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Scenarios of annual and seasonal runoff for Norway based on climate scenarios for 2030-49

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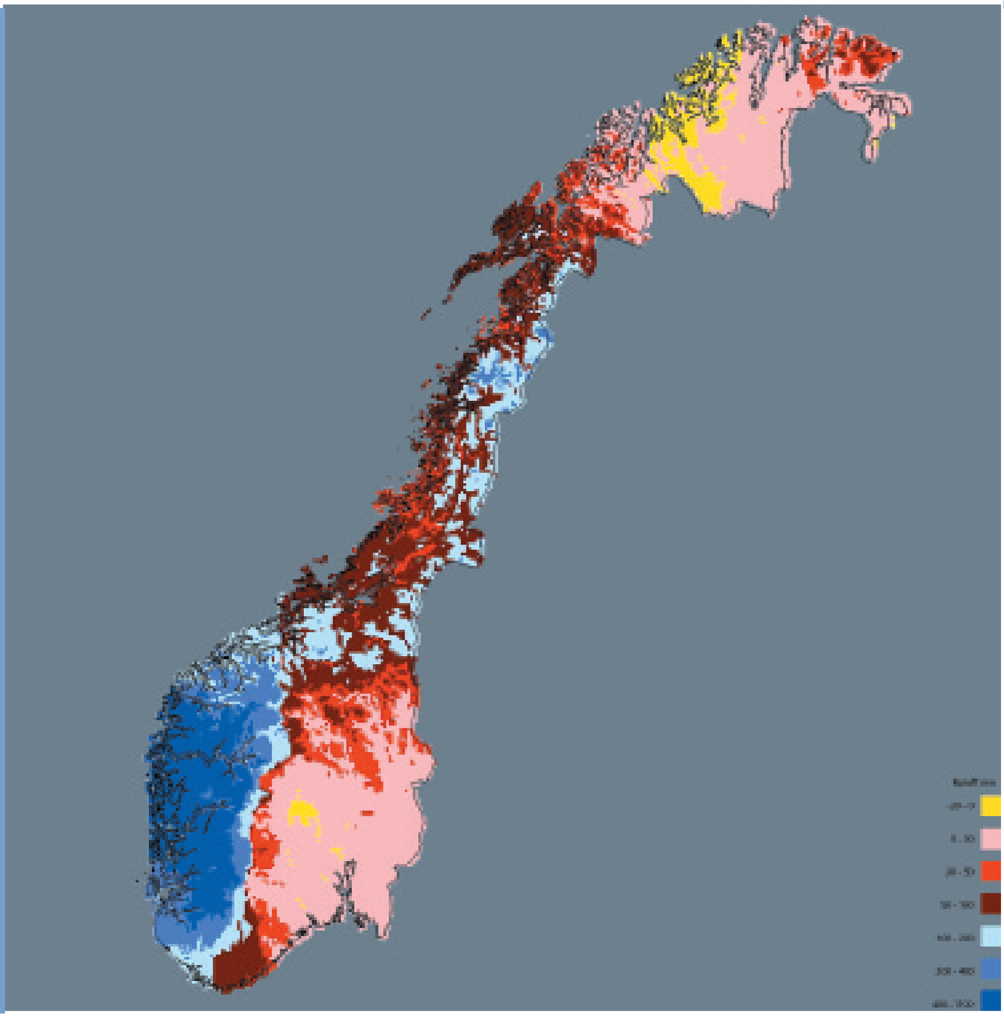

OPPDRAGSRAPPORT A

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Based on climate scenarios for 2030-49.

Norges vassdrags- og energidirektorat
2003

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Scenarios of annual and seasonal runoff for Norway

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Content

Preface

The Norwegian Meteorological Institute (met.no) and the Norwegian Water Resources and Energy Directorate (NVE) have co-operated in the project ”Climate change and Energy Production Potential”. The project started in 2001 and is completed at the end of 2002, and has been funded by the Norwegian Electricity Industry Association (EBL) and the Research Council of Norway (NFR) as well as by own contributions from NVE and met.no..

The report presents scenarios of the runoff in Norway for the period 2030-49, based on climate scenarios of the RegClim project.

Oslo, February 2003

Director Hydrology Dept.

Section manager (acting)

Summary

This project is a part of the project “Climate change and Energy Production Potential” funded by EBL-Kompetanse AS and the Research Council of Norway (NFR) (contract no. H1.00.5.0)

Scenarios are developed for the mean annual and seasonal runoff over Norway for the period 2030-49 based on dynamically downscaled series of temperature and precipitation based on the most recent scenarios from RegClim. Two alternative modelling approaches have been used. The scenarios are partly obtained using a catchment-based HBV-model, which also produces series of daily runoff for each catchment, and partly by using a gridded version of the model, which is used to produce maps showing regional changes in the runoff. Data of the scenario period is compared to data of a control period covering the years 1980 to 1999.

The daily series from selected catchments are used as input to a subproject by SINTEF Energiforskning as (Sefas) for simulating expected changes in the hydropower production and by the VAKLE project.

1. Introduction

This report is one of several reports from the project "Climate Change and Energy Production Potential". The main objective of the project is to provide scenarios of the runoff over Norway for the period 2030-2049. The scenarios are based on daily temperature and precipitation series derived from the research project: Regional Climate Development Under Global Warming (RegClim) in Norway. Information of the project is available at the Internet: www.nilu.no/regclim. The first attempt of providing runoff scenarios for Norway was based on the use of the HBV-model for six catchments (Sælthun et al., 1990). The meteorological scenarios were based on series of observed daily temperature and precipitation at climate and precipitation stations in or near each catchment. The future projection of temperatures and precipitation were constructed by scaling each series with factors assumed to represent a climate with a doubling of the atmospheric CO_2-content. The work was continued in the Nordic Study: Climate change impacts on runoff and hydropower in the Nordic countries (Sælthun et al., 1998). This study was also based on the use of a specially modified version of the HBV-model (Sælthun, 1996), and the use of modified observed data series. Dankers (2002) has studied consequences of climate change in the Tana River Catchment. Similar studies have been performed in many countries. A major study was performed by the Rhine Commission applying both catchment models and regional modelling (Grabs et al., 1997).

The current study utilises dynamically downscaled series for a control period 1980-99 resulting from simulations based on the GSDIO-simulation with the Global Climate Model ECHAM4/OPYC3 obtained at the Max Planck-Institute für Meteorologie in Hamburg (Roeckner et al., 1999). Temperature and precipitation for the control period is just representing natural variations of present climate, and are thus not equal to the observed time series at the station. The modelled temperature and precipitation data should however have similar statistical properties as the observed series. A scenario of dynamically downscaled temperature and precipitation data, based on the GSDIO-simulation for the period 2030-2049 is available (Bjørge et al., 1999). The series for the scenario period is compared to the control period. The modelled data had to be adjusted to represent the station sites (Skaugen et al., 2002). The adjusted temperature and precipitation data are further described in Chapter 2.

The runoff scenarios are based on two modelling strategies. HBV-models have been developed for a number of catchments, utilising meteorological data from nearby climate stations as described in Chapter 4. Daily series of temperature and precipitation have been developed for the control period and scenario period for most of these catchments. The resulting daily runoff series are used in a supplementary study to examine the consequences for the hydropower production. The other approach utilises a gridded version of the HBV-model, the Gridded Water Balance Model (GWB)-model, which has been used to develop the new water balance map 1961-90 for Norway (Beldring et al., 2002). The model operates with a raster size of 1 km^2. The ratio of the annual and seasonal mean runoff is shown on maps. The GWB-model and the simulated scenario are presented in Chapter 3. The results are discussed in Chapter 5. Chapter 6 comprises the conclusions.

2. The meteorological control series and scenarios

Temperature and precipitation scenarios are obtained by different global climate models (IPCC, 2001). The different models give rather different scenarios for the future, but they all indicate that Norway will get a warmer and wetter climate (Räisänen, 2001). Projections of future climate in Norway have been established in the RegClim project (http://www.nilu.no/regclim). The project has two overall aims: to estimate probable changes in the regional climate in Northern Europe, bordering sea areas and major parts of the Arctic, given a global climate change. Secondly to quantify, as far as possible, uncertainties in these estimates by investigating the significance of regional scale climate forcing pertaining specifically to our region.

The RegClim project has, up to now, worked on the results from the global climate model of the Max Planck-Institut für Meteorologie in Hamburg (MPI) with the ECHAM4/OPYC3 GSDIO integration, which describes the climate from 1860 up to 2050. This is a transient integration up to year 2050, including greenhouse gases, tropospheric ozone, and direct as well as indirect sulphur aerosol forcings (Roeckner et al., 1999). In this integration, the concentration of greenhouse gases have been specified according to the IPCC IS92a scenario, with an annual 1% increase in CO2 from 1990, giving a near doubling in concentration in 2050. The model gives a realistic description of the present climate in Norway and is therefore chosen as a basis for the downscaling of temperature and precipitation in Norway.

Two downscaling techniques are available: dynamical and empirical (or statistical), downscaling. Empirical downscaling techniques involve the use of empirical links between observed large-scale atmospheric fields, such as air pressure or sea surface temperature, and local climate elements, such as temperature or precipitation. These relations are used to estimate temperature and precipitation values locally. The result is obtained at co-ordinate-referred points. The limitations concerning the current empirical downscaled results for Norway is the time resolution, which is given at a monthly scale (Hanssen-Bauer et al., 2000, 2001). There is, however, ongoing work to obtain daily resolution from empirically downscaling techniques.

The results from the global climate model are used as input to a regional weather forecast model HIRHAM[1] in dynamical downscaling. This is the regional climate model at MPI, which is based on the dynamics of HIRLAM[2] and the physics of ECHAM[3]. The HIRHAM model has a higher resolution (55x55 km^2) and a 6 hourly time resolution. The

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[1] The Regional Climate Model at MPI (based on HIRLAM dynamics and ECHAM physics)

[2] **HI**gh **R**esolution **L**imited **A**rea **M**odel. The project with this model started with the Nordic countries in 1985. Ireland, the Netherlands and Spain have later joined the project.

[3] The atmospheric global climate model at MPI-Hamburg, based on an earlier version of the ECMWF model.

dynamical downscaling in the RegClim project covers a geographically limited area in Northern Europe. Both time slices of present climate (1980-1999) and the climate of the future (2030-2049) are dynamically downscaled in (Bjørge et al., 2000). Hydrological modelling is based on a daily time resolution. The temperature and precipitation data obtained by the dynamical downscaling technique is therefore used in the work presented in this report.

Calibrated HBV-models is daily in use at the operational flood forecast office at the Norwegian Water Resources and Energy Directorate (NVE). Temperature and precipitation stations used in the work presented in this report were selected with respect to these HBV models, and with respect to geographical location of the station. The aim was to obtain a set of stations covering all regions of Norway, and to take advantage of the existing HBV-models. The locations of the selected stations, a total of 55, are presented in Figure 2.1.

The dynamically downscaled data represents a grid square covering an area of 55x55 km^2. The cubic spline method was used to interpolate the modelled data to the station sites. Three time periods with dynamically downscaled temperature and precipitation data are available:

- Evaluation: HIRHAM run with input from ERA during (1979-1993)
- Control period: HIRHAM run with input from GCM from the time slice 1980-1999
- Scenario period: HIRHAM run with input from GCM for the time slice 2030-2049

The ERA period is the ECMWF (European Centre for Medium-Range Weather Forecast) Re-Analysis project based on 15 years of global analysis. The HIRHAM model is in this period run with the same conditions on a daily basis as was observed in the period. This means that the ERA data is supposed to be comparable with observations from the same period. Although there will be differences between downscaled and observed values, the modelled data should preferably come up with the same statistical moments as the observed data. The HIRHAM model is run with the same initial conditions as in the GCM (ECHAM4/OPYC3 GSDIO integration) for the scenario period.

Figure 2.1 Meteorological stations used in the present paper

Because of the difference between dynamical downscaled values and observations, the interpolated temperature and precipitation data had to be adjusted to represent the station site. The ratio between the sums of observations and the ERA-15 data set within the same period is used as an adjustment factor for the precipitation. Such factors were established for each month at each station. The adjustment factors were used on the interpolated daily data set for the control period, and for the scenario period. The adjustment was found to reconstruct the mean values quite satisfactory. The increase in precipitation in the scenario period compared to the control period is maintained. The variance, however, is changed.

For temperature data, a regression equation was found between the ERA-15 data and the observed data for the same period [$T_{obs} = a*T_{ERA} + b$]. This was found not to be an optimal method. Using regression on temperature data, we found that for all stations the regression coefficient, a, is less than one. Adjusting temperature data with regression thus leads to systematically reduced temperature increase as [(a*scen – b) – (a*ctr – b) = a*(scen-ctr)]. Also, the use of regression equation to adjust the temperature data leads to a reduction in variance. The highest temperatures will be tuned down and vice versa. This will affect the simulation of extreme values. It was concluded that using regression equation to adjust temperature data is not an optimal solution. Evaluation of the adjusted dynamically downscaled precipitation and temperature series are documented in Skaugen et al. (2002).

3. Water scenarios for Norway

3.1 The HBV-model

The HBV model was developed at the Swedish Meteorological and Hydrological Institute in the early seventies (Bergström, 1976). It has gained a widespread use for a large range of applications in Scandinavia and other countries and a great number of versions have come to exist. The model can be classified as a semi-distributed conceptual model with sub-catchments as primary hydrological units. Each of these units is divided into area-altitude zones with a simple classification of land use (vegetation, lakes, glaciers). The sub-catchment option is used in a geographically or climatologically heterogeneous catchment.

The model used in this project is a version of the HBV model developed for the project “Climate Change and Energy Production” (Sælthun et al., 1998). The general model structure can be divided into four modules: the snow module, the soil moisture zone module, the dynamic module and the routing model. The model has a simple structure and the requirements of input data are moderate (precipitation and temperature). Even for the different area-altitude zones, the parameters are generally the same for all sub-models. Interception, snowmelt parameters and soil moisture capacity can however be varied according to vegetation type. Simulations are run on a daily time step. For more information on model structure and algorithms the reader is referred to Sælthun (1996).

3.2 The GWB- model

The HBV-model (Bergström, 1976) is established in a spatially distributed version called Gridded Water Balance (GWB) model (Beldring et al., 2002). The GWB model was used in this study. The model performs water balance calculations for square grid-cell (1x1 km^2) landscape elements, which are characterised by their altitude and land use. Each grid cell may be divided into two land-use zones with different vegetation, a lake area and a glacier area. The model is run with daily time step, using precipitation and air temperature data as input. It has components for accumulation: sub-grid scale distribution and ablation of snow, interception storage, sub-grid scale distribution of soil moisture storage, evapotranspiration, groundwater storage and runoff response, lake runoff response and glacier mass balance. The model considers the effects of seasonally varying vegetation characteristics on potential evaporation. Daily precipitation and temperature values for the model grid cells are determined by inverse distance interpolation of observations from the three closest precipitation stations and the two closest temperature stations. Differences caused by elevation are corrected by site-specific precipitation altitude gradients and fixed temperature lapse rates for days with and without precipitation. The algorithms of the model were described in Sælthun (1996).

3.3 Calibration of the GWB-model

In order for a precipitation-runoff model to simulate the relationship between input, state variables and output with minimal uncertainty, it is necessary to select appropriate values for the model parameters. A global set of parameters must be determined in order to use a hydrological model within a region with ungauged catchments. In a distributed hydrological model, the approach of finding a regionally applicable set of parameters is based on using information about physical landscape characteristics (Gottschalk et al., 2001). The model discretization units should represent the significant and systematic variations in the properties of the land surface, and representative parameter values must be applied for different soil and vegetation types, lakes and glaciers (Refsgaard, 1997). The model is then calibrated using the available information about climate and hydrological processes from gauged catchments within the region, and model parameters are transferred to other parts of the region based on information about landscape characteristics. It is calibrated with respect to the recent normal period (1961-1990) (Beldring et al., 2002).

The parameter values assigned to the computational elements of the precipitation-runoff model should reflect that hydrological processes are sensitive to spatial variations in soil properties (e.g. Merz and Plate, 1997) and vegetation (e.g. VanShaar et al., 2002). As the Norwegian landscape is dominated by shallow surface deposits overlying a relatively impermeable bedrock (Beldring, 2003), the capacity for subsurface storage of water is small. Monthly runoff which was used during model calibration is therefore more sensitive to the intensity of evapotranspiration and the occurrence of snow accumulation and ablation, than to soil properties controlling temporary storage of water and runoff event hydrographs. However, the spatial variability in maximum soil moisture storage must be taken into account, as allowance for storage of more water in the summer leads to higher evapotranspiration rates (Zhu and Mackay, 2001). Vegetation characteristics such as stand height and leaf area index influence the water balance at different time scales through their control on evapotranspiration, snow accumulation and snow melt (Matheussen et al., 2000). The following land use classes were therefore used for describing the properties of the 1 km^2 landscape elements of the model:

(i) Areas above the tree line with extremely sparse vegetation, mostly lichens, mosses and grass

(ii) Areas above the tree line with grass, heather, shrubs or dwarfed trees

(iii) Areas below the tree line with sub-alpine forest

(iv) Lowland areas with coniferous or deciduous forests

(v) Non-forested areas below the tree line.

