Master's thesis

2019

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Master's thesis

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Science and Technology
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Climate Change Assessments for the Gaula River

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Climate Change Assessments for the Gaula River

Kamrun Naher

Hydropower Development
Submission date: July 2019
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M.Sc. THESIS IN

HYDROPOWER DEVELOPMENT

Candidate: Kamrun Naher

Title: Climate change assessments for the Gaula river.

1 BACKGROUND

The rise in global temperature provide challenges for the management of water resources, related to water availably, timing of runoff and changes in extremes as reported in numerous studies. Much focus has been on the extreme values and particularly extreme precipitation and floods. But changes in climate will have an effect on several components of the hydrological cycle, and also on river hydraulics, water temperature, sediment processes, vegetation and other elements of the catchment. Further, these factors will influence the use of water in rivers and lakes both for industrial, municipal and recreational use.

In this thesis we will study climate change and impacts on changed flow on processes in the Gaula catchment in Norway. Based on downscaled precipitation and temperature from the Norwegian Climate Service Center we will evaluate the impacts on flow regime changes, river flow and associated processes. In addition, effects on hydropower production in Lundesokna will be evaluated.

2 MAIN QUESTIONS FOR THE THESIS

The thesis shall cover, though not necessarily be limited to the main tasks listed below.

The following main steps will be carried out during the thesis work:

1. Literature review on climate impacts on flow regimes changes in northern regions, associated water quality issues (like temperature) and hydropower production. The review should build a

foundation for the further work.

2. Prepare climate data for the region and provide an overview of changes in the driving factors like precipitation and temperature. This should include both magnitude and timing of high and lows and the variability of each variable.

3. Run the PINEHBV model for Gaula to prepare runoff series for the climate data prepared in 2). This should build on work done for the Gaulfoss gauge by Lars de Graaff in his ongoing thesis. It should be discussed if other gauges could be useful for the analysis.

4. Do an analysis of the effect climate has on the power production in the Lundesokna power system. Model setup and data for this analysis will be provided, and more information can be found in Casas-Mulet et al. Fisheries Management and Ecology, 2014.

5. Setup of the HEC-RAS model for Gaula (reach to be decided later) to model flow and water temperature. Investigate the effect of a warming climate on the water temperature in the river. Evaluate the applicability of the model to estimate water temperature in the future climate.

6. Evaluate how changes in temperature and other factors would influence catchment vegetation and evapotranspiration. Investigate if this can be modelled and how this could be implemented.

3 SUPERVISION, DATA AND INFORMATION INPUT

Professor Knut Alfredsen will be the formal supervisor the thesis work. Abebe Girmay Adera will assist with processing climate data for the project. PhD-student Jo Halvard Halleraker is working on catchment management in Gaula and will be available for discussions and input for the analysis.

Discussion with and input from colleagues and other research or engineering staff at NTNU, SINTEF, power companies or consultants are recommended. Significant inputs from others shall, however, be referenced in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are therefore free to introduce assumptions and limitations, which may be considered unrealistic or inappropriate in a contract research or a professional engineering context.

4 REPORT FORMAT AND REFERENCE STATEMENT

The thesis report shall be in the format A4. It shall be typed by a word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary, a table of content, a list of literature formatted according to a common standard and other relevant references. A signed statement where the candidate states that the presented work is his own and that significant outside input is identified should be included.

The report shall have a professional structure, assuming professional senior engineers (not in teaching or research) and decision makers as the main target group.

The thesis shall be submitted no later than 11th of June 2018.

Trondheim 15th of January 2018

____

Knut Alfredsen

Professor

ABSTRACT

The effects of climate change were assessed for Gaula, south of Trondheim in Norway as a wetting winter and drying summer are predicted to occur in the future. The research was done in six steps to find the effect of a warming climate in Gaula. Ten climate models with two emission scenarios were used since there is uncertainty in both natural and anthropogenic changes. Periods 2040-2069 and 2070-2099 were compared with period 1976-2005 and the climate data was downloaded from https://nedlasting.nve.no/klimadata/kss.

In the beginning, the climate model's data was checked with the observed data and then the climate data was used to obtain future changes in precipitation, temperature and runoff. For all scenarios, it was found that the precipitation, temperature and runoff are increasing. Summer precipitation increase is extreme, and the runoff is changing seasonally. An increasing precipitation will lead to frequent floods and temperature rise to droughts. The spring peak is reduced and moved. Compared to the control period the increase in annual runoff is not so high 0.9, 4.7, 2.7 and 5.6% for RCP4540, RCP4570, RCP8540 and RCP8570 respectively. Snowpack reduction (70%) is highest for RCP8570 due to high air temperature.

Future runoff was scaled and taken to the nMAG model to find the effect of climate change on Lundesokna power plant in the current strategy. The result achieved showed that there is a small increase in annual power production for future climate scenarios. However, the annual change in inflow is zero and the production is increasing in winter and decreasing in summer following the higher winter flow and lower summer flow. Sama power plant will be benefited most among the other power plants (maximum 8.84% annual increase for RCP8570).

