25 HBV parameter sets. For each simulation, the percentage change in a particular flow quantity was calculated by comparing the values for the reference and the future periods. For projected changes in peak flows of a given return period (*e.g*. the 200-year flood), the Gumbel two-parameter distribution was used to estimate the magnitude of the flow in each period, and the percentage change was calculated as the difference between the 200-year flood given by the two fitted distributions (*i.e.* as illustrated in Figure 3.4). The results from all of the simulations were compiled for each catchment as a cumulative distribution function representing the range of results from the modelling ensemble. From this distribution, the median value was used as the most representative projected change. In order to present the spread in the projections around this value, the 10^{th} and 90^{th} percentiles from the cumulative distribution function were used to illustrate the level of agreement between the simulations with respect to the direction and magnitude of the projected change. In addition, changes in flood seasonality have been assessed, as this is particularly relevant in the interpretation of regional differences in flood patterns under the current climate and in the future.

5.1.1 Projected changes in extreme floods

In Norway, the 200-year flood is used for flood hazard mapping, and the 500-year and 1000-year floods are used in dam safety analyses. Projected changes in the 200-year flood discharge between the 1961-1990 reference period and the 2071-2100 future period are illustrated in Figure 5.1.

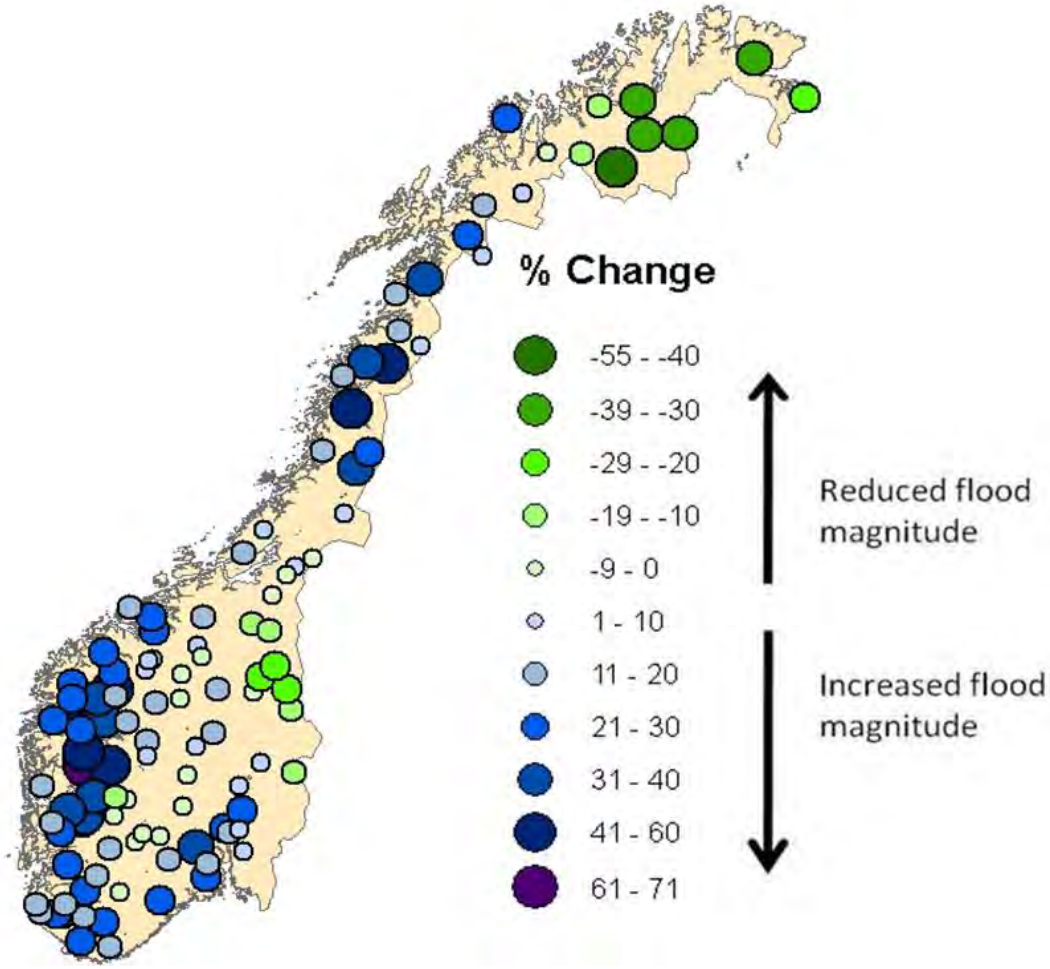


Figure 5.1 **Projected percentage changes in the 200-year flow between the 1961-1990 reference period and the 2071-2100 future period, based on the median of the ensemble of hydrological projections.**

The general pattern of change is characterised by significant variation between regions. The projections indicate that the northernmost areas (Finnmark and parts of Troms) and middle and southern inland areas (Hedmark, Oppland, and parts of Buskerud, Telemark and Trøndelag) will experience a decrease in peak flood discharges under a future climate. It is worth noting here that the three localities for which pilot flood risk management plans are being developed as part of the SAWA project all lie in these areas (Gaula – Trøndelag, Trysil – Hedmark, Tana – Finnmark). Catchments located in western and south-western regions (Vestlandet), coastal regions of southern and south-eastern Norway (Sørlandet and Østlandet) and in Nordland will, however, experience a significant increase in the 200-year flood discharge, based on the ensemble median. The largest projected increases are found in western Norway and in Nordland. A similar

spatial pattern was found for the period 2021-2050, although the changes are not as large for this near future period. In addition, projections for the 1000-year flood were found to exhibit a very similar spatial pattern to Figure 5.1. This is not particularly surprising, as both of the sets of projections are based on flood frequency analysis using a Gumbel distribution, and the modelled flood frequency curves are often roughly parallel for floods of large magnitude (as in Figure 3.4).

Differences in the response of the catchments in the various regions largely reflect the role of snowmelt *vs*. rainfall in inducing flood discharges. Increased winter temperatures will generally lead to a reduction in snow storage because a higher proportion of winter precipitation falls as rain. Consequently, areas associated with spring peak flows under the current climate will in many cases see a reduction in the magnitude of peak flows during the snowmelt season under a future climate. An exception to this is possibly small catchments at higher elevations in areas where winter precipitation continues to fall predominantly as snow and higher spring and early summer temperatures produce a rapid snowmelt. These cases were found to have relatively modest increases in the mean annual flood (< 10%). Simultaneous with the generally decreased magnitude of the snowmelt flood, increases in autumn and winter rainfall will increase the magnitude of peak flows during the autumn and winter in most areas. In areas where rainfall-induced runoff dominates peak flows under the current climate, increased rainfall in the future will contribute directly to an increase in flood magnitudes.

5.1.2 Changes in seasonality

In addition to changes in the magnitude of flood discharges, changes in the seasonality of peak flows are also expected in many areas. Changes in seasonality can occur due to two differing sets of processes: 1) warmer spring temperatures and reduced snow storage leading to an earlier peak in snowmelt runoff (i.e. spring as opposed to summer); or 2) increased autumn and winter rainfall in areas currently dominated by spring or summer snowmelt leading to a change in the dominant flood type and season. In neither of these cases is a change in seasonality necessarily associated with an increased flood magnitude, although in some cases it is. The balance between the reduction in peak flows from snowmelt and the increase in flows from heavy rainfall determines whether or not the overall flood hazard increases or decreases. However, a change in seasonality can also have significance for floods resulting from other processes such as river ice breakup and jamming.

The season in which the maximum flow for the entire 30-year period occurs is illustrated for the 1961-1990 reference period and the 2071-2100 future period in Figure 5.2. A comparison of the two periods indicates an increase in the number of catchments associated with spring (green) as opposed to summer (yellow) floods in the future, reflecting an earlier peak snowmelt flood. There are also several smaller catchments, for example in south-eastern Norway, which exhibit a change in seasonality from spring (green) to autumn (orange), indicating a change in the role of snowmelt *vs*. rainfall in flood generation. There is also an increase in the number of catchments associated with winter flooding, particularly in Nordland.

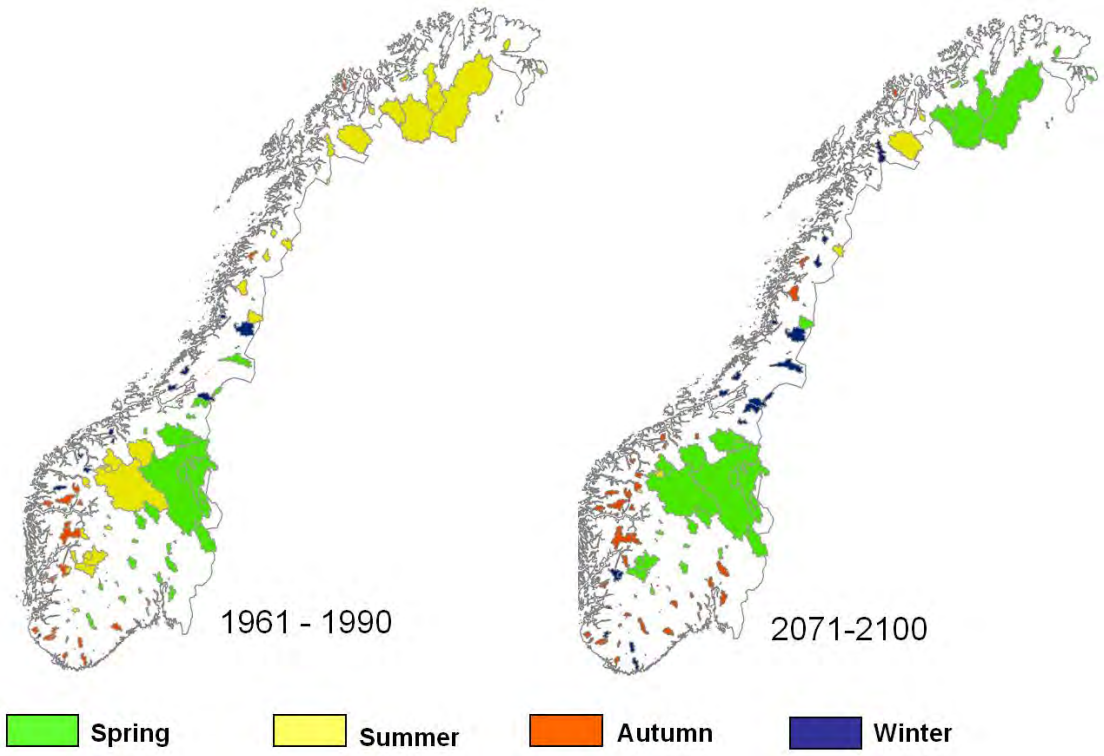


Figure 5.2 **Season in which the maximum flow occurs for the 30-year period indicated.**

5.1.3 Uncertainty in projected changes

Figure 5.1 illustrates the median of all of the 325 simulations for each catchment. The median value is the value for which 50% of the projections are equal to or greater than the value given, and is used by NVE as the most representative value for the ensemble of simulations for the catchment. It is, however, also informative to consider other quantiles from the ensemble of simulations, as they represent more extreme cases and also highlight the level of agreement between simulations as to the direction and magnitude of projected changes. The 10th percentile of the ensemble of results for the percentage change in the 200-year flood between the 1961-1990 reference period and the 2071-2100 future period is illustrated in Figure 5.3. The 10th percentile is the value for which 90% of all of the projected changes are larger than the value illustrated. For catchments with negative values (*i.e.* projected decreases at the 10th percentile), this means that 90% of the simulations indicate a smaller decrease or a possible increase in the percentage change. For catchments with positive values (*i.e.* projected increases at the 10th percentile), 90% of the simulations indicate larger increases than the value illustrated. With respect to climate change impacts on flood hazard, Figure 5.3 illustrates an 'optimistic', but nevertheless, a possible scenario. Most of the catchments in this case are associated with a decreased flood magnitude. However, there are still catchments, most notably in western and south-western Norway and in Nordland that exhibit small to moderate increases in flood magnitude. Many catchments in other regions are associated with small decreases at the 10th percentile, and the most inland catchments are projected to have very large decreases.