The model was run with specific parameters for each land use class controlling snow processes, interception storage, evapotranspiration processes and maximum soil moisture storage. These parameters were determined by the calibration procedure. The remaining parameters were fixed and equal for all land use classes. This classification does not identify bogs or agricultural areas as separate land use classes. Bogs were classified according to the characteristics of the vegetation by which they were covered, while agricultural areas are of minor importance in Norway as they constitute less than 3 % of the land surface, and they were therefore included in the non-forested areas below the tree-line. Furthermore, all land use classes were assumed to have identical parameters for runoff response. Evapotranspiration and runoff from lakes and glaciers were controlled by parameters with global values. The ranges of values for the parameters which were subject to optimisation and the fixed parameter values were based on previous experience with the HBV-model in Sweden (Bergström, 1990) and Norway (Sælthun, 1996).

The non-linear parameter estimation method PEST (Doherty et al., 1994) was used in order to determine the parameters of the distributed model. PEST adjusts the parameters of a model within individually specified lower and upper bounds until the discrepancies between selected model outputs and a complementary set of observed data are reduced to a minimum in the weighted least squares sense. A multi-criteria calibration strategy was applied, where the residuals between model simulated and observed runoff from several catchments were considered simultaneously. Although the model was run with a daily time step, it was calibrated against monthly data. Although it would have been more realistic to apply daily values, model simulations considered the separation between evapotranspiration and runoff and consequently the water which appeared as streamflow at the catchment outlet. The multi-criteria calibration strategy constrained model behaviour to runoff from catchments located in areas with different climate and land surface characteristics. The entire range of variations in hydrological processes in the Norwegian landscape was considered during this process, and the model was therefore forced to simulate all possible combinations of natural conditions. The possibility of finding a robust parameter set increases if all operational modes of the model are activated during calibration (Sorooshian and Gupta, 1995).

3.4 Results of the GWB-model

The GWB model was calibrated for the normal period as described in Chapter 3.2. The model was run on two different time slices: the control period (1980-1999) and the scenario period (2030-2049), with fewer climate station than used in the calibration period. The change in runoff and evapotranspiration due to climate change (scenario period – control period) was obtained by raster calculation within a Geographical Information System (GIS). The countrywide change in runoff and evapotranspiration in Norway are presented in the Figures 3.1 and 3.2. The maps present the change in millimetres of water. The ratio between the scenario period and the control period is presented in Figure 3.3. The estimated change in the annual precipitation is shown in Figure 3.4. The map is based on the spatial interpolation of precipitation based on the downscaled values at the 55 climate stations.

The GWB model produced also daily values of other variables, such as the water equivalent of the snow storage in each grid cell. Figure 3.5 present a scenario of changes in the water equivalent of the snow on 1. April between the scenario period and the control period. Similar maps can be produced of changes at other dates or changes in other state variables calculated by the model.

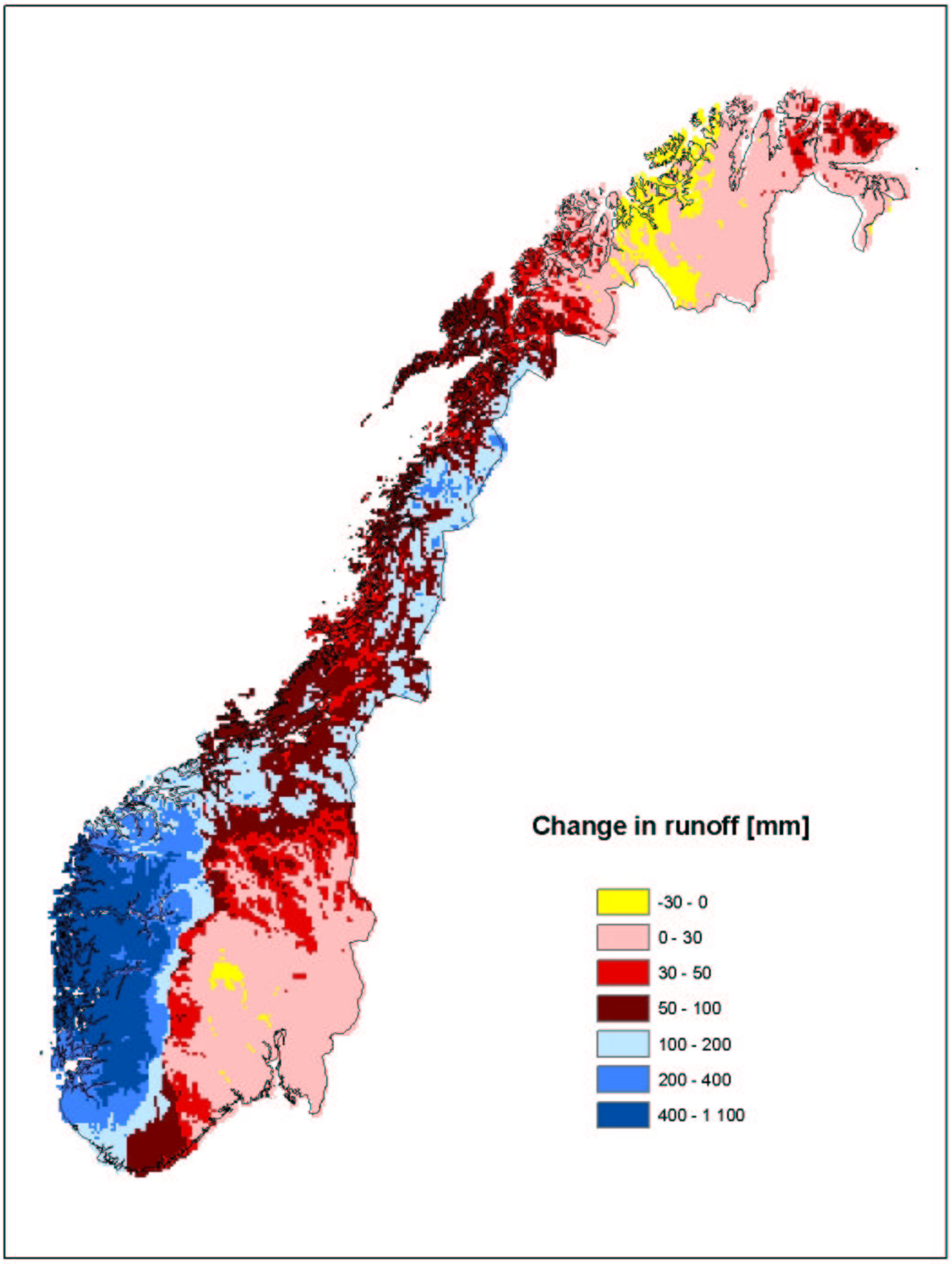

Figure 3.1 Countrywide change in the annual runoff in Norway in the scenario period (2030-2049) compared to the control period (1980-1999).

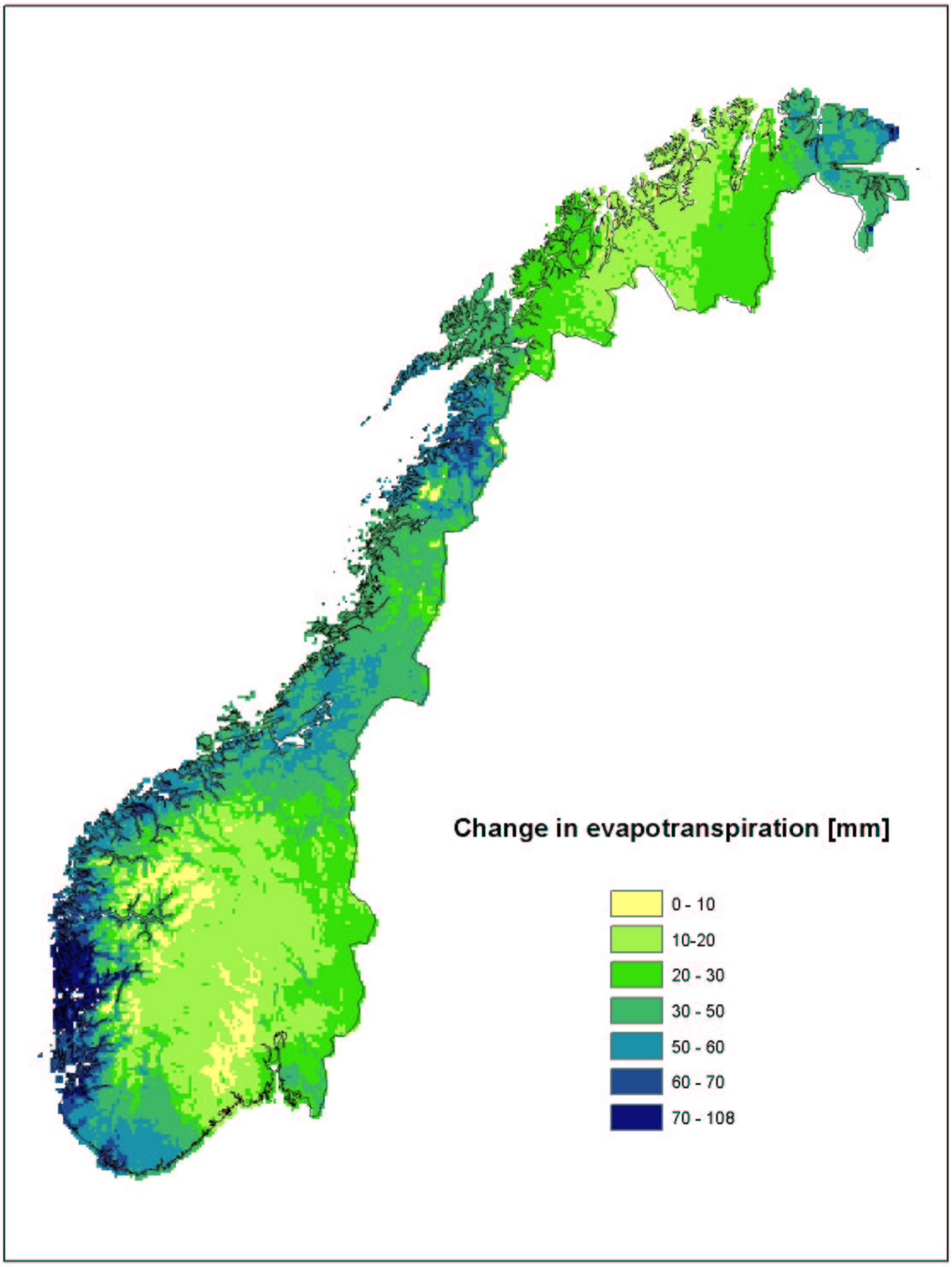

Figure 3.2 Countrywide change in the annual evatranspiration in Norway in the scenario period (2030-2049) compared to the control period (1980-1999).

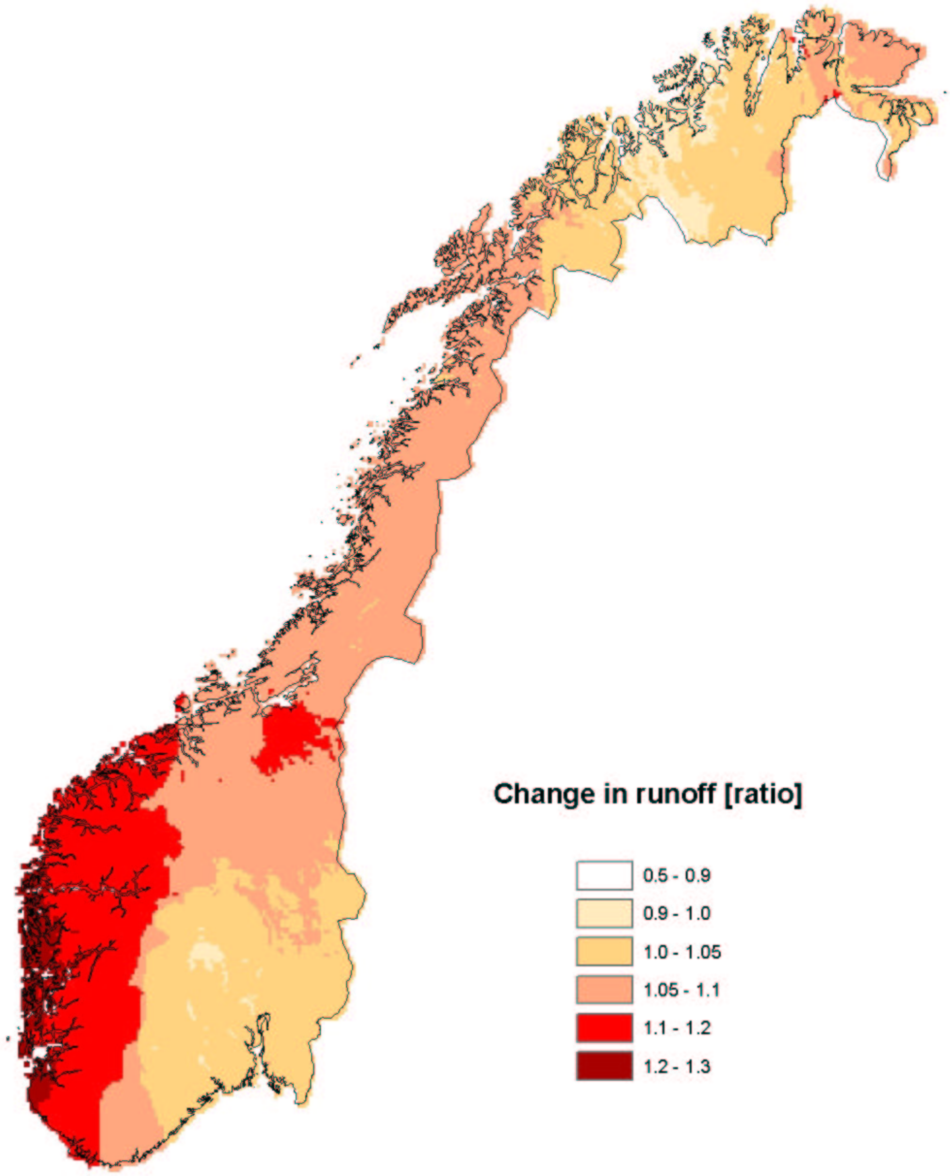

Figure 3.3 Ratios between annual runoff in the scenario period (2030-2049) and the control period (1980-1999).

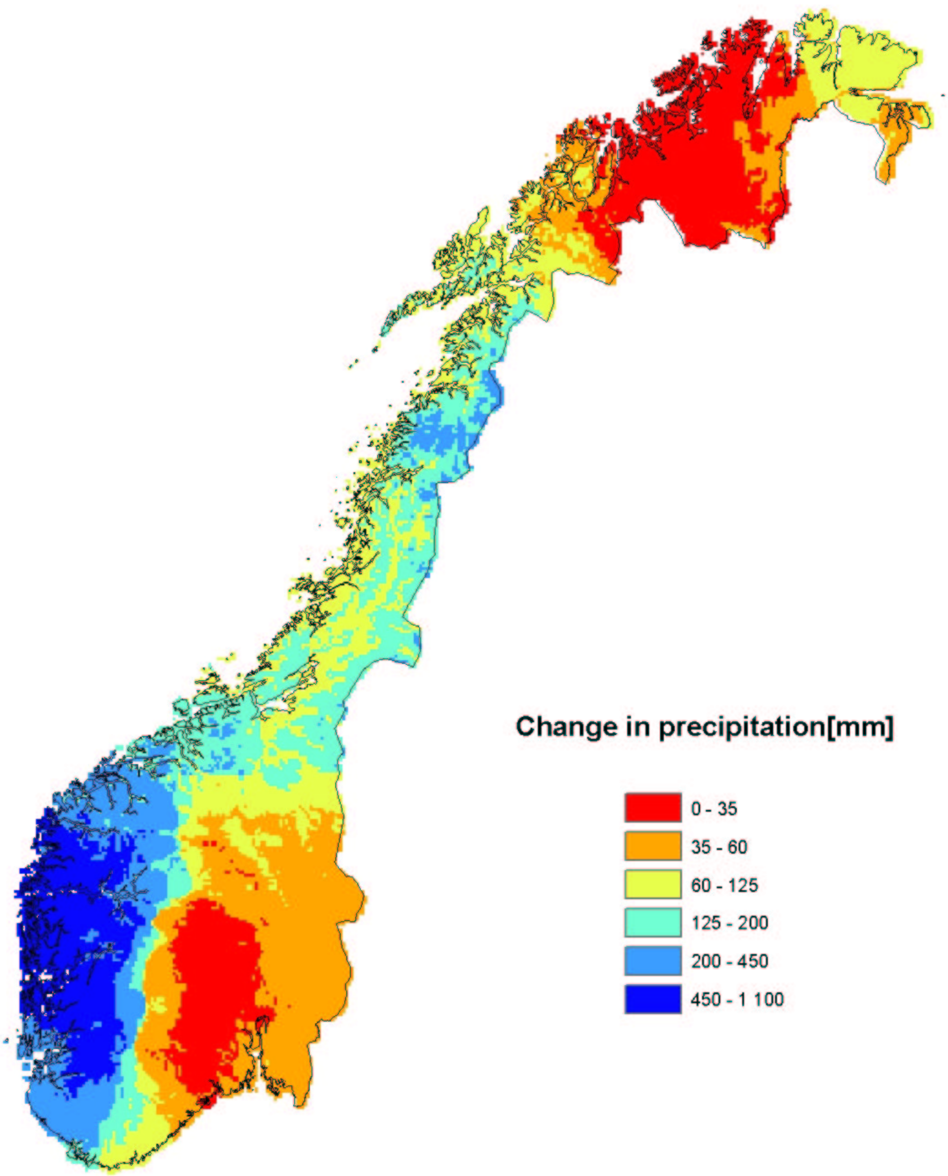

Figure 3.4 Countrywide change in the annual precipitation in Norway in the scenario period (2030-2049) compared to the control period (1980-1999).

