Hydrological projections for floods in Norway under a future climate

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REPORT

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Abstract: An ensemble of regional climate scenarios, calibrated hydrological models and flood frequency analyses are used to assess likely changes in hydrological floods under a future climate in Norway for two periods, 2021-2050 and 2071-2100. Analyses are based on detailed modelling for 115 catchments, and changes in the mean annual flood, the 200-year and the 1000-year floods are estimated. Regional guidance for using the projections in climate change adaptation planning is also presented.

Key words: Climate change adaptation, HBV hydrological model, uncertainty, flood risk

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Preface

Hydrological modelling and flood frequency analyses have been used together with climate scenario data to develop projections for the impact of climate change on floods.The scientific basis for this work and an overview of the results are presented in this report. General guidelines for taking account of potential changes in flows of long return periods (*e.g.* 200-year and 1000-year flood) under a future climate in Norway are also given on a regional basis. These guidelines contribute to NVE's climate change adaptation strategy with respect to flood risk management and dam safety. This work has received partial financial support from the EU Interreg IVB SAWA (Strategic Alliance for Water management Actions) project (2008-2011), and from the CES (Climate and Energy Systems) project (2007-2010), funded by Nordic Energy Research, in addition to internal research funding from NVE received from OED (Ministry of Petroleum and Energy) in Norway.

Oslo, June 2011

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Summary

Ensemble modelling based on locally-adjusted precipitation and temperature data from 13 regional climate scenarios is used to assess likely changes in hydrological floods between a reference period (1961-1990) and two future periods (2021-2050) and (2071-2100). The adjusted climate scenario data are input to hydrological models for 115 catchments distributed throughout Norway. The ensemble of models also includes 25 calibrated parameter sets for each catchment, so that uncertainty introduced by hydrological modelling can be considered, in addition to differences between alternative climate scenarios. Simulated hydrological time series are analysed using flood frequency estimation to determine the magnitude of flows of given return periods, and the uncertainty introduced by this analysis is also considered for a subset of results.

Projections for changes in the mean annual flood, the 200-year flood and the 1000-year flood are given for each catchment based on the median value of the ensemble for the catchment. Although there is considerable variation in the range of projections for individual catchments, consistent regional patterns in the projections are evident. The western region of Norway and Nordland are associated with the largest percentage increases in the magnitude of the mean annual flood and floods of longer return periods. In addition, catchments located near the coast tend to have an increased flood magnitude in all regions, with the exception of Finnmark. Large catchments with source areas located in inland regions, such as Oppland and Hedmark and parts of Trøndelag, and in the northernmost region, Finnmark and Trøms, are generally expected to have reduced flood magnitudes under a future climate. Differences between regions largely reflect the relative roles of snowmelt *vs*. rainfall in the flood regimes in the catchments. Warmer winter and spring temperatures leading to reduced snow storage and earlier snowmelt will most likely bring about a reduction in the magnitude of floods derived primarily from snowmelt in the future. Simultaneously, increases in autumn and winter rainfall throughout Norway will increase the magnitude of peak flows during these seasons. In areas already dominated by autumn and winter floods, the projected increases in flood magnitude are large. There are also areas currently dominated by snowmelt floods in which autumn and winter rainfall floods are expected to become increasingly important in the future. In some cases, this change in seasonality will also lead to an overall increase in the magnitude of the mean annual flood and of floods of longer return periods.

Variations in projected changes in flood magnitude between catchments in the same region are also evaluated with respect to differences in catchment area, steepness, median elevation, and inland location. Catchments with areas < 100 km^2 are in most cases associated with projected increases in flood magnitude. Similarly, steeper catchments are generally found to have larger projected increases than less steep catchments. Catchments with median elevations of < 500 m and catchments with midpoints < 100 km from the coast are both associated with increased flood magnitudes in most cases.

Due to the uncertainties in the detailed projections for individual catchments and to the need to generalise the results to areas outside the calibrated catchments, three categories are proposed for use in climate change adaptation planning: 0% change, 20% change and 40% change. The final section of this report presents regional guidance for determining which of these three categories is most appropriate for a given water course.

1 Introduction

Climate change projections for Norway indicate changes in both temperature and precipitation regimes in the future (Hanssen-Bauer*, et al*., 2009). 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. 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. The largest increases in precipitation are expected during the autumn and winter months at most locations. 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 must therefore be used to assess the impact that changes in precipitation and temperature will have on land surface processes, such as stream flow generation leading to floods.

In this report, the likely consequences of climate change on low frequency high flow events (*e.g*. the 200-year flood) are evaluated based on the results of HBV hydrological modelling at 115 locations distributed throughout Norway. The locations represent unregulated catchments for which local observed stream flow data forms the basis for calibrating the HBV model for historical time periods, as previously reported in Lawrence *et al*. (2009). Input data from several climate scenarios are used in the hydrological models to simulate runoff time series for a reference period (1961-1990) and two future periods (2021-2050 and 2071-2100). The runoff time series simulated by the hydrological models are evaluated using flood frequency analysis based on the annual maximum series, and the percentage changes in the magnitude of the mean annual flood, the 200-year flood and the 1000-year flood are assessed. Likely changes in the seasonality of peak flows are also evaluated from the simulated runoff series.

Climate change adaptation planning is necessarily reliant on model simulations for future conditions, as observed runoff data are, of course, unavailable for future periods. Additionally, traditional flood frequency analyses for predicting the magnitude of events such as the 200-year and 1000-year flood are often based on a limited period of record (typically 30-50 years) when compared with the return period of the estimated flood. In this case, short- and long-term patterns of climate variability, either man-induced or otherwise, are not necessarily well-represented by the available observed data. Most flood frequency analyses are also based on the assumption of stationarity. This assumption requires that both the observed time series and the future conditions for which the likelihood of events are estimated do not have trends. This requirement is no longer met as climate change begins to alter patterns of rainfall and runoff over the time periods considered. Both of these factors can undermine the robustness of many analyses based on observed data. Flood frequency analyses based on modelled, rather than observed, data therefore makes an important contribution in the assessment of flood hazards. A significant drawback with the use of modelled data, however, is that results can vary between models and, in the case of climate change, between the greenhouse gas emissions scenarios considered. Therefore, in the work presented here, an "ensemble" approach has been applied in which several climate scenarios, hydrological model calibrations and flood frequency analyses are used to develop a range of projections for each catchment. This methodology also enables the quantification of some of the uncertainties inherent in the projections.

The detailed quantitative results presented in the first several sections of this report relate to the 115 unregulated catchments for which the HBV hydrological model has been calibrated. To use these results in practical applications, such as flood hazard mapping and dam safety analyses, they must be generalised to other catchments and areas. Therefore, the final sections of this report present an assessment of expected changes in floods on a regional basis, as interpreted from the spatial pattern of results for the 115 catchments. Factors which contribute to local variation in the response to climate change, such as catchment size, topography, and location relative to coastal influences, are also considered. Guidance is then presented for six regions in Norway in which expected changes in flood magnitude are classified into three categories: 0%, 20%, and 40% for different catchment types in each of the regions. Due to the many uncertainties in the simulations for future periods, it is not considered appropriate at this point in time to develop more detailed projections based, for example, on the use of regional regression equations. In addition, future generations of regional climate models and methods for locally adjusting precipitation and temperature data will most likely modify the detailed catchment-scale projections. It is expected, however, that the general regional patterns will remain unchanged. The classification of likely changes based on three simple categories is therefore considered to be the most robust use of currently available knowledge regarding climate change impacts on future floods.

2 Background

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). The 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. It is also proposed that intensive local rainfall floods will become more frequent. In similar work, Beldring *et al.* (2006) evaluate the percentage change in the mean annual flood and the 50-year flood in four catchments based on an ensemble of climate scenarios derived from two alternative global climate models run under two different greenhouse gas emission scenarios. The 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 for 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 *et al*., 2009) and come from updated climate models and methods for linking global and regional climate models. Therefore, in order to generate a set of hydrological projections that can contribute to an adaptation strategy for managing expected climate change impacts on floods throughout Norway, the work presented in this report was undertaken. The report presents analyses based on the most up-to-date climate scenario data currently available and also considers a denser and more uniform selection of catchments for hydrological modelling, so that regional patterns of expected change can be evaluated.

3 Methods

3.1 Ensemble methodology for analysis of hydrological impacts

To assess climate change impacts on flood frequency, a modelling scheme comprised of a series of linked models is required (Figure 3.1). 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 so-called 'SRES' emission 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 (IPCC, 2000). The output from the GCM model runs must be dynamically downscaled to a higher resolution grid (*e.g.* 25 x 25 km) using Regional Climate Models (RCMs) before they are suitable for regional scale impact analyses. At each stage in this climate modelling chain, the alternative SRES scenarios and GCM/RCM models can produce dissimilar results. Therefore, for climate impact analyses, it is considered to be good practice to use several models and to evaluate the range of results, rather than to limit consideration to a single GCM/RCM combination (*e.g.* Wilby and Harris, 2006). The impact of the alternative SRES emission scenarios is more significant towards the end of the century than over shorter timescales. It is, thus, also necessary that impact analyses which assess changes over this time period consider GCMs run under alternative SRES scenarios.

For use in catchment-based hydrological analyses (such as are required to evaluate flood frequency) the output series from RCMs must be further adjusted to a local scale corresponding to observed precipitation and temperature data. 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. There are different methods for achieving this correction, and these methods entail assumptions as to how the statistical moments will change in future periods. Consequently, the alternative methods can lead to differing results when the adjusted input data are used in hydrological modelling (*e.g.* Beldring *et al*., 2008).

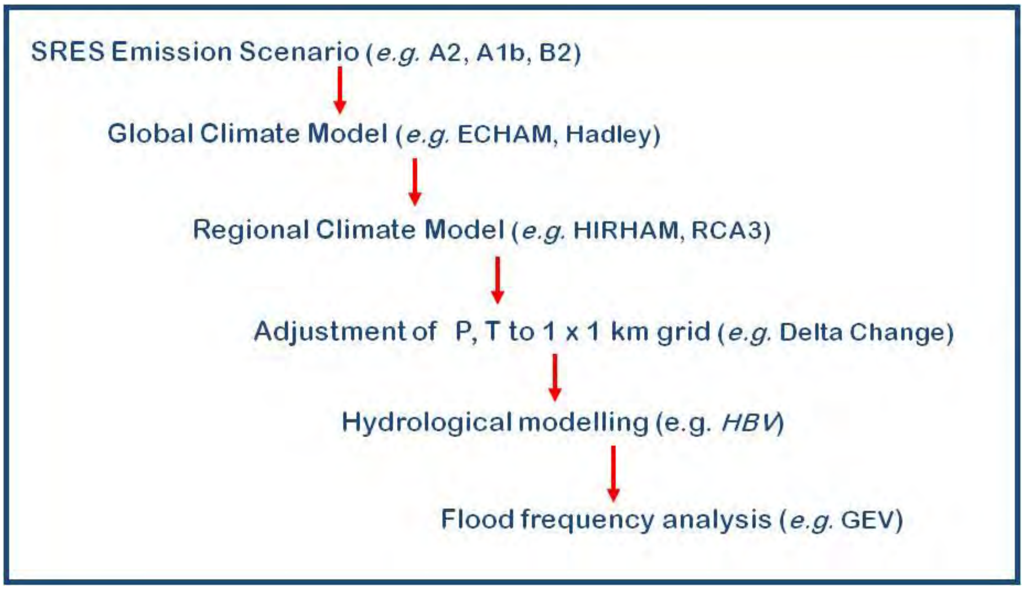

Figure 3.1 Linkages between models and data used for estimating changes in flood frequency under a future climate.

Hydrological modelling and flood frequency analysis also involve methods which can produce dissimilar results. This reflects, in part, so-called 'equifinality' in which different combinations of model parameters or processes produce the same fit to observed data and therefore are not differentiated during model calibration. Recent analyses of uncertainty in hydrological projections for climate change impacts on the mean annual flood indicate that, in some cases, uncertainty derived from hydrological model parameters is as large as that introduced by alternative climate models and emission scenarios (Lawrence and Haddeland, 2011). Similarly, uncertainty in the parameters estimated in flood frequency analysis and in the selection of the extreme value distribution for the estimation lead to a best-fit model that represents only one of many alternative models for the flood data and for the projections derived from those data.

Due to the factors highlighted above, each step illustrated in Figure 3.1 is associated with a selection of alternative models, methods and approaches. Therefore, in order to capture the range of possible changes in flood magnitudes under a future climate, an ensemble methodology is applied here in which data from several GCM/RCM combinations are used for hydrological modelling of climate change impacts on floods. Simulations for the 2071-2100 period also sample alternative SRES scenarios. Two alternative techniques for adjusting precipitation and temperature data to a local scale are also represented in both future periods. The hydrological modelling is based on several alternative best-fit HBV model parameter sets such that uncertainty introduced by model parameterisation can be quantified. The general framework is similar to that applied in Lawrence and Haddeland (2011), although here the additional uncertainty associated with flood frequency analysis is also considered.

3.2 Hydrological modelling

The HBV hydrological model (Bergström, 1995; Sælthun, 1996) was calibrated and validated for 115 catchments distributed throughout Norway as described in Lawrence, *et* *al*. (2009). These catchments are also used for hydrological modelling in connection with NVE's flood warning services. Catchment area varies from approximately 3 km^2 to 15,500 km^2 (Figure 3.2), with a median value of 190 km^2. Thus, smaller catchments are fairly well represented in the modelling, and the overall spatial distribution of the catchments is reasonably uniform (Figure 3.3). The spatial distribution of larger catchments is, however, not so uniform. Larger catchments are generally associated with the inland and northernmost areas, and for some of these catchments, smaller nested catchments within these larger catchments also form part of the sampled set in these areas. Such a nested hierarchy is not feasible in other areas due to regional physiographic differences and to the need for long-time series of historical data for unregulated catchments for model calibration. This requirement limits the selection of gauged catchments available for modelling.

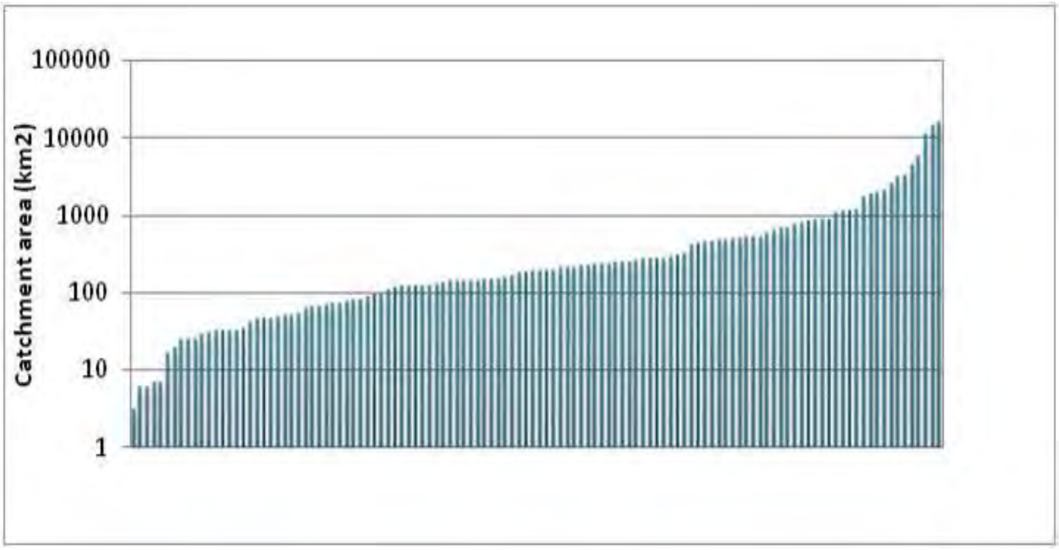

Figure 3.2 Distribution of catchment areas for the 115 catchments with calibrated models.