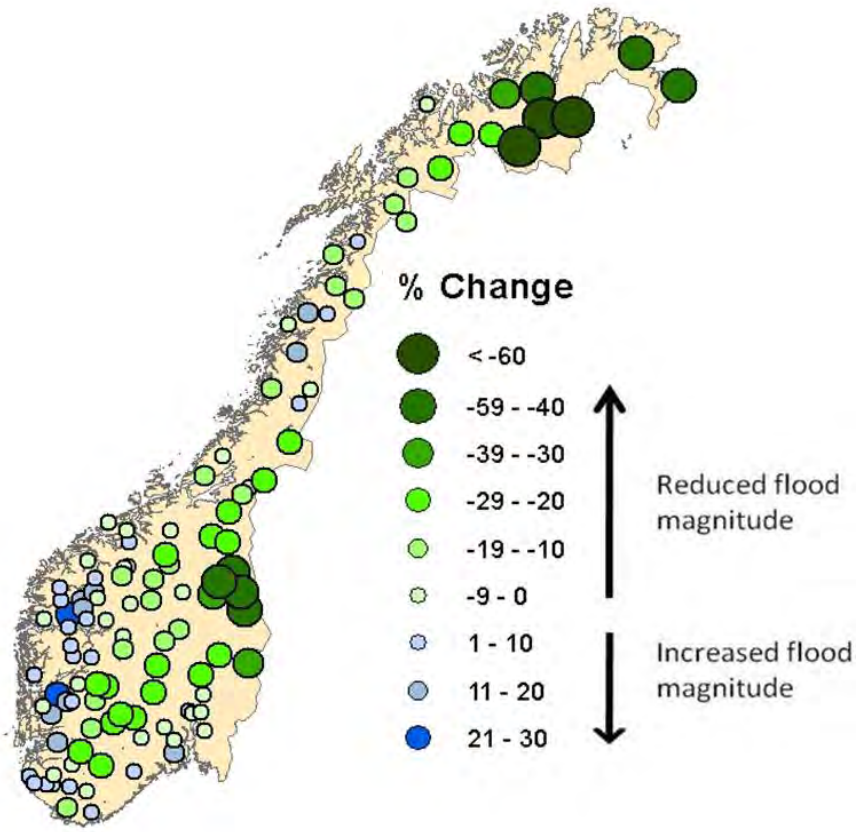


Figure 5.3 **Percentage change in the 200-year flood between 1961-1990 and 2071-2100 as given by the 10th percentile of the ensemble for each catchment.**

The 90th percentile of the ensemble of results for the percentage change in the 200-year flood between the 1961-1990 reference period and the 2071-2100 future period is illustrated in Figure 5.4. The 90th percentile is the value for which 10% of all of the projected changes are larger than the value illustrated, and 90% are smaller. In contrast with Figure 5.3, this figure illustrates a more 'pessimistic', but nevertheless a possible scenario, in which nearly all areas of Norway are associated with at least small increases in the magnitude of the 200-year flood, excepting some inland catchments in southern and mid-Norway, where small decreases are projected at the 90th percentile, and Finnmark, where moderate decreases are expected based on this percentile.

Taken together, Figure 5.3 and Figure 5.4 indicate that projections for a significant increase in flood magnitude in western Norway and in some catchments in Nordland, and a decrease or no change in flood magnitude for Finnmark and parts of mid- and southern Norway are quite robust, based on the ensemble of simulations considered. In each of these cases, over 80% of all of the simulations give consistent results as to the direction (increase *vs*. decrease) of the projected change. In addition, there is good agreement between simulations for other catchments, where the overall magnitude of projected change is not as large as in western Norway and Finnmark.

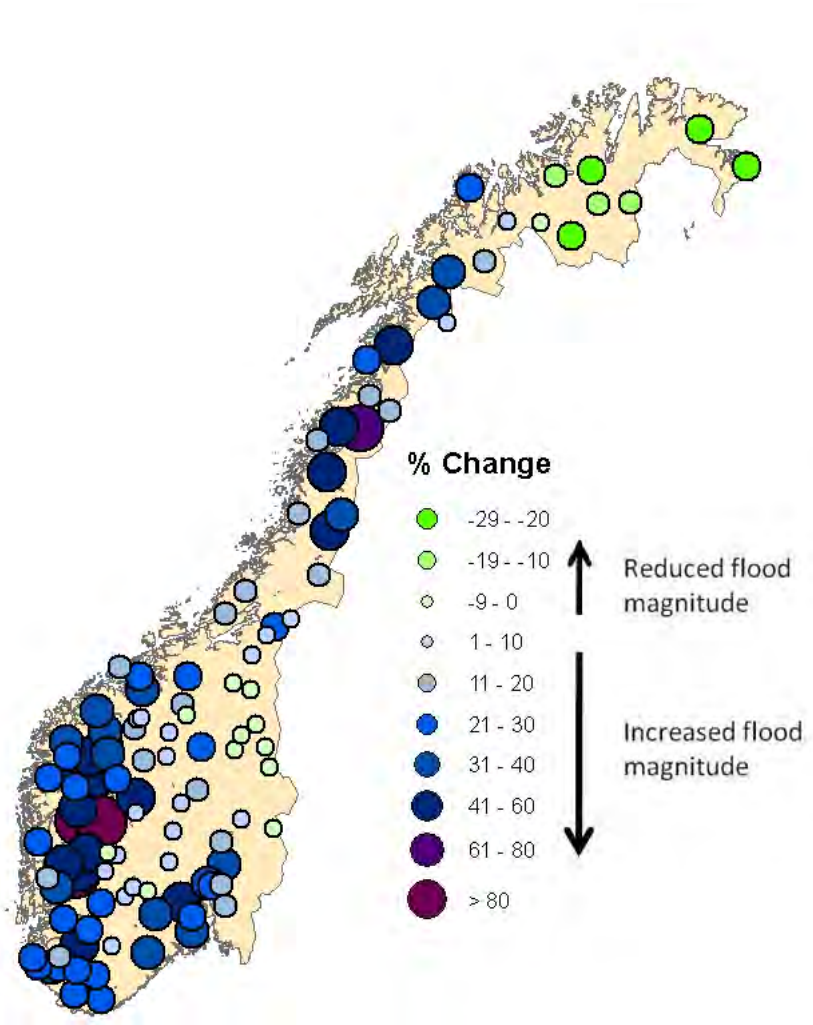


Figure 5.4 **Percentage change in 200-year flood between 1961-1990 and 2071-2100 as given by the 90th percentile of the ensemble for each catchment.**

There are several factors which contribute to the large range of projections given by the ensemble including a) differences between climate scenarios used in hydrological modelling (Table 4.1), b) differences between the locally scaled scenarios based on the delta change *vs.* the empirical adjustment method (Section 4.2.1), and c) uncertainty in the hydrological model parameters (Section 3.2.1). The relative importance of each of these factors has been evaluated in other work and is reported in Lawrence and Haddeland (2011) and Lawrence and Hisdal (2011). From this work it has been concluded that each of these factors can be significant in individual catchments. Example graphs illustrating the magnitude of the uncertainty and the relative contributions of various factors to that uncertainty are illustrated in Figures 5.5 and 5.6 for the four catchments evaluated by Lawrence and Haddeland (2011). Figure 5.5 illustrates the magnitude of the expected change in the mean annual flood and the uncertainty around this projection for the four catchments. The large projected decreases for the northern catchment (Masi - Alta) and the inland catchment (Nybergsund – Trysil) and the projected increases for the western (Viksvatn - Gaular) and southern (Flaksvatn - Tovdal) catchments reflect the regional patterns for the 200-year flow illustrated for in Figure 5.1.

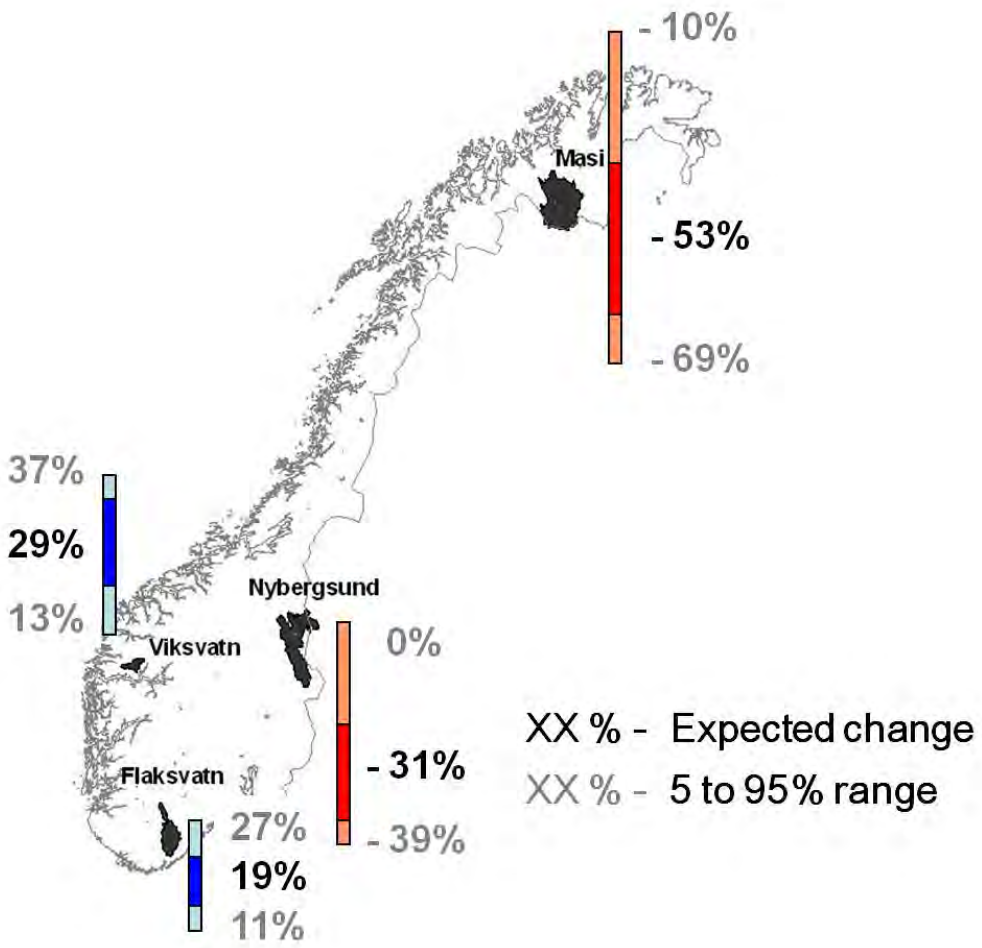


Figure 5.5 **Projected percentage change in the mean annual flood for four catchments (black numbers). Red indicates a decrease and blue an increase. The 5th and 95th percentiles of the ensemble of model results are also indicated (grey numbers), and the length of the columns illustrates the relative magnitude of the uncertainty in the projections. (The figure is from Hanssen-Bauer, *et al*., 2009, and is also discussed in Lawrence and Haddeland, 2011).**

The breakdown of the relative contributions to this uncertainty illustrated in Figure 5.6 indicates that the importance of particular sources varies between the catchments. The uncertainty introduced by hydrological modelling is relatively more important in the southern and western catchments, than in those dominated by snowmelt flooding (*i.e.* inland areas and Finnmark). The differences between downscaling methods are most significant in the inland and northern catchments where factors related to modelling snowmelt dominate uncertainty. This earlier work is based on four catchments and only two different global climate models (GCMs) were used in the model ensemble. In the more recent work covered in this report and in Lawrence and Hisdal (2011), a larger number of GCMs and RCMs has been considered, so there are larger differences between them within the ensemble. Similar analyses to those illustrated in Figure 5.6 have been undertaken for all of the catchments illustrated in Figure 5.1 and are reported in Lawrence and Hisdal (2011).