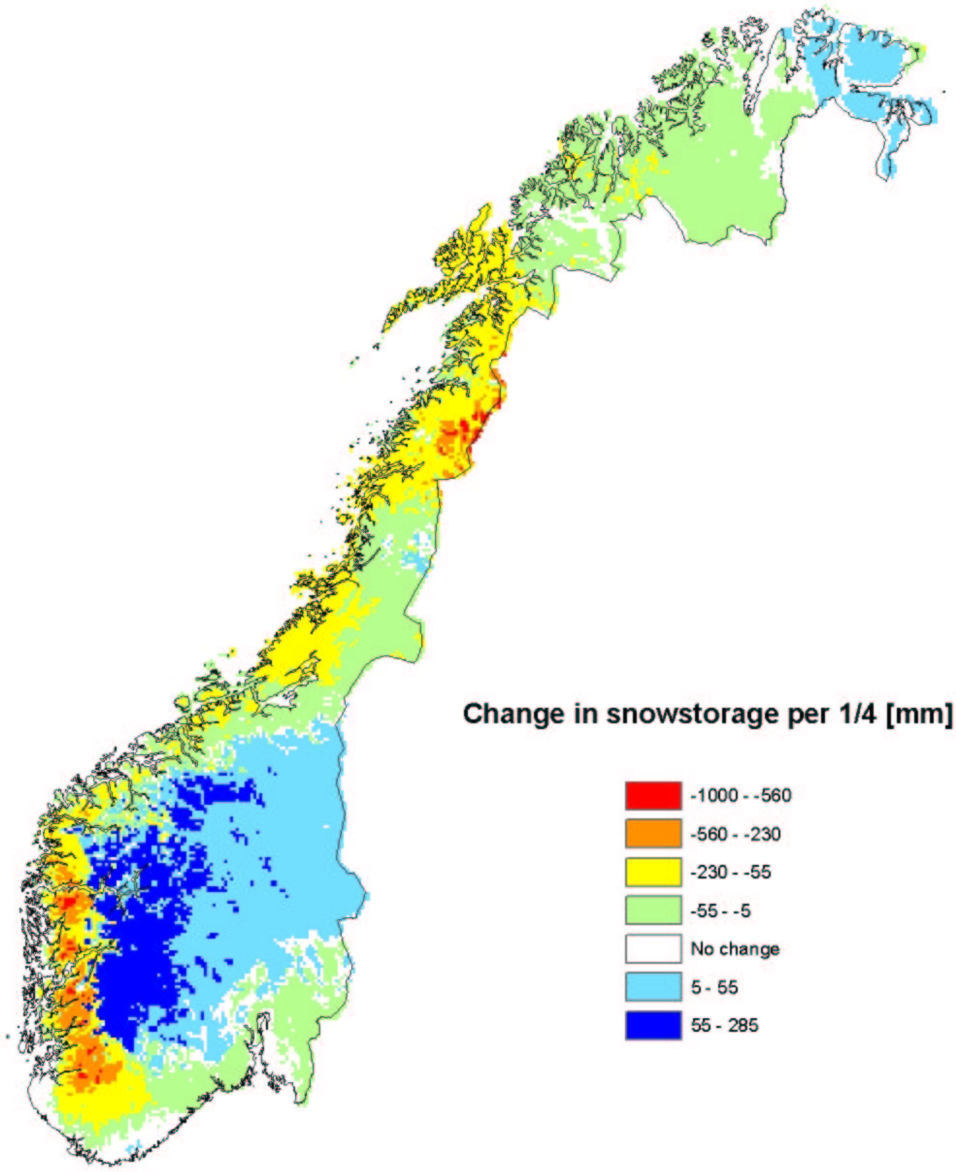

Figure 3.5 Change in the snow storage on 1.April between the scenario and control period.

4. Water scenarios for selected catchments in Norway

4.1 Choice of catchments

The series used in calibration of catchment-based HBV-models were required to comprise of at least 20-30 year of observed data. The runoff should not be affected by upstream regulations. The selection of catchments suitable for at-site modelling had furthermore to be based on the set of climate stations for which downscaled series could be provided. NVE has already established HBV- models for a number of catchments for flood forecasting and other objectives. Some of these models could be used directly. Other models had to be re-calibrated because the original models were based on other climate or precipitation stations. The set of catchments was supplemented with other catchments, in order to obtain a countrywide coverage. The additional catchments were selected according to their suitability for modelling. The selected catchments are shown in figure 4.1. An overview of the catchments and their field characteristic are given in table 4.1. The catchments were with two exceptions small (<100 km^2) or medium sized (100-1000 km^2), and not affected significantly by regulation in the calibration period.

A scenario of energy production in Norway is to be performed based on the resulting runoff series from the HBV-catchment models. Estimates of energy production are simulated in Norway based on runoff series from a countrywide set of catchments as input to the energy production model (VANSIMTAP). The runoff scenarios should ideally be developed for the series, which has greatest weight in the models for the energy production. Many of these series are from medium sized or large catchments, and strongly affected by regulation. The energy production models utilises runoff data corrected for the effect of regulation. The runoff series from some rivers, which are important for hydropower production, are affected in such a way that the natural runoff cannot be calculated reliably.

Correcting the runoff data for the effect of regulation was found to be less suitable to HBV-modelling experiments, especially as one of the objectives of the study is to look at the extremes in addition to the annual and seasonal means. The choice of catchments with respect to hydropower production was therefore as optimal as possible, given the set of climate stations with scenarios available.

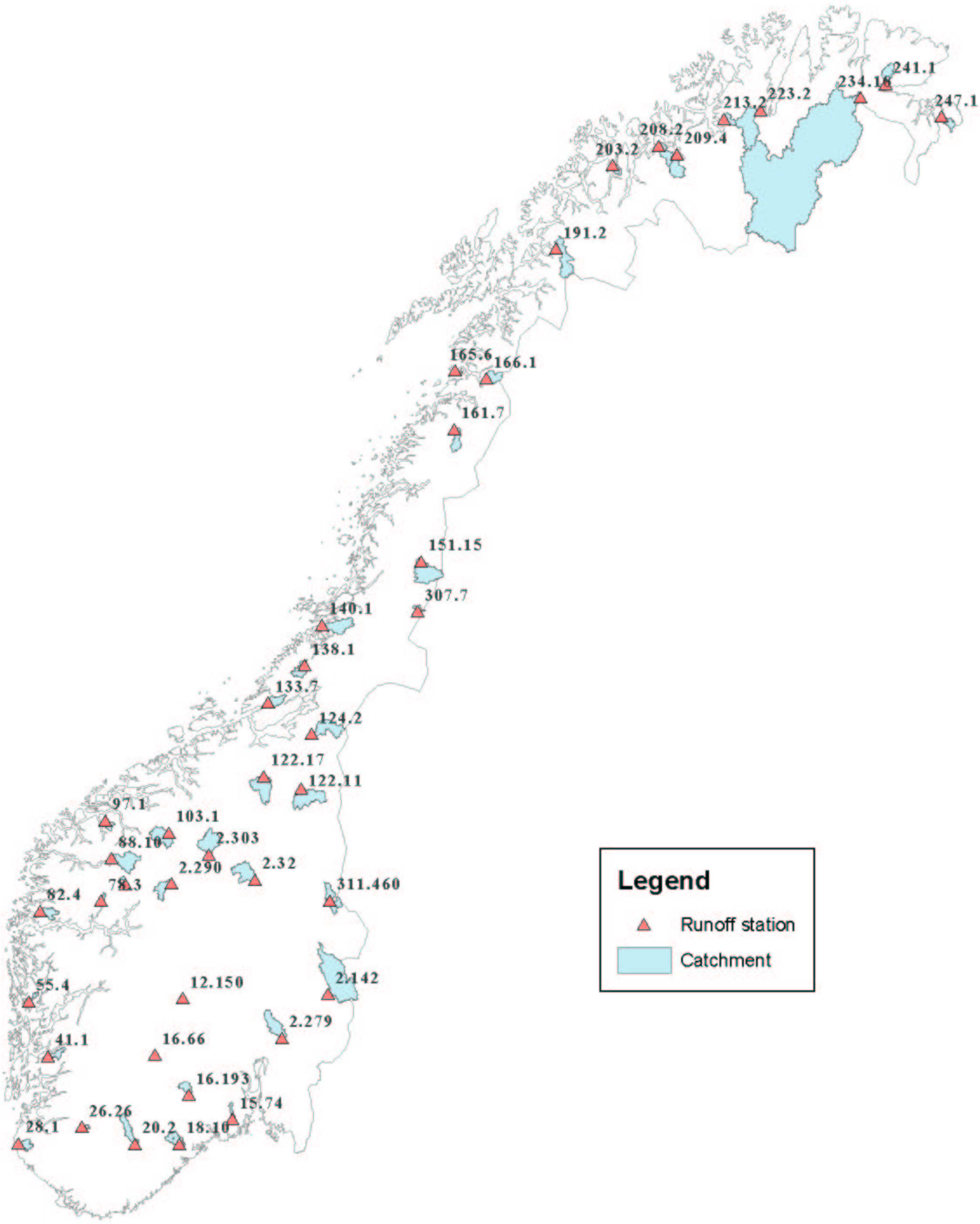

Figure 4.1 Runoff stations with scenarios developed. Models have been developed for additional stations, but necessary climate scenarios are not available for these basins.

Table 4.1 Overview of the catchments considered for hydrological modelling.

Station number	Station name	River	From year	To year	UTM-WGS84			Catch-ment area	Lake	Glac.	Altitude	
					Zone	East	North	km^2	%	%	low	high
2.616	Sagstua	Glomma/Kuggerudåa	1977	2000	32	650768	6694091	47	2.9	0	170	472
2.142	Knappom	Glomma/Flisa	1916	2000	32	338530	6726448	1625	2	0	166	809
2.11	Narsjø	Glomma/Nøra	1930	2000	32	628269	6916891	119	4.1	0	737	1595
2.32	Atnasjø	Glomma/Atna	1916	2000	32	564319	6858291	465	1.9	0.2	697	2114
2.279	Kråkfoss	Glomma/Leira	1966	2000	32	615543	6668092	418	3.2	0	140	812
2.303	Dombås	Glomma/Jora	1967	2000	32	505319	6883891	490	3.0	0.3	570	2253
2.268	Akselen	Glomma/Bøvra	1967	2000	32	471000	6852350	791	2.2	12	480	2469
2.290	Brustuen	Glomma/Bøvra	1967	2000	32	462719	6843892	251.3	4.1	8.4	685	2222
2.275	Liavatn	Glomma/Ostri	1965	2000	32	434919	6858792	733	3.5	11.9	733	2088
2.291	Tora	Glomma/Tora	1967	2000	32	440619	6875882	260	5.8	5.4	700	2014
2.415	Espedalsvatn	Glomma/Vinstra	1976	2000	32	526369	6811641	908	10.1	0	720	1480
3.22	Høgfoss	Mosselva	1976	2000	32	604918	6602942	297	2.3	0	40	349
6.10	Gryta	Akerselva	1967	2000	32	600450	6651300	7.63	2.8	0	163	440
12.70	Etna	Drammeselva/Etna	1919	2000	32	533918	6757592	557	4.7	0	400	1686
12.171	Hølervatn	Drammenselva/Hølera	1968	2000	32	525118	6730542	79	6.8	0	780	1205
12.92	Vindevatn	Drammenselva/Vinda	1972	2000	32	503019	6782492	262	6.1	0	490	1686
12.178	Eggedal	Drammenselva/Simoa	1972	2000	32	524118	6668392	304	2.8	0	170	1469
12.150	Buvatn	Drammenselva/Rukkedøla	1962	2000	32	489918	6705592	25	17.6	0	838	1091
15.74	Skorge	Numedalslågen/	1980	2000	32	563718	6563492	59,1	1.7	0	30	450
16.193	Hørte	Skienselva/	1961	2000	32	507618	6588192	157	1.7	0	80	1172
16.66	Grosettjern	Skienselva/Grosetbekken	1949	2000	32	464918	6633292	6.51	12	0	939	1121
18.10	Gjerstad	Gjerstadelv	1980	2000	32	501918	6527092	235	2.6	0	50	659
20.2	Austenå	Tovdalselv	1924	2000	32	448118	6522560	286	8.4	0	225	1101
20.11	Tveitdalen	Tovdalselv	1972	2000	32	455700	6471870	0.41	0	0	190	270
22.22	Søgne	Søgneelv	1973	2000	32	431368	6439393	192	4.7	0	10	464
24.1	Tingvatn	Lygna	1922	2000	32	396168	6474693	266	6.8	0	188	966
26.26	Jogla	Sira/Jogla	1972	2000	32	381400	6537142	30.7	1.2	0	610	1198
28.1	Haugland	Håelva	1914	2000	32	305000	6510600	134	5.1	0	18	424
41.1	Stordalsvatn	Etneelv	1912	2000	32	331719	6619892	127	17.0	0	51	1294

Table 4.1 Cont. Overview of the catchments considered for hydrological modelling.

Station	Station name	River	From	To	UTM-WGS84			Catch-	Lake	Glac.	Altitude	
					Zone	East	North	km^2	%	%	low	high
55.4	Røykenes	Oselva	1934	2000	32	650768	6694091	50.0	5.9	0	53	962
62.5	Bulken	Vosso	1892	2000	32	351850	6724550	1625	1.8	0.3	47	1583
76.5	Nigardsjøen	Jostedøla	1962	2000	32	406919	6838292	66.0	1.5	71.3	285	1960
78.3	Bøyumselv	Suphellelv	1965	2000	32	379640	6815250	39.6	0.4	4.1	40	1734
82.4	Nautsundvatn	Guddalselv	1908	2000	32	306669	6860242	220	7.9	0	47	920
88.4	Lovatn	Loelva	1900	2000	32	388969	6860342	234	5.2	36.4	52	2083
88.10	Strynsvatn	Strynselva	1967	1999	32	388669	6868342	493	5.5	14.3	29	1938
88.16	Hjelledøla	Strynselva	1982	1999	32	401519	6866292	228	1.9	17.4	58	1938
91.2	Dalsbøvatn	Mørkedalselva	1934	1999	32	300319	6898192	25.8	15.4	0	47	540
97.1	Fetvatn	Velledalselva	1946	2000	32	375319	6913542	88.4	1.5	4.7	0	1540
103.2	Storhølen	Rauma/Ulvåa	1971	2000	32	454219	6905740	416	3.0	0	611	1868
107.3	Farstad	Farstadelva	1965	2000	32	406819	6983891	23.7	4.3	0	23	667
122.11	Eggafoss	Gaula	1941	2000	32	611019	6975191	653	3.0	0	330	1230
122.14	Lillebudal bru	Gaula	1969	2000	32	578819	6966891	168	1.2	0	515	1332
122.17	Hugdal bru	Gaula	1972	2000	32	563069	6985591	35	1.0	0	135	1258
124.2	Høggås bru	Stjørdalselva	1912	2000	32	617419	7042691	491	7.5	0	93	1249
127.13	Dillfoss	Verdalsela	1973	2000	32	696369	7073661	479	2.6	0	60	1035
133.7	Krinsvatn	Stjørna	1915	2000	32	560719	7075791	205	6.3	0	87	653
138.1	Øyungen	Årgårdselva	1916	2000	32	600949	7125831	237	6.4	0	103	675
140.1	Salsvatn	Moelv	1916	2000	32	611719	7177030	422	14.8	0	9	753
150.1	Sørra	Sørelv	1952	2000	33	389532	7319670	6.0	0	0	75	150
151.15	Nervoll	Vefsna	1968	2000	33	452982	7257497	650	0.95	1.4	345	1703
157.3	Vassvatn	Kjerringå	1916	2000	33	418712	7364857	16.1	16.6	0	108	1173
161.7	Tollåga	Beiarelv	1972	2000	33	493632	7419897	225	1.0	0	370	1416
163.6	Jordbrufjell	Saltelv/Russå	1945	2000	33	506432	7424297	69.2	7.2	0	435	1022
165.6	Strandå	Strandvasså	1916	2000	33	494632	7491547	23.0	4.4	0	15	950
166.1	Lakshola	Lakså	1916	2000	33	532582	7481897	230	12.9	1.3	20	1327

Table 4.1 Cont. Overview of the catchments considered for hydrological modelling.