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 daily precipitation and temperature data for the period 1961-2008. Hydrological modelling was based on 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. For catchments where discharge data are not available for the entire period (for example, catchments with records beginning after 1961), the calibration and validation periods were adjusted to fit the available data. Further details regarding the available discharge records for individual catchments can be found in Lawrence *et al*., 2009.

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) varies by no more than 2%. The Nash-Sutcliffe values for the fitted models for the catchments are illustrated in Figure 3.3 and indicate good to excellent model fits in most areas. The best model fits (> 0.85) tend to be associated with larger catchments in regions where the annual flow regime is dominated by a spring or summer 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 parameters for each catchment based on input data from climate scenarios, as described in Section 4.1 later in this report.

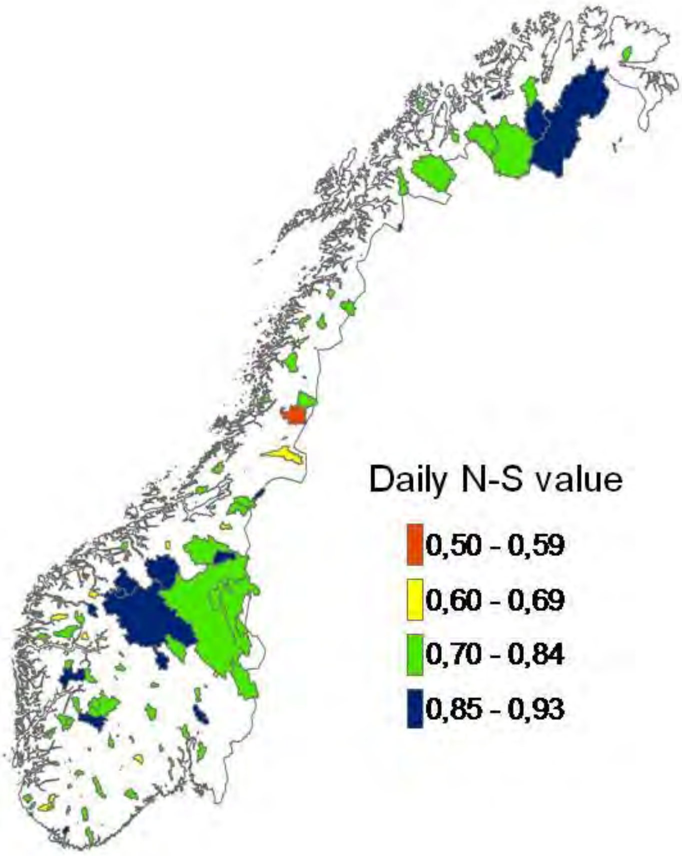

Figure 3.3 Location of the 115 catchments used for HBV model calibration, with the catchment boundaries indicated. The value for the Nash-Sutcliffe criterion based on daily discharge values is indicated by colour.

3.3 Flood frequency analysis

In order 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. These methods have been used for many years in hydrology to estimate the likelihood of low frequency events with long return periods. Observed hydrological time series are typically between 20 and 50 years in length, which is usually shorter than the design periods for which extreme events are estimated. In Norway, flood frequency analysis is undertaken in connection with 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.

As is the case with all types of modelling, either statistically-derived or based on numerical simulation models, estimates obtained using flood frequency analysis are associated with uncertainty. For the analysis of historical time series, the observed data can have significant error or bias. In the analyses presented here, simulated hydrological data are analysed, and in this case, the lack of a perfect hydrological model fit to peak flows can also introduce error in the analysis. Flood frequency analysis is also based on the assumptions that the events analysed are independent of each other, that they represent the same flood generating mechanism, and that there are no trends in the sequence of events. These assumptions are rarely fully satisfied in practise, and thus, deviations from these assumptions also introduce error. In addition, the choice of the extreme value distribution used for the analysis, the methods used to estimate the model parameters, and the techniques for plotting events introduce uncertainty. As is true for all statistical analyses, uncertainty in the statistical model parameters increases as the number of observations available for analysis decreases. In flood frequency analysis, uncertainty increases with increasing return period, due to the larger discrepancy between the length of the record used for the analysis and the return period.

Flood frequency analysis in Norway is usually based on block maxima methods in which the analysed series is comprised of, for example, the annual maximum flows from the observed data series. A statistical function (*e.g.* LogNormal, Generalised Extreme Value) is fitted to the annual maximum series, and the resulting curve is used to estimate the magnitude of flows of a given return period (Figure 3.4). These fitted functions represent statistical models for the likely occurrence of extreme events, and the two or three model parameters define the shape of the curve. The standard practise in flood frequency analysis in Norway for specific sites is to consider several types of model fits before the best alternative is selected.

To analyse the percentage change in the magnitude of a flow of a given return period (*e.g.* the 200-year flood), flood frequency analysis is applied to the annual maximum series from the simulated daily flows for each of two periods, a reference period representing historical conditions (1961-1990) and a future period (2021-2050 or 2071-2100). The two-parameter Gumbel distribution (equivalent to the Generalised Extreme Value type I distribution) is used to model the annual maximum series, and the percentage change in flood magnitude is estimated as the difference between the two curves (Figure 3.4) divided by the flood magnitude for the reference period (1961-1990). The Gumbel distribution was chosen for the analysis due to the limited length of the data series (*i.e.* 30 values of the annual maximum for each time period) which makes the fitting of a three-parameter distribution very uncertain. It is also a suitable distribution according to extreme value theory (Coles, 2001) and has 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). The Gumbel distribution was fitted to the annual maximum series by the probability weighted moments method using the fExtremes package in the R statistical programming language. The uncertainty introduced by the fitting of model parameters was also considered for the simulations for the 2071-2100 period, and for this case, both a two-parameter Gumbel distribution and a three-parameter GEV distribution were used for flood estimation. Note that in the application here, it is only the percentage change which is reported, rather than the absolute flood magnitudes. This approach is used to minimise the impact of the uncertainties described previously in this section. A critical assumption, however, is that the underlying extreme value distribution used (whether a two-parameter Gumbel or a three-parameter GEV distribution) is suitable both for the present and for the future climate.

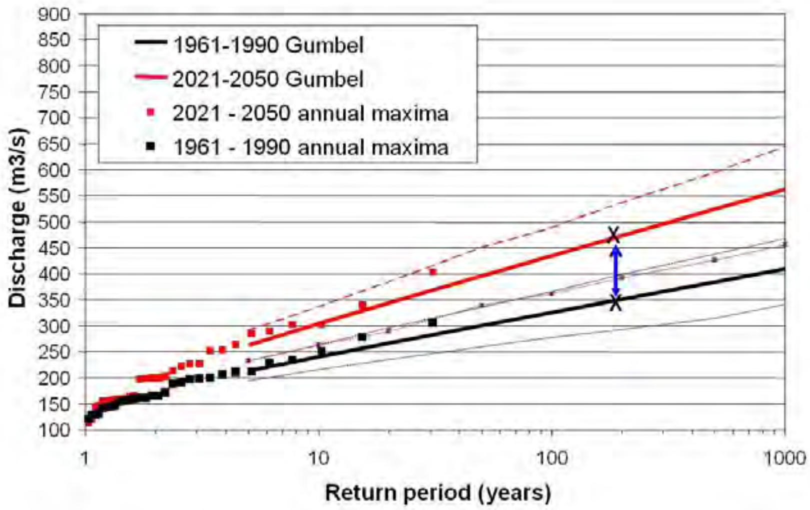

Figure 3.4 Example flood frequency analysis of annual maximum series from simulated data for a reference (1961-1990) and a (2071-2100) future period, based on the two-parameter Gumbel distribution. The 10th and 90th percentile confidence bounds are indicated to illustrate the uncertainty in the estimation of a 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.

4 Climate scenario data

4.1 Sources of RCM data

The locally-adjusted precipitation and temperature data sets available for the hydrological simulations are based on the SRES/GCM/RCM combinations listed in Table 4.1. Three of the RCM scenarios were generated in the RegClim (Regional Climate Development under Global Warming) project (Bjørge *et al*., 2000) and have a spatial resolution of 55 x 55 km, prior to local adjustment. One of these GCM/RCM combinations (ECHAM4/HIRHAM B2) is also available at a 25 x 25 km resolution. The remaining scenarios come from the EU FP6 ENSEMBLES project (van der Linden, *et al*., 2009), a collaborative European project focusing on generating climate simulations representing different combinations of state-of-the-art GCMs and RCMs. All ENSEMBLES scenarios have a 25 x 25 km grid cell resolution prior to local adjustment. In total, there are 13 scenarios available for assessing changes between a 1961-1990 reference period and a 2021-2050 future period, and 13 scenarios for the 2071-2100 future period. The 13 available scenarios differ somewhat, as only nine of the scenarios are common to both periods. The scenarios 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 (see Meehl, *et al*., 2007 for further details). Although three of these scenarios come from the coarser-gridded (55 x 55 km) RegClim simulations, they are used here so that uncertainties as to how greenhouse gas emissions will develop during the latter half of the 21st century are also covered in this analysis. All of the ENSEMBLES simulations are based on the A1b (medium) SRES emission scenario.

Table 4.1 *Climate change scenarios providing precipitation and temperature data*

GCM	SRES (Emission scenario)	Domain/RCM (institution)	Spatial Resolution (km^2)	Local adjustment	Future periods used
HadAm3H	A2	RegClim/HIRHAM (met.no)	55 x 55	Empirical adjustment	2071-2100
HadAm3H	B2	RegClim/HIRHAM (met.no)	55 x 55	Empirical adjustment	2071-2100
ECHAM4	B2	RegClim/HIRHAM (met.no)	55 x 55	Empirical adjustment	2071-2100
ECHAM4	B2	NorAciaNorClim/ HIRHAM (met.no)	25 x 25	Empirical adjustment	2071-2100
BCM	A1B	Ensembles/RCA3 (SMHI)	25 x 25	Empirical adjustment	2021-2050 2071-2100
HadCM3ref	A1B	Ensembles / HIRHAM (met.no)	25 x 25	Empirical adjustment	2021-2050
ECHAM5	A1B	Ensembles / HIRHAM5 (DMI)	25 x 25	Empirical adjustment	2021-2050 2071-2100
BCM	A1B	Ensembles /RCA3 (SMHI)	25 x 25	Delta change	2021-2050
HadCM3ref	A1B	Ensembles /HIRHAM (met.no)	25 x 25	Delta change	2021-2050
ECHAM5	A1B	Ensembles / HIRHAM5 (DMI)	25 x 25	Delta change	2021-2050
Arpege	A1B	Ensembles / HIRHAM5 (DMI)	25 x 25	Delta change	2021-2050 2071-2100
HadCM3ref	A1B	Ensembles /HadRM (Hadley Centre)	25 x 25	Delta change	2021-2050 2071-2100
HadCM3high	A1B	Ensembles /HadRM (Hadley Centre)	25 x 25	Delta change	2021-2050 2071-2100
HadCM3low	A1B	Ensembles /HadRM (Hadley Centre)	25 x 25	Delta change	2021-2050 2071-2100
ECHAM5	A1B	Ensembles /REMO (Max Planck Inst.)	25 x 25	Delta change	2021-2050 2071-2100
ECHAM5	A1B	Ensembles /RCA3 (SMHI)	25 x 25	Delta change	2021-2050 2071-2100
HadCM3low	A1B	Ensembles /RCA3 (SMHI)	25 x 25	Delta change	2021-2050 2071-2100

4.2 Adjustment of regional climate data

The RCM data for daily precipitation and temperature were further adjusted from the RCM grid cell resolution to the 1 x 1 km grid covering the whole of Norway. For Norway, this adjustment is made relative to the 1 x 1 km gridded precipitation and temperature data now available for the country (Mohr, 2008; Mohr and Tveito, 2008). Two methods were used for the adjustment: the widely applied "delta change" method (Reynard *et al*., 2001) and an empirical adjustment method developed by the Norwegian Meteorological Institute (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, one 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 corrected relative to observed data. 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. 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 here.

5 Projections for changes in floods

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). The core 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 the projections for 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). For the case of the 2071-2100 simulations, the ensemble was expanded to also consider uncertainty introduced by flood frequency estimation, and this is described in Section 6.2.

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. The projections presented in this section for the change in the mean annual flood, the 200-year flood and the 1000-year flood are based on the median value of the ensemble for each catchment. Thus, half of the estimated values for the percentage change are larger and half are smaller than the median value given. The range of the results for each catchment is, therefore, also of interest as it reflects the level of agreement between the simulations as to the direction and magnitude of the projected change. This variability within the ensemble and the factors contributing to it are presented and discussed in Section 6.

5.1 Mean annual flood

The general characteristics of observed peak stream flows are often assessed and reported based on the mean annual flood. This quantity is also relevant because the annual maximum flood series is used for estimating the 200-year and 1000-year floods. The projected percentage changes in the mean annual flood between the reference period 1961-1990 and the future periods 2021-2050 and 2071-2100 are illustrated in Figure 5.1 and Figure 5.2, respectively.

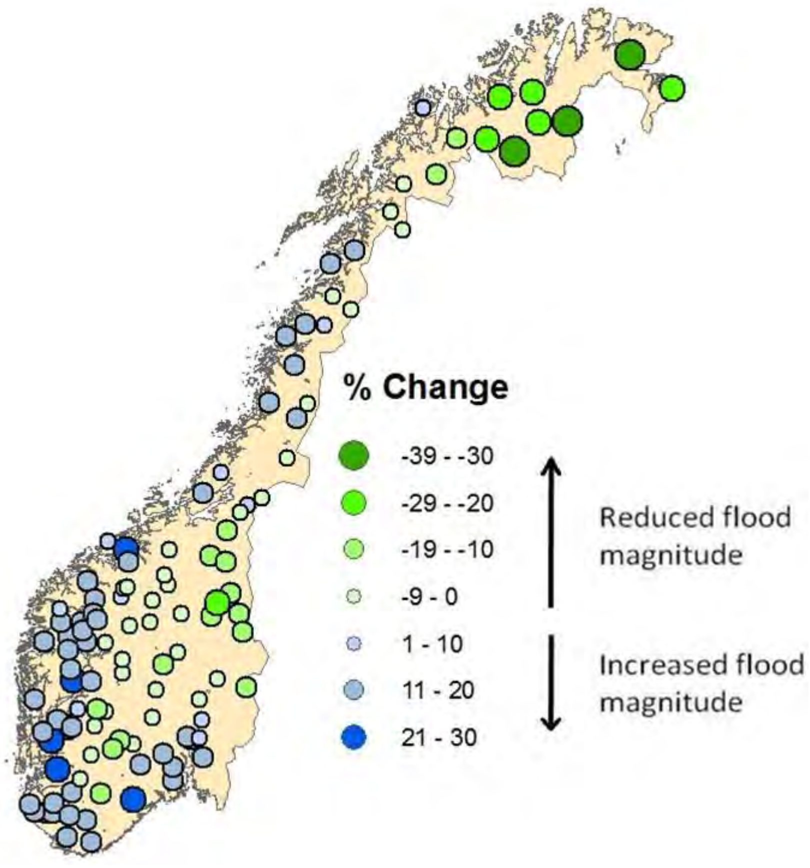

Figure 5.1 Projected percentage changes in the mean annual flood between the 1961-1990 reference period and the 2021-2050 future period, based on the median of the ensemble of hydrological projections for each catchment. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

The general pattern of change illustrated by the figures for both periods is one in which there is significant variation from region to region. 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 the mean annual flood. Catchments located in western and south-western regions (Vestlandet) and coastal regions of southern and south-eastern Norway (Sørlandet and Østlandet) will experience an increase in the mean annual flood, as interpreted from the ensemble median. In addition, the more coastal catchments of Nordland are associated with an increase in this quantity.