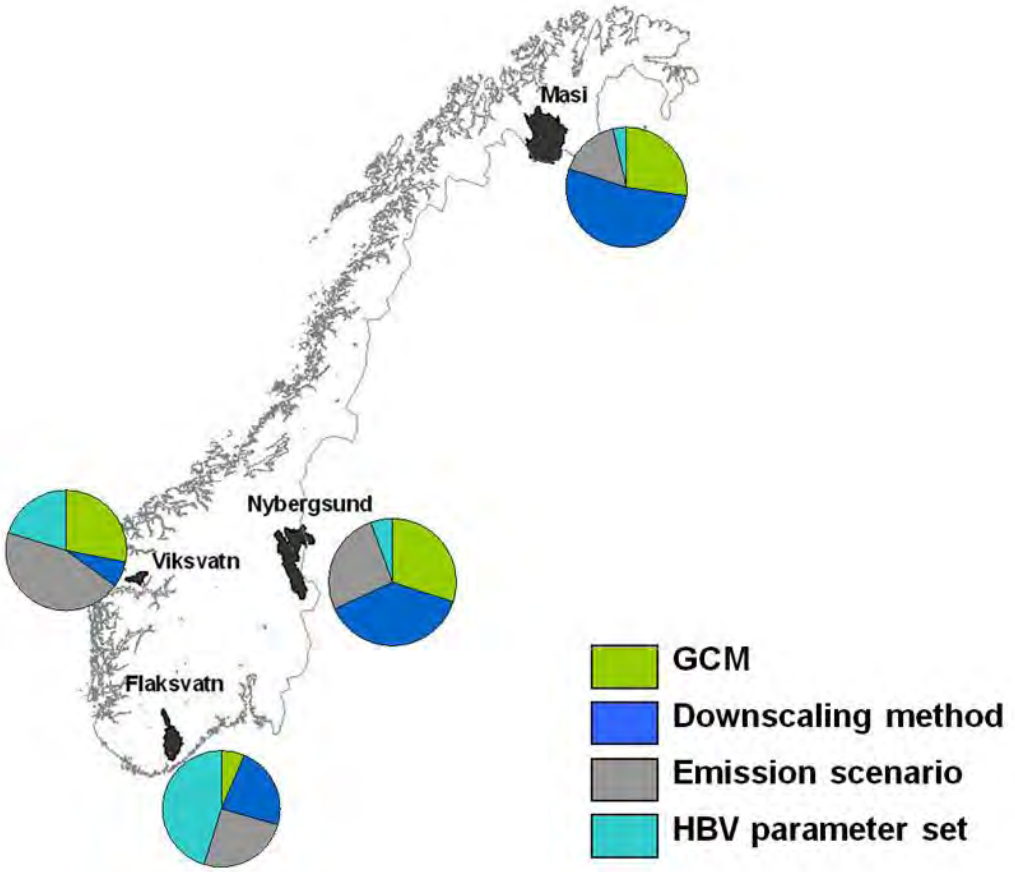


Figure 5.6 **Relative contribution to the total uncertainty in the ensemble projections for the mean annual flood in four catchments. The absolute magnitude of the uncertainty is illustrated in Figure 5.5. A table of values can be found in Lawrence and Haddeland (2011).**

5.2 Norway – Projected changes in extreme precipitation

5.2.1 Changes in 1-day precipitation

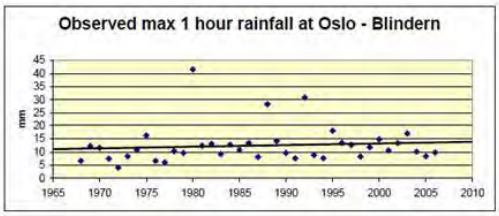
Increased total precipitation amounts have been observed in most regions in Norway during the last century (Hanssen-Bauer *et al*., 2009). With respect to extreme precipitation, Alfnes and Førland (2006) found positive trends in the annual maximum 1-day rainfall during the 20th century, although the trends were found to be statistically significant at only four locations. In a recent study, Engen-Skaugen and Førland (2011) present estimates of extreme 1-day precipitation for 141 catchments for two "present climate" periods (1961-1990 and 1981-2008) and for two future periods (2021-2050 and 2071-2100). As an indicator of extreme precipitation, the 1-day precipitation with a five-year return period value (M5) is used. This was estimated for the control and scenario periods for seven RCM runs (Table 4.1), producing ten analyses. The analyses indicate that there is a large spread in the results, both spatially and between the RCMs. The simulations, however, tend to confirm that 1-day M5-values will increase during the 21st century. Engen-Skaugen and Førland (2011) also show that M5 estimates based on adjusted RCM output (see section 4.2.1) are larger than estimates based on unadjusted RCM output.

Projections of changes in extreme rainfall are associated with a high degree of uncertainty due, in part, to differences between the climate simulations and to the downscaling procedures including bias correction (or empirical adjustment) methods used. In addition, the length of the time series available for estimating M5 (~30 years) is relatively short, thus undermining the validity of the estimates for long return periods. In addition, the method used for estimating extreme 1-day precipitation based on M5 is also associated with uncertainty.

5.2.2 Analyses of 1-hour precipitation for Oslo

The methods described in section 3.5 have been used to analyse extreme rainfall with a one-hour duration at Blindern in Oslo. Figure 5.7 (upper graph) shows annual maxima of 1-hour precipitation in the Oslo region for the period 1967 to 2006. Simulations from two Regional Climate Models (RCM) with a 25 km spatial resolution have been analysed to study whether the modelled 1-hour rainfall values are realistic relative to the observed values. The two control runs for the present climate (Figure 5.7, lower graph, MPI CNn and MPI P2n) indicate that the modelled maximum 1-hour rainfall values for the Oslo region are generally in agreement with observations (in that annual values are in the range of 5-20 mm/h and the highest peaks are approximately 40-50 mm/h). The projections for two future periods are also shown and indicate a general increase in the magnitude of the annual extreme 1-hour precipitation and in the rarer, more extreme values in Oslo.

Oslo: Observed 1-hour precipitation (Annual maximum value)



Oslo: Simulated 1-hour precipitation (Annual maximum) from HIRHAM regional climate model (RCM) based on two MPI global climate model (GCM) simulations

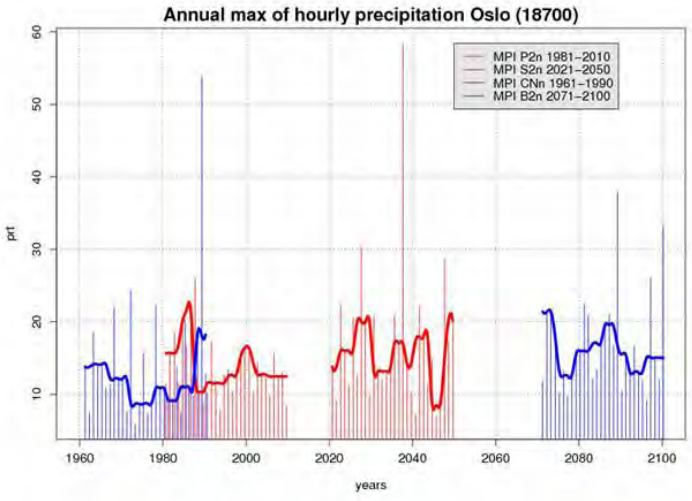


Figure 5.7**. Observed (upper graph) and modelled (lower graph) 1-hour precipitation in the Oslo region. The modelled values are based on simulations with the HIRHAM Regional Climate Model at a spatial resolution of 25 x 25 km and are shown for two control periods (1961-90 and 1981-2010) and for two scenario periods (2021-2050 and 2071-2100).**

5.3 Sweden – Projected changes in the 100-year flow

An analysis based on the progressive calculation of the 100-year flows (Section 3.3) was undertaken for 1001 modelled drainage basins covering Sweden. The highlights of that work are presented here, and further details are available in Andréasson *et al*. (2011). The results from the hydrological modelling were spatially interpolated for two time periods, 2021-2050 and 2069-2098, relative to a reference period 1963-1992. The results for the 2069-2098 period are illustrated in Figure 5.8. The map shown is based on the mean (*cf*. median used in Norway) value from the hydrological modelling based on the 12 projections available for this period (Table 4.2).The map collectively represents all of the rivers in Sweden, but does not take into account river regulation effects from dams. As the map is based on catchment rather than national boundaries, parts of Norway and Finland are included for the transnational basins, along the borders with these countries.

Similar to the results for Norway, there is significant regional variation, with some areas projected to have an increase in the 100-year flow and some areas a decrease. There is an obvious difference between north and south in Sweden, whereby the northern basins mainly show decreasing 100-year flows toward the end of the century, while the southern basins show increasing 100-year flows. The border between these two regimes generally lies along an east-west line just north of Stockholm. Exceptions to this are the very far north, isolated regions in the south and the two large islands in the Baltic, Gotland and Öland. A comparison of Figure 5.8 with the spatial distribution of changes in the 200-year flood projected for Norway (Figure 5.1) indicates a very good correspondence in terms of the expected pattern of change for catchments adjacent to the Swedish/Norwegian border. The northern part of Figure 5.8 that shows a projected increase corresponds to the Nordland region of Norway, and this zone also indicates an increase under the Norwegian calculations (Figure 5.1). Similarly, the remaining western boundary of Figure 5.8 corresponds to the inland and southern coastal zones of Norway in Figure 5.1, where decreases and increases are projected, respectively.

Figure 5.9 complements Figure 5.8 and illustrates the minimum and maximum values, and values of the 25th and 75th percentiles from the ensemble of results for the 2069-2098 period. The results in Figure 5.9 indicate that the range of the projections from the 12 scenarios is quite large. The most ‘optimistic’ scenario with respective to flooding (i.e. the minimum) indicates a decreased 100-year flow throughout most of the country, whilst the most ‘pessimistic’ (i.e. the maximum) indicates an increased flood in all areas, except for an eastern zone along the northern Swedish/Finnish border.

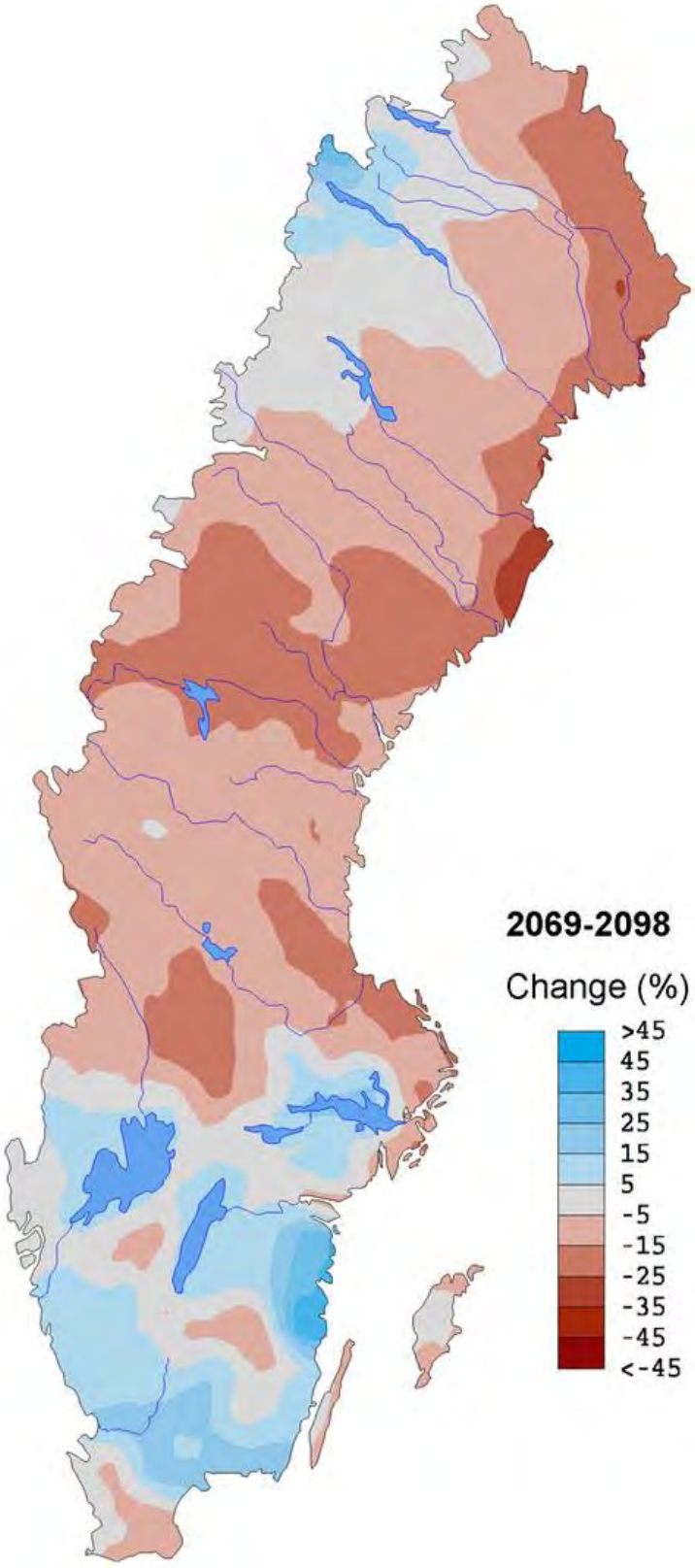


Figure 5.8 **Percentage change in the 100-year HBV modelled river flow for 2069-2098 relative to reference period 1963-1992 for the ensemble mean from 16 of the climate model projections in Table 4.2.**