Station number	Station name	River	From year	To year	UTM			Catch-ment area	Lake	Glac.	Altitude	
					Zone	East	North	km^2	%	%	low	high
173.8	Coarveveij	Elvegårdselv	1972	1999	33	620950	7547550	62.7	8.0	4.8	947	1582
185.1	Gåslandsvatn	Ringstadelv	1934	2000	33	484833	7617897	110	28.6	0	16	209
191.2	Øvrevatn	Salangselva	1916	2000	33	618400	7641300	524	3.24	4.6	8	1507
203.2	Jægervatn	Jægerelv	1955	2000	34	456000	7736350	93.6	3.9	5.6	1	1550
206.3	Manndalen	Manndalselv	1971	2000	34	484510	7712550	199	0	0	15	1308
208.2	Oksfjordvatn	Reisaelv	1955	2000	34	514450	7754800	266	4.2	1.5	5	1337
209.4	Lillefossen	Kvænangselv	1961	2000	34	535400	7742200	324	3.9	0	30	1326
212.1	Masi	Alta	1966	2000	34	603345	7703425	5693	4.5	0	272	1089
213.2	Leirbotnvatn	Leirbotnelv	1966	2000	34	596945	7779801	136	5.4	0	161	719
232.2	Lombola	Stabburselv	1920	1999	35	415110	7783030	870	4.0	0	58	1139
234.18	Polmak	Tana	1911	2000	35	538650	7774040	14169	6.8	0	20	1067
241.1	Bergeby	Bergebyelva	1960	1999	35	571470	7784650	239	3.5	0	20	470
247.1	Karpelv	Karpelv	1927	1999	36	398560	7730300	124	6.8	0	5	405
307.7	Landbru limn.	Linvasselv	1943	2000	34	448720	7196265	59.8	12.0	0	470	1183
311.460	Engeren	Trysilelv	1911	2000	33	344631	6827248	400	3.6	0	472	1139

4.3 Calibration of the HBV-model

Calibrated HBV-models have been developed for flood forecasting in a number of Norwegian catchments. The selection of catchments was extended to include a number of other catchments, which required the development of new HBV-model, see Figure 4.1 and Table 4.1. Some of the older models utilise data from other climate or weather stations than the stations with scenarios of temperature and precipitation available. Most of the catchments used in this study needed therefore either a re-calibration of an existing parameter set due to a different choice (limited selection) of meteorological stations or establishing of a completely new parameter set. In the latter case, some physical characteristics of the catchments needed to be determined. These characteristics included hypsographic curve, catchment area, lake percentage (altitude distributed), glacier percentage (altitude distributed) and vegetation type (altitude distributed). Some other characteristics, i.e. monthly potential evaporation, were taken from already calibrated neighbouring and/or similar catchments.

The 15 calibrated model parameters are listed in Table 4.2. The choice of parameters to calibrate and calibration method are based on suggestions from an earlier study (Kolberg et al. 1999). The range of variation for the parameter values is based upon physical interpretation and tentative recommendations in Sælthun et al. (1996). To obtain an objective and good model fit, an automatic calibration routine, PEST – Model-Independent Parameter Estimation (Doherty et al., 1994) was used. It applies a local optimising routine to find a set of parameter values. Since it searches locally, it is possible there are combinations of parameter values that give better simulation results. To reduce this problem, the calibration process was started from a number of different initial parameter values and then each result were considered. The optimising routine takes both mean daily discharge values and accumulated runoff into consideration. The length of the calibration period varies due to differences in observed data, but mainly the period exceeded 10 years of daily observations. When choosing calibration and verification period, the homogeneity of the runoff series (Astrup, 2000) were taken into account.

Interpretation of the simulation results is based upon visual inspection, simulated water balance and an error function. The HBV model uses the Nash-Sutcliffe efficiency criterion as one of its error function (Nash and Sutcliffe, 1970). It is defined as

$$R2 = 1 - \frac{\sum (Q_m - Q_o)^2}{\sum (Q_o - \overline{Q}_o)^2}$$

and a value of 1 indicates a perfect fit. The R2 value gives an objective indication of the model fit. The R2-log value corresponds to the R2 value, but calculated on the logarithms of the observed and simulated runoff and thus gives more weight on low flow data.

Table 4.2 Parameters to be calibrated in the HBV model.

Parameter	Description
TX	Threshold temperature snow/ice
TS	Threshold temperature for snow melt
CX	Melt index
PKORR	Precipitation correction for rain
SKORR	Additional precipitation correction for snow
TTGRAD	Temperature gradient for days without precipitation
TVGRAD	Temperature gradient for days with precipitation
PGRAD	Precipitation altitude gradient
FC	Maximum soil water content
BETA	Non-linearity in soil water zone
KUZ2	Quick time constant upper zone
UZ1	Threshold quick runoff
KUZ1	Slow time constant upper zone
KLZ	Time constant lower zone
PERC	Percolation to lower zone

An independent set of observations, usually a few years shorter than the calibration period, served as a verification period. Simulation fit for a robust parameter set should not vary significantly for different periods. I.e. the Nash-Sutcliffe efficiency criterion (R2-value in the HBV model) should not differ by more than a few hundred parts between the calibration period and verification period. In case of significant differences, other parameter sets were evaluated.

Calibration of the HBV model is normally based only on discharge. This often results in a number of different combinations of parameter values with approximately the same simulation results. Between these parameter sets, internal model processes as i.e. snow melt and snow cover, varies in their behaviour. Some simulates the observed processes well, while other deviates more. In the initial calibration process, this aspect was not emphasised, and the parameter set that simulated the observed discharge best was chosen. The correlation obtained with calibration for the selected catchments is shown in Table 4.3. The observed and simulated monthly means of the calibration period for some catchments in southern Norway are presented in Figure 4.2, in Trøndelag and northern Norway in Figure 4.3.

While the calibration of the HVB-model was based on observed daily values of the runoff for each catchment, the calibration of the GWB-model was based on monthly runoff observed at 141 stations from 1967 to 1984 for all the 323 000 gridcells comprising the Norwegian mainland. The methods for obtaining an optimal parameter set was nevertheless similar in the two modelling approaches.

Table 4.3 Result of the calibration of the HBV-model. Scenarios have been developed for series marked with *.

Station number	Station name	Met.st.1	Met.st.2	Met.st.3	Parameter set	R^2	R^2-log
2.11	Narsjø	10400			param.dat_1	0.79	0.81
2.32	Atnasjø *	8710			param_dat_Atnasjo	0.84	0.87
2.142	Knappom *	6040			param.dat_1	0.82	0.70
2.268	Akslen	15060	13670		param.dat_2	0.78	0.88
2.275	Liavatn	15660	58700		param.dat_12	0.83	0.73
2.279	Kråkfoss *	4780			param.dat_manuell	0.75	0.71
2.290	Brustuen *	55290			param.dat_2	0.87	0.90
2.291	Tora	15660	60500		param.dat_2	0.81	0.78
2.303	Dombås *	16740	16610		param.dat_11	0.88	0.87
2.415	Espedalsvatnet	13670			param.dat_2	0.83	0.72
2.616	Sagstua	5350	4780		param.dat_22	0.73	0.65
3.22	Høgfoss	17250	17150		param.dat_1	0.74	0.70
6.10	Gryta	18700	18450		param.dat_1	0.71	0.58
12.150	Buvatn *	24880			param.dat_2	0.81	0.75
12.70	Etna	13670	22730		param.dat_2	0.73	0.73
12.92	Vindevatn	13670	22730		param.dat_1	0.77	0.72
12.171	Hølervatn	22730	23160	24880	param.dat_1	0.85	0.78
12.178	Eggedal	26370/80	24600	24880	param.dat_2	0.80	0.69
15.74	Skorge *	17150			param.dat_2	0.63	0.61
16.66	Grosettjern	31620			param.dat_2	0.83	0.67
16.193	Hørte *	32100			param.dat_1	0.67	0.65
18.10	Gjerstad *	37230			param.dat_1	0.70	0.65
20.2	Austenå *	37230			param.dat_2	0.75	0.69
20.11	Tveitdalen	37230	39040		param.dat_1	0.55	0.40
22.22	Søgne	39100	39040		param.dat_1	0.67	0.43
24.1	Tingvatn	42160	42920		param.dat_21	0.81	0.71
26.26	Jogla *	42920			param.dat_12	0.68	0.76
28.1	Haugland *	44560			param.dat_Haugland	0.70	0.79
41.1	Stordalsvatn *	46610			param.dat_Stordalsvatn	0.70	0.81
55.4	Røykenes *	50540			param.dat_2	0.74	0.81
62.5	Bulken	51590	51470		param_dat_1	0.83	0.86
76.5	Nigardsjøen *	55430			param.dat_11	0.92	0.92
78.3	Bøyumselva *	55840			param.dat_12	0.74	0.81
82.4	Nautsundvatn *	52860			param.dat_Nautsundvatn	0.74	0.81
88.4	Lovatn	58480	58320	58700	param.dat_11	0.91	0.91
88.10	Strynsvatn *	58700			param.dat_11	0.92	0.92
88.16	Hjelledøla	58700			param.dat_2	0.87	0.90
91.2	Dalsbøvatn	59100			param.dat_2	0.69	0.78
97.1	Fetvatn *	60500	60990		param.dat_Fetvatn	0.64	0.77
103.1	Storhølen *	60500			param.dat_2	0.87	0.87
107.3	Farstad	62480	60990		param.dat_1	0.64	0.64
122.11	Eggafoss *	66730			param.dat_1	0.82	0.77

Table 4.3 Cont. Result of the calibration of the HBV-model. Scenarios have been developed for series marked with *.

Station number	Name	Met.st.1	Met.st.2	Met.st.3	Parameter set	R^2	R^2-log
122.14	Hugdal bru	66730			param.dat_1	0.82	0.81
122.17	Lillebudal bru	66730			param.dat_2	0.74	0.74
124.2	Høggås bru *	69100			param.dat_2	0.70	0.71
127.13	Dillfoss	69100	72100		param.dat_22	0.67	0.69
133.7	Krinsvatn *	70850	72100	69100	param.dat_21	0.72	0.51
138.1	Øyungen *	72100			param.dat_Oyungen	0.81	0.69
140.1	Salsvatn	72100			param.dat_1	0.76	0.71
150.1	Sørra	80700	80200	72100	param.dat_1	0.25	0.37
151.15	Nervoll *	72100			param.dat_2	0.84	0.82
157.3	Vassvatn	80700	80200		param.dat_1	0.71	0.79
161.7	Tollåga *	80700			param.dat_2	0.83	0.76
163.6	Jordbrufjell	82290			param.dat_2	0.84	0.85
165.6	Strandå *	82290			param.dat_Strandaa	0.64	0.54
166.1	Lakshola *	82290			param.dat_Lakshola	0.70	0.65
173.8	Coarveij	88000			param.dat_2	0.92	0.90
185.1	Gåslandsvatn	86500			param_dat_1	0.79	0.73
191.2	Øvrevatn *	88000			param.dat_1	0.85	0.88
203.2	Jægervatn *	91750/60	91370		param.dat_2	0.83	0.79
206.3	Manndalen bru	91370			param.dat_2	0.86	0.86
208.2	Oksfjordvatn *	91750/60	92350		param.dat_2	0.90	0.90
209.4	Lillefossen *	92350			param.dat_1	0.76	0.82
212.1	Masi	93300	93900		param.dat_Masi	0.83	0.85
213.2	Leirbotnvatn *	93140			param.dat_1	0.85	0.86
223.2	Lombola *	93140			param.dat_1	0.90	0.90
234.18	Polmak *	97250			param.dat_Polmak	0.87	0.78
241.1	Bergeby *	99370	98550		param.dat_2	0.71	0.78
247.1	Karpelv *	98550	99370		param.dat_1	0.78	0.79
307.7	Landbru limn. *	72100			param.dat_2	0.87	0.80
311.460	Engeren *	700			param.dat_2	0.81	0.74

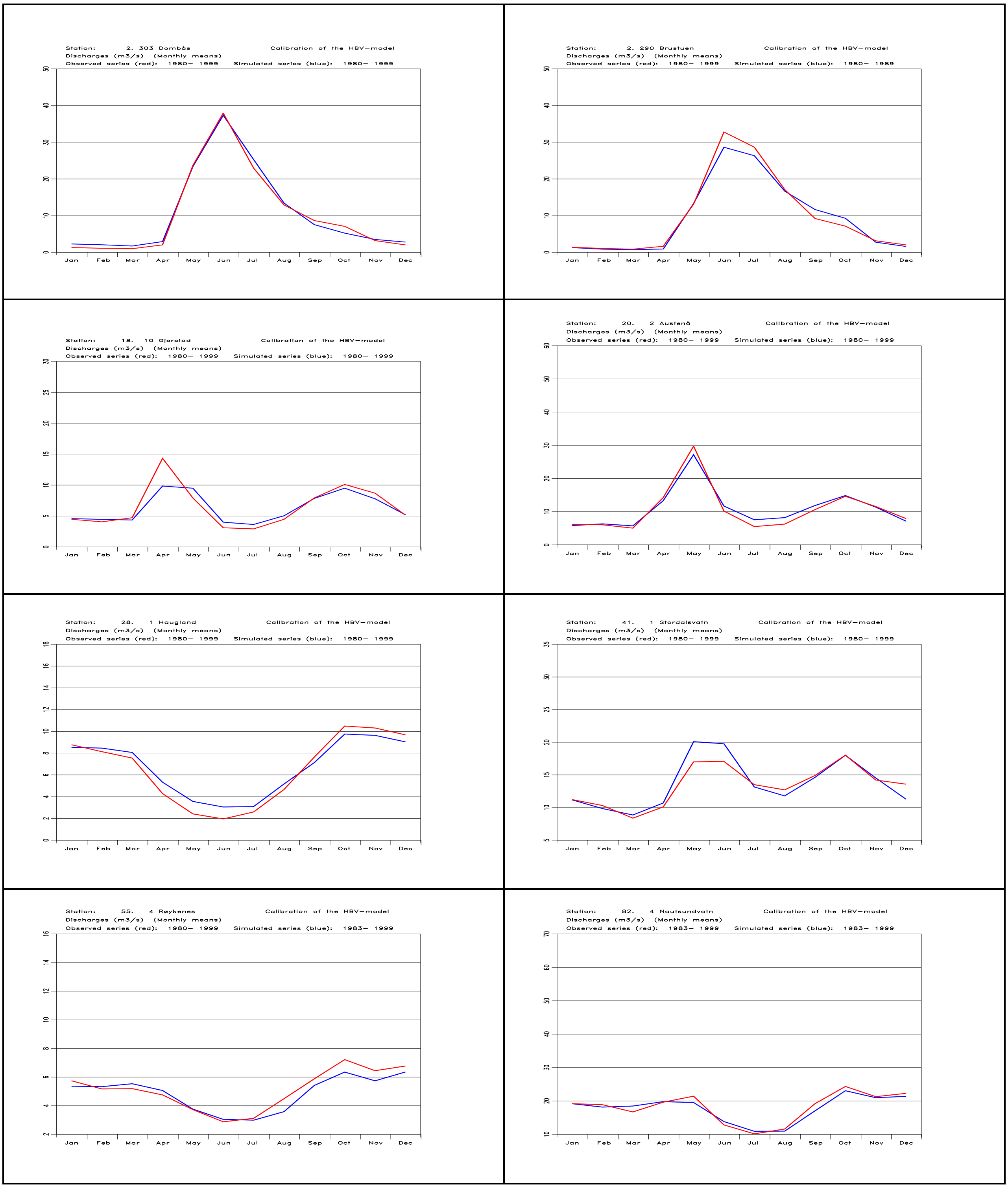

Figure 4.2 Observed and simulated monthly mean runoff for the calibration period for selected catchments in South Norway with the HBV-model. Unit: m^3/s.