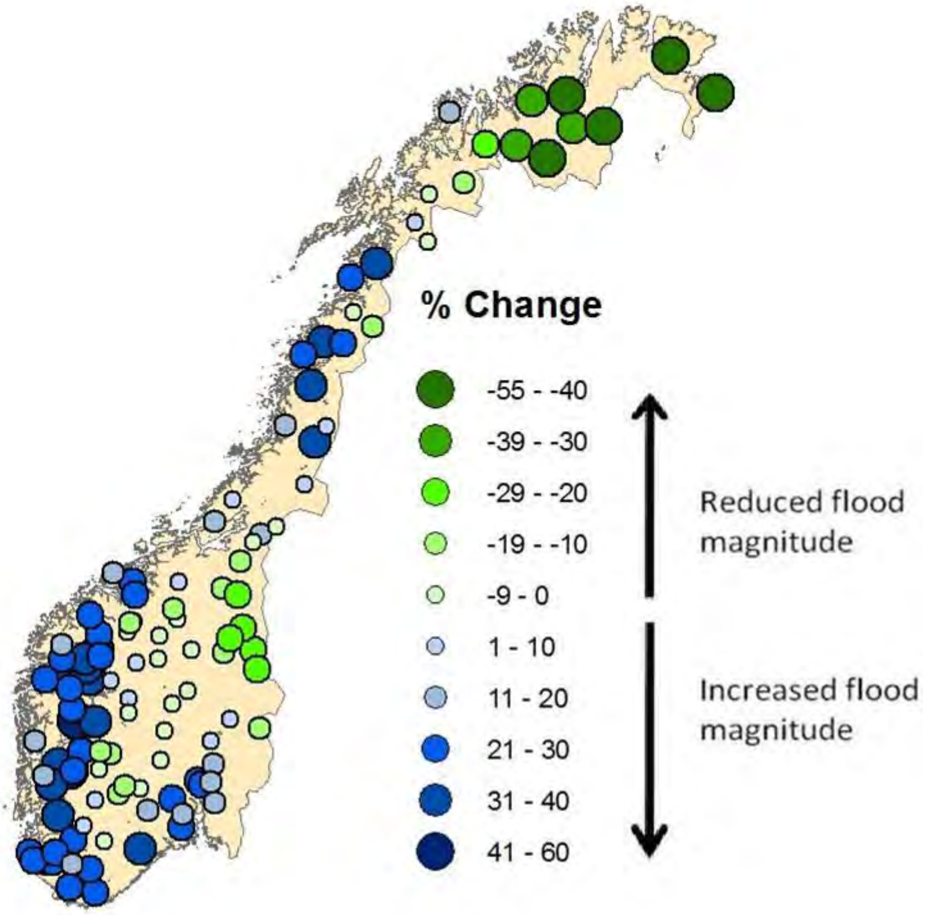

Figure 5.2 Projected percentage changes in the mean annual flood between the 1961-1990 reference period and the 2071-2100 future period, based on the median of the ensemble of hydrological projections for each catchment. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

The regional patterns illustrated for the two future periods are similar, although the magnitude of the changes, and thus, the differences between the regions is amplified as the end of the century is approached (Figure 5.2). In particular, Vestlandet, most of Sørlandet and Nordland, as well as the coastal region of south-eastern Norway, are associated with projected increases in the magnitude of the mean annual flood of > 20%. Large decreases in the mean annual flood are projected for Finnmark and for the areas adjacent to the Swedish border in Hedmark. The remaining areas represent transitional areas in which neither large increases nor large decreases are projected.

Differences in the response of the catchments in the various regions largely reflect the role of snowmelt *vs*. rainfall in inducing the highest flows during the course of a year. 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 the mean annual flood. There are also catchments which are dominated by spring snowmelt floods under the current climate and which exhibit an increased tendency towards autumn and winter peak flows in the future.

5.2 Changes in seasonality of peak flows

In addition to changes in the magnitude of peak flows described in the previous section, changes in the seasonality of peak flows are also projected. 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; or 2) increased autumn and winter rainfall in areas currently dominated by spring snowmelt leading to a change in the dominant flood type, as well as the dominant flood season. In neither of these cases is a change in seasonality necessarily associated with an increased flood magnitude, although in some cases it is. A change in seasonality can also have significance for floods associated with other processes such as river ice breakup and jamming.

The change in the seasonality of the mean annual flood was considered for both future periods, 2021-2050 and 2071-2100. The analysis considered the percentage of the annual peak flows occurring outside the period March – July, which was taken to broadly represent the period in which snowmelt is likely to have contributed significantly to the peak flow. For the four catchments with a > 25% glacier cover, this period was extended to August. The annual peak flows occurring outside of this period are thus considered to represent annual maximum flows in which rainfall is primarily responsible for the high flow, although rapid snowmelt potentially also makes a contribution in some areas. The results of the analysis are illustrated in Figure 5.3 and Figure 5.4 for both the reference and the two future periods. It should be noted that the two sets of 13 scenarios available for the two future periods differ (Table 4.1). There are, therefore, minor differences in the distribution for the reference period, and the results for 2071-2100 do not represent a direct progression from the state shown for the 2021-2050.

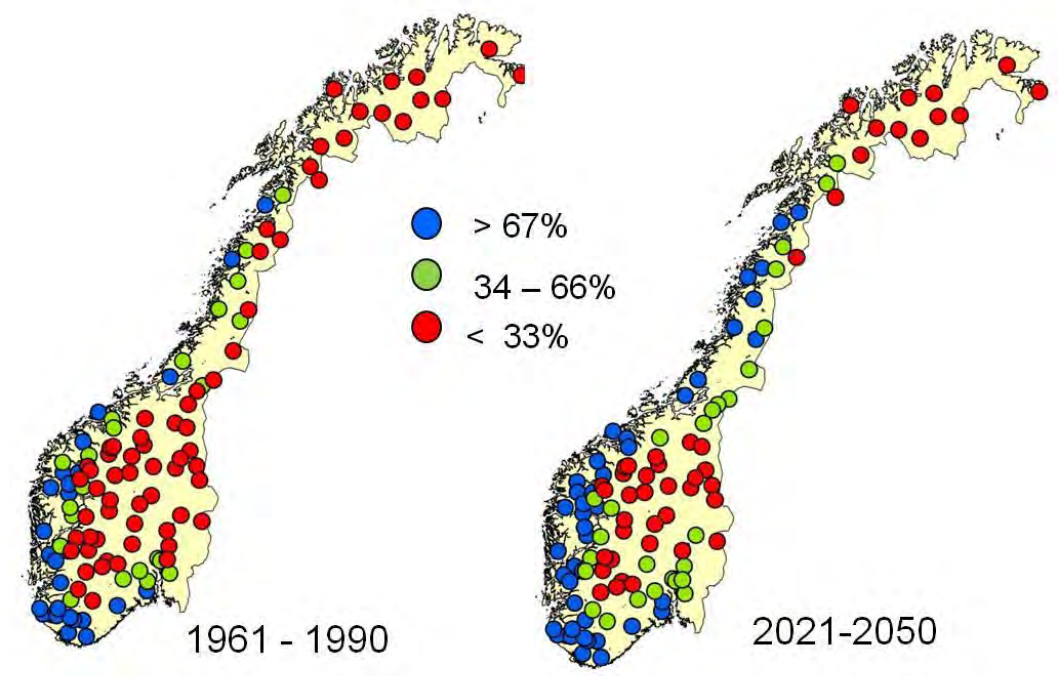

Figure 5.3 Percentage of annual maximum flows occurring during the period August – February (September - February for four catchments with a significant glacial cover) for the 1961-1990 reference period as compared with the 2021-2050 future period.

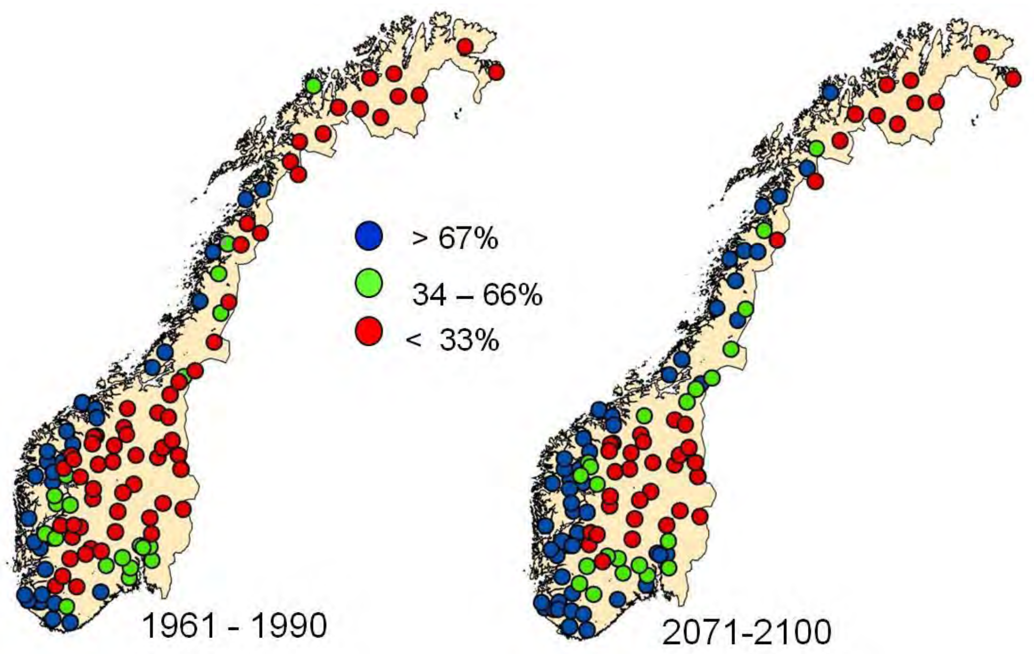

Figure 5.4 Percentage of annual maximum flows occurring during the period August – February (September - February for four catchments with a significant glacial cover) for the 1961-1990 reference period as compared with the 2071-2100 future period.

The results illustrated in Figure 5.3 and Figure 5.4 indicate a clear expansion of the regions currently dominated by autumn and winter peaks flows (blue points), particularly in western Norway, and a contraction of the areas currently dominated by spring and summer peak flows (red points). For the 2071-2100 period, only the most inland catchments in southern Norway, two inland catchments in Nordland, and most of the catchments in the Troms/Finnmark region continue to be associated with predominantly spring and early summer peak flows. Both sets of scenarios for the two future periods, exhibit similar spatial patterns during the reference period and an increased number of catchments dominated by autumn and winter peaks flows in the future period.

The season in which the maximum flow for the entire 30-year period occurs has also been compared between the 1961-1990 reference period and the 2071-2100 future period (Figure 5.5). (The seasons presented are based on the following months: Spring – March, April and May; Summer – June, June and August; Autumn – September, October and November; Winter – December, January and February.) The comparison illustrates the increase in the number of catchments associated with spring (green) as opposed to summer (yellow) floods in the future. There are also several smaller catchments, for example in south-eastern Norway, which exhibit a change in seasonality from spring (green) to autumn (orange), also suggesting a change in the role of snowmelt *vs*. rainfall in flood generation.

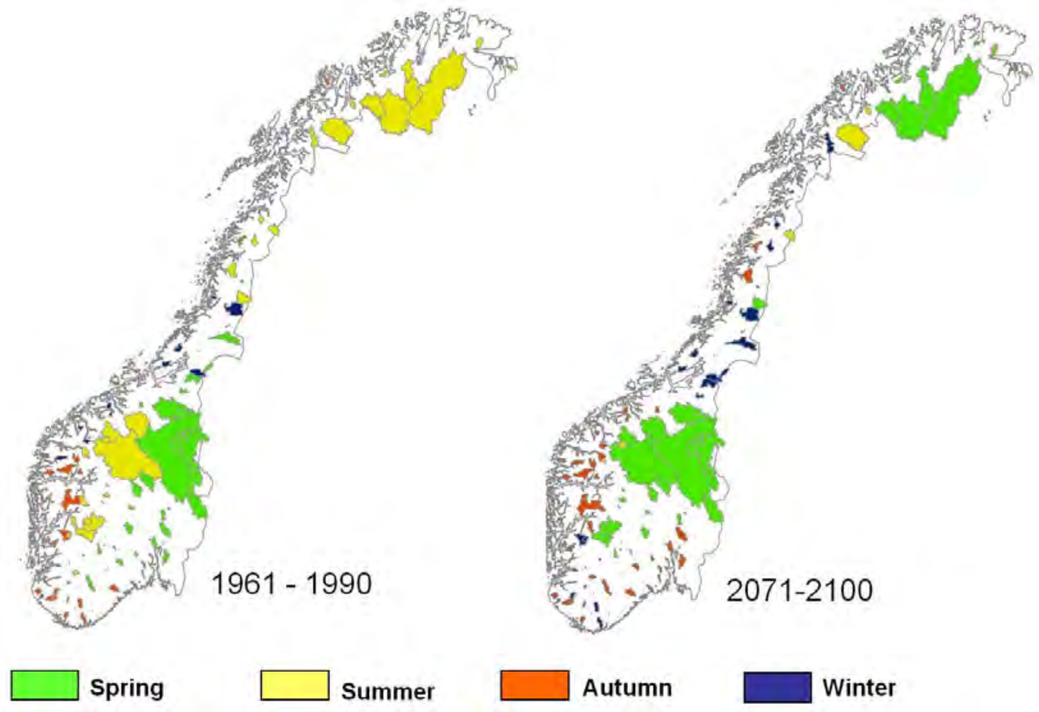

Figure 5.5 Season in which the maximum simulated discharge occurred for the 30-year period indicated.

5.3 200-year flood

The results presented in the previous sections are based on the annual maximum flood series from the simulated data for each catchment. The quantities presented are estimated directly from the series, *i.e.* without the use of extreme value analysis. For planning purposes, however, floods with long return periods are often considered, and a flood frequency analysis based on the fitting of an extreme value function is used, as described in Section 3.3. The resulting projections for the percentage change in the 200-year flood between the 1961-1990 reference period and the two future periods are shown in Figure 5.6 and Figure 5.7, based on fitted two-parameter Gumbel functions for the annual maximum series for each simulation. The values illustrated in the figures represent the median of all of the percentage changes calculated from the ensemble of simulations for each catchment.