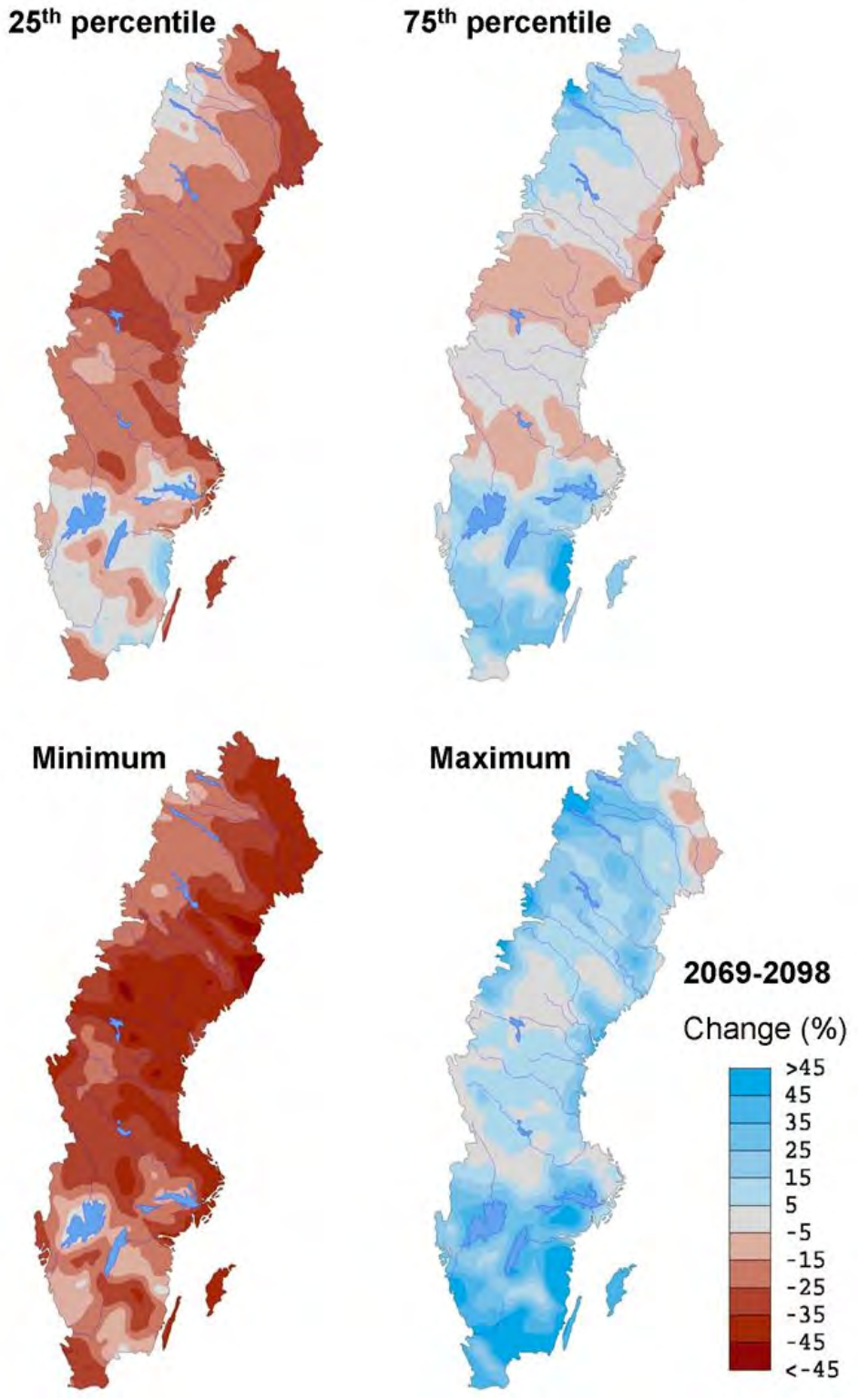


Figure 5.9 **Percentage change in the 100-year HBV modelled river flow for 2069-2098 relative to reference period 1963-1992 for the ensemble of 16 of climate model projections in Table 4.2. Shown are the 25th and 75th percentiles, and the minimum and maximum from the ensemble of hydrological results.**

5.4 Sweden - Projected changes in Lake Vänern

Work by SMHI for the SAWA project has included extensive analysis of likely climate change effects on Lake Vänern using the projections described in Table 4.2. For this work, the progressive evolution of hydroclimatological variables and their impact on inflow and lake levels in Lake Vänern have been assessed for the entire period 1961-2100.

5.4.1 Development of temperature and precipitation

An example of the development of temperature and precipitation from the ensemble of climate projections is shown in figures 5.10 and 5.11 for the drainage basin to Lake Vänern in southwestern Sweden. Annual values of both temperature and precipitation increase as the coming century progresses. Much of the increase in precipitation occurs during the autumn and winter months, however, and this is not specifically shown here.

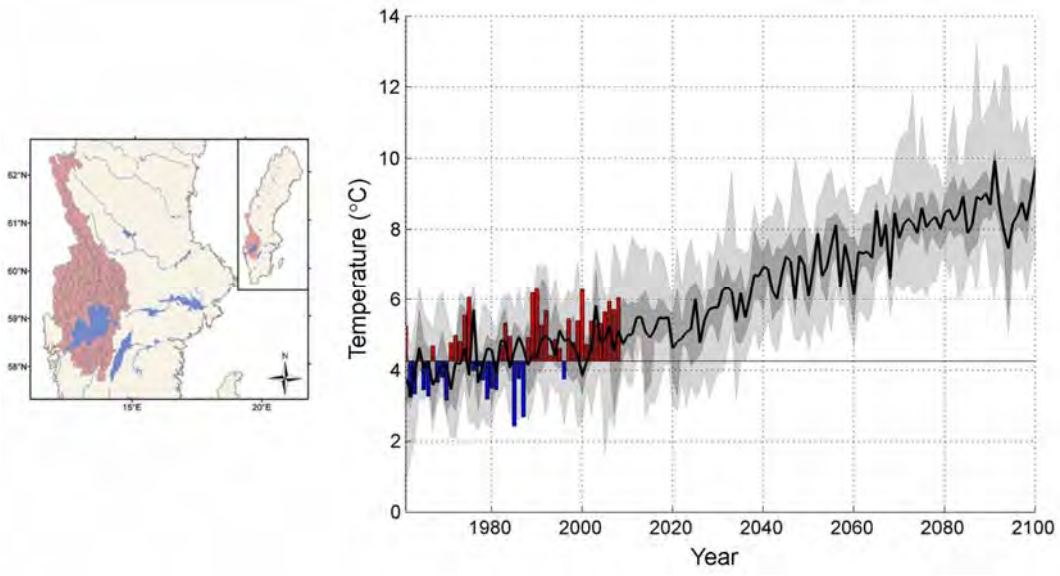


Figure 5.10 **Mean annual temperature for the Lake Vänern drainage basin from the ensemble of 16 of the climate model projections shown in Table 4.2. Historical observations are also shown as bars, where blue is below and red is above the mean for the observed reference period (1961-1990). The ensemble mean from the climate models is shown as a black line; the shaded areas are, from top to bottom, maximum, 75th percentile, 25th percentile and minimum. A location map is shown on the left.**

5.4.2 Development of river flow into Lake Vänern

An example of the development of river flow from hydrological modelling driven by the ensemble of climate projections is shown in Figure 5.12 for the drainage basin to Lake Vänern. As different seasons of the year are shown, it is obvious that wintertime flows are expected to increase while spring and summer flows will generally decrease during the 21st century.

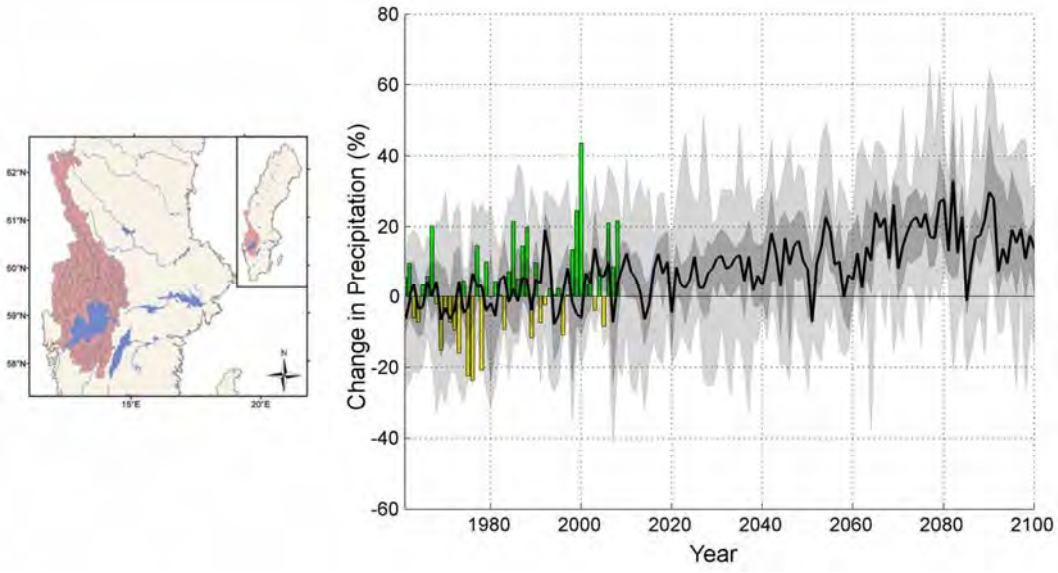


Figure 5.11 **Mean annual precipitation change in per cent compared to the reference period for the Lake Vänern drainage basin from the ensemble of 16 of the climate model projections shown in Table 4.2. Historical observations are also shown as bars, where yellow is below and green is above the mean for the observed reference period (1961-1990). The ensemble mean from the climate models is shown as a black line; the shaded areas are, from top to bottom, maximum, 75th percentile, 25th percentile and minimum. A location map is shown on the left.**

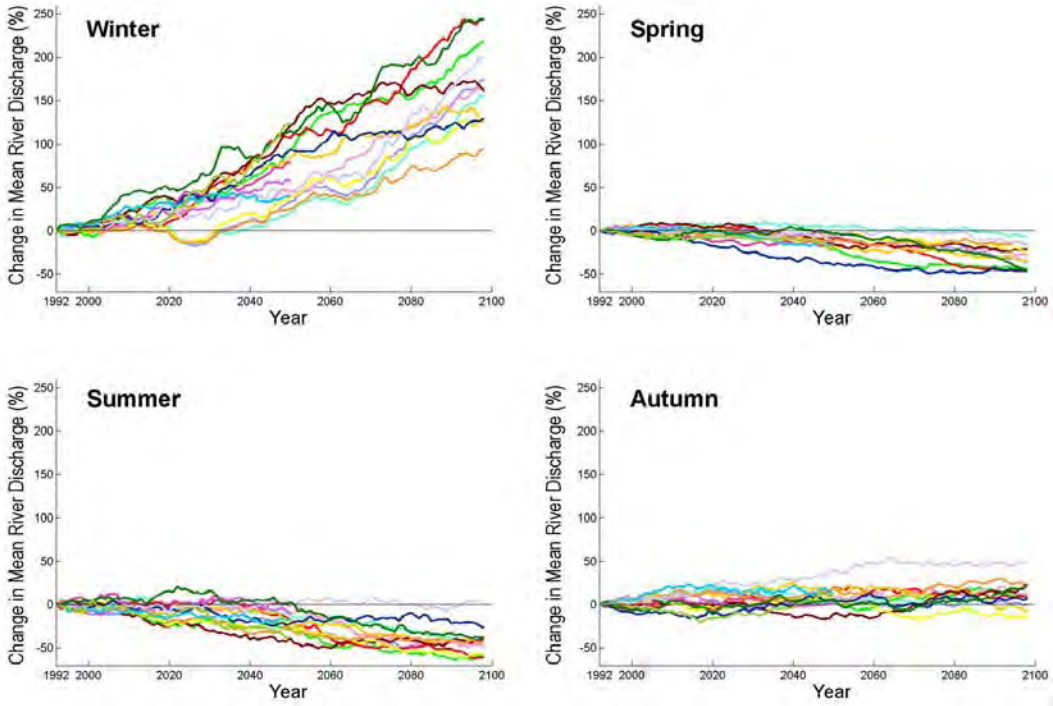


Figure 5.12 **Seasonal change in total river flow into Lake Vänern according to HBV hydrological modelling with the ensemble of 16 of the climate model projections in Table 4.2. Change is given as a percentage of the seasonal mean for reference period 1963-1992 for each of the respective seasons; winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug) and autumn (Sep-Oct-Nov).**