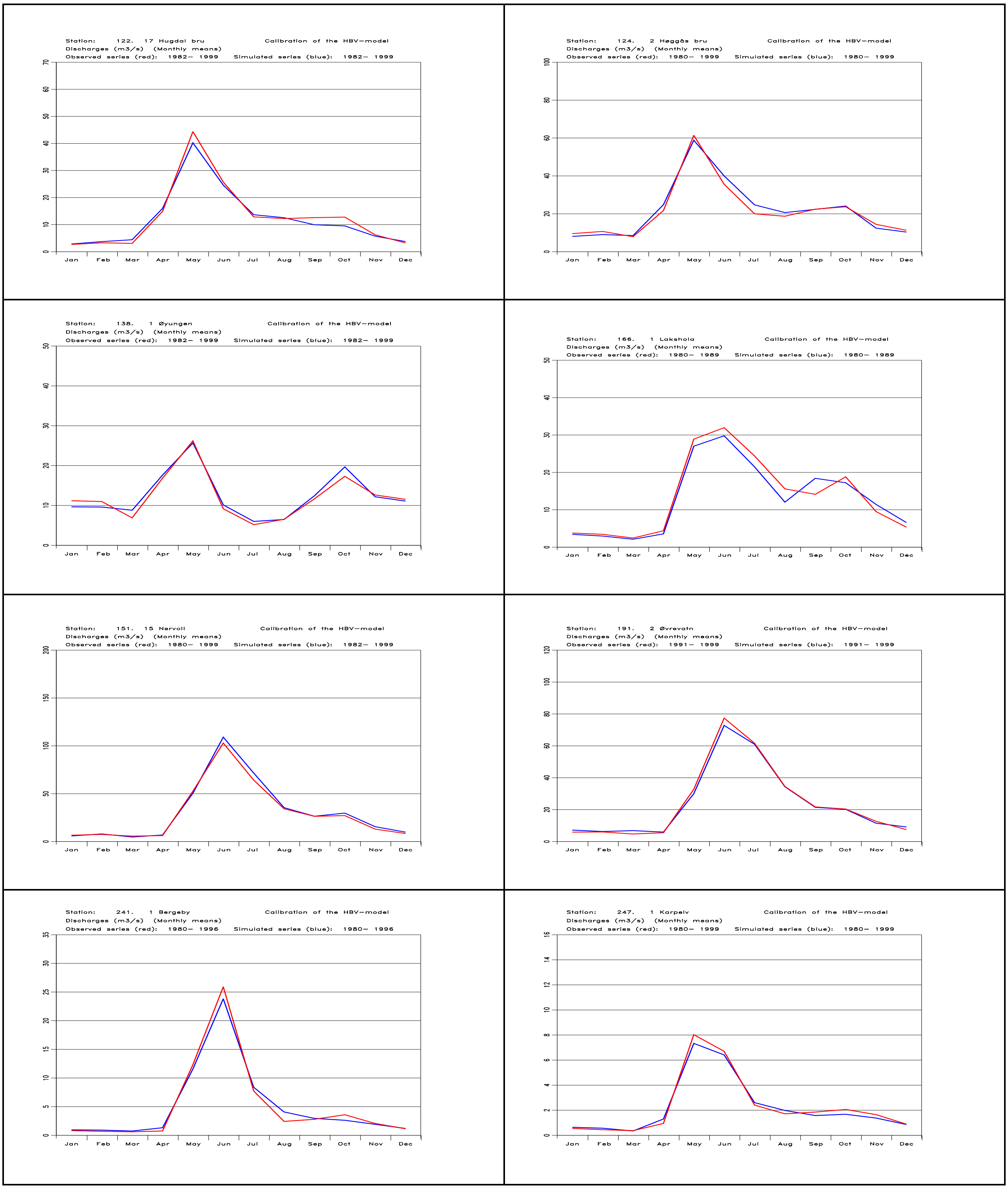

Figure 4.3 Observed and simulated monthly means of the calibration period for a number of catchments in Trøndelag and North Norway with HBV-models.

4.3.1 Model calibration with glacier mass balance and snow reservoir

To obtain more physical correct simulation results and decreased confidence intervals of parameter values, other data sources must be considered. For Norwegian conditions two possible additional data sources are snow cover and mass balance of glaciers. A glacier serve as a natural storage, contributing extra melt water in warm and dry summers, and storing water as snow and ice in cold and wet years. Some hydropower stations utilise this difference in runoff to produce energy in dry years. The applied HBV model simulates both the glacier (the mass balance) and the snow reservoir. These reservoirs may modulate the hydrological response to climate change over time-scales from season and decades.

76.5 Nigardsjøen is the catchment with the highest relative glacier coverage (71.3 percent glacier).The mass balance modelling work carried out in the project "Climate change impacts on runoff and hydropower in the Nordic countries" (Jóhannesson et al., 1993; Sælthun et. al., 1998) was extended applying the MBT model. MBT is a HBV-type glacier mass balance model

The HBV-model was calibrated based on mean daily discharge, accumulated runoff and measured glacier mass balance twice a year (at the beginning and the end of the ablation season). Glacier-relevant parameters were set to initial values corresponding to those determined from calibration of the MBT model in this HBV calibration. Calibration based on discharge only gave a negative glacier mass balance total over the last thirty years while observations show a large accumulation of snow and ice. By incorporating mass balance in addition to discharge as basis for the calibration, simulation results improved significantly for mass balance, without reducing the models ability to simulate discharge, as shown in Table 4.4. Figure 4.4 show the observed and estimated mass balance of the glacier estimated by the recalibrated HBV-model. While the initial calibration, which did not utilise the observed mass balance resulted in a severe underestimation of the mass balance, the recalibrated model is capable of representing the observed mass balance quite well.

Table 4.4 HBV model simulation results based on calibration against discharge (1) and discharge and glacier mass balance (2) for 76.5 Nigardsjøen.

HBV model results	Calibration based on discharge (1). 1989 – 1999	Calibration based on discharge and glacier mass balance (2). 1989– 1999
R2 R2-log	0.92 0.92	0.92 0.90
Observed glacier mass balance (mm)	7940	7940
Simulated glacier mass balance (mm)	-6445	7519

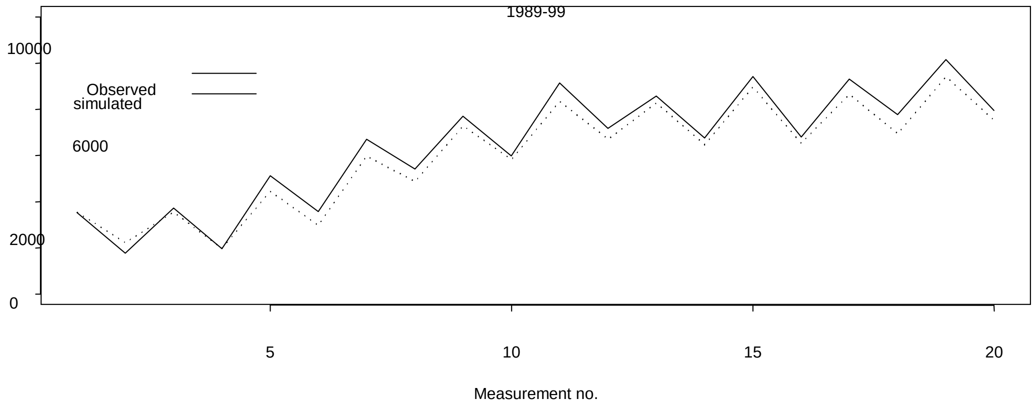

Figure 4.4.Observed and HBV simulated glacier mass balance in mm water equivalent of Nigardsbre based on the recalibrated HBV-model of the runoff at Nigardsjøen.

The calibration process simulates series for the actual calibration period. This data series can be compared to the observed series in order to examine the capabilities of the HBV-model further, as a supplement to the R2 and log-R2 values as shown in Table 4.3. Table 4.5 compares selected runoff statistics of the annual mean runoff, standard deviation of the daily values, the maximum daily runoff, mean annual flood and standard deviation of the annual floods. The model representation of the seasonality of the series is examined by calculating the monthly mean runoff for each month in the year as shown in Figures 4.2 and 4.3 for selected catchments.

The model is generally able to simulate the mean annual runoff quite well. The standard deviation of the daily runoff are generally moderately underestimated. The model tend to underestimate the floods substantial in most cases. Some models are capable of representing the annual cycle quite well, other have marked deviations.

An underlying assumption is that the control series (1980-1999) should have similar statistical properties as the observed series for the same period. The statistics of the observed series and the control series are shown in Table 4.6. The table shows that the model usually simulates the mean values quite well, with a small underestimation of the standard deviation, and that the model tends to underestimate the floods quite in many catchments.

Table 4.5 Comparison of annual means, standard deviations, annual maxima and mean annual maxima and standard deviations of the observed and the simulated runoff series during the calibration of the at-site HBV- models. Unit: m^3/s.

Number	Name	Annual means		Standard deviations		Maximum value		Mean annual flood		Std. deviation	
		observed	calibrated	observed	calibrated	observed	calibrated	observed	calibrated	observed	calibrated
2.32	Atnasjø	11.1	9.94	11.1	10.9	94.1	91.6	67.5	70.4	13.0	13.5
2.142	Knappom	23.7	24.6	32.3	31.4	391	360	214	200	75.3	70.9
2.279	Kråkfoss	8.05	8.0	10.7	9.52	171	81.2	69.0	55.7	30.2	12.3
2.290	Brustuen	9.9	9.6	13.7	12.4	119	71.2	76.2	61.5	16.0	7.55
2.303	Dombås	10.3	10.7	15.5	15.0	195	133	98.6	79.9	32.7	22.2
12.150	Buvatn	0.375	0.388	0.557	0.553	22.9	19.6	3.44	3.12	1.12	0.97
15.74	Skorge	1.21	1.11	2.04	1.55	19.9	18.6	14.0	10.3	3.84	3.21
16.66	Grosettjern	0.117	0.126	0.202	0.187	2.66	1.47	1.40	1.03	0.50	0.28
16.193	Hørte	5.07	5.33	7.03	6.87	83.4	60.8	46.5	35.6	18.2	11.3
18.10	Gjerstad	6.48	6.31	10.8	9.54	169	125	90.1	72.9	29.4	20.8
20.2	Austenå	10.7	10.9	12.0	11.6	115	104	67.9	60.1	18.0	15.7
26.26	Jogla	2.31	2.30	2.86	2.79	27.7	15.8	17.2	12.6	4.30	2.50
28.1	Haugland	6.54	6.73	7.10	6.58	68.9	59.9	45.3	38.6	9.91	8.54
41.1	Stordalsvatn	13.4	13.7	11.1	11.6	120	84.9	67.2	60.7	17.9	10.7
55.4	Røykenes	5.12	4.88	6.54	5.97	74.4	53.8	48.1	39.1	11.9	8.20
76.5	Nigardsjøen	6.26	6.19	8.40	8.07	67.3	35.5	35.1	30.0	8.41	3.19
78.3	Bøyumselva	4.43	4.44	4.86	4.40	35.3	25.0	26.6	18.4	5.54	2.85
82.4	Nautsundvatn	18.1	17.8	22.8	19.7	234	180	167	126	50.4	23.4
88.10	Strynsvatn	30.6	31.2	28.0	26.8	152	133	122	109	18.4	15.5
97.1	Fetvatn	8.21	8.36	8.30	6.96	92.3	74.9	59.8	44.8	18.4	11.3
103.1	Storhølen	15.7	15.7	22.6	20.6	168	139	128	102	21.3	21.4
122.11	Eggafoss	18.1	17.3	26.8	25.9	262	216	150	142	40.6	34.6

Table 4.5 Cont. Comparison of annual means, standard deviations, annual maxima and mean annual maxima and standard deviations of the observed and the simulated runoff series during the calibration of the at-site HBV- models. Unit: m^3/s.

Number	Name	Annual means		Standard deviations		Maximum value		Mean annual flood		Std. deviation	
		observed	calibrated	observed	calibrated	observed	calibrated	observed	calibrated	observed	calibrated
122.17	Hugdal bru	12.9	12.3	18.1	16.5	159	147	115	96.3	23.5	26.8
124.1	Høggås bru	21.5	22.1	24.4	23.3	206	184	139	109	29.2	27.7
133.7	Krinsvatn	13.9	13.8	19.5	16.8	250	181	149	111	47.3	32.5
138.1	Øyungen	12.2	12.5	18.3	15.4	279	149	142	97.6	50.0	26.3
140.1	Salsvatn	27.8	30.1	18.8	19.9	127	133	97.4	87.5	15.7	18.9
151.15	Nervoll	29.7	31.3	38.4	38.2	284	258	201	169	41.0	37.5
161.7	Tollåga	9.89	10.2	14.2	14.0	108	90.1	75.6	60.7	19.3	13.3
165.6	Strandå	1.54	1.38	1.93	1.64	29.5	21.2	14.2	11.9	4.67	3.99
166.1	Lakshola	13.6	13.1	16.6	14.3	172	107	113	66.9	33.2	17.4
191.2	Øvrevatn	24.3	24.9	29.9	28.1	286	195	188	134	51.8	37.7
203.2	Jægervatn	4.73	4.49	3.99	3.90	32.7	23.4	18.2	15.7	4.50	4.14
208.2	Oksfjordvatn	10.2	9.99	12.8	12.1	100	77.6	70.2	59.1	16.2	13.4
209.4	Lillefossen	11.1	11.4	23.5	20.8	304	185	163	120	50.9	29.4
213.2	Leirbotnvatn	3.74	3.72	6.57	6.63	54.9	46.4	42.2	36.9	8.95	4.73
223.2	Lombola	17.7	17.8	29.9	28.6	342	249	196	160	59.7	43.5
234.18	Polmak	182	185	260	309	2038	2349	1544	1656	397	522
241.1	Bergeby	5.08	5.05	9.82	8.60	82.8	65.9	50.5	47.8	13.2	12.2
247.1	Karpelv	2.31	2.23	3.82	3.37	45.7	31.9	26.2	20.9	9.45	5.00
307.7	Landbru limn.	2.74	2.80	3.82	2.46	36.9	25.6	20.4	18.8	5.70	4.16
311.460	Engeren	7.46	7.77	10.0	9.95	164	88.5	61.1	52.1	29.1	15.8

Table 4.6 Comparison of statistics for the observed runoff series and the control series both representing the present climate. Unit: m^3/s.

Number	Name	Annual means		Standard deviations		Maximum value		Mean annual flood		Std. deviation	
		observed	control	observed	control	observed	control	observed	control	observed	control
2.32	Atnasjø	11.1	12.1	11.1	14.3	94.1	125	67.5	70.4	13.0	13.5
2.142	Knappom	23.7	31.1	32.3	31.1	391	313	214	209	75.3	63.5
2.279	Kråkfoss	8.05	10.4	10.7	12.6	171	132	69.0	71.7	30.2	22.9
2.290	Brustuen	9.9	11.2	13.7	15.9	119	94.8	76.2	68.0	16.0	13.9
2.303	Dombås	10.3	12.9	15.5	17.2	195	113	98.6	78.8	32.7	16.5
12.150	Buvatn	0.375	0.558	0.557	0.778	22.9	5.51	3.44	3.94	1.12	0.80
15.74	Skorge	1.21	1.145	2.04	1.81	19.9	23.6	14.0	12.8	3.84	5.20
16.66	Grosettjern	0.117	0.161	0.202	0.251	2.66	2.03	1.40	1.20	0.50	0.30
16.193	Hørte	5.07	6.53	7.03	8.53	83.4	79.7	46.5	44.8	18.2	13.8
18.10	Gjerstad	6.48	8.14	10.8	11.0	169	138	90.1	71.6	29.4	26.4
20.2	Austenå	10.7	14.3	12.0	15.9	115	125	67.9	72.9	18.0	21.6
26.26	Jogla	2.31	2.80	2.86	3.28	27.7	21.9	17.2	14.2	4.3	2.99
28.1	Haugland	6.54	7.76	7.10	7.00	68.9	76.6	45.3	41.3	9.9	11.6
41.1	Stordalsvatn	13.4	15.8	11.1	12.3	120	100	67.2	58.1	17.9	13.9
55.4	Røykenes	5.12	5.46	6.54	5.98	74.4	57.8	48.1	41.3	11.9	10.1
76.5	Nigardsjøen	6.26	6.75	8.40	8.92	67.3	35.7	35.1	29.1	8.4	2.6
78.3	Bøyumselva	4.43	4.97	4.86	5.32	35.3	31.8	26.6	21.1	5.5	4.42
82.4	Nautsundvatn	18.1	21.1	22.8	20.0	234	205	167	138	50.4	36.6
88.10	Strynsvatn	30.6	32.4	28.0	29.0	152	128	122	102	18.4	14.2
97.1	Fetvatn	8.21	9.38	8.30	7.54	92.3	104	59.8	52.2	18.4	18.3
103.1	Storhølen	15.7	14.6	22.6	18.4	168	97.3	128	73.7	21.3	11.7
122.11	Eggafoss	18.1	20.7	26.8	30.2	262	184	150	137	40.6	22.9

Table 4.6 Cont. Comparison of statistics for the observed runoff series and the control series both representing the present climate. Unit: m^3/s.