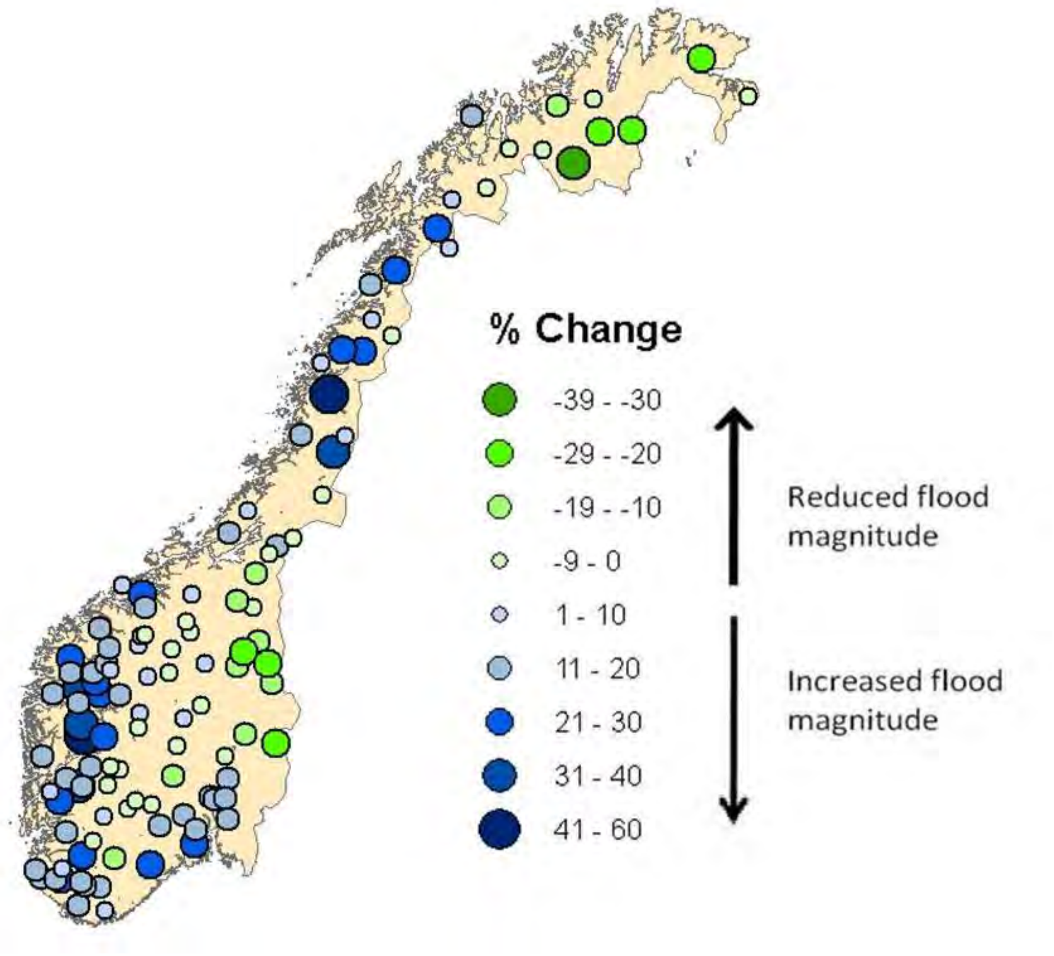

Figure 5.6 Projected percentage changes in the 200-year flood between the 1961-1990 reference period and the 2021-2050 future period, based on the median of the ensemble of hydrological projections. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

The general pattern of projected change is similar to that for the mean annual flood in that increases in the magnitude of the 200-year flood are seen in western and coastal regions of Norway whilst decreases dominant inland and the northernmost areas. The patterns illustrated for the two future time periods are also similar, although the changes are more pronounced towards the end of the century. In addition, several catchments in the inland area of southern Norway exhibit small to moderate increases in the magnitude of the 200-year flood in the 2071-2100 period. These results point towards a significant increase in flood magnitudes in western Norway, in the county of Nordland, and in coastal areas of southern and south-eastern Norway and Troms. The largest projected increases are found in western Norway and in Nordland.

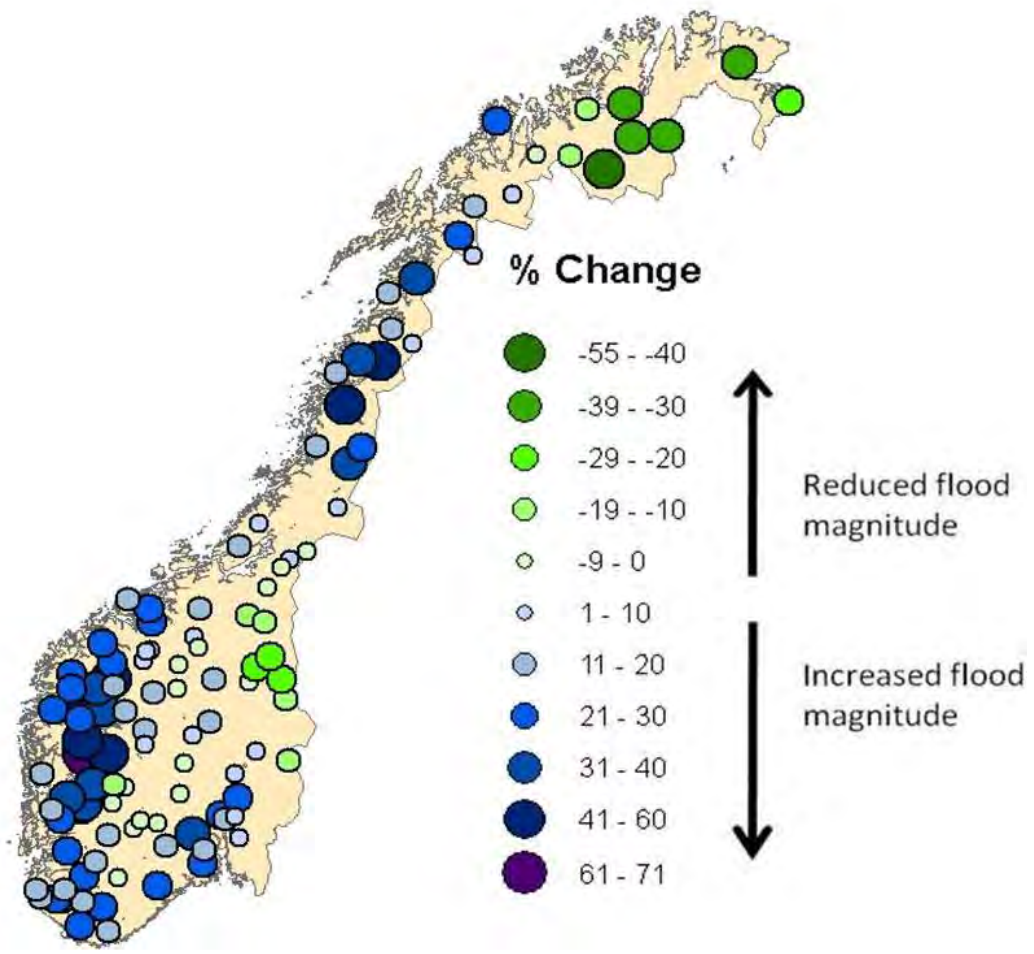

Figure 5.7 Projected percentage changes in the 200-year flood between the 1961-1990 reference period and the 2071-2100 future period, based on the median of the ensemble of hydrological projections. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

5.4 1000-year flood

Projections for changes in the 1000-year flood have also been estimated due to their relevance in dam safety analyses. These are illustrated for the 2071-2100 future period in Figure 5.8. The spatial pattern of change and the projected magnitudes of the percentage change are very similar to those obtained for the 200-year flood (Figure 5.7). The similarity between the projections for the 200-year and the 1000-year flood is anticipated because the two-parameter Gumbel distribution used here produces flood frequency curves for the reference and future periods which often lie roughly parallel to each other for long return periods (*i.e.* Figure 3.4). Similar results would also be expected for the 500-year flood, which is also used in dam safety analyses.

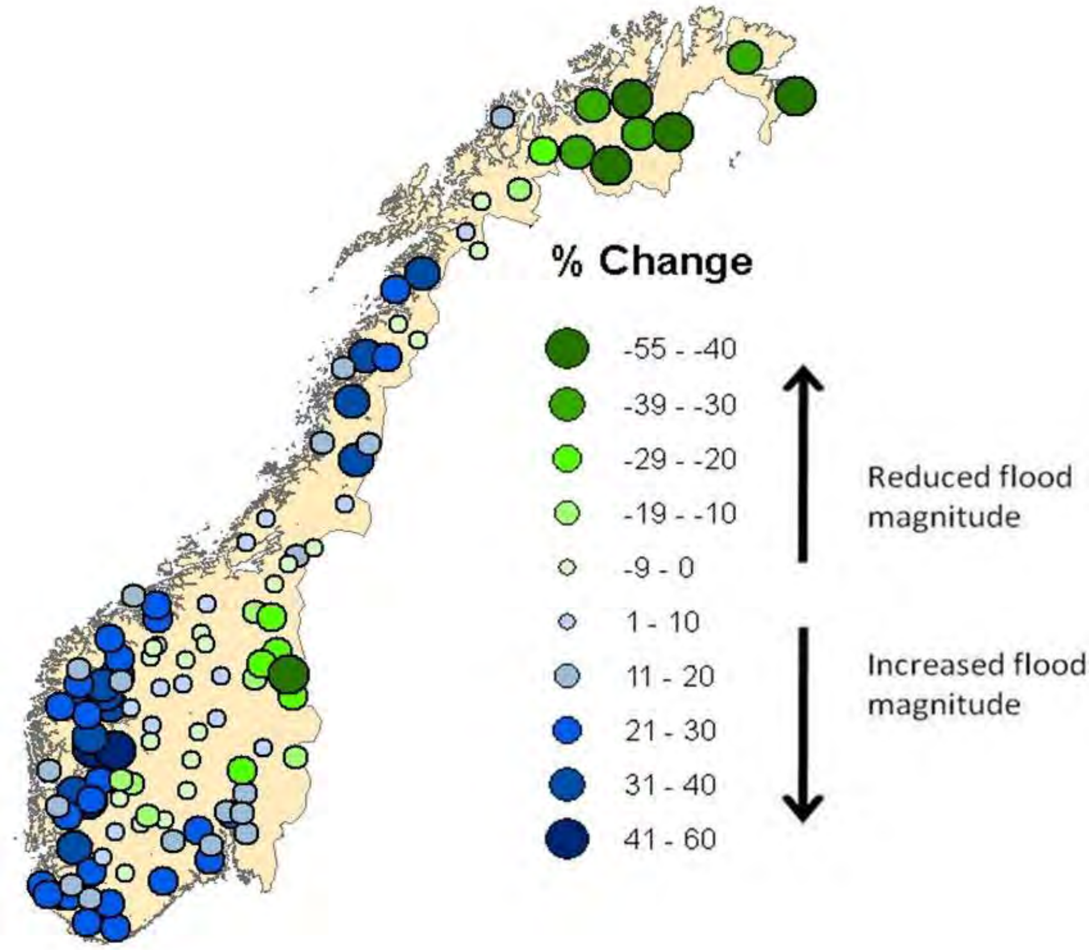

Figure 5.8 Projected percentage changes in the 1000-year flood between the 1961-1990 reference period and the 2071-2100 future period, based on the median of the ensemble of hydrological projections. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

5.5 Regional patterns of projected change

The projected changes in the mean annual flood, the 200-year flood and the 1000-year flood all exhibit similar spatial patterns in which moderate (15 – 30%) to large increases (> 30%) in the magnitude of the maximum daily averaged discharge are expected in western and south-western Norway, in south-eastern Norway in catchments located near the coast, and in Nordland. Projected increases for the 200-year flood exceed 40% for some of the catchments in western Norway and in Nordland. On the other hand, large decreases are projected for inland regions such as Hedmark and in Finnmark. The regions between the zones of large increases *vs*. large decreases generally have transitional values of projected change (*i.e.* small increases or decreases of < 15%). Catchments with source areas in the mountainous regions of southern Norway (east of the north-south water divide), and in the Trøndelag, and Troms regions tend towards small to moderate changes, although there are local exceptions.

6 Variability in ensemble projections

By using ensemble modelling, one can also consider the range and distribution of all of the results for a catchment, thus giving an indication as to the variability amongst the projections represented by the ensemble. The figures illustrating projected changes shown in the previous section are based on the median of all of the estimated changes for the catchment. The median value is the value for which at least 50% of the projections are equal to or greater than the value given, and is used here as the most representative value for the ensemble of simulations for each 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.

6.1 10th to 90th percentile range in projections

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 6.1. 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 6.1 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.

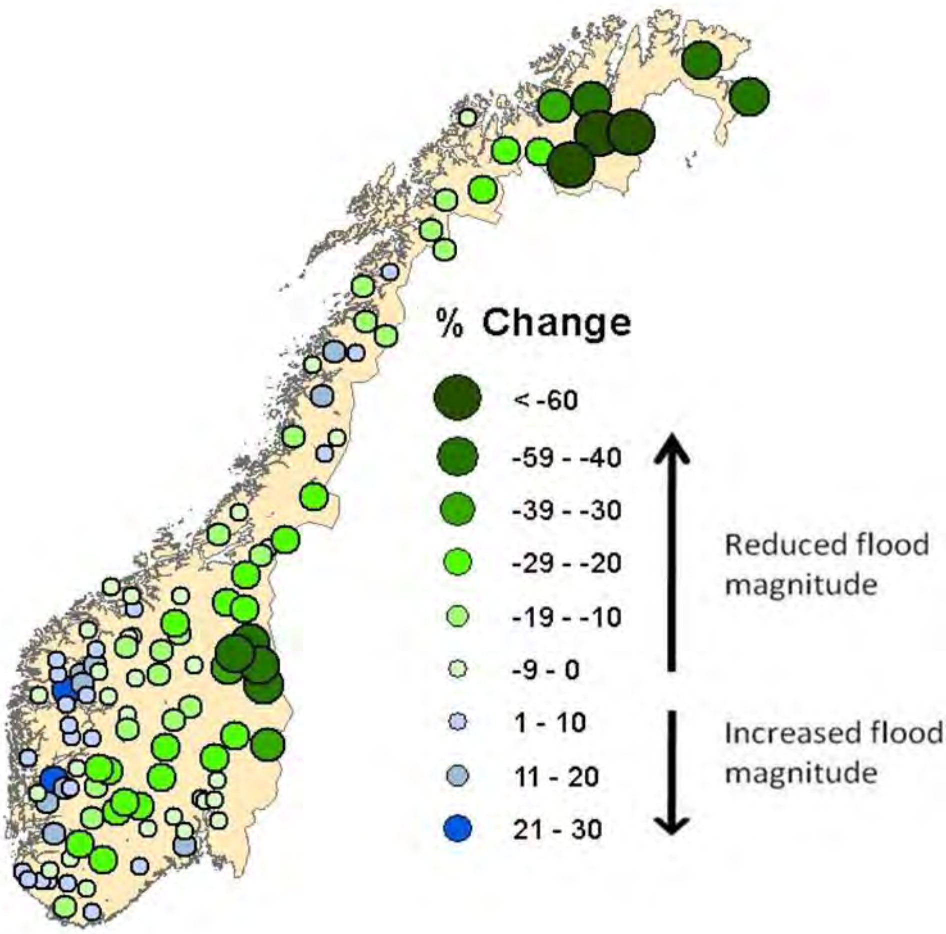

Figure 6.1 Percentage change in the 200-year flood between 1961-1990 and 2071-2100 given by the 10th percentile of the ensemble for each catchment. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

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 6.2. The 90th percentile is the value for which 10% of all of the projected changes are larger than the value illustrated. In contrast with Figure 6.1, 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 6.1 and Figure 6.2 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 used here. In each of these cases, over 90% 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 in Finnmark.