5.4.3 Projected changes in the 100-year flow to Lake Vänern

From results of the hydrological model, the 100-year flows can be estimated for different future time periods. Figures 5.13 and 5.14 show examples from two basins in Sweden where the 100-year flow is progressively calculated as warming develops over the coming century. These figures indicate potential trends in whether such extreme flows will increase or decrease. According to this analysis, the 100-year inflows to Lake Vänern are shown to increase while the 100-year inflows to Höljes Dam (which is in an upstream subbasin to Lake Vänern, slightly downstream of the Trysil catchment in Norway) are shown to decrease. The calculation of these extreme flows are based on daily maximum values. Due to the size of Lake Vänern (3rd largest lake in Europe) and thus the volume of water flowing into it, this daily-based metric is not necessarily the best one for indicating changing flood conditions in the lake itself, but more indicative of the subbasins flowing into it.

Not shown in Figures 5.13 and 5.14 is the natural variability of the 100-year flows, which can be calculated and presented in the same way using observed river flows. Such analysis for other basins in Sweden puts the climate projections into perspective and indicates that the projected mean change in 100-year flows will lie within the bounds of natural variability for some time to come, despite the trends that the figures below show.

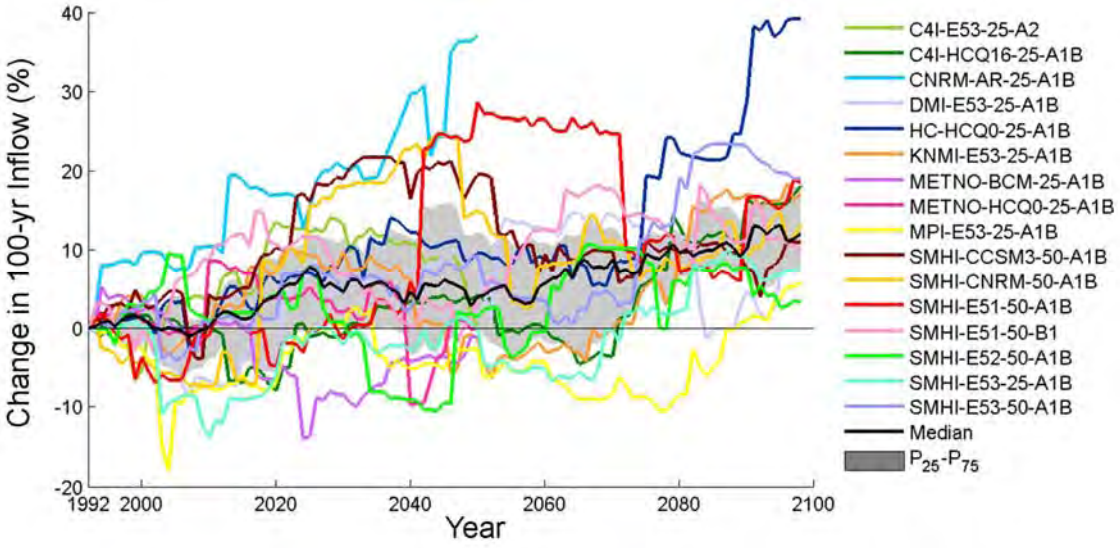


Figure 5.13 **Per cent change in the 100-year HBV modelled inflow into Lake Vänern relative to reference period 1963-1992 for the ensemble of 16 of the climate model projections in Table 4.2. The values for each year are determined from the maximum values of the preceding 30 years. The black line shows the ensemble mean; grey shading shows the variation between the 25th and 75th percentiles. Note that four of the projections end in 2050.**

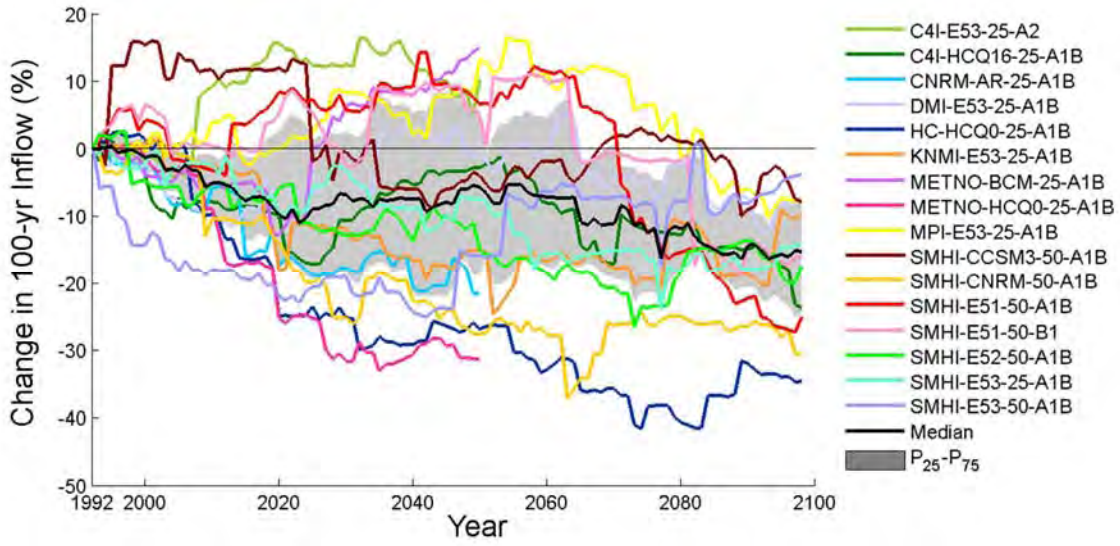


Figure 5.14 **Percentage change in the 100-year HBV modelled inflow into Höljes Dam relative to reference period 1963-1992 for the ensemble of 16 of the climate model projections in Table 4.2. The values for each year are determined from the maximum values of the preceding 30 years. The black line shows the ensemble mean; grey shading shows the variation between the 25th and 75th percentiles. Note that four of the projections end in 2050.**

5.4.4 Projected changes in design flood to Lake Vänern

Figure 5.15 shows an example for Lake Vänern that summarises the outcomes from re-generating the Swedish Design Flood using inputs from the RCM projections in Table 4.2 for the periods 2020-2049 and 2067-2096. Shown are the percentage change in the input values for volume of the critical precipitation sequence, the maximum sequence value and the critical snow pack. Modelling results are shown as percentage change in mean inflow for the snowmelt period, the maximum inflow for the identified maximum flood period, and the resulting change in the lake water level. All changes are given relative to the reference period 1961-1990. The figure shows a general increase in inflows and lake water levels for the Swedish Design Flood as the century progresses. A factor not shown in Fig. 5.15 is that the timing of such events is shifted from occurring both during spring and summer to occurring only in summer by the end of the century.

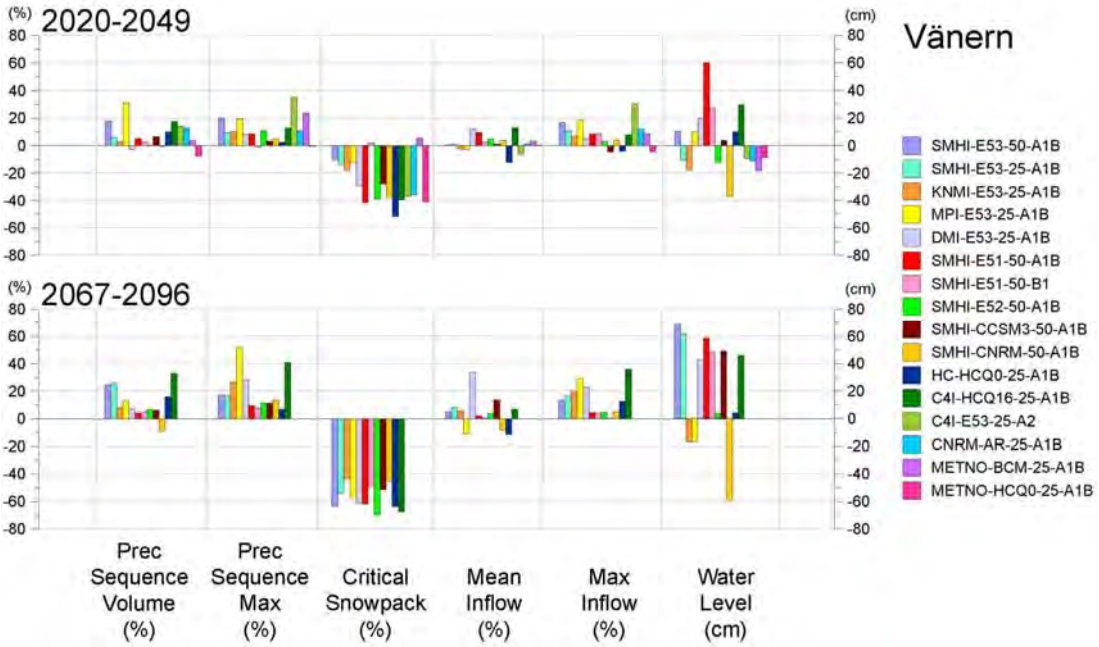


Figure 5.15 **Swedish Design Flood calculations for Lake Vänern using 16 of the RCM climate projections from Table 2. Shown from left to right are percent change in the volume of the critical precipitation sequence, maximum values from the precipitation sequence, critical snow pack, mean inflow for snowmelt period and maximum inflow for the identified maximum flood period, together with the resulting change in the lake water level (cm). All changes are in comparison to the reference period 1961-1990.**

Figure 5.16 provides another summary of these results, looking specifically at Lake Vänern water levels. This analysis considered the effects of operating the outlet dam according to the current allowed maximum discharge and regulation rules, as well as using an increased discharge capacity corresponding to changes in the regulation rules. From these results, the mean change in water levels is not dramatic. However, differences in the range of results from different climate projections are considerable. This demonstrates how the choice of which climate projections can have a large impact on outcomes, and hence, on decisions on related to climate change adaptation.