Number	Name	Annual means		Standard deviations		Maximum value		Mean annual flood		Std. deviation	
		observed	control	observed	control	observed	control	observed	control	observed	control
122.17	Hugdal bru	12.9	14.6	18.1	21.3	159	149	115	107	23.5	18.9
124.2	Høggås bru	21.5	25.2	24.4	28.9	206	149	139	117	29.2	19.2
133.7	Krinsvatn	13.9	15.5	19.5	19.3	250	132	149	101	47.3	13.7
138.1	Øyungen	12.2	14.0	18.3	18.1	279	143	142	103	50.0	18.2
140.1	Salsvatn	27.8	33.9	18.8	25.9	127	123	97.4	99.8	15.7	12.8
151.15	Nervoll	29.7	36.5	38.4	47.1	284	202	201	177	41.0	21.8
161.7	Tollåga	9.89	8.26	14.2	11.8	108	64.8	75.6	49.5	19.3	6.80
165.6	Strandå	1.54	1.43	1.93	1.40	29.5	18.0	14.2	9.20	4.7	3.74
166.1	Lakshola	13.6	13.4	16.6	13.3	172	98.1	113	58.5	33.2	14.1
191.2	Øvrevatn	24.3	20.6	29.9	25.8	286	163	188	108	51.8	21.8
203.2	Jægervatn	4.73	4.54	3.99	4.61	32.7	23.3	18.2	16.2	4.5	3.10
208.2	Oksfjordvatn	10.2	10.2	12.8	12.5	100	78.7	70.2	55.1	16.2	8.82
209.4	Lillefossen	11.1	10.8	23.5	20.4	304	130	163	98.6	50.9	15.8
213.2	Leirbotnvatn	3.74	3.70	6.57	6.40	54.9	43.5	42.2	32.1	8.9	4.38
223.2	Lombola	17.7	18.3	29.9	29.9	342	204	195	157	59.7	24.6
234.18	Polmak	182	187	260	310	2038	231	1544	1622	397	287
241.1	Bergeby	5.08	4.80	9.82	8.58	82.8	63.5	50.5	46.4	13.2	8.29
247.1	Karpelv	2.31	2.18	3.82	3.45	45.7	26.0	26.2	19.7	9.4	2.67
307.7	Landbru limn.	2.74	3.24	3.82	4.19	36.9	19.5	20.4	16.7	5.7	1.90
311.460	Engeren	7.46	8.87	10.0	12.9	164	97.3	61.1	63.9	29.1	16.0

4.4 Results of the HBV-model

The model produced daily runoff for 42 catchments with HBV-models and with temperature and precipitation scenario data available. The observed and simulated series from the calibration period have been stored on the NVE database HYDRA II together with the simulated data series for the control and scenario period. The annual and seasonal means and ratios between the scenario and control period for the runoff are obtained, and shown in Table 4.7 and 4.8. The results are shown graphically in Figure 4.5 and 4.6. Monthly means for the two periods are shown for 16 catchments in Figure 4.7 and 4.8.

Simulation of glacier mass balance for the control and scenario periods indicates high accumulation of snow and ice in both periods, as shown in Table 4.9. The control series gives ca 30 percent higher accumulation of snow and ice compared to the simulation based on observed meteorological data, probably because of more precipitation in the "present" series of Bjørkehaug.

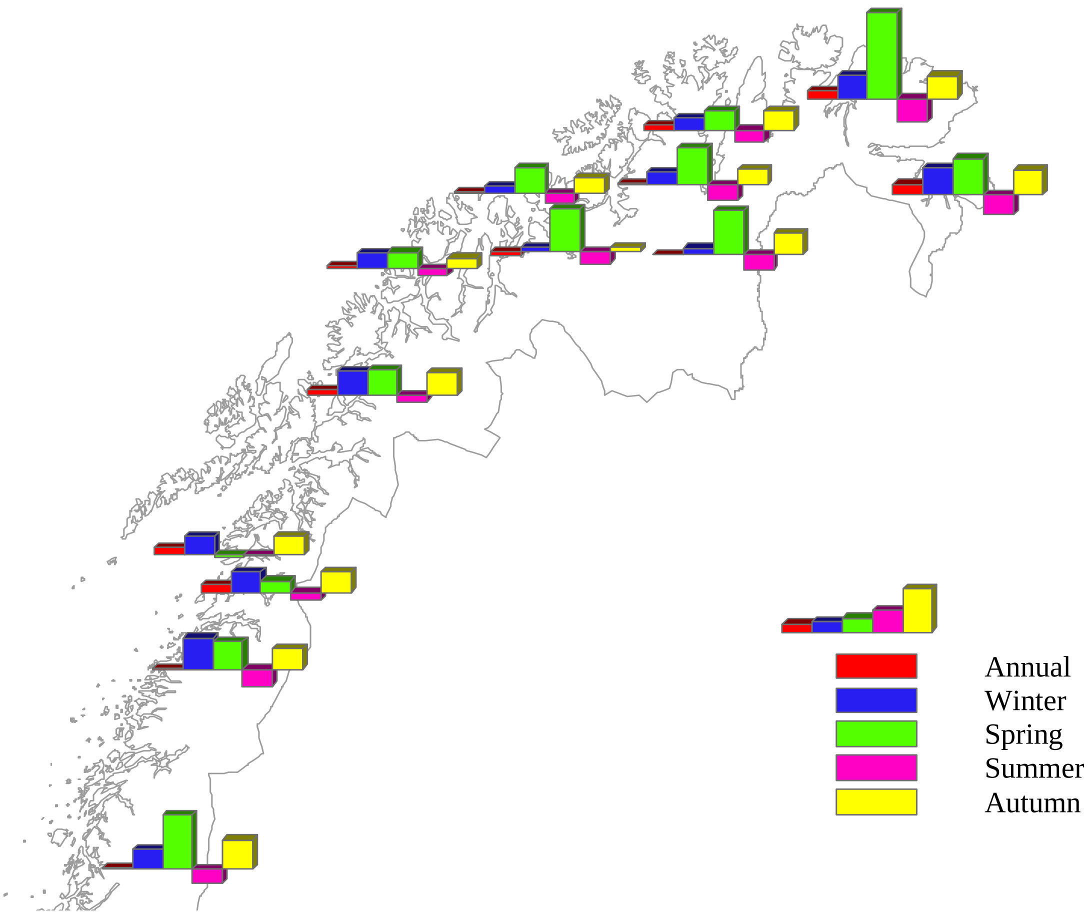

Figure 4.5 Changes in the annual and seasonal runoff in catchments with HBV-models in northern Norway according to the scenarios.

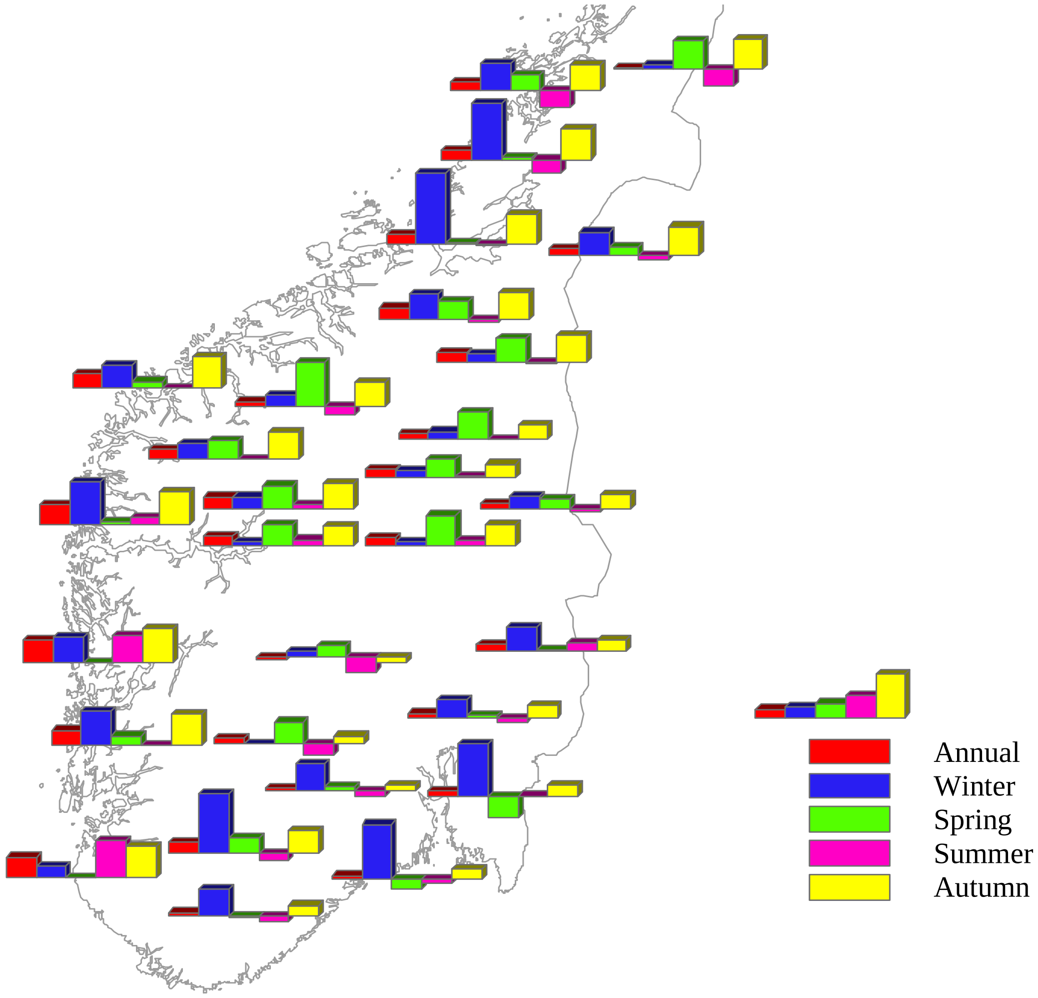

Figure 4.6 Changes in the annual and seasonal runoff in catchments with HBV-models in southern Norway according to the scenarios.

Table 4.7 Annual and seasonal means for the scenario and control period. Unit: m^3/s.

Station	Station name	Annual means		DJF-means		MAM-means		JJA-means		SON-means	
		Scenario	Control	Scenario	Control	Scenario	Control	Scenario	Control	Scenario	Control
2.32	Atnasjø	13.0	12.0	2.47	2.30	12.2	10.2	28.3	27.9	8.99	7.88
2.142	Knappom	33.0	30.8	9.03	7.18	55.3	54.7	38.0	34.9	29.6	26.4
2.279	Kråkfoss	10.8	10.3	3.79	3.18	18.9	18.4	9.26	9.64	11.3	9.96
2.290	Brustuen	12.3	11.1	1.29	1.23	2.88	2.16	37.1	34.8	7.91	6.41
2.303	Dombås	13.5	12.8	2.33	2.16	9.86	7.69	36.1	36.2	6.00	5.25
12.150	Buvatn	0.54	0.55	0.17	0.16	0.86	0.77	0.76	0.89	0.37	0.39
15.74	Skorge	1.54	1.45	1.50	0.96	1.43	1.84	1.18	1.17	2.03	1.82
16.66	Grosettjern	0.17	0.16	0.04	0.04	0.27	0.22	0.22	0.25	0.14	0.13
16.193	Hørte	6.65	6.53	0.82	0.64	11.6	11.2	7.16	7.69	6.99	6.59
18.10	Gjerstad	8.47	8.15	4.50	2.84	10.4	11.6	7.45	7.76	11.4	10.3
20.2	Austenå	14.7	14.2	6.85	5.36	20.7	20.8	14.7	15.6	16.5	14.9
26.26	Jogla	30.9	2.77	1.09	0.67	3.23	2.75	4.32	4.67	3.68	2.97
28.1	Haugland	9.46	7.75	9.71	8.64	5.98	5.98	8.58	6.17	13.4	10.1
41.1	Stordalsvatn	18.3	15.7	10.5	7.69	16.5	14.9	22.6	22.5	23.3	17.6
55.4	Røykenes	6.71	5.46	6.27	4.97	5.59	5.58	5.81	4.54	9.07	6.69
76.5	Nigardsjøen	7.41	6.69	0.41	0.39	1.35	1.10	20.8	19.4	7.03	5.83
78.3	Bøyumselva	5.58	4.92	0.59	0.52	3.02	2.42	12.4	11.8	6.28	4.95
82.4	Nautsundvatn	25.4	21.1	22.2	15.3	24.5	23.9	21.7	20.3	33.1	24.6
88.10	Strynsvatn	35.5	32.1	8.48	7.34	21.7	18.2	73.0	72.9	38.5	29.9
97.1	Fetvatn	10.6	9.32	6.90	5.63	8.84	8.32	12.9	12.8	13.8	10.4
103.1	Storhølen	15.1	14.4	2.17	1.93	11.4	7.82	35.9	39.3	10.9	8.76
122.11	Eggafoss	22.6	20.6	3.00	2.75	31.6	25.4	43.5	44.5	12.8	9.99
122.17	Hugdal bru	16.4	14.6	2.42	1.91	28.5	23.8	23.5	24.0	11.2	8.69
124.1	Høggås bru	27.0	25.0	3.80	3.05	41.1	37.8	39.7	41.5	23.5	17.9

Table 4.7 Cont. Annual and seasonal means for the scenario and control period. Unit: m^3/s.

Station number	Station name	Annual means		DJF-means		MAM-means		JJA-means		SON-means	
		Scenario	Control	Scenario	Control	Scenario	Control	Scenario	Control	Scenario	Control
133.7	Krinsvatn	16.98	15.42	3.72	2.13	27.85	27.47	17.43	17.77	18.80	14.29
138.1	Øyungen	15.36	13.97	6.44	4.04	25.64	25.24	11.06	12.81	18.17	13.75
140.1	Salsvatn	36.55	13.97	19.40	15.11	46.11	39.64	39.60	48.02	40.86	32.11
151.15	Nervoll	36.81	36.08	5.72	4.72	25.96	16.55	84.05	99.26	31.60	24.18
161.7	Tollåga	8.25	8.17	10.6	0.80	9.71	7.50	15.39	18.81	6.86	5.64
165.6	Strandå	1.55	1.43	1.32	1.11	1.56	1.61	1.21	1.23	20.9	1.75
166.1	Lakshola	14.33	13.30	6.04	4.96	15.25	13.67	18.91	20.56	16.96	13.95
191.2	Øvrevatn	21.64	20.47	2.94	2.36	21.88	17.36	44.93	48.55	16.93	13.80
203.2	Jægervatn	4.64	4.50	0.73	0.63	4.46	3.80	9.19	9.83	4.18	3.77
208.2	Oksfjordvatn	10.25	10.12	1.47	1.37	7.96	6.25	23.34	25.81	8.26	7.14
209.4	Lillefossen	10.16	10.66	0.83	0.80	7.29	5.04	29.13	33.57	3.61	3.46
213.2	Leirbotnvatn	3.64	3.66	0.89	0.84	3.66	2.50	8.13	9.76	1.96	1.61
223.2	Lombola	18.29	18.07	4.63	4.11	20.91	15.1	36.95	44.02	10.93	9.45
234.18	Polmak	194	185	52.82	46.77	319	267	292	336	114	94.9
241.1	Bergeby	5.14	4.74	1.10	0.88	7.88	4.15	8.73	11.67	2.92	2.35
247.1	Karpelv	2.40	2.16	0.68	0.53	4.19	3.03	2.83	3.57	1.91	1.52
307.7	Landbru limn.	3.27	3.21	0.88	0.84	3.59	2.77	5.87	7.18	2.76	2.09
311.460	Engeren	9.38	8.83	2.63	2.30	14.39	13.07	13.41	13.84	7.17	6.21

Table 4.8 The ratio between the runoff of the scenario and control periods for the annual and seasonal means

Station number	Station name	Annual means Scenario/Control	DJF-means Scenario/Control	MAM-means Scenario/Control	JJA-means Scenario/Control	SON-means Scenario/Control
2.32	Atnasjø	1.08	1.07	1.19	1.01	1.14
2.142	Knappom	1.07	1.26	1.01	1.09	1.12
2.279	Kråkfoss	1.05	1.19	1.03	0.96	1.13
2.290	Brustuen	1.10	1.05	1.33	1.06	1.23
2.303	Dombås	1.06	1.08	1.28	1.00	1.14
12.150	Buvatn	0.98	1.06	1.12	0.85	0.95
15.74	Skorge	1.06	1.56	0.78	1.01	1.12
16.66	Grosettjern	1.06	1.00	1.23	0.88	1.08
16.193	Hørte	1.02	1.28	1.04	0.93	1.06
18.10	Gjerstad	1.04	1.58	0.90	0.96	1.11
20.2	Austenå	1.04	1.28	0.99	0.94	1.11
26.26	Jogla	1.12	1.63	1.17	0.93	1.24
28.1	Haugland	1.22	1.12	1.00	1.39	1.33
41.1	Stordalsvatn	1.16	1.36	1.10	1.00	1.33
55.4	Røykenes	1.23	1.26	1.00	1.28	1.36
76.5	Nigardsjøen	1.11	1.05	1.23	1.07	1.21
78.3	Bøyumselva	1.13	1.13	1.25	1.05	1.27
82.4	Nautsundvatn	1.21	1.45	1.03	1.07	1.35
88.10	Strynsvatn	1.10	1.16	1.19	1.00	1.28
97.1	Fetvatn	1.14	1.23	1.06	1.00	1.32
103.1	Storhølen	1.05	1.12	1.46	0.91	1.25
122.11	Eggafoss	1.10	1.09	1.25	0.98	1.28
122.17	Hugdal bru	1.13	1.27	1.20	0.98	1.29
124.1	Høggås bru	1.08	1.25	1.09	0.96	1.31

Table 4.8 Cont. The ratio between the runoff of the scenario and control periods for the annual and seasonal means.