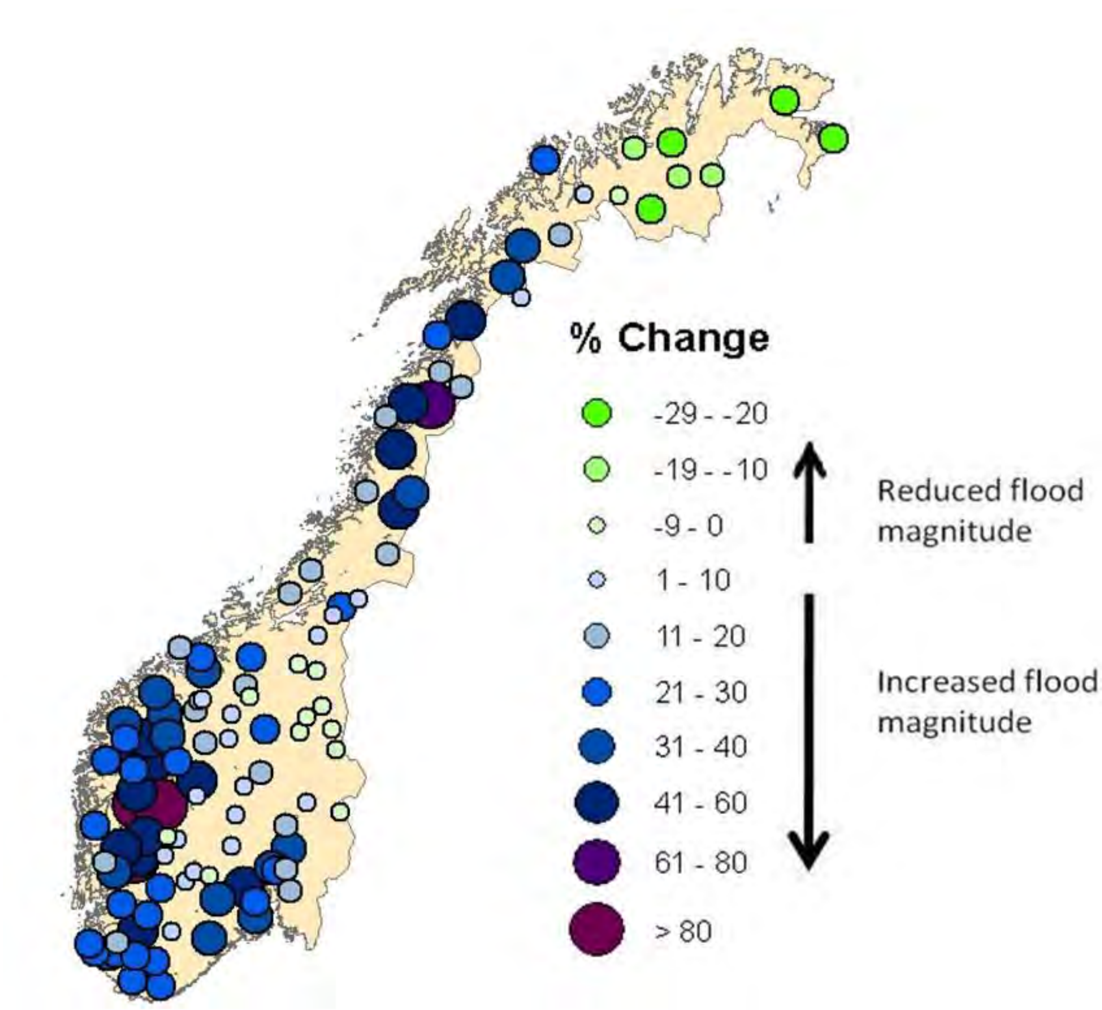

Figure 6.2 Percentage change in 200-year flood between 1961-1990 and 2071-2100 as given by the 90th percentile of the ensemble for each catchment. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

The spread of the results around the median value for the projections given in Section 5 is illustrated in Figure 6.3. The spread in the projections is here calculated as the difference between the 10th and 90th percentiles of the ensemble (*i.e.* the values illustrated for each catchment in Figures 6.1 and 6.2). This represents one method for assessing the magnitude of the disparity or incongruity around the projection based on the median value. Figure 6.3 illustrates that over half of the catchments have projected increases which are associated with relatively low to moderate levels of incongruity (*i.e.* dissimilarity) in that the difference between the 10th and 90th percentiles of the ensemble is less than or equal to 33 percentage points (*i.e.* the green points). Other catchments have wider ranges of projections based on this analysis, and there is no strong regional pattern underlying the extent to which simulations are in agreement for individual catchments.

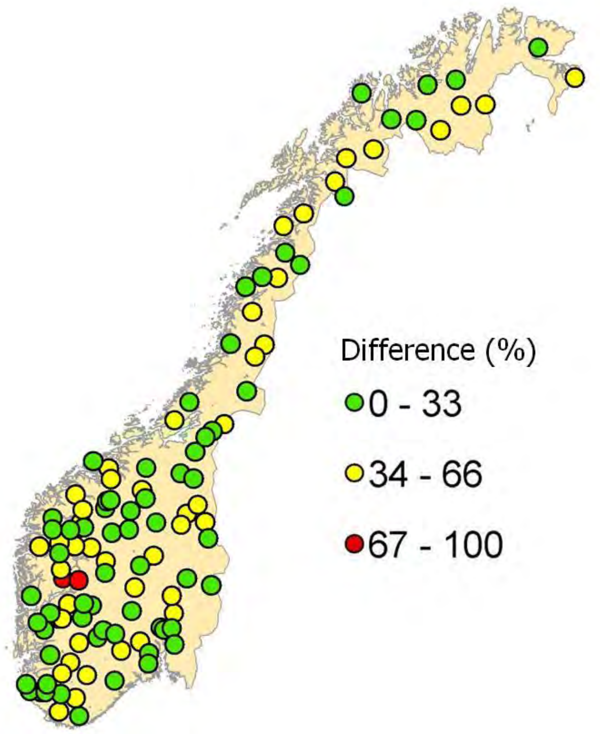

Figure 6.3 Difference between the 10th and 90th percentile of the ensemble of projections for each catchment.

6.2 Factors contributing to differences between projections

The differences amongst the projections for each catchment illustrated in Figure 6.3 are a consequence of five factors represented in the model ensemble: 1) differences between climate models (both global and regional) and methods for linking global and regional models in regional simulations; b) differences between SRES emission scenarios for the 21st century; c) differences between the delta change and empirical adjustment methods for locally adjusting precipitation and temperature data from regional climate scenarios; 4) uncertainty associated with the calibration of the hydrological model for the catchment; and 5) uncertainty arising from the application of flood frequency analysis methods. Previous work by Lawrence and Haddeland (2011) has considered the relative contributions of the first four of these factors to the total uncertainty in hydrological projections for four catchments in Norway. The results demonstrated that all of these factors can contribute significantly to the spread of projections for future changes in the mean annual flood, and that the importance of the individual factors varies between catchments. Other work (Lawrence and Engen-Skaugen, 2010) based on six scenarios for the period 2021-2050 has considered the relative contribution of different climate models, methods for locally adjusting precipitation and temperature data, and hydrological model parameters to total uncertainty in the projections for the 115 catchments considered in this report. The factor making the largest contribution to the spread of results is illustrated for each catchment in Figure 6.4 and, again, demonstrates that all three factors can be significant. There are also some weak regional patterns, in that differences between climate models tend to be most important in most catchments in northern Norway, and in the inland southern region, whereas uncertainty derived from hydrological (HBV) model parameters tends to dominate more often in western Norway.

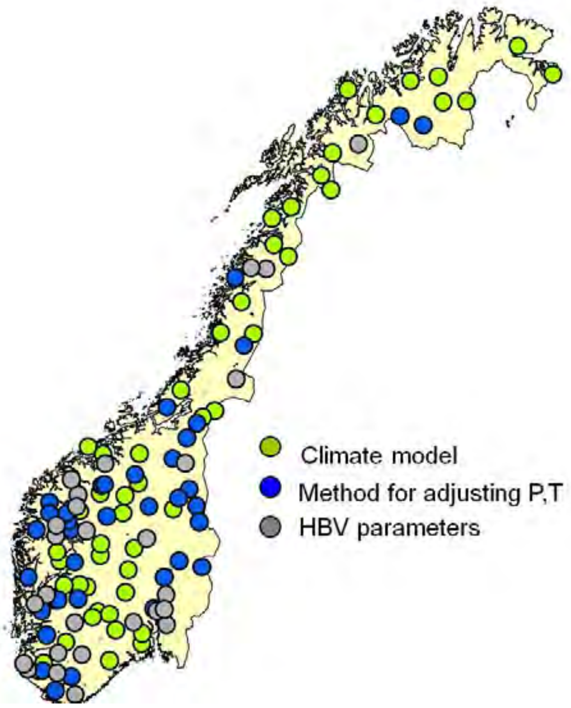

Figure 6.4 Factor making the largest contribution to the range of projections for the change in the 200-year flood, based on six climate scenarios for the period 2021-2050.

For the set of projections presented in this report, the spread in the projections for the 200-year flood illustrated in Figure 6.3 was evaluated by distinguishing three factors: 1) differences between 'climate scenarios', representing various global and regional climate models, two techniques for locally adjusting data, and three SRES emissions scenarios; 2) uncertainty in hydrological model (HBV) parameters; and 3) uncertainty introduced by the use of flood frequency analysis to estimate the 200-year flood from the simulated data. Uncertainty introduced by flood frequency analysis has not been previously considered in ensemble modelling of climate change impacts, although it is of relevance where floods of long return periods are estimated. To assess the uncertainty introduced by flood frequency estimation, a resampling technique was applied in which alternative values for the 200-year flood were selected from the fitted Gumbel (two-parameter) distribution for each annual maximum series for both the reference and the future (2071-2100) time periods. The percentage change was then estimated based on the resampled values. This procedure was repeated 25 times for each of the 325 sets of simulations for each catchment. In addition, flood frequency analysis using a three-parameter Generalised Extreme Value (GEV) was also applied to the annual maximum series, and a similar technique was used to generate a distribution of values for the percentage change in the 200-year flood.

The magnitude of the differences between simulations representing the three factors was then estimated using the techniques described in Lawrence and Haddeland (2011), and the factor making the largest relative contribution in each catchment is illustrated in Figure 6.5. The projections presented in Section 5 are based on the two-parameter Gumbel distribution, and Figure 6.5 indicates that in this case the spread in the projections for a given catchment is predominantly a consequence of differences between climate scenarios in most catchments. This is anticipated, as a wide range of climate scenarios has been used for the analysis, which for the 2071-2100 period also sample different SRES emission scenarios. However, as also previously reported by Lawrence and Haddeland (2011), uncertainty derived from hydrological modelling can in some cases be larger than that introduced by climate models, and this is seen in several catchments in western and south-western Norway and in two catchments in the Nordland region. In all catchments, uncertainty in the parameter fits based on the Gumbel distribution is secondary to that introduced by other factors. The analysis of projections based on the three-parameter GEV distribution indicates, however, that in most catchments, the uncertainty introduced by this flood frequency estimation is larger than that derived from either differences between climate scenarios or hydrological modelling. The larger uncertainty from the three-parameter *vs*. the two-parameter analysis is expected, as three-parameter distributions have an additional degree of freedom and are more sensitive to outliers (Maidment, 1993). This larger uncertainty does not necessarily indicate that the Gumbel distribution is a more reliable estimator. In order to analyse this issue further, comparisons between several possible fitted distributions must be undertaken for individual catchments. However, Figure 6.5 illustrates that uncertainty introduced by flood frequency estimation can be of a similar magnitude or larger than differences introduced by alternative climate scenarios. In addition, the results analysed here consider uncertainty for projected changes in the 200-year flood (based on an annual maximum series of 30 years), and it is expected that the relative contribution of flood frequency methods to total uncertainty would be much larger for the case of the 1000-year flood (*i.e*. Figure 3.4).

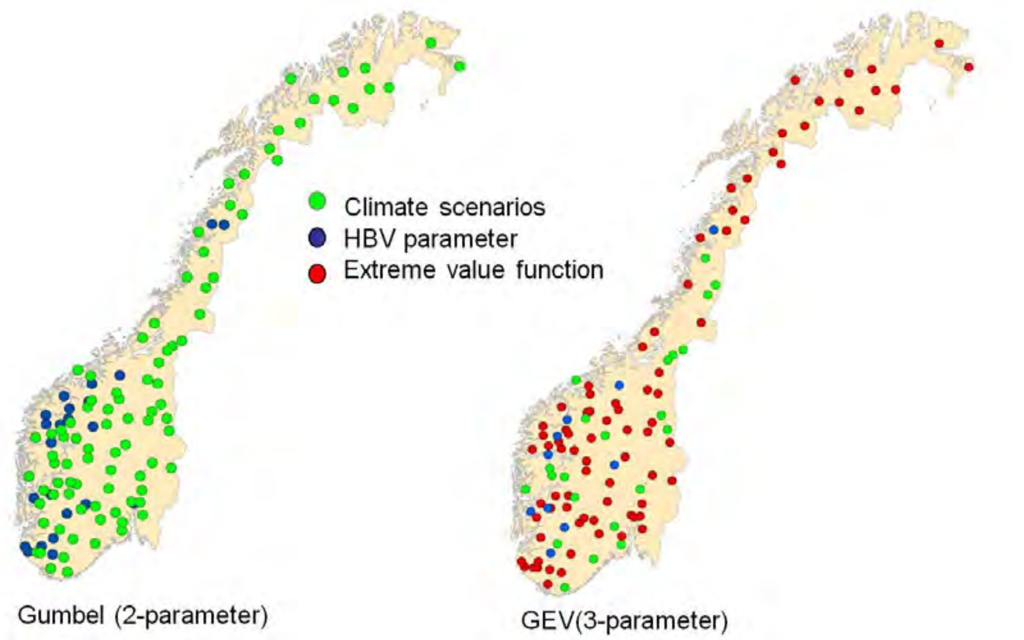

Figure 6.5 Factor making the largest contribution to the spread in the projections for flood frequency estimates based on the Gumbel distribution *vs*. the GEV distribution.

6.3 Other factors contributing to uncertainty

The analysis presented above evaluates the level of agreement between the ensemble of projections for individual catchments. The range in the projections for a catchment (*i.e.* Figure 6.3) reflects differences in climate data and in methods used to generate and analyse the simulations. There are, however, a number of other factors which cannot be sampled or fully quantified which contribute to uncertainty in these projections. Of primary importance in the analysis of floods is the ability of regional climate models to capture likely changes in rainfall patterns, particularly the occurrence and intensity of extreme rainfall. The hydrological modelling presented here is based on a daily time step, consistent with the daily precipitation and temperature data generally available from regional climate models. There is evidence that short-duration extreme rainfall events will be more common and of higher intensity under a future climate in Norway (Hanssen-Bauer *et al*., 2009), and this may contribute to increased flood magnitudes in small catchments in areas otherwise dominated by snowmelt floods, and in urban areas. Additionally, methods for adjusting precipitation data from regional climate models to a local scale have an influence on the resulting daily rainfall intensities. Two methods for this adjustment have been considered in the ensemble used for this report such that this factor has been partially evaluated. However, there are now newer techniques (*e.g.* Piani, 2010) which produce a better correspondence between the statistical distribution of observed *vs*. simulated rainfall, and further work is required to evaluate their significance in determining likely climate change impacts on future floods.

7 Local factors

Although there are strong regional patterns illustrated by the results, there is also considerable variation between catchment within regions due to local factors. As discussed in Section 5, variations between regions largely reflect differences in the role of snowmelt *vs*. rainfall in generating the highest flows in a river. In addition, rivers in the same region can exhibit different responses to climate change, depending on the relative importance of these two flood generating mechanisms in the upstream contributing areas. For example, the distribution of altitude in a catchment and particularly the altitude of catchment source areas play an important role in determining the magnitude and timing of peak flows derived from snowmelt. Temperature regimes also vary within regions as a function of location relative to coastal climatic influences, and this also affects the balance between snowmelt- *vs*. rainfall-induced floods. Similarly, the size of a catchment has a strong control on its response to extreme rainfall, so that smaller catchments are generally more sensitive to rainfall-induced floods associated with shorter duration storms. In this section, local factors which may contribute to differing responses to climate change are briefly discussed using the following six regions: 1) Finnmark and Troms; 2) Nordland; 3) Trøndelag ; 4) Møre og Romsdal, Sogn og Fjordane and Hordaland (MR/SF/Hordaland); 5) Rogaland and Agder; and 6) Østlandet. The local factors considered here include catchment area, catchment relief, median catchment elevation, and the location of the catchment relative to the coastline. These are investigated using a series of diagrams which illustrate the relationship between the projected change in the 200-year flood (between 1961-1990 and 2071-2100) and the local variables. Due to the similarity in the regional patterns of change for both future periods (2021-2050 and 2071-2100) and for both of the return periods considered (200-year vs. 1000-year), the analysis presented here considers only the 200-year flood for the period 2071-2100. It is assumed, however, that the results also generally apply to both future periods and flood return periods.