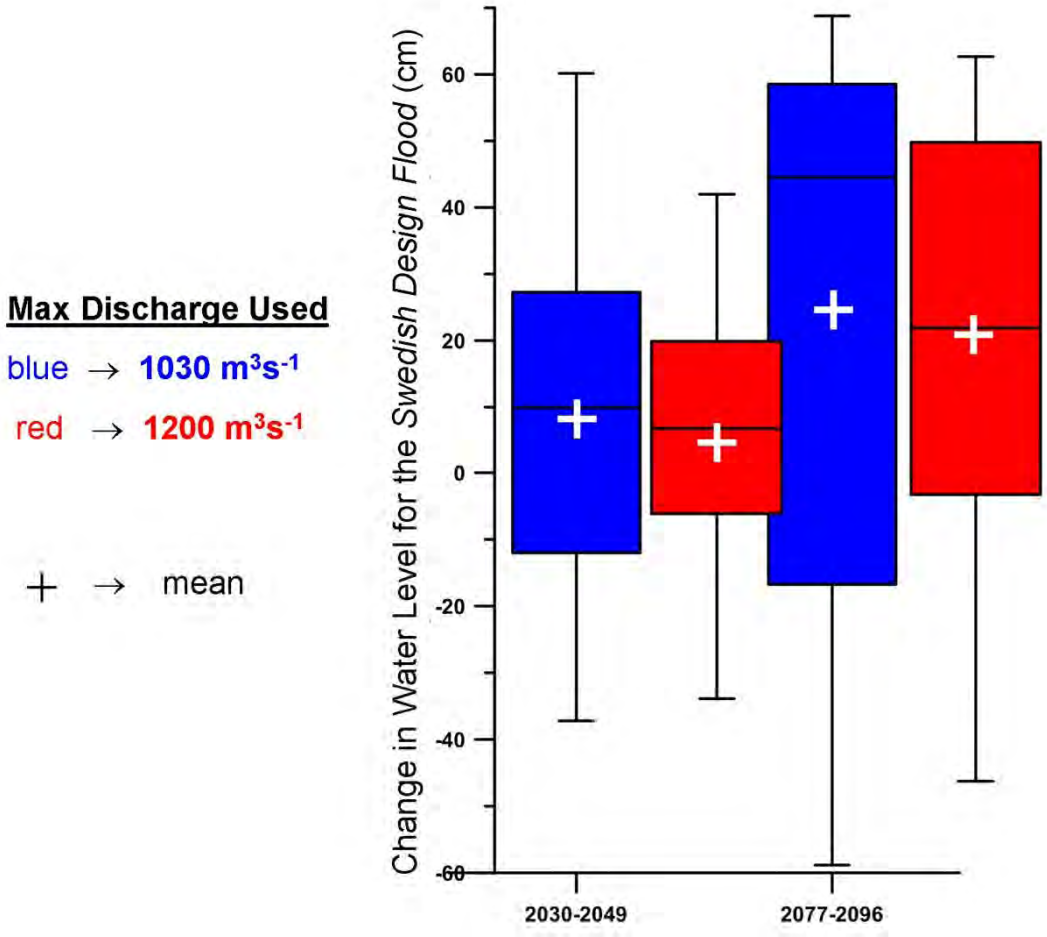


Figure 5.16.**Summary of Lake Vänern water level changes for the Swedish Design Flood for two future periods, 2030-2049 and 2077-2096, compared to the reference period 1961-1990 for 12 of the RCM projections shown in Table 4.2. Blue shows results using the current maximum discharge of 1030 m^3s^{-1} and the lake regulation rules in force since 2008. Red shows results using a hypothetical maximum discharge of 1200 m^3s^{-1} and adjusted lake regulation rules. Box and whiskers: 50% of the results lie within the coloured rectangles where the horizontal lines show the median values, maximum and minimum values are indicated by the ends of the vertical lines. Mean values are shown with a "+" sign.**

5.4.5 Projected changes in extreme short-term rainfall

Extreme value analysis of short-term rainfall as outlined in Section 3.5 was performed for RCM data from a 200 by 200 km region covering the central part of the Vänern catchment (Figure 5.17). To date, only regional projections downscaled by RCA3 (SMHI) have been analysed, which is a limitation. The main reason for this is that 30-min precipitation are not commonly available from regional climate projections. Efforts to collect this type of data from other institutes are underway. The small ensemble considered includes three IPCC scenarios, two GCMs and three initial conditions. The analysis focused on the change of the 10-year rainfall between periods 1961-1990 and 2071-2100 for durations ranging from 30 min (i.e. the highest available temporal resolution for RCM data) to 1 day.

For duration 30 min, all projections indicate an increase of the 10-year rainfall, ranging from 12% to 34% with a mean value of 25%. For duration 1 day, the increase is generally

lower with a mean value of 20%. The range of variation is however larger, with one projection (HC_A1B) indicating a nearly 40% increase and one (E5_A1B_2) indicating a slight decrease. The overall increase in 10-year rainfall with decreasing duration is in line with the theoretically expected increase of the highest rainfall (short-term) intensities in a warmer climate (*e.g.* Trenberth *et al.*, 2003).

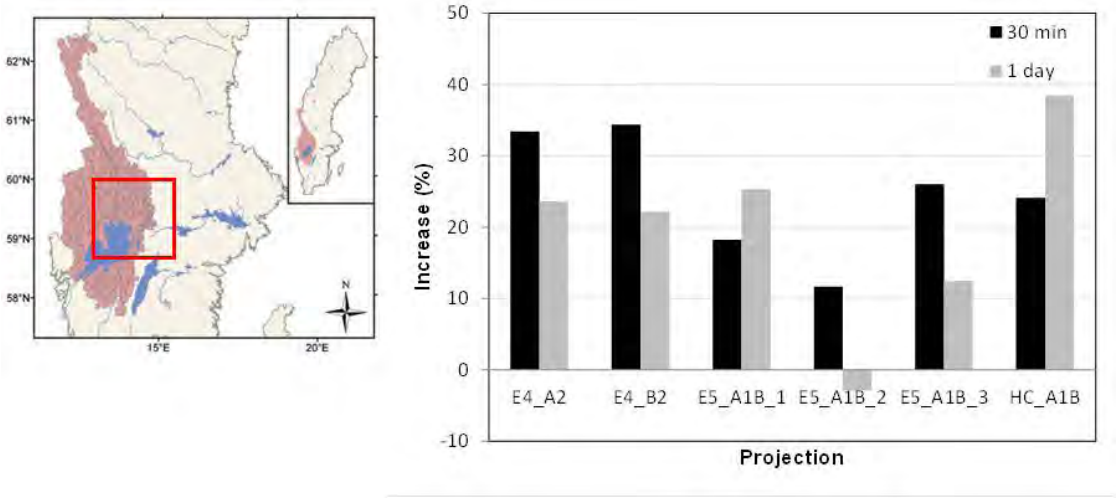


Figure 5.17 **Change of the 10-year rainfall between periods 1961-1990 and 2071-2100 for durations 30 min and 1 day in six regional projections. The bars (right) represent the average change from 16 RCM grid boxes in the Vänern catchment (left). E4, E5 and HC are ECHAM4, ECHAM5 and HadCM3, respectively, as shown in Table 4.2**

It should be emphasised that the resolution of the RCM data used (50 km) is substantially lower than the typical size of urban catchments (1-2 km). Thus, to use the results in urban hydrological engineering it must be assumed that the 50 km results are representative also for smaller scales. This is not certain as different rainfall mechanisms come into play at the different scales. Maxima at urban scales are exclusively related to small-scale systems, convective cells and thunderstorms, whereas maxima at 50 km scale may also be related to large-scale frontal-type synoptic systems. In line with the higher increase for shorter durations (Figure 5.17), it can be anticipated that there is also an increase at smaller scales. Some such indications have been found in statistical downscaling experiments (Olsson *et al.*, 2011b).

The spatial resolution of RCMs has increased with time. In the analysis presented above, six 50 km projections were used as they gave the largest ensemble available at the time of the analysis, but today 25 km is the standard and 12.5 km projections are also available. Preliminary analyses indicate that by increasing resolution, a much better reproduction of observed local short-term rainfall extremes is obtained, which increases the credibility of the results with respect to local applications. The analyses undertaken so far do not however indicate any clear dependency of the future change on RCM resolution, and the results in Figure 5.17 are also generally representative of what is found using 25 km and 12.5 km projections.

5.5 Norway/Sweden - Trysil/Klärälven transboundary catchment

A comparison between the projected changes in the 100-year flood and the design flood estimated by NVE for the Trysil river at Nybergsund in Norway has been made with those estimated by SMHI at Höljes Dam on the Klarälven river in Sweden. This represents analyses on the same river at two nearby locations. This work is reported in Bergström *et al*. (2012) and is briefly summarised here.

With respect to the 100-year flood, the two analyses indicate similar expected changes, in that both point towards a decreased 100-year flow for most of the scenarios considered (e.g. Figure 5.13 above for Höljes Dam). The magnitude of the decrease, however, varies significantly between scenarios. With respect to the design flood, there are considerable differences in the estimates based on the methods used by the two countries. (See section 3.4 for a description of the methods). SMHI's calculation using the HBV model with a design precipitation sequence indicates a decrease in the design flood for most of the scenarios, whereas NVE's application of PQRUT with PMP estimated from climate scenarios by met.no indicates an increase in the design flood of between 3 and 11%. This increase reflects, in part, the projected increase in PMP throughout Norway, with some of the largest increases occurring in inland regions. However, the methods also differ in their treatment of changes in snow storage and snowmelt under a future climate. Therefore, NVE has also used a full HBV model for the Trysil catchment, together with PMP, so that the anticipated reduction in the snowmelt contribution to flooding is accounted for. That work produced variable outcomes, ranging from an increase of 11% to a decrease of -7%. Further work is continuing on this topic with a particular focus on projections for changes in precipitation with a duration of less than 24 hours and on alternative methods for taking the snowmelt contribution to flooding into account.

5.6 The Netherlands – Climate change impacts on river discharge

In the Netherlands climate change effects on seasonal discharge in the large rivers Rhine and Meuse have been studied using hydrological models and the climate projections for the Netherlands (Section 4.3) by Wit *et al*., 2007. The results vary between the projections used but generally indicate higher winter flows in the Rhine and the Meuse (Figure 5.18).

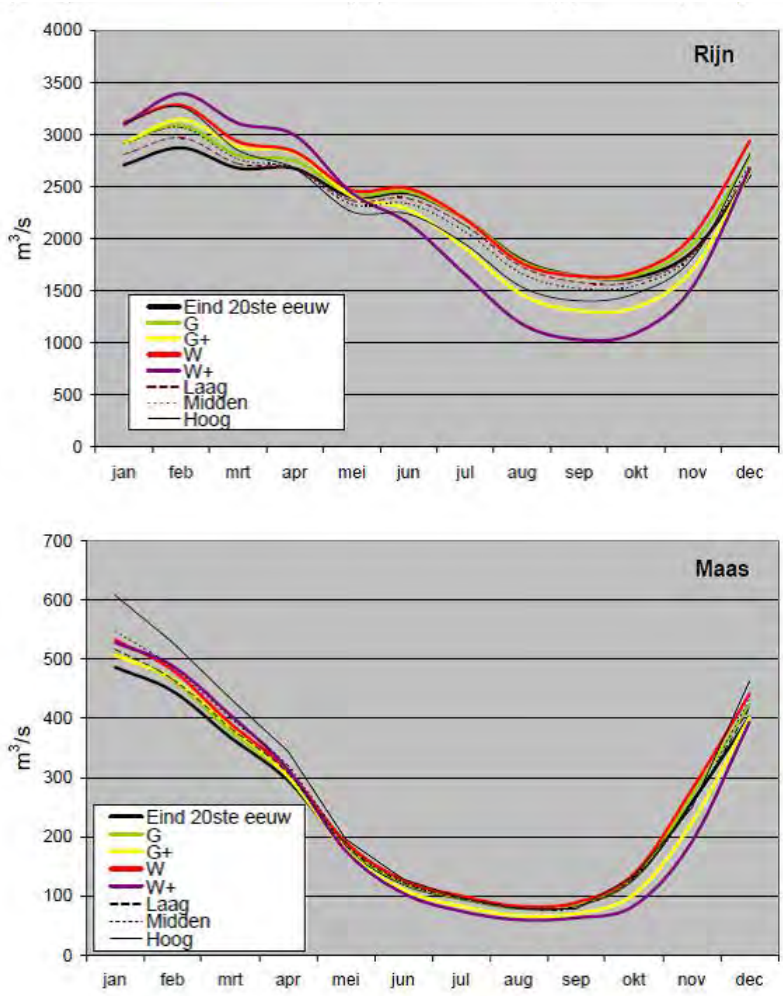


Figure 5.18 **Average monthly discharge of the rivers Rhine and Meuse. The current average discharge is indicated in black and the coloured lines are based on climate projections (Section 4.3).**

The dikes along these large rivers are designed for 1250-year discharges. These extreme discharges are expected to increase from 16000 m³/s to 18000 m³/s by 2100 for the Rhine, whereas the Meuse extreme discharge is expected to increase from 3800 m³/s to 4600 m³/s. The projected discharges for 2100 are now used in the design of river dikes for flood protection. However, the uncertainty underlying these projections is large due, in part, to differences between climate projections (Figure 5.18).