Number	Name	Annual means Scenario/control	DJF-means Scenario/Control	MAM-means Scenario/Control	JJA-means Scenario/Control	SON-means Scenario/Control
133.7	Krinsvatn	1.10	1.75	1.01	0.98	1.32
138.1	Øyungen	1.10	1.59	1.02	0.86	1.32
140.1	Salsvatn	1.08	1.28	1.16	0.82	1.27
151.15	Nervoll	1.02	1.21	1.57	0.85	1.31
161.7	Tollåga	1.01	1.33	1.29	0.82	1.22
165.6	Strandå	1.08	1.19	0.97	0.98	1.19
166.1	Lakshola	1.08	1.22	1.12	0.92	1.22
191.2	Øvrevatn	1.06	1.25	1.26	0.93	1.23
203.2	Jægervatn	1.03	1.16	1.17	0.93	1.11
208.2	Oksfjordvatn	1.01	1.07	1.27	0.90	1.16
209.4	Lillefossen	0.95	1.04	1.45	0.87	1.04
213.2	Leirbotnvatn	0.99	1.06	1.46	0.83	1.22
223.2	Lombola	1.01	1.13	1.39	0.84	1.16
234.18	Polmak	1.05	1.13	1.20	0.87	1.20
241.1	Bergeby	1.08	1.25	1.90	0.75	1.24
247.1	Karpelv	1.11	1.28	1.38	0.79	1.26
307.7	Landbru limn.	1.02	1.05	1.30	0.82	1.32
311.460	Engeren	1.06	1.14	1.10	0.97	1.15

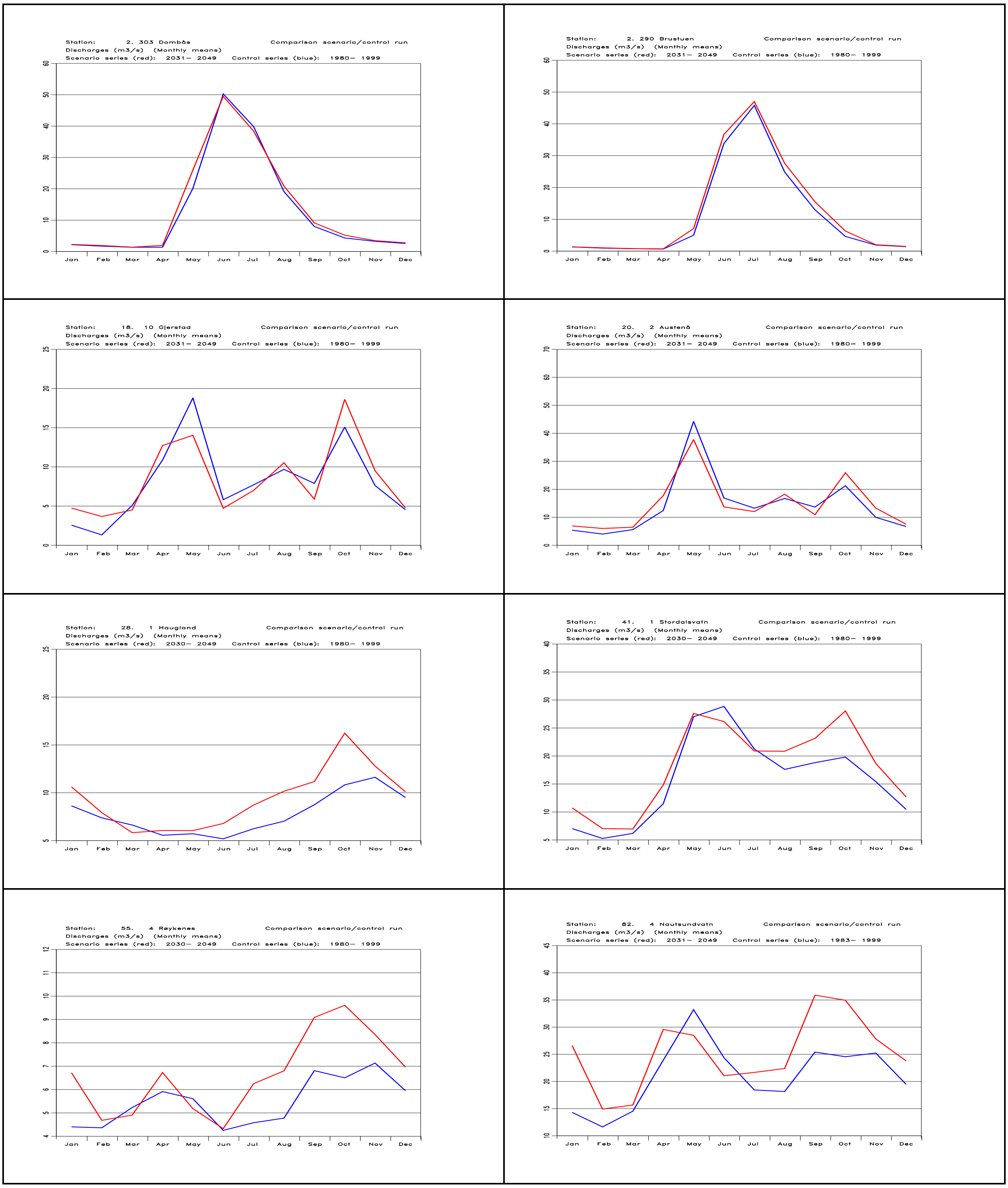

Figure 4.7 Monthly mean runoff for the scenario period and the control period for selected catchments in southern Norway. Unit: m^3/s.

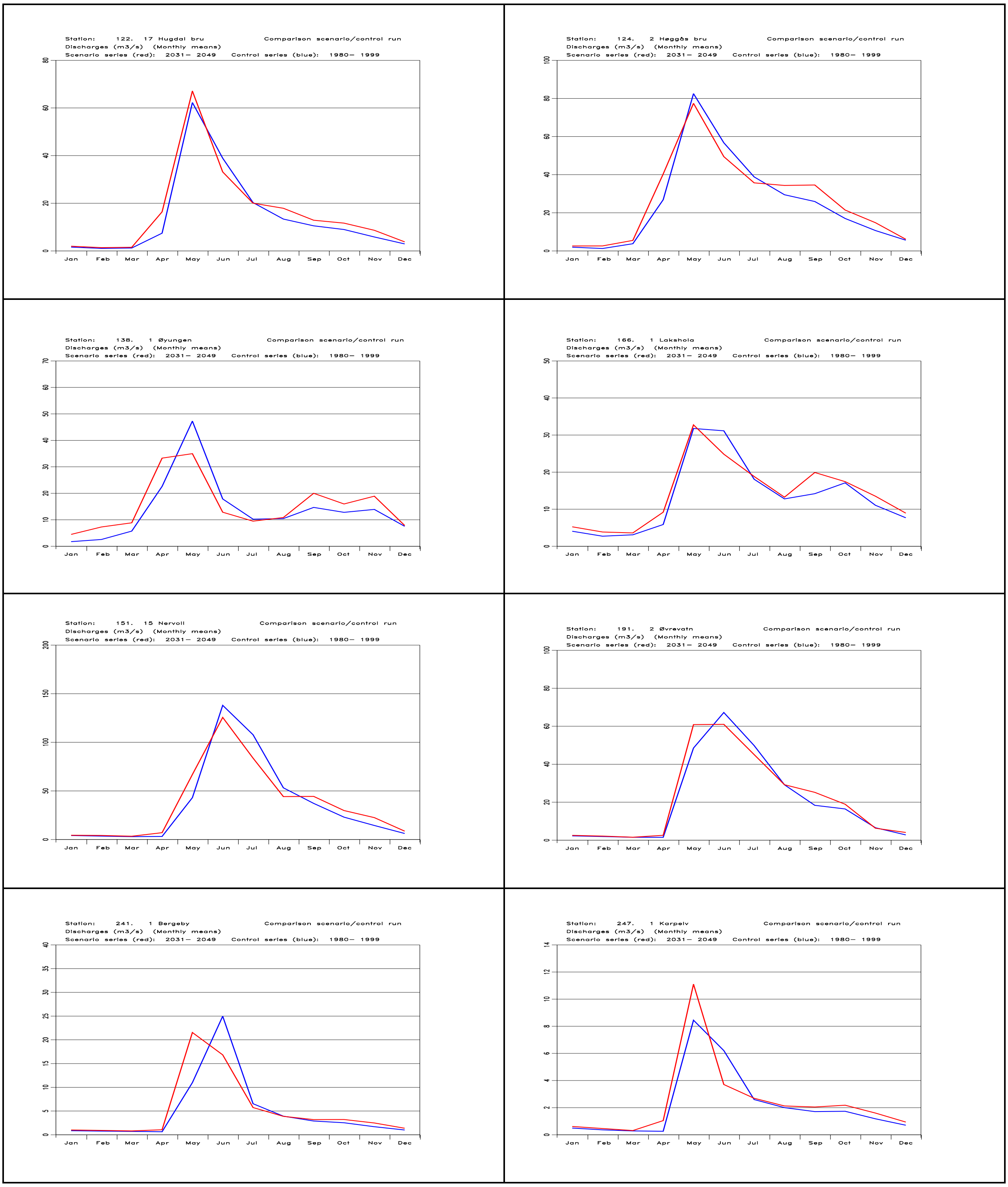

Figure 4.8 Monthly mean runoff for the scenario period and the control period for a number of catchments in Trøndelag and North Norway. Unit: m^3/s.

Table 4.9 Accumulated glacier mass balance at Nigardsbre for the control and scenario period based on the HBV-simulation. Unit: mm water equivalent.

HBV model results	*Simulated period*	
	1980 – 1999	2030 – 2049
Simulated glacier mass balance (mm)	21916	22794

5. Discussion

5.1 Basic assumptions

Interpretation of the results must take into account a number of assumptions underlying the calculation of the climate series both of the control period and the scenario period as well as the use of rainfall/runoff models in simulating the runoff under different climate conditions. The climate series are established by downscaling results of one global climate model, both under a present and a future climate. The change between the present (control) climate and the future (scenario) climate is calculated from simulated runoff series in both cases. This is based on the assumption that the temperature and precipitation series really represent present and future climate.

Another assumption is that similar modelling errors are present in both time slices, and that the difference gives a reasonable estimate of the change between the underlying climate in both cases. A comparison of long term statistical moments of the observed runoff and simulated runoff in the control period will give some information of the uncertainty of the modelling approach.

It is also assumed that the same set of model parameters are valid both under present and future climate. This requires that the land use of each catchment does not change with the climate. Warmer climate is likely to result in changes in the elevation of the tree-line. The evapotranspiration will then increase as larger parts of a catchment are covered by forest. A HBV-model calibrated for a given catchment area cannot be expected to model the effect of changing land use. A gridded model is based on a partition of the landscape into grid cells where the landscape elements are described separately for each cell. By calibrating the model regionally, where the parameter values are linked to the properties of each grid cell, it is possible to modify the distribution of the landscape elements and thereby model the hydrological response of a change in the land use. The model should however based on physical principles of the flow-generating processes.

5.2 GWB-model

The increase in runoff as shown in Fig. 3.1 is largest at the western part of the country (> 400 mm), and in the eastern part of Nordland (100-400 mm). The change in runoff at the eastern part of southern Norway and in Finnmark is least (< 30 mm). The coastal area of Nordland, the southernmost and the northern most part of the country will have an increase in runoff between 30 – 50 mm. Some small areas; in Southeast Norway and in

East Troms and West Finnmark will have a reduction in runoff compared to the control period (1980-1999). The change in runoff is found to be in accordance with the change in precipitation for the same period, which is found to increase annually in all parts of Norway in the future climate compared to the present situation (Bjørge et al., 2000, Førland et al., 2000). The ratio in annual precipitation between the scenario period and the control period is presented in Fig. 3.4. This map is interpolated from the adjusted precipitation stations presented in Chapter 2. The increase is projected to be largest at the western part of the country and at the northern most area (annual). The changes are smaller in the eastern part of southern Norway and in parts of Finnmark. The same pattern is found in Fig. 3.3, which presents the ratio in annual runoff between the two time slices.

The largest increase in temperature will occur in the winter and the autumn (Hanssen-Bauer et al., 2000). This is a period when the evapotranspiration is absent (or at a minimum). The change in evapotranspiration is therefore rather small, as shown in Figure 3.2. The largest increase in evapotranspiration will be up to 100 mm along the western part of the country. The normal evapotranspiration value (1961-1990) in this area was between 500 to 1000 mm (Beldring et al., 2002).

The temperature data used in this study was not optimally adjusted to obtain station values as described in Chapter 2. The change in temperature in the scenario period compared to the control period has therefore been reduced compared to the unadjusted temperature data. The temperature change is, however, largest during winter, when the evapotranspiration is at a minimum.

5.3 HBV-model

The results from the HBV-model are presented in Section 4.5 for the selected catchments in Norway. The largest increase in the annual runoff occurs in catchments close to the west coast. The runoff at 55.4 Røykenes, 82.4 Nautsundvatn and 41.1 Stordalsvatn will increase by 23, 21 and 16% respectively according to the results of the HBV-model. Catchments in River Glomma and on Sørlandet have an increase of 4 – 8%. 12.150 Buvatn in and catchments in Troms and West Finnmark will have a small reduction or no change in the annual runoff. This is in good agreement with the results of the GWB-model ,Section 5.2.

Changes in the seasonal runoff is presented in Section 4.5. The winter runoff will increase significantly in catchments in the southern part of East Norway and along the coast of West Norway to Trøndelag as a result of increasing winter rainfall. The results indicated that winter floods will be more common in the low land, probably with increasing transport of sediments and nutrients in the rivers. The spring runoff will increase in the mountainous part of South Norway, in inland catchments in North Norway and on coastal catchments in Finnmark. The increase may partly be the result of increased snow storage, but it is probably also the results of earlier spring floods, which earlier tended to fall in part into June. The snow storage may increase in the spring in the alpine areas in East

Norway. As the intensities of rainfall in the spring may increase as well, there may be a potential of large spring floods in some years in spite of the expected warming. The summer floods will decline in much of Norway, with the exception of a couple of catchments on the west coast. This decline is partly caused by the change towards earlier spring floods, and partly to reduced summer rainfall and increasing evapotranspiration. The autumn runoff will increase in most regions, most significant in West Norway and Trøndelag. A possible consequence of increasing autumn and winter precipitation, may be an increased risk of avalanches of slush in the steeper part of the country.

The change in the annual runoff is generally larger than predicted by Sælthun et al. (1998) for a time horizon of 30 years and in most cases less than the predicted change for a time horizon of 100 years. Sælthun predicts a small reduction at Masi and this agrees with the results of the GWB- model in east Troms and West Finnmark. The GWB-model and the HBV-model used in the current study indicates both higher increase at Høggås bru and at Austenå in River Tovdalselv, which drains a sub-catchment of the Flaksvatn catchment.

Sælthun et al. (1998) produced scenarios for ten Norwegian catchments on the mainland and one catchment on Spitsbergen. The catchments were: 2.25 Lalm at River Otta, 16.19 Møsvatn at River Måna, 20.1 Flaksvatn at River Tovdalselv, 62.5 Bulken in River Vosso, 98.2 Øye at River Stadheimselv, 124.2 Høggås at River Stjørdalselv, 138.1 Øyungen at River Årgårdselv, 162.2/3 Skarsvatn at River Lakselv, 196.12 Lundberg at River Målselv, and 212.10 Masi at River Alta. The simulated increases of the study is presented in Table 5.2. Most of the catchment of the Swedish station Höljes is in River Trysilelv in Norway. The station analysed in the current study do only partly coincide with the stations used by Sælthun et al. Some of the catchments are regulated, and other requires downscaled series from more climate station that could be provided for in the current study. A comparison of the results can be made by comparing the annual and seasonal changes at the Møsvatn and Groset catchments, at Flaksvatn and Austenå, and at Höljes and Engeren. Direct comparison can be made between the results at Høggås bru and at Øyungen between the two studies.