7.1 Catchment area

The percentage change in the 200-year flood as a function of catchment area is illustrated in Figure 7.1, with the individual regions indicated by colour. Taken as a whole, the most notable feature is that, with the exception of two catchments in Østlandet, all catchments with an area of less than 100 km^2 have a projected increase in the 200-year flood. This partly reflects the sampling bias associated with the modelled catchments, in that two of the regions (Troms/Finnmark and Trøndelag) have no catchments in this size class, and these regions generally have catchments showing little change or a decrease in the 200-year flood. However, the diagram also illustrates that three of the regions, Østlandet, Troms/Finnmark and Trøndelag (two of which have a large range of catchment sizes), show a weak tendency towards a decreased magnitude in the percentage change in the 200-year flood with increased catchment area. The other three regions are all associated with an increased flood magnitude for all catchments, with the exception of one catchment in Rogaland/Agder with a negligible change. The eight catchments exhibiting the largest increases in flood magnitude (> 40%) have catchment areas of between 100 and 1000 km^2 and are located in the Nordland and MR/SF/Hordaland regions.

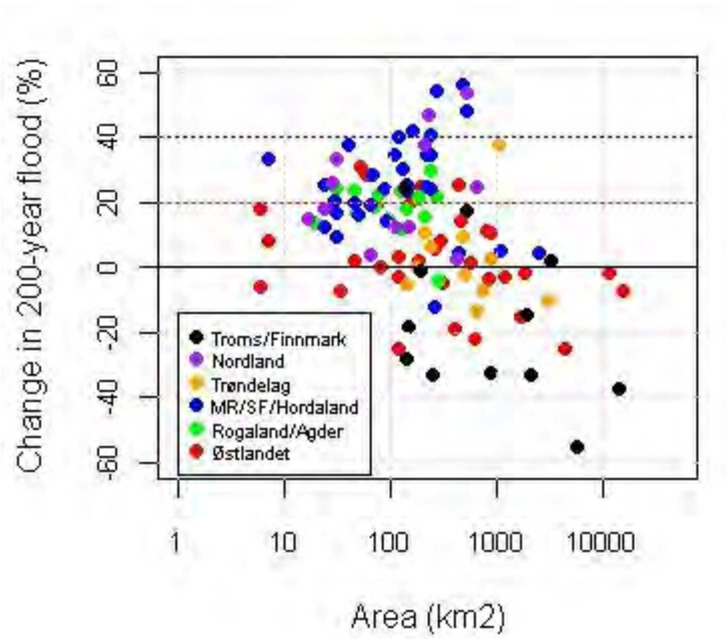

Figure 7.1 Percentage change in the 200-year flood as a function of area by region.

7.2 Catchment relief

To evaluate the potential effects of catchment slope on the catchment response to climate change, the variable H_L which is used for dam safety analyses to describe catchment relief, is used here. This is defined as

$$H_L = (H_{75} - H_{25})/L_F$$

where H_{75} and H_{25} correspond to the 75th and 25th percentiles of the hypsographic curve for the catchment, and L_F is the length of the catchment, measured as the longest straight-line distance between the catchment outlet and its upstream boundary. The projected percentage change in the 200-year flood as a function of the relief variable H_L is illustrated in Figure 7.2, with the individual regions indicated. Taken as a whole, the dataset for all of Norway present a clear tendency towards larger increases in the magnitude of the 200-year flood with increasing catchment relief. This upward trend again, though, partly reflects regional sampling biases in that the steepest catchments are only represented in the Nordland and MR/SF/Hordaland regions, and catchments with low relief are only found in Troms/Finnmark and Østlandet. Nevertheless, there are four regions, Troms/Finnmark, Trøndelag, Rogaland/Agder and Østlandet, which individually exhibit a tendency towards larger increases in the magnitude of the 200-year flood for higher values of the catchment relief factor, H_L.

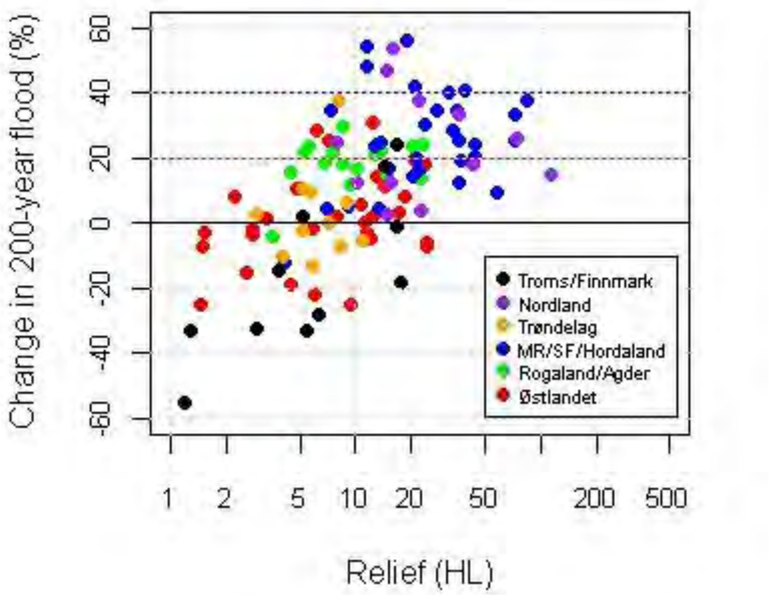

Figure 7.2 Percentage change in the 200-year flood as a function of catchment relief.

7.3 Catchment median elevation

The percentage change in the 200-year flood as a function of the median elevation of the catchment H_{50} is illustrated in Figure 7.3. If all points are considered as a whole, there is no clear relationship between the change in the 200-year flood and the median elevation of a catchment. However, it is noteworthy that if one considers only those catchments with median elevations of less than 500 m.a.s.l., then with the exception of catchments in Troms/Finnmark (and one catchment in Østlandet) all of the remaining catchments are associated with increased flood magnitudes, independent of the region represented. All of the regions are represented in this group of lower elevation catchments, such that this similarity in response is not a consequence of a regional sampling bias.

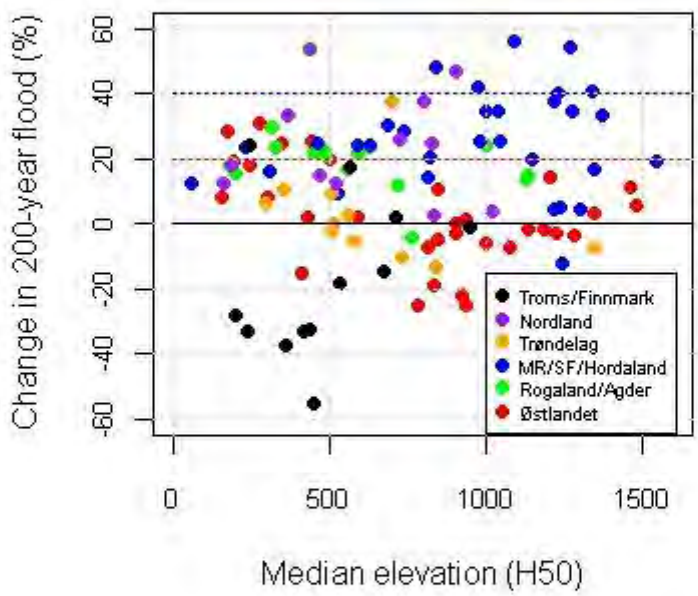

Figure 7.3 Percentage change as a function of median catchment elevation with the region indicated by colour.

7.4 Location relative to coastline

The location of the catchments relative to the coastline is also considered to be a relevant factor in determining catchment response to climate change, as maritime locations tend to be warmer during winter periods and are more likely to be dominated by autumn and winter floods (*e.g.* Figures 5.3 and 5.4). The percentage change in the 200-year flood as a function of the distance from the coastline (estimated as the distance between the catchment mid-point and a regionally-averaged coastline) is illustrated in Figure 7.4. If one excludes the catchments in Troms/Finnmark, then taken as a whole, the remaining points exhibit a weak tendency towards a decrease in the percentage change in the 200-year flood with increasing distance from the coast. This relationship is somewhat stronger for Østlandet if this region is considered on its own. The other five regions exhibit only very weak (*e.g.* Rogaland/Agder and Trøndelag) or no clear relationship with this variable. However, this is most likely due in part to sampling biases in that only Østlandet has catchments with catchment midpoints which are more than 200 km from the coastline.

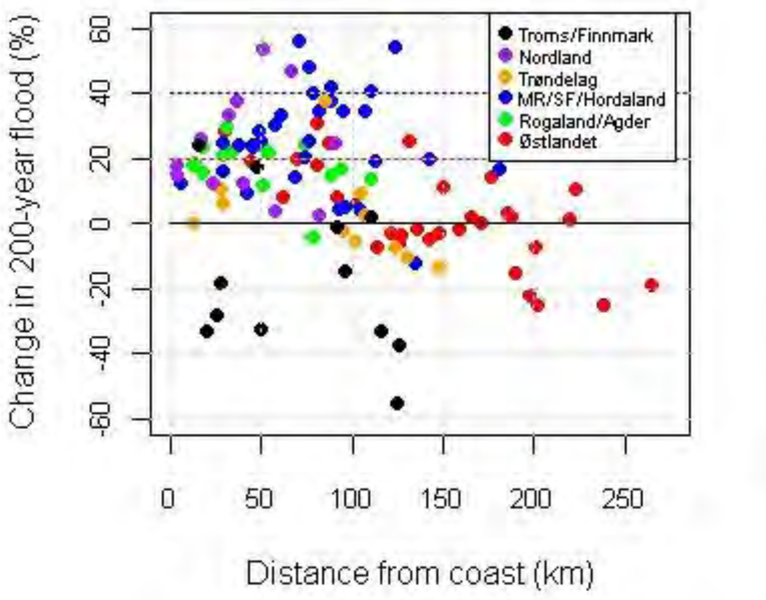

Figure 7.4 Percentage change as a function of distance from coastline.

7.5 Summary of local factors

In summary, the figures illustrated in this section indicate that there are, in some cases, relationships between the factors considered and the projected percentage change in the 200-year flood, either for individual regions or for all regions taken as a whole. Increased catchment area is generally associated with a decrease in the percentage change in the flood magnitude for all regions (Figure 7.1), with the exception of MR/SF/Hordaland and Nordland. Additionally, virtually all catchments with areas of less than 100 km^2 are projected to have an increased flood magnitude under a future climate. There is a clear relationship between catchment relief and the projected change (Figure 7.2), with steeper catchments being associated with larger increases when all regions are considered together. Østlandet and Troms/Finnmark also exhibit this tendency when considered as individual regions. The catchments associated with the largest changes in the 200-year flood (> 40%) are all located in Nordland and MR/SF/Hordaland. These catchments are, however, of both moderate size (*i.e.* 100 to 1000 km^2) and steepness (*i.e.* H_L of 10 to 20) when compared to other catchments in these regions. Median catchment elevation is also of importance in that (outside of Troms/Finnmark) virtually all catchments with a median elevation of less than 500 m.a.s.l. have a projected increase in the magnitude of the 200-year flood. Increased distance of the catchment mid-point from a regionally-averaged coastline is associated with a decrease in the percentage change in the 200-year flood in Østlandet, where a large range of values for this distance is available for analysis. Two other regions, Trøndelag and Rogaland/Agder show a similar tendency, although the relationship is weaker and a smaller range of values is available for analysis. Due to the limited number of catchments available for some of the individual regions and to sampling biases between regions, it has not been considered appropriate to undertake a fully quantitative analysis of the effect of the four local factors on the projected percentage change in the 200-year flood. Additionally, there are other factors which can have an influence on the character of peak flow regimes in catchments and which are included in the hydrological modelling on the catchments, but have not been analysed here. These include, for example, the distribution of vegetation and land use cover in the catchment, and the presence of water bodies such as lakes and bogs or marshes. Some of the variability between otherwise similar catchments in the same region can also be due to these factors.

8 Guidance for use of results in climate change adaptation

The results presented in Section 5 are based on detailed hydrological modelling for a set of 115 unregulated catchments distributed throughout Norway. The spread of results for the individual catchments is large (Section 6), 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 appropriate at this point in time to formulate precise recommendations for individual water courses due to the range in the projections and to additional uncertainty introduced by generalising these results to areas without calibrated hydrological models. Therefore, three simple categories are used here for distinguishing likely changes in flood hazard resulting from climate change: 0% change, +20% change, +40% change, where the percentage change refers to the projected increase in the maximum daily (average) discharge. In this section, recommendations for applying these three categories are presented for different catchment types and locations for each of the six regions. A map is presented for each region illustrating the location and boundaries of the modelled catchments, together with the projected change using a symbol located at the centre point of the catchment. The topography and river systems are also illustrated, and the boundaries of the larger catchments within the region are indicated. The characteristics of the modelled catchments are also plotted relative to the four local factors presented in Section 7, and the projected change for each catchment is also illustrated in these diagrams.

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 Figure 7.1, which illustrates the tendency for catchments with areas of < 100 km^2 to have an increased flood magnitude under a future climate.

8.1 Troms and Finnmark

Twelve catchments have been modelled for the Troms and Finnmark region, 7 in Finnmark and 5 in Troms. Figure 8.1 illustrates the location of the modelled catchments, and Figure 8.2 displays the catchment characteristics. Much of this region is characterised by peak flow regimes dominated by spring to early summer snowmelt, and this is expected to continue in the future, although peak flows are expected to come earlier (Figure 5.5) and be of a reduced magnitude. All of the modelled catchments in Finnmark are projected to have a reduction in flood magnitude of at least 10%. In some cases, the projected reduction is greater than 30%. In Troms, the projections are more variable, ranging from a reduction of at least 10% for an inland catchment to an increase of over

20% for a coastal catchment. The coastal catchment is currently more prone to autumn/winter peak flow events than other modelled catchments in the region (Figure 5.4), and so is vulnerable to increased autumn and winter precipitation contributing to floods. Therefore, the following recommendations are given for calculating changes in the 200-year, 500-year and 1000-year flood until 2100 for Troms and Finnmark:

0% change – Catchments throughout the area dominated by spring/early summer snowmelt floods in today's climate

20% increase – Catchments in coastal locations, particularly in Troms, in which peak annual flows derived from rainfall are not uncommon in today's climate

20% increase – All catchments with areas less than 100km^2

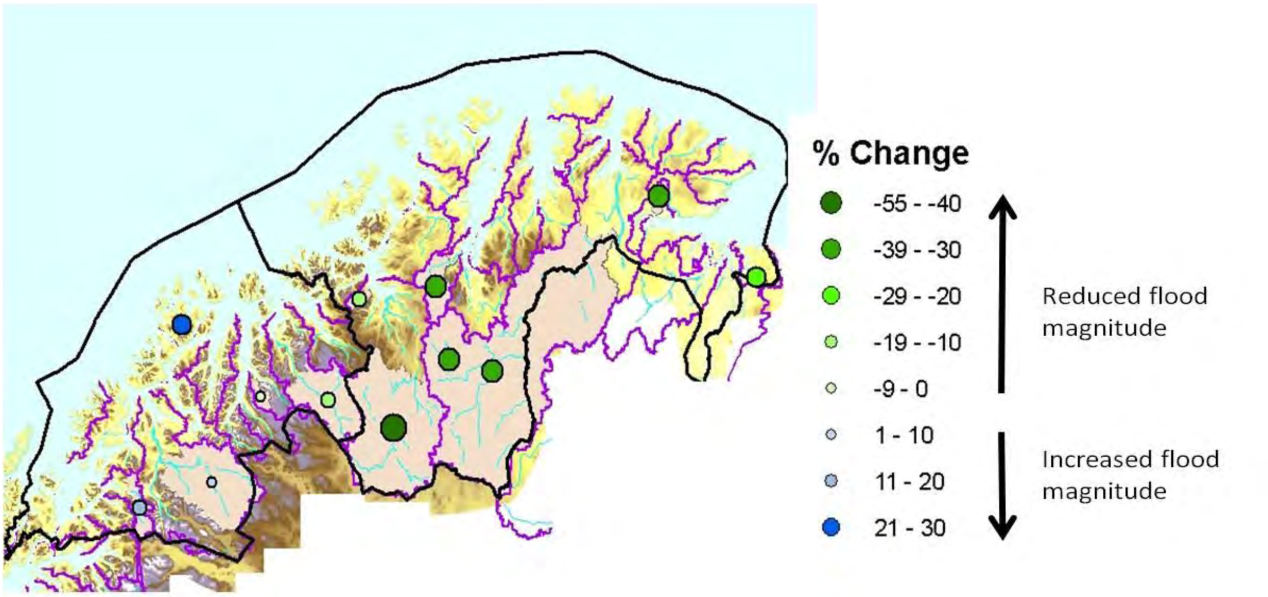

Figure 8.1. Projected percentage changes in the flood magnitude for catchments in Troms and Finnmark. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