5.7 The Netherlands – Climate change impacts on agriculture

In the Netherlands, the risk of flooding is increasing due to climate change and subsidence throughout the country. This is in sharp contrast with Norway and Sweden, which both have areas of expected increase and decrease in the flood hazard. In response to impending climate change, the province of Flevoland has undertaken work in which climate scenarios and water management models are combined with knowledge regarding the economic and spatial development of Flevoland. In the SAWA-related project

'Climate and Agriculture in Flevoland', predictions regarding long-term land use have been developed, taking climate change into effect.

The work has relied on the climate change scenarios for the Netherlands described in Section 4.1.3, and the impact of the changes given by those scenarios on a variety of crops and farm animals were assessed. Adaptation measures were also identified for the impacts. The study indicates that the impact of water-related climate change impacts, i.e. changes in drought occurrence and duration and in flood risk, are the most important impact of those considered. This reflects the contribution of warmer winters and warmer, wetter summers to increased risk of pests and diseases. Flooding and extreme wet conditions were found to have the largest financial impact. The study has concluded that water management is the principal factor for successful climate change adaptation with respect to agriculture in Flevoland. In particular, it is important for the economic value of agriculture that a high level of water quality is maintained and that measures are taken to prevent deterioration of water availability and quality and increases in flood risk.

6 Commmunicating climate change impacts

6.1 Norway – Climate change and flood hazard mapping

6.1.1 Development of regional guidance

The results presented for changes in the 200-year flow in Norway in Section 5.1 are based on detailed hydrological modelling for a set of 115 unregulated catchments. The spread of results for the individual catchments is large, particularly when all of the relevant factors contributing to uncertainty are considered. Taken as a whole, the results nevertheless give a clear and consistent indication of the regions which are most vulnerable to an increased risk of floods under a future climate. However, it is not considered appropriate at this point in time to formulate precise recommendations for individual water courses due to the range in the projections (as shown in Figures 5.3 and 5.4) and to additional uncertainty introduced by generalising these results to areas without calibrated hydrological models. Nevertheless, it is important that climate change impacts are taken into account in flood risk assessment and flood management, and this policy is part of a national strategy for climate change adaptation (Hamarsland *et al*., 2009). NVE has, therefore, interpreted the results illustrated in Figure 5.1 to establish simple categories for use by flood managers to distinguish likely changes in flood hazard resulting from climate change in Norway. The results from the 115 catchments have also been further analysed with respect to catchment characteristics, including catchment area, steepness, median elevation and location relative to the coast, so that reference to these factors can also be given in the guidance. (See Lawrence and Hisdal, 2011, for details of this analysis).

Three categories have been established for use in analysing the impact of climate change on flood discharge: 0% change, +20% change, +40% change, where the percentage change refers to the projected increase in the maximum flow. Note that some regions of Norway are expected to have a decreased flood hazard in the future, and in these areas, a 0% expected change is proposed for use (rather than an actual decrease). This implies that analyses based on historical observations are preferred in these areas over climate change projections. In other areas, the proposed 20 or 40% increase is recommended for evaluation, in addition to analyses based on historical data. For all regions, it is recommended that a +20% change is considered for catchments with areas of < 100 km^2. This is in response to evidence that short-term extreme precipitation will increase throughout the country under a future climate, and that smaller catchments are most vulnerable to this increase. The recommendation is also supported by the analysis of catchment characteristics which indicates a tendency for catchments with areas of < 100 km^2 to have an increased flood magnitude under a future climate in all regions.

In order to develop regional guidance for use by flood managers, six regions have been distinguished and guidance has been developed for each region. A map is presented for each region illustrating the location and boundaries of the modelled catchments, together with the projected change for the modelled catchments. The topography and river systems are also illustrated, and the boundaries of the larger catchments within the region are indicated. The maps and diagrams are supplemented by a few brief guidelines for the individual region. An example of the regional guidance is given for one of the regions below (extract from Lawrence and Hisdal, 2011):

There are 30 modelled catchments for Østlandet (Figure 6.1), and they represent the broadest range of catchment characteristics of all of the six regions (Figure 6.2). Both snowmelt and rainfall-dominated flood regimes under the current climate are represented, and the results also indicate an increased tendency for autumn/winter peak flows in catchments located within 100 km of the coastal zone. Large (> 1000 km^2), inland catchments currently dominated by snowmelt-driven flood regimes will continue to be dominated by such regimes in the future, although peak flows are expected earlier in the season and to be generally of a reduced magnitude. However, due to projected increases in extreme precipitation, smaller catchments, even in areas currently dominated by snowmelt floods, are considered to be at risk for increased floods in the future. Therefore, the following recommendations are given for calculating changes in the 200-year, 500-year and 1000-year flood until 2100 for Østlandet:

0% increase – Inland catchments dominated by spring/early summer snowmelt floods in the current climate

20% increase – Catchments in more coastal locations with local source areas (*e.g*. see location of catchments indicating a > 20% increase in Figure 6.2 This includes, for example, catchments with local source areas in Vestfold, Akershus, Oslo and Østfold.

20% increase – All catchments with areas < 100 km^2.

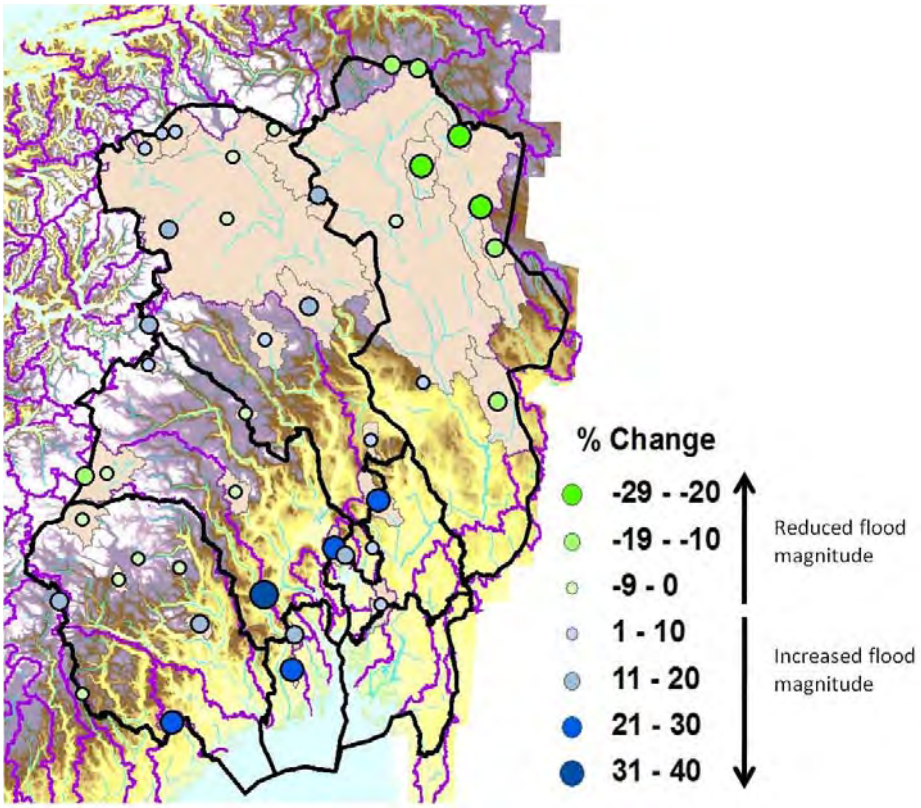


Figure 6.1 **Projected percentage changes in flood magnitude for catchments in Østlandet.**

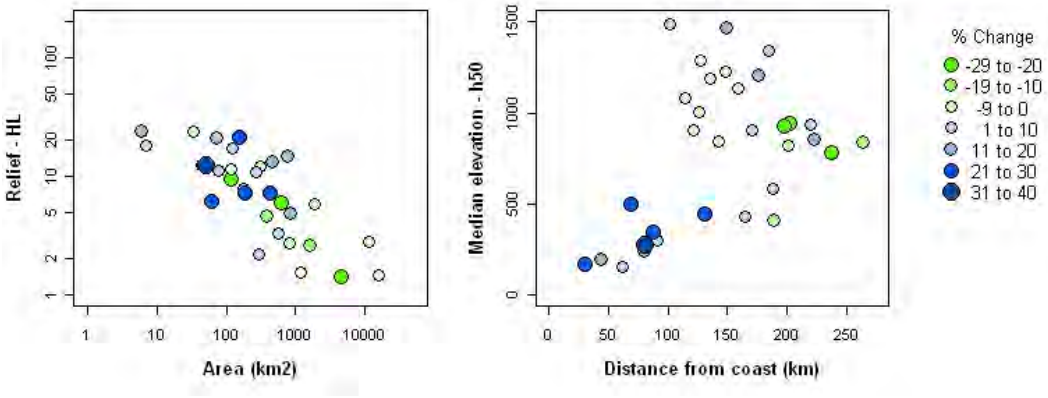


Figure 6.2 **Projected percentage changes as a function of catchment characteristics for catchments in Østlandet.**

Feedback thus far from individuals in Norway who work with flood hazard mapping or with local communities in conjunction with flood risk management is very positive with respect to the guidance that is offered in Lawrence and Hisdal (2011). In particular, the use of simple categories and the availability of guidance for individual regions have been well received.

6.1.2 Methods for communicating climate change impacts

For work with Flood Risk Management Plans (FRMPs) in Norway within the SAWA project, the regional projections given in Lawrence and Hisdal (2011) have been consulted. The three regions for which pilot FRMPs are being considered and developed,

Gaula, Trysil and Tana, all lie in areas where the projected change in flood discharge for use in climate impact analyses is 0% for all catchments > 100 km^2. Consideration of climate change effects is therefore limited to the effects of increased extreme precipitation in urban zones and in smaller tributaries to the river reaches covered by flood hazard maps.

There are other areas in Norway, however, where moderate to large increases in flood discharge are projected. For these areas, NVE is recommending that effects of the increase in flood discharge on patterns of flood inundation are evaluated. As an example, this has been considered for a locality in southwestern Norway where a 20 to 40% increase in the 200-year flow is projected by the end of the 21st century. As this is a coastal community, it will also be subjected to a rise in sea level. A recent study of the possible effects of climate change on sea level and storm surge activity for coastal communities in Norway (Vasskog *et al*, 2009) indicate an increase of 1.16 m as a 'worst case' scenario and a small increase in storm surge magnitude (set to 0.1 m) for a total increase of 1.26 m.a.s.l. The increase in the 200-year flood discharge and the increased sea level at storm surge were used to develop a 'Climate map' for the area based on the existing flood hazard map and simulations using the two-dimensional hydraulic model for the zone (Figure 6.3). This map could be used to communicate the effects of climate change by either displaying it together with today's flood map for the area (published in Orvedal and Peereboom, 2010), or modifying the contours on the map in Figure 6.3 to illustrate the increase in inundation due to climate change effects.