Sælthun et al (1998) utilised the same version of the HBV-model as used in this study. Since the climate series used in the modelling was based on scaling of observed 30 year series and were used to produce scenarios over 30 and 100 years , the results are not fully comparable. The temperatures were scaled by a factor of 0.35ºC per 10 year on the coast in West Norway increasing to 0.40-0.45º in the inland. The precipitation was scaled by a factor of 2% per 10 year at the coast in West and North Norway and by a factor of 1.5% per 10 year in the inland. Scenarios were also produced based on no change in the precipitation

Table 5.1 Estimated changes in the annual water balance in 30 and 100 years after Sælthun et al. (1998)

Station	Control			30 years						100 years					
	Precip.	Evap.	Runoff	Precipitation		Evaporation		Runoff		Precipitation		Evaporation		Runoff	
	mm	mm	mm	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
Lalm	1025	130	915	1075	5	150	15	955	4	1190	16	225	73	1000	9
Møsvatn	1175	145	1030	1230	5	170	17	1060	3	1355	15	255	76	1100	7
Flaksvatn	1440	385	1055	1505	5	435	13	1070	1	1660	15	565	47	1095	4
Bulken	2270	250	2020	2410	6	295	18	2115	5	2780	22	400	60	2380	18
Øye	2070	190	1860	2200	6	220	16	1990	7	2515	21	300	58	2240	20
Høggås bru	1635	290	1345	1730	6	345	19	1385	3	1885	15	485	67	1400	4
Øyungen	1955	315	1640	2055	5	365	16	1690	3	2370	21	490	56	1880	15
Skarsvatn	1235	205	1030	1295	5	240	17	1055	2	1430	16	340	66	1090	6
Lundberg	1515	110	1407	1610	6	130	18	1483	5	1760	16	205	86	1555	11
Masi	580	200	380	605	45	225	13	380	0	665	15	295	48	370	-2
Höljes	820	345	475	860	5	390	13	440	-6	940	15	500	45	440	-6

5.4 Comparison of the two modelling approaches

Both modelling approaches are based on the same underlying rainfall/runoff model. The difference is that the HBV-model is established for entire catchments, while the GWB-model models the runoff and other state variables for each grid cell. The runoff of a given catchment can be calculated as the average runoff of all grid cells within each catchment from the GWB-simulations based on the digital catchment boundaries of each catchment with HBV-model simulations. Table 5.2 comprises a comparison of the change in the runoff simulated by the two models. The difference is generally quite small, 30 of the 42 catchments differ by 2 % or less. The largest difference is at Karpelv, where part of the catchment is outside Norway.

Dankers (2002) has studied climate change at Tana River in a detailed study looking at sub-catchments with special weight on the different parts of the water balance. He utilised scenarios for the period 2070-2100 based on dynamical downscaling from the RCM HIRHAM4 model based on the global model ECHAM/OPYC and the emission scenario A2 of IPCC (2001). The input to the rainfall/runoff model was based on interpolated fields from several climate stations. The increase in precipitation in this study was 24.6%, in evapotranspiration –30.3%, in sublimation 15.0% and in runoff 39.3% compared to the 5 % rise found in the current study. The current scenario is however closer to the present time, and the emission scenario used in Dankers study, results in a strongly rise in temperatures after 2050.

Table 5.2 Comparison of simulated change in the runoff by the two modelling approaches. * partly located in Sweden or in Finland.

Station No.	Station name	Area		Ratio	
		GWB	HBV-felt	GWB	HBV-felt
241.1	Bergeby	248	248	1.06	1.08
223.2	Lombola	885	878	1.02	1.01
213.2	Leirbotnvatn	136	136	1.00	0.99
247.1	Karpelv*	98	139	1.05	1.11
208.2	Oksfjordvatn	269	265	0.99	1.01
209.4	Lillefossen	334	331	1.00	0.95
203.2	Jægervatn	92	92.5	1.01	1.03
191.2	Øvrevatn	520	525	1.05	1.06
165.6	Strandå	25	23.9	1.05	1.08
151.15	Nervoll*	664	653	1.06	1.02
307.7	Landbru limn.	56	59	1.06	1.02
140.2	Salsvatn	424	431	1.06	1.08
138.1	Øyungen	246	244	1.06	1.10
311.46	Engeren*	358	395	1.05	1.06
78.3	Bøyumselv	43	39.8	1.14	1.13
55.4	Røykenes	46	50	1.22	1.23
12.15	Buvatn	24	23.3	1.00	0.98
16.66	Grosettjern	5	6.48	1.03	1.06
16.193	Hørte	155	156	1.01	1.02
15.74	Skorge	61	59.7	1.03	1.06
26.26	Jogla	31	31.1	1.12	1.12
18.1	Gjerstad	242	237	1.04	1.04
161.7	Tollåga	226	222	1.06	1.01
97.1	Fetvatn	90	89.2	1.13	1.14
20.2	Austenå	276	277	1.06	1.04
2.32	Atnasjø	464	463	1.06	1.08
2.142	Knappom*	1271	1650	1.05	1.07
2.279	Kråkfoss	434	433	1.03	1.05
2.29	Brustuen	255	254	1.10	1.10
2.303	Dombås	492	495	1.06	1.06
103.1	Storhølen	436	437	1.10	1.05
122.11	Eggafoss	654	653	1.10	1.10
122.17	Hugdal Bru	557	546	1.10	1.13
124.2	Høggås Bru	508	495	1.09	1.08
133.7	Krinsvatn	205	207	1.08	1.10
166.1	Lakshola	209	228	1.06	1.08
28.1	Haugland	138	142	1.21	1.22
41.1	Stordalsvatn	129	129	1.17	1.16
76.5	Nigardsjøen	67	65.3	1.12	1.11
82.4	Nautsundvatn	199	196	1.18	1.21
88.1	Strynsvatn	486	484	1.11	1.10
234.18	Polmak nye*	9489	14160	1.04	1.05

5.5 Snow and glaciers

The climate scenarios indicates that the winter will be warmer and with more precipitation in East Norway. The snow storage will probably decline at low altitudes both in East and West Norway, as shown in Figure 4.6. The snow storage will increase in the higher mountains in eastern Norway and at the northernmost part of the country.

The simulation with the MBT model suggests that both winter and summer balances will increase in a future climate, which increase the net balance by 0.1 m to 1.0 m water equivalent. The effect on runoff continues to be negative as the glacier accumulates water as ice and thus reduces runoff, as opposed to a state of equilibrium. The scenario reduction in a changed climate equals 700 mm for the Nigardsbre catchment, which is 80 mm higher than the average reduction for the control period 1980-1999.

5.6 Low flow

Monthly mean values over the year have been compared for the observations and the control period in order to verify that the control period have similar statistical properties, as shown in Table 3.6. The mean annual runoff is mostly biased towards higher values for the control series. The mean value of five series of the 42 series is more than 20% higher for the control series than the observations. The standard deviation of the control series is closer to the standard deviation of the observed series, than the standard deviation of the simulated series from the calibration as shown in Table 3.5. The annual maxima and flood statistics are likewise closer to the observations in many catchments than those of the simulated series from the calibration. The flood statistics, especially the standard deviation of the flood, differ however significantly from the flood statistics of the observations.

Annual minima have been extracted from a number of catchments for durations of 1, 15, 30, 60 and 120 days in order to examine whether the low flows have changed from the present to the scenario period. Each of these series have been analysed by low flow frequency analysis, and the low flow statistics have been compared to observations, simulated series by calibration, the control period and the scenario period. The statistics between the observations and the simulated low-flow values differ considerably for many catchments. The difference decreases generally with increasing duration. Table 3.9 comprise low flow statistics for one station with fair agreement between the statistics and the low flow quantiles. The low flow frequency curves of the four series are shown in Figure 5.2.

The low flows tend to be biased upward for simulated series compared to the observation for many catchments. A general trend is nevertheless that the quantile is higher in the scenario than in the control period at small return period and lower at high return periods, as shown in Table 5.3 for 41.1 Stordalsvatn. This can indicate that the extreme low flows may become more severe under a warmer climate.

Table 5.3 Low flow statistics at 41.1 Stordalsvatn

Duration		Low flow statistics			Return period (years)				
days		Mean	Std.dev	CV	5	10	20	50	100
1	Obs.	1.418	0.537	0.378	0.96	0.79	0.67	0.55	0.48
	Sim.	1.780	0.656	0.369	1.22	1.18	0.97	0.77	0.61
	Cont.	1.557	0.424	0.272	1.20	1.05	0.93	0.82	0.75
	Scen.	2.041	0.748	0.367	1.36	1.11	0.93	0.75	0.64
15	Obs.	2.031	0.962	0.473	1.25	0.98	0.79	0.61	0.51
	Sim.	2.292	0.986	0.430	1.47	1.18	0.97	0.77	0.65
	Cont.	1.961	0.649	0.331	1.42	1.21	1.05	0.89	0.79
	Scen.	2.599	1.055	0.406	1.66	1.33	1.09	0.86	0.72
30	Obs.	3.211	1.416	0.441	1.91	1.48	1.17	0.89	0.73
	Sim.	2.987	1.256	0.420	1.90	1.52	1.24	0.98	0.83
	Cont.	2.656	1.047	0.394	1.78	1.46	1.22	0.99	0.85
	Scen.	3.720	2.014	0.542	2.06	1.54	1.19	0.86	0.68
60	Obs.	5.423	2.601	0.480	3.03	2.27	1.75	1.27	1.01
	Sim.	4.879	2.444	0.501	2.80	2.12	1.66	1.22	0.99
	Cont.	3.984	1.357	0.341	2.76	2.30	1.96	1.62	1.42
	Scen.	5.537	3.081	0.556	2.84	2.04	1.51	1.03	0.78
120	Obs.	8.248	3.480	0.422	5.08	4.00	3.23	2.49	2.07
	Sim.	8.025	3.244	0.404	5.16	4.14	3.42	2.71	2.30
	Cont.	7.398	1.942	0.263	5.63	4.90	4.35	3.79	3.44
	Scen.	9.483	3.886	0.410	5.95	4.71	3.84	3.00	2.51

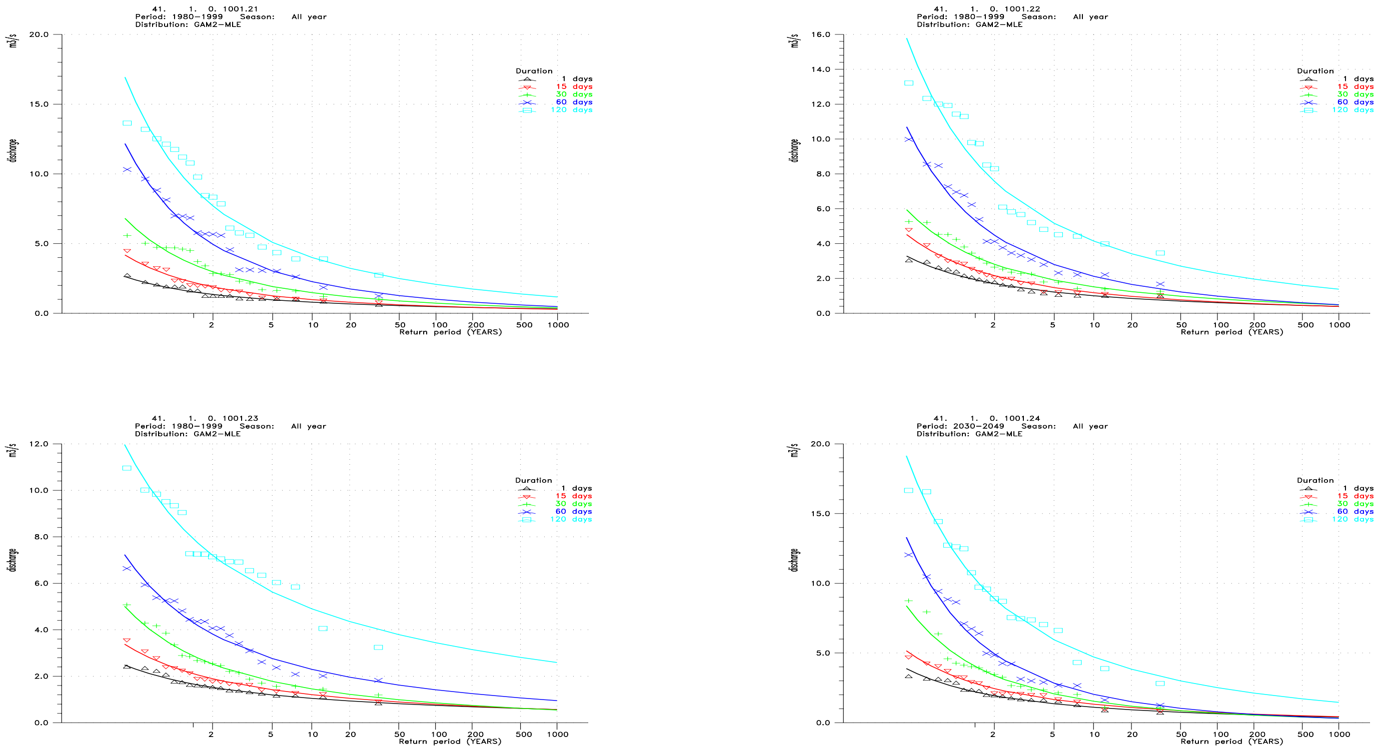

Figure 5.1 Low flow frequency analysis of 41.1 Stordalsvatn for the observed series (1980-99) (upper left), simulated series (upper right), control series (1980-1999) (lower left) and scenario series (2030-49) lower right. The low flow values are the annual lowest values over durations of 1, 15, 30, 60 and 120 days.

6. Conclusions

6.1 Annual values

Given the downscaled climate series the increase in mean annual runoff between the control period (1980-99) and the scenario period (2030-49) is largest at the western part of the country (> 400 mm), and in the eastern part of Nordland (100-400 mm). The change in runoff at the eastern part of southern Norway and in Finnmark is supposed to be smallest (< 30 mm). The coastal area of Nordland, the southernmost and the northern most part of the country will have an increase in runoff between 30 – 50 mm. Some small areas; in Southeast Norway and in East Troms and West Finnmark will have a small reduction in runoff compared to the control period.

The use of HBV-models in glacier catchments demonstrates that the optimisation routine can result in a parameter set, which simulates the runoff very well, but without correct modelling of the mass balance. The recalibrated model for 76.5 Nigardsjøen, described in Section 4.3.1, indicates that the mass balance of this glacier may increase in a changed climate as a result of higher winter precipitation. The effect is an increasing net storage of water as glacier ice. The scenario of changes in the snow storage indicates that glaciers with low-lying accumulation areas most likely would decline, while glaciers with the accumulation area at high altitudes would continue to grow. However large variance of snow accumulation and thus mass balance due to topographic effects are expected.

Sælthun et al. (1998) repeated the modelling for three altitude zones of 0 -500 m, 500 – 1000 m and 1000 – 1500 m and showed how the annual cycle would change in the different zones. The largest difference would occur in the lowest zone, because of strongly reduced snowmelt. The change would be least in the highest zone, but the spring flood would tend to occur earlier, with a moderate increase in the autumn and winter runoff.

6.2 Seasonal values

The winter runoff will increase significantly in catchments in the southern part of East Norway and along the coast of West Norway to Trøndelag. The spring runoff will increase in the mountainous part of South Norway, in inland catchments in North Norway and in coastal catchments in Finnmark. The increase may partly be the result of increased snow storage, but it is probably also the results of earlier spring floods, which earlier tended to fall in part into June. The snow storage will possibly increase in the spring in the alpine areas in East Norway, forming a potential of large spring floods in some years in spite of the expected warming. The summer floods will decline in much of Norway, with the exception of a couple of catchments on the west coast. This decline is partly caused by the change towards earlier spring floods, and partly to reduced summer rainfall and increasing evapotranspiration. The autumn runoff will increase in most regions, most significant in West Norway and Trøndelag.

6.3 Recommendations for further work

The project has succeeded in developing efficient tools for further studies, but these tools can be improved further. It is important to continue to improve the methods of regional downscaling of results of the global climate models although this falls within the scope of other research programs.

The GWB- model produces information of state variables (such as snow, ground water indices etc), which allows a more detailed study on various aspects of the runoff in a changed climate. An immediate improvement would be to provide scenarios for more catchments of greater importance for the hydropower production. This requires scenarios at more climate stations. It could be possible to provide more detailed scenarios for a watercourse or a region. It would also be possible to extend the scenarios to year 2100, although with much higher uncertainties.

Some initial simulations of the mass balance of Nigardsbre indicate that glaciers with accumulation areas at large elevation may continue to grow and thereby retain water from the glacier rivers. Use of dynamical models can simulate the glacier dynamics, which determines the location of the glacier front. A more active glacier can cause more accidents. Glaciers at lower altitudes may experience large losses and will contribute with extra water to the glacier streams. This has not been examined in the present study, and will have implications for the future hydropower production.

The uncertainties of the runoff scenario can be examined by looking at alternative climate scenarios, which can be used to assess the uncertainty of scenario of the energy production and heating season.

Floods and dry years are linked to certain weather patterns, and the stability of these patterns. Shifts in these patterns have a serious effect on the extreme year and on the potential of hydropower production in dry years. The study has mostly focussed on scenarios of the annual and seasonal means, not so much the variability of the runoff. The climate models and historical data sets give opportunities for analysing this important variability.

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