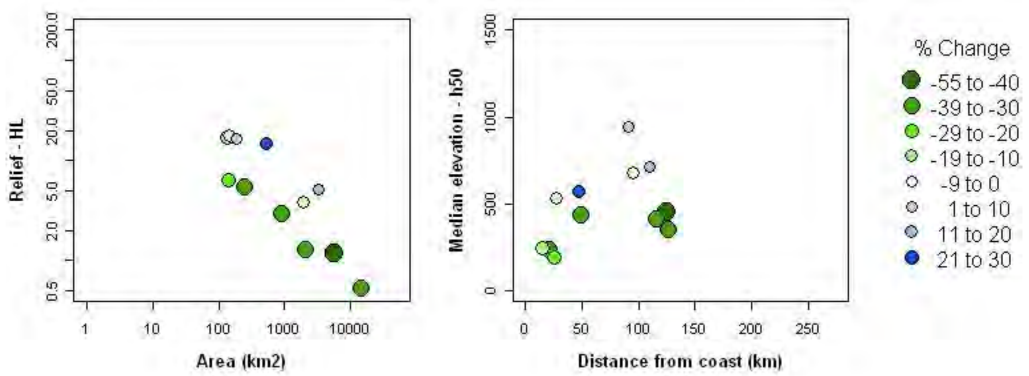

Figure 8.2 Projected percentage changes as a function of catchment characteristics for catchments in Troms and Finnmark. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

8.2 Nordland

Twelve catchments have been modelled for the region, and these are fairly evenly distributed throughout the mainland portion of the region (Figure 8.3). Catchment characteristics are illustrated in Figure 8.4. All of the catchments are projected to have an increase in flood magnitude, with the largest increases (> 40%) associated with catchments of moderate size (100 – 1000 km^2). The smallest increases (< 10%) are found for catchments along the border with Sweden, and moderate increases (10 – 20%) are found at the most coastal locations. Most of the catchments are associated with an increase in the occurrence of peak flows during autumn and winter periods (Figure 5.4), and some of the catchments also exhibit a change in seasonality of the maximum flow from summer to autumn/winter (Figure 5.5). Therefore, the following recommendations are given for calculating changes in the 200-year, 500-year and 1000-year flood until 2100 for Nordland:

20% increase – All catchments throughout the region

40% increase – It is advised that calculations for catchments within or adjacent to those catchments exhibiting large (*i.e.* > 40%) increase also consider the effect of a 40% increase

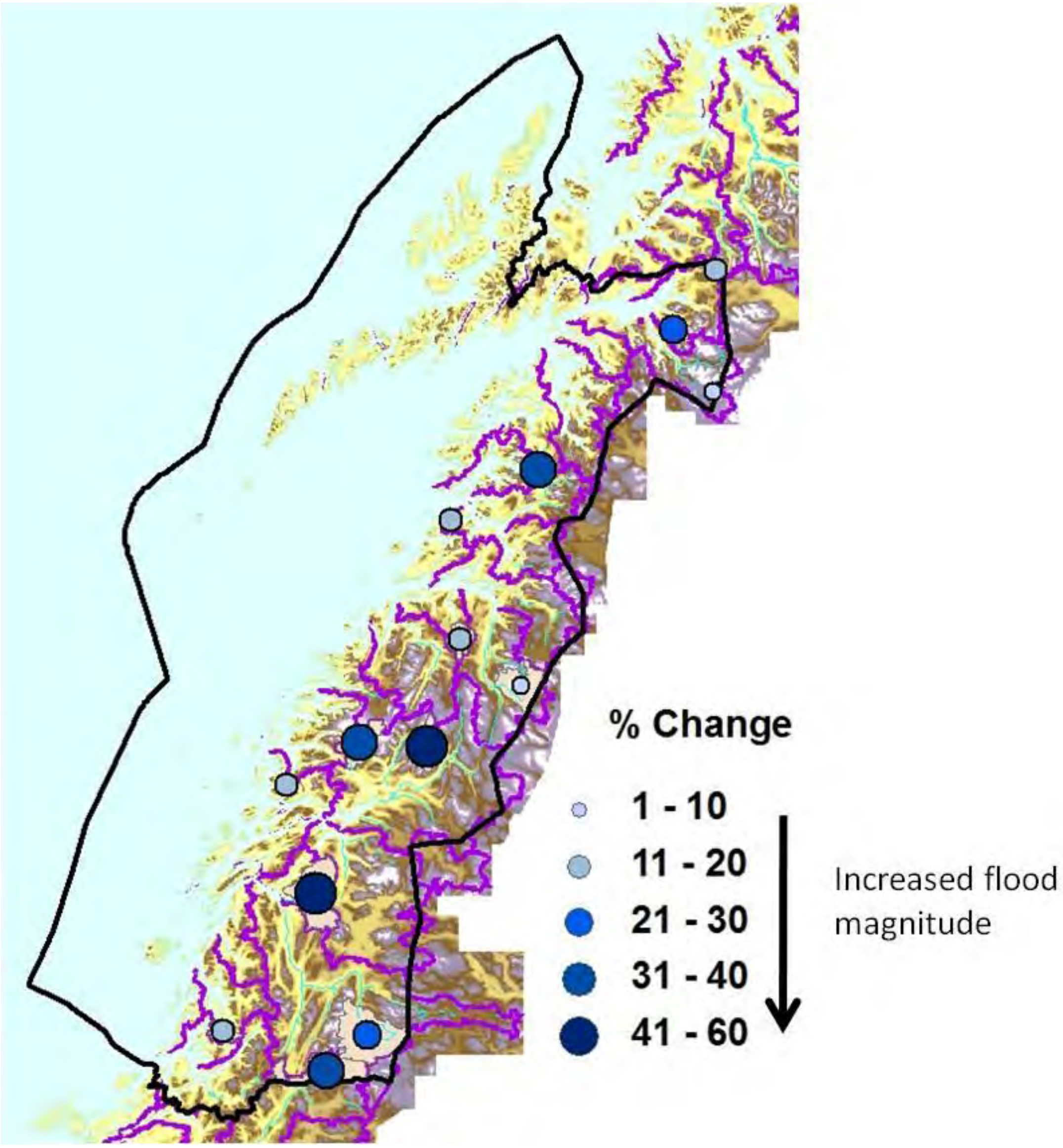

Figure 8.3. Projected percentage changes in flood magnitude for catchments in Nordland.

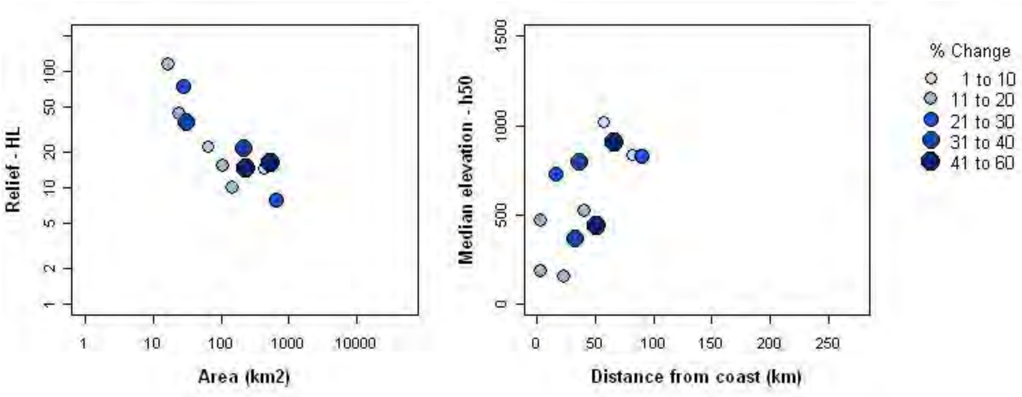

Figure 8.4 Projected percentage changes as a function of catchment characteristics for catchments in Nordland.

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8.3 Trøndelag

Twelve of the modelled catchments are located in the Trøndelag region (Figure 8.5 and Figure 8.6). Catchments in this region have varying responses to climate change, ranging from a reduction of between 10 and 20% for inland catchments in Sør-Trøndelag to an increase of > 30% in the northernmost catchment in Nord-Trøndelag, which straddles the boundary with Nordland. However, the majority of catchments in Trøndelag exhibit either small increases or decreases (Figure 8.5). This is in contrast with catchments in Nordland and Vestlandet, and reflects the smaller increase in precipitation which is projected for Trøndelag. Therefore, the following recommendations are given for calculating changes in the 200-year, 500-year and 1000-year flood until 2100 for Trøndelag:

0% increase – Catchments in inland locations dominated by spring/early summer snowmelt floods in today's climate.

20% increase – Catchments in coastal locations, and catchments with source areas in northernmost Nord-Trøndelag (Figure 8.5).

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

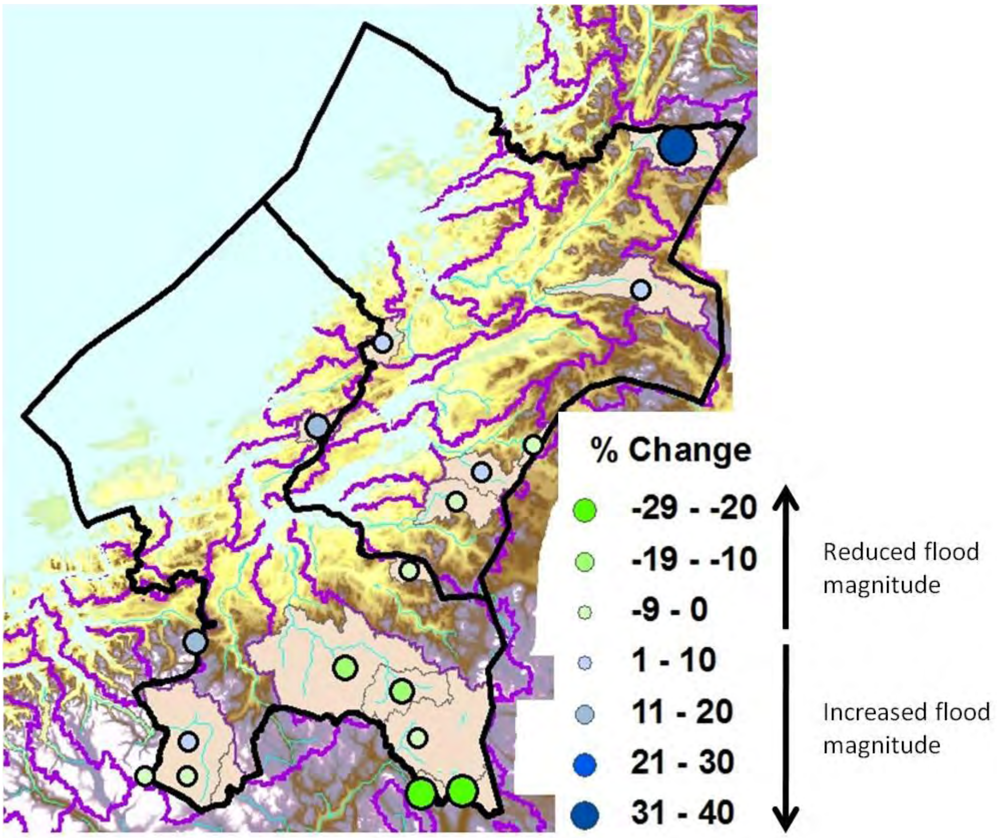

Figure 8.5. Projected percentage changes in flood magnitude for catchments in Trøndelag. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

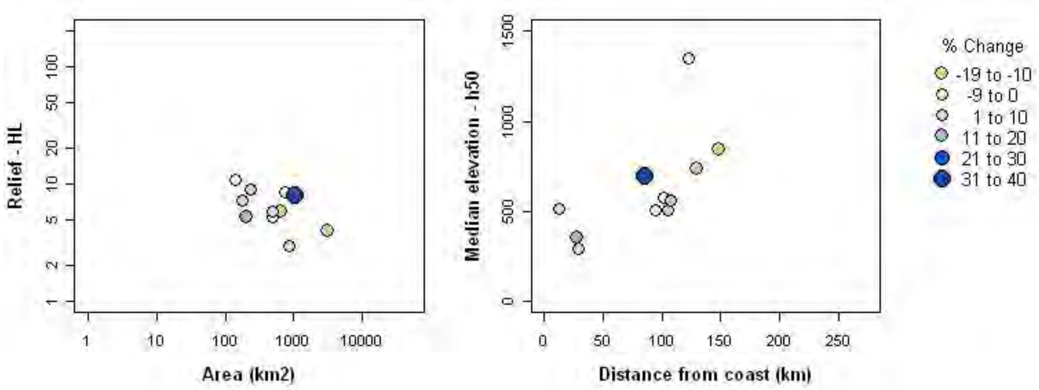

Figure 8.6 Projected percentage changes as a function of catchment characteristics for catchments in Trøndelag. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

8.4 Møre and Romsdal, Sogn and Fjordane, Hordaland

There are 30 catchments representing this region (Figure 8.7 and Figure 8.8), and similar to Nordland, the modelled catchments are generally steeper than those found in the other four regions (Figure 8.8). Nearly all the modelled catchments (*i.e.* 29 out of 30) exhibit an increased flood magnitude. The largest projected increases for Norway are found in this region, with six of the catchments (located in Sogn and Fjordane and in Hordaland) having a projected increase of > 40%. The large increases in the region reflect the effect of increased autumn and winter precipitation in a region which is already largely dominated by rainfall-induced floods (*e.g.* Figure 5.4). Catchments with the largest increases are of moderate size (100 – 1000 km^2), and are located somewhat inland from the coastal zone (50 to 125 km for the catchment midpoint). Therefore, the following recommendations are given for calculating changes in the 200-year, 500-year and 1000-year flood until 2100 for Møre og Romsdal, Sogn og Fjordane and Hordaland:

20% increase – All catchments throughout the region

40% increase – It is advised that calculations for catchments in Sogn og Fjordane and Hordaland which are within or adjacent to those catchments exhibiting large (*i.e.* > 40%) increases also consider the effect of a 40% increase