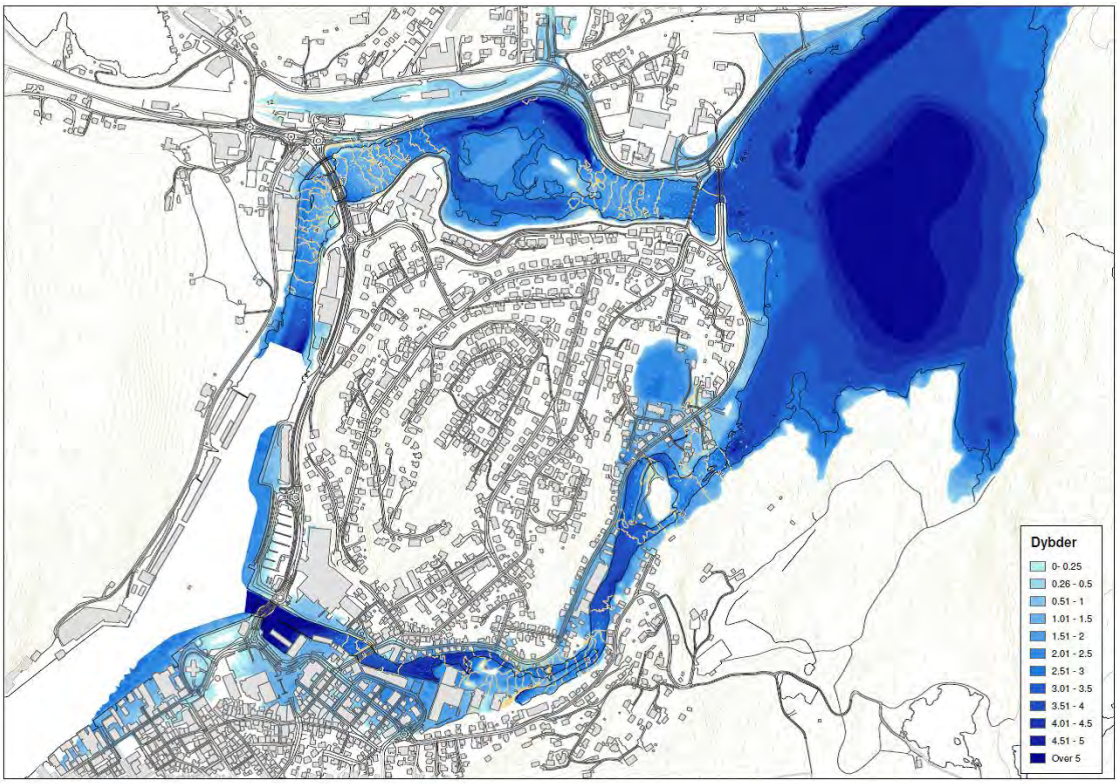


Figure 6.3 **Inundation depths for the 200-year flood for an area in southwestern Norway, taking account of a 40% increase in peak discharge and a 1.26 m increase in sea level.**

Figure 6.3 represents one of several possible methods for communicating the expected impact of climate change on flood hazard, and a decision has not yet been taken in Norway as to the most appropriate method for this purpose. As NVE has the national responsibility for flood hazard mapping, the directorate plays a key role in conveying this information to the municipalities which use these maps. Flood hazard maps based on today's climate already include a margin of safety, and in some cases (for example, those areas where flood hazard is expected to decrease under a future climate), this would be sufficient to cover uncertainty in future changes. A standard two-page text on climate change has been developed for inclusion in the report which accompanies the flood hazard map prepared by NVE for a particular area. This text gives general information on projected climate change impacts on flooding throughout Norway (including Figure 5.1 shown in the previous section), and a specific interpretation of these for the area covered by the flood hazard map. An example of this can be found in Naserzadeh and Peereboom (2010, pg. 2-3) for the newly released flood hazard map for Moss and Rygge in southeastern Norway. In this case, it is pointed out that a 10% increase in today's 200-year flow will produce a flood magnitude corresponding to today's 500-year flood in this area. The associated increase in inundation depths is given for two locations covered by the flood hazard map. Similar sections may be included in all future flood hazard map reports (and reports covering map revisions).

Several alternative approaches for communicating information about the expected effects of climate change on flood hazard are currently being discussed for implementation in conjunction with flood hazard mapping. These include, for example: a) illustrating patterns of inundation under a future climate directly on the flood hazard map, together with those for today's climate; b) creating a separate map illustrating patterns of inundation under a future climate (*i.e.* Figure 6.3) for consultation by the local community; c) reporting expected changes in, for example, depths of inundation in the report which accompanies the flood hazard map, but not actually illustrating the changes spatially (as has been used in Naserzadeh and Peereboom, 2010); and d) reporting expected changes in a separate letter to the municipality. There are several factors that will influence which of these strategies is used, including the availability of time and resources for producing extra 'climate maps' for each municipality with an existing flood hazard map, the preferences of local communities as to the type of information that is considered most useful, as well as whether or not it is reasonable to illustrate specific inundation depths on a map based on estimates which have such a high degree of uncertainty (e.g. Figures 5.3 and 5.4). In many cases, it may be preferable to simply communicate to a municipality that increased flood inundation is expected under a future climate, without quantifying the magnitude of the expected increase.

6.2 Sweden - Climate change and flood risk management

In Sweden there is an on-going discussion as to how to incorporate climate change impacts into flood hazard determination and mapping. As yet, there is no real mandate on how to proceed or on who is ultimately responsible for carrying out such work. Thus far, there are no concrete examples of adjusting the existing flood hazard mapping to take account of projected climate change. However, initiatives are underway that will likely

lead to more dedicated applications on this in the near future. Toward this end, SMHI, as the national hydrological institute, has developed the necessary modelling tools to perform hydraulic analyses for flood mapping that can be coupled to hydrological climate change projections such as those presented in this report.

6.2.1 Climate change in design flood estimation

A leading actor in assessing impacts on flood safety in Sweden due to climate change is the hydropower industry in co-operation with the mining industry, the dam safety authority and SMHI. The new edition of the Swedish guidelines for the determination of design floods for dams prescribes that climate change shall be considered in all design studies, as stated below:

> In the light of the uncertainties created by climate change, among other things, it is advisable that the calculation assumptions are revised regularly. Comparisons should continuously be made between actual flood occurrences and calculated design floods. The sensitivity of the system to climatic change should be analysed, using climate scenarios. New conditions could produce a need for a revision of the design calculations. Uncertainties about the climate in the future should however not stop the implementation of measures to increase dam safety. Furthermore, flexibility and margins should be created where appropriate, in view of these uncertainties. (Swedenergy *et al*., 2007)

This requirement was the starting point for research carried out between 2007 and 2011 with the aim to analyse possible impacts of climate change on the design floods and to find means to account for climate change in future design studies (Andréasson *et al.*, 2011). This was carried out together with the work done for the SAWA project, with much synergy between the two. Aside from being applicable to Swedish dams, results from this work are highly applicable for assessing design floods to be used in assessing flood hazard for local communities. The work will thus contribute directly to future applications for flood hazard mapping.

6.2.2 Climate change and urban flooding in Arvika, Sweden

Based on the results for extreme short-term precipitation described in Section 5.4.5, a study on the impacts on urban flooding in the town of Arvika, north-west of Lake Vänern, was performed (Olsson *et al*., 2011c). Arvika has experienced frequent flooding problems in recent years. The most severe ones are related to a high water level in the bay which the town faces, but the town is also susceptible to intense rainfall events which cause flooding in streets and basements.

The flooding impact of a 20% increase of a 1-hour precipitation event with a 10-year return period, corresponding to the results in Figure 5.16, was estimated by hydraulic modelling using two models: MOUSE and Tokyo Storm Runoff model (Amaguchi *et al*., 2011). It was found that the sewer system is not up to today's design standards, mainly because it was designed using earlier standards. Various alternatives to upgrade the system using a combination of increased pipe diameters and retention ponds were developed. Upgrading the system to a capacity sufficient for the expected extremes by the end of the century was found to be approximately twice as expensive as upgrading to fulfill today's standards. This case illustrates the difficult decisions which can arise when consideration is given to climate change impacts in practical engineering applications.

6.3 The Netherlands - Climate change and water management

6.3.1 Promoting awareness of climate change impacts

In The Netherlands a public campaign has been held in recent years to increase awareness of the impacts of climate change. Rising sea level, more frequent heavy rain and higher temperatures have been explained in advertisements on television, education programmes at primary and secondary schools, and as public information on government websites (*e.g.* www.levenmetwater.nl, www.nederlandleefmetwater.nl)

A current project is undertaking 2D-calculations of inundation during flooding from the main water system. The results are available to the public and are published on websites (http://nederland.risicokaart.nl/ and http://flooding.lizardsystem.nl/flooding/). An example flood risk map for the public is shown in Figure 6.4. In 2008 a national commission proposed national strategies for dealing with the impacts of climate change on flood risks and increasing water shortage in the "Second Delta Program". Based on this advice a 'Delta Law' has been approved that controls an interactive process for developing proposals to reduce future flood risks and water shortage. A national decision on measures is expected to be taken in 2015. Further details are available at (http://www.rijksoverheid.nl/onderwerpen/deltaprogramma)

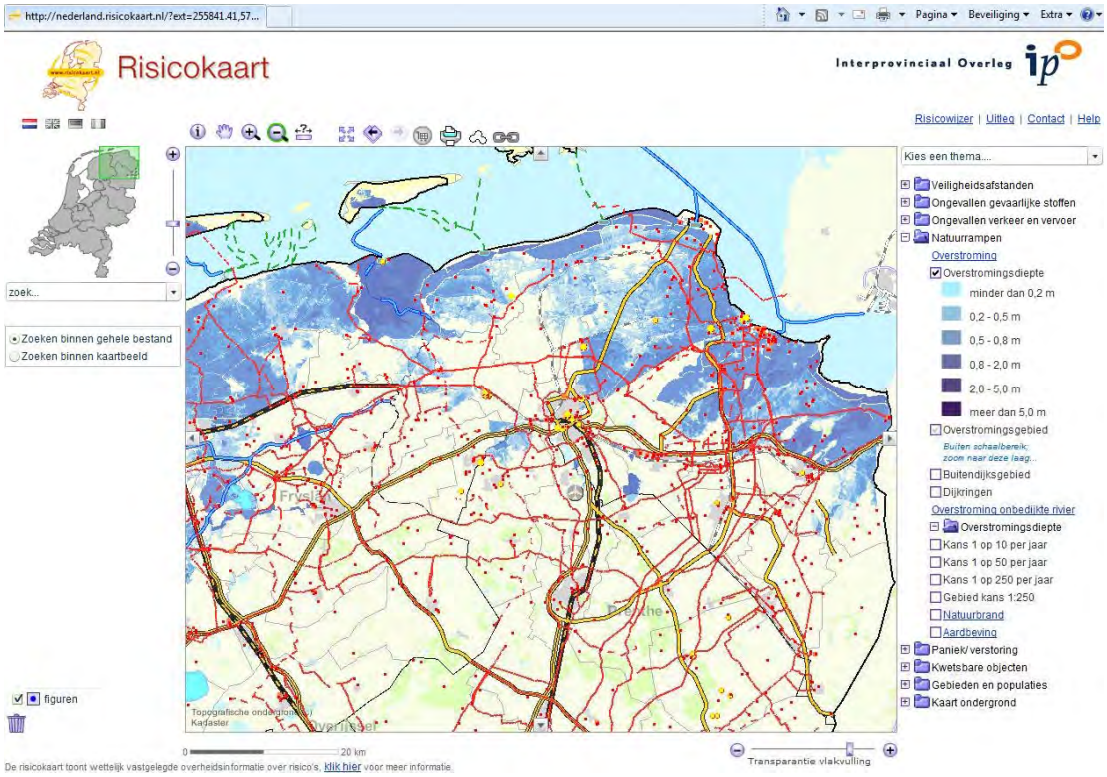


Figure 6.4 **Example flood inundation map available for the Netherlands.**

6.3.2 Regional studies of climate change impacts on flooding

On a regional level, the results of climate studies are being applied in the development of flood risk management plans, with consideration mainly given to fluvial and pluvial flooding. The use of the national climate change scenarios (described in Section 4.1.3) is compulsory in the development of flood risk management plans. These plans will be revised under a six-year cycle, using the most recent climate scenarios available. The climate scenarios will be used in conjunction with hydrological and hydraulic models to calculate the inundation risk at certain points in the future. The same models are being used to consider the effects of mitigation measures, leading to a flood risk management plan with measures based on the projected climatic conditions for the year 2050. In Flevoland, for example, the most recent FRMPs were developed in 2006. New climate scenarios from KNMI are expected in 2013, and Flevoland is also currently making a new estimate of subsidence. These will be used by the waterboard of Zuiderzeeland to generate new inundation risk maps and a new flood risk management plan. At the national level, guidelines have been developed on how to deal with different potential problems with respect to the different climate change scenarios available.
For example, for water systems in new urban areas it is advised to use the 'wetter' scenarios W and G because an underestimation of the increased rainfall would have strong financial implications in the future. For design of water systems in rural projects, the moder climate change scenario G can be used.

6.3.3 Adaptation to climate change for agriculture in Flevoland

In conjunction with the study described in Section 5.7, two workshops were conducted with farmers in Flevoland. In these workshops, scientists presented climate change impacts and possible adaptation measures. Two categories of measures were considered: "doing things differently" and "doing different things". The farmers discussed strategies, evaluated possibilities, and proposed additional measures. During the workshops it became apparent that different farmers took very different strategies, depending on their market approach. It was also evident that they were confident that a wide range of adaptation measures was available. Important measures identified in the category "doing things differently" included improving soil structure and water management, irrigation, cooling potato ridges using water, and innovative machine design. For the category "doing different things", important measures included new crops such as sunflower and artichoke, and rotating arable crops with grassland.

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