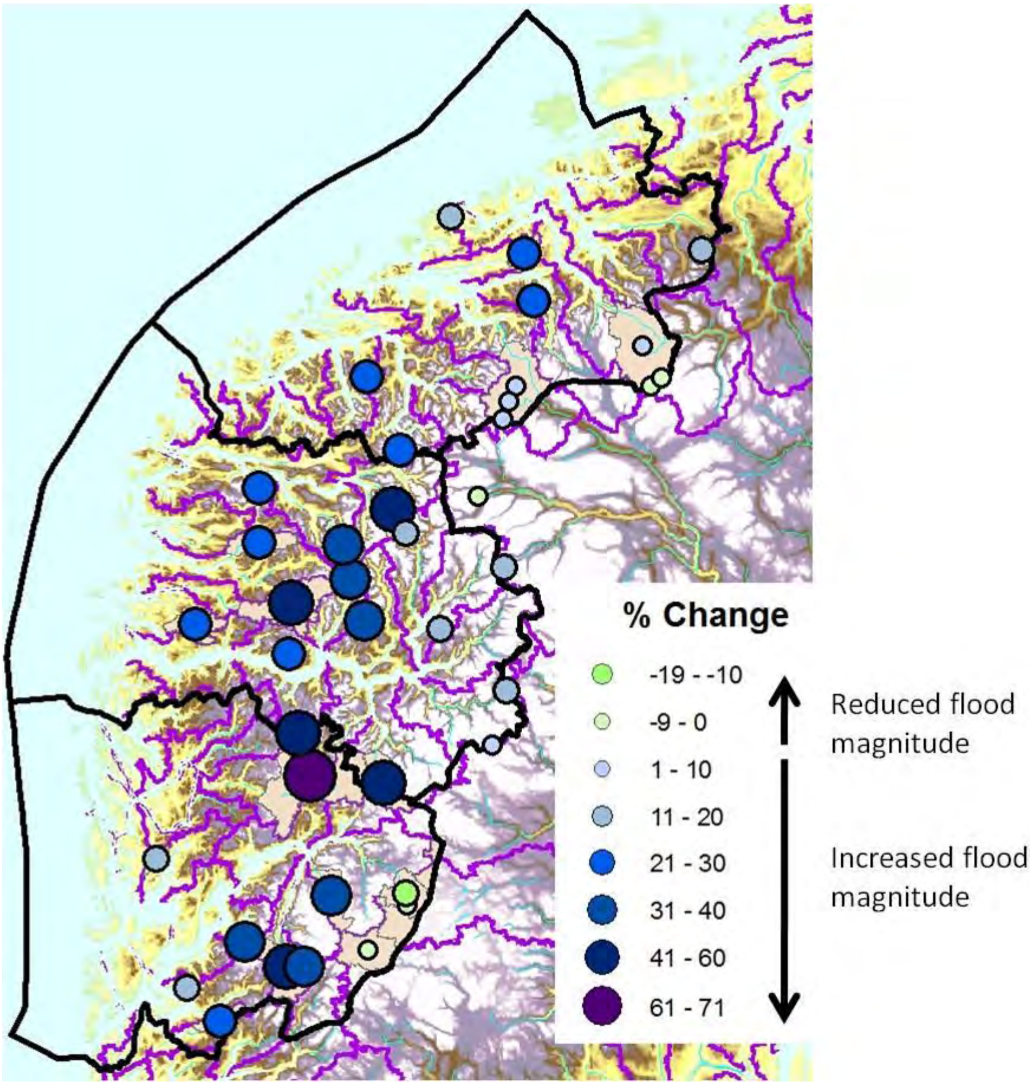

Figure 8.7. Projected percentage changes in flood magnitude for catchments in Møre og Romsdal, Sogn og Fjordane, and Hordaland. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

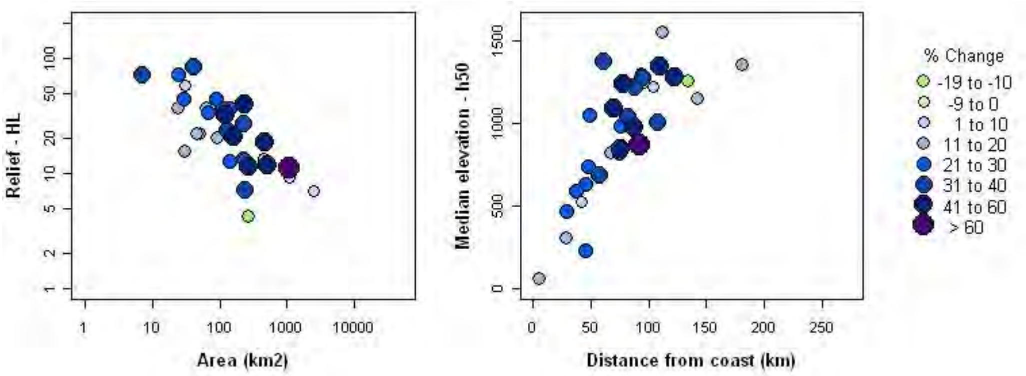

Figure 8.8 Projected percentage changes as a function of catchment characteristics for catchments in Møre og Romsdal, Sogn og Fjordane, and Hordaland. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

8.5 Rogaland and Agder

There are 14 modelled catchments for Rogaland and Agder (Figure 8.9), and all of the catchments are of small to moderate size and are of moderate steepness (Figure 8.10). With the exception of one upland catchment in Aust-Agder, all of the remaining catchments have a projected increase in flood magnitude of between 10 and 29%. Many catchments in this region are dominated by autumn and winter rainfall floods, and this tendency is increased in the future (Figure 5.4). However, the large increases projected for Sogn og Fjordane and for Hordaland are not found in Rogaland or Agder. Therefore, the following recommendations are given for calculating changes in the 200-year, 500-year and 1000-year flood until 2100 for Rogaland and Agder:

20% increase – All catchments throughout the region

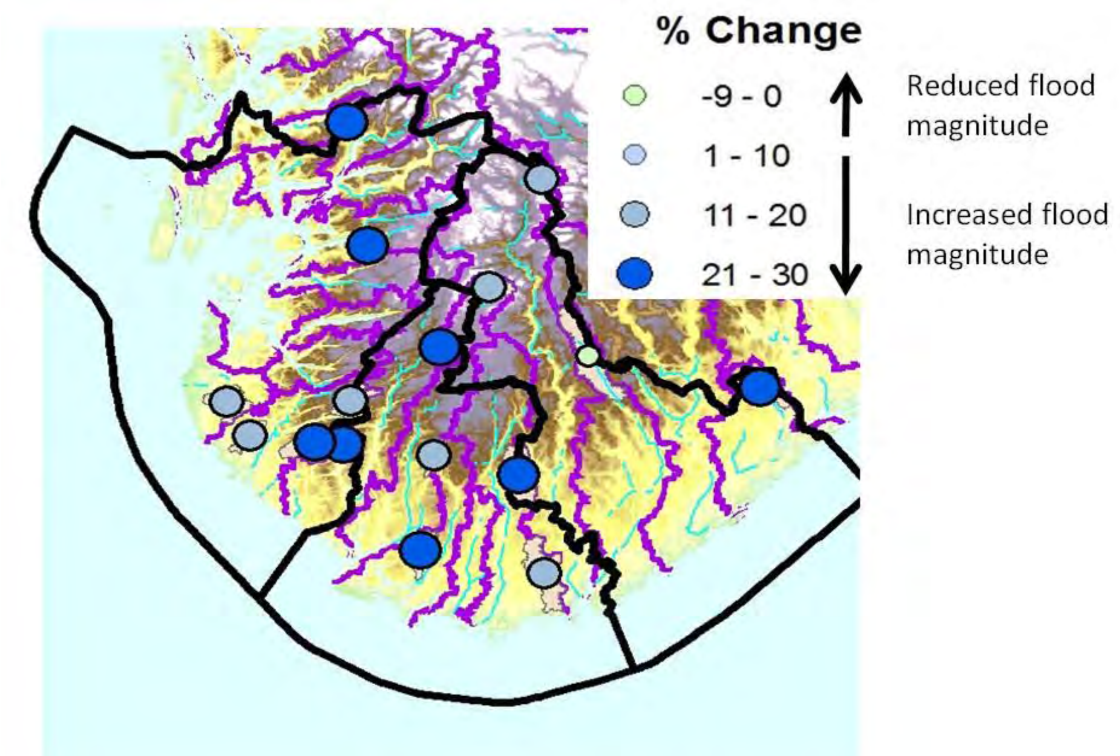

Figure 8.9. Projected percentage changes in flood magnitude for catchments in Rogaland and Agder. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

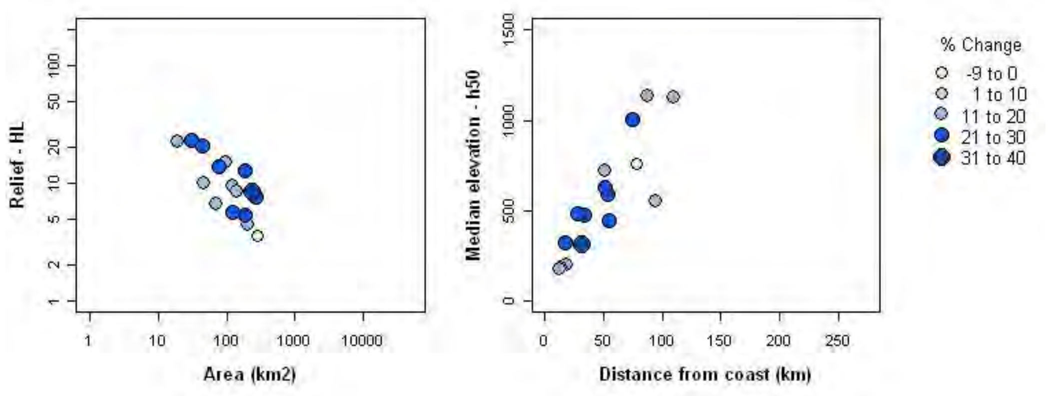

Figure 8.10 Projected percentage changes as a function of catchment characteristics for catchments in Rogaland and Agder. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

8.6 Østlandet

There are 30 modelled catchments for Østlandet (Figure 8.11), and they represent the broadest range of catchment characteristics of all of the six regions (Figure 8.12). 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 8.11. This includes, for example, catchments with local source areas in Vestfold, Akershus, Oslo and Østfold.

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

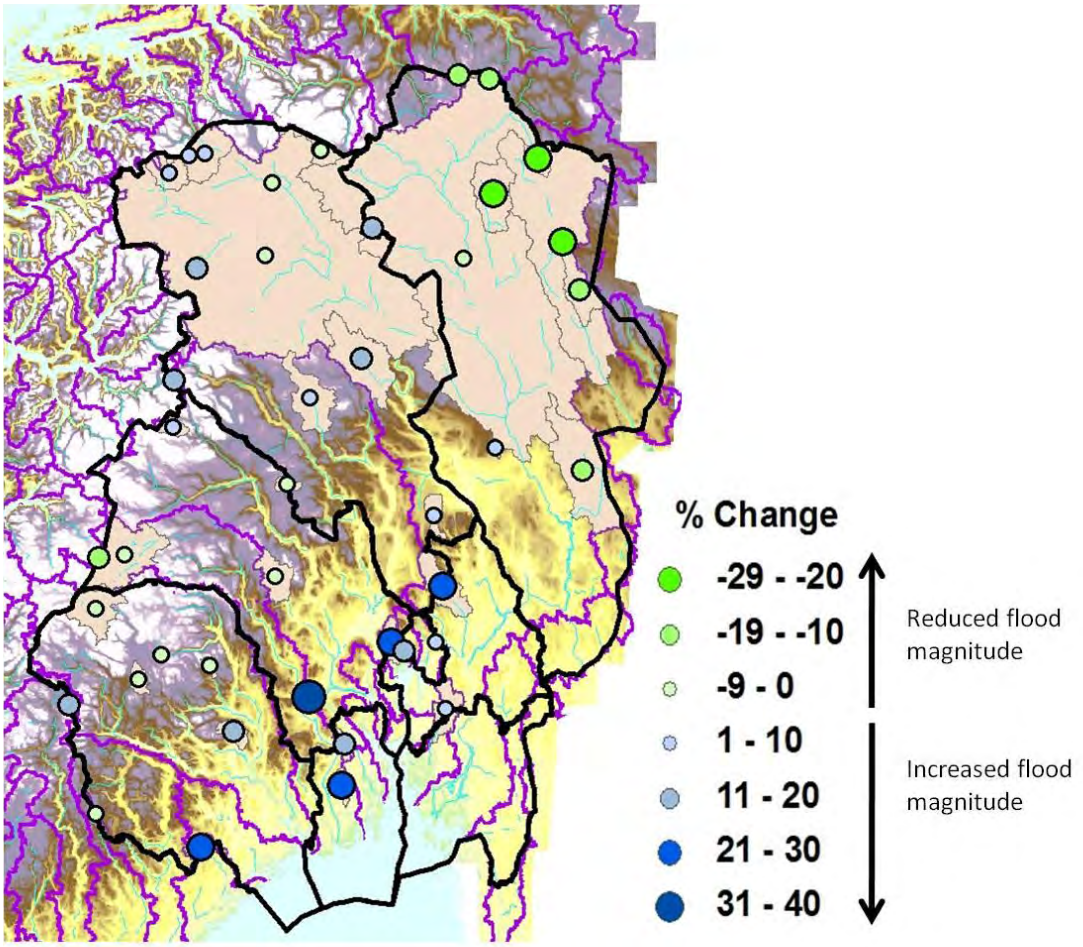

Figure 8.11 Projected percentage changes in flood magnitude for catchments in Østlandet. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

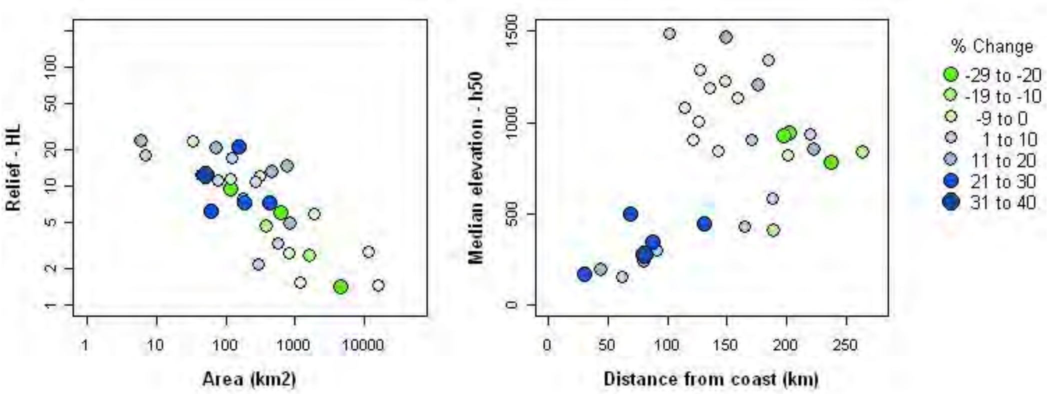

Figure 8.12 Projected percentage changes as a function of catchment characteristics for catchments in Østlandet. Green indicates a reduced flood magnitude and blue indicates an increase in flood magnitude.

9 Further comments

The recommendations given in the previous section apply to hydrological floods and do not include the potential effects of sea level rise and increased coastal storm surges on flood hazard in coastal areas. This topic is covered in a separate report prepared by (Vasskog, *et al*., 2009), in which likely changes in sea level and storm surge are given for coastal areas. In addition, it is not currently possible to assess the magnitude of likely changes in floods associated with short-duration high-intensity rainfall events which can occur in urban areas or induce floods on other impermeable surfaces (*e.g*. road or frozen ground). It is anticipated, however, that extreme rainfall contributing to such floods will be more frequent under a future climate (Hanssen-Bauer, *et al*., 2009).

The projections given in this report are based on the most up-to-date regional climate model simulations and reflect the best knowledge regarding data and methods available at the time of its publication. It is anticipated that future developments in climate modelling and in climate impact analysis may alter some of the results presented here. It is also expected, however, that the large-scale regional patterns supporting the recommendations given in Section 8 are fairly robust. In addition, the recommendations given are rather conservative in that median values have been used from a wide range of simulations to establish three different categories of expected change for different catchment types in six regions. In many cases, the projected changes in flood magnitude based on individual scenarios are somewhat higher for some of the catchments in some of the regions.

Acknowledgements

The regional climate scenario data used here are derived from the EU FP6 ENSEMBLES project and from the RegClim project funded by the Norwegian Research Council. These data were adjusted to a local 1 x 1 km grid for Norway by Torill Engen-Skaugen (Norwegian Meteorological Institute) using the empirical adjustment method and by Stein Beldring and Gusong Ruan (NVE) using the delta change method as contributions to the CES project funded by Nordic Energy Research and the EU Interreg IVB SAWA project. Hilde Bergheim Naustdal is thanked for assistance with report figures.

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