To observe the effect of drying summer and wetting winter, January 5 percentile and July 25 percentile flow were simulated in HEC-RAS5.0.6. The reach was selected from Haga bru station to Trondheim fjord and a steady flow analysis was done to observe the drying and wetting conditions in Gaula. Results obtained showed that drying summer and wetting winter have effects on the river and these drying areas will lead to vegetation, fish migration problems, water quality deterioration in the future. High flow in winter might improve the salmon fish conditions, still there is uncertainty regarding other species and chemical processes in the river.

Water temperature in Gaula was measured only for RCP8570. The average temperature is increasing in water by 1.97^{o}C for RCP8570 compared to the control period. Minimum summer temperature obtained from this research is 6.8^{o}C in future whereas for the control

period it is 0.6°C. Increasing water temperature has many impacts regarding species in the river and agricultural problems.

Summarizing the results, it can be said that, Gaula is having a different hydrograph in future climate and snowpack is reducing tremendously. Since tourism and recreational activities in Norway depend on snow, this might affect severely. The increasing runoff will give higher production for hydropower in present strategies. In contrast to that, future consumption and electricity price would be different, thus the power company needs to take adaptive strategies in the future. Though in winter, increasing runoff might improve the salmon fishing in Gaula, there remains uncertainty in the water quality for both summer and winter since both low and high flows have their changing capability to the aquatic ecosystem in different ways.

Nevertheless, further research is recommended on the power production using adaptive strategies and also for the ecosystem change in Gaula since the ecosystem has a great influence on the aquatic species, agriculture, recreation, human health, etc.

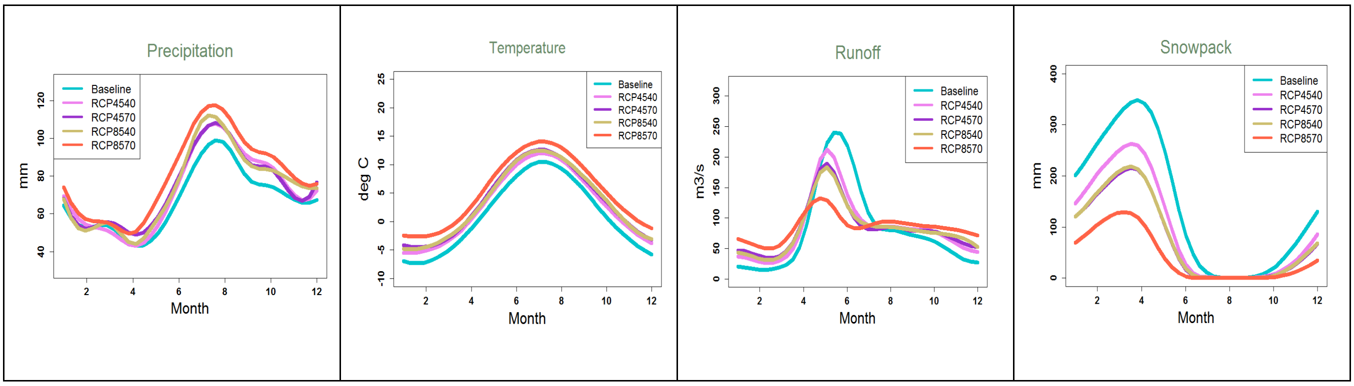

Figure A: Altered hydrological regime for Gaula in a warming climate

ACKNOWLEDGEMENT

Foremost, I would like to express my gratitude to my supervisor Prof. Knut Alfredsen for the remarkable support in my thesis, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in the time of research and writing of this thesis. I could not have imagined having a better supervisor and mentor for my study. This thesis dealt with a massive amount of data which was not easy to process, and I got continuous direction from my professor about processing, using the right software/tools and getting precise outcomes.

Special thanks to the Department of Hydraulic and Environmental Engineering, NTNU for giving me the opportunity to use the lab with multiple computers which was urgent to finish the thesis within a limited time. Multiple computers accelerated the speed of my task greatly that was impossible with a single computer. Besides, I would like to thank Abebe Adera at NTNU who contributed in this thesis time to time with proper help and advises.

Last but not the least, I express my gratitude to my family for providing continuous support and encouragement throughout my years of study and my friend Elhadi, who helped and encouraged me a lot during this thesis.

Kamrun Naher

DISCLAIMER

I hereby declare that this thesis is my own and autonomous work. All sources and aids used have been referenced.

Kamrun Naher

July 2019

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ABBREVIATIONS

Control period/ Reference period/ Baseline-1976-2005

RCP-Representative Concentration Pathways

RCP4540- Emission Scenario4.5; time period 2040-2069

RCP4570- Emission Scenario4.5; time period 2070-2099

RCP8540- Emission Scenario8.5; time period 2040-2069

RCP8570- Emission Scenario8.5; time period 2070-2099

NVE- Norges Vassdrag-og Energidirectorat

Winter-DJF

Spring-MAM

Summer-JJA

Autumn-SON

1. INTRODUCTION

During the 20th-century earth's average temperature was increased 1~1.2 degree Celsius. Not too much! But is that insignificant? One example can clarify the situation. At the end of the last ice age, Northeast United States was covered by more than 900~1000 meter of ice, the average temperature of the earth was just 2.5~5 degree Celsius less than today.

Climate change threatens the Earth's temperature equilibrium. Although it is not scientifically possible to assign individual weather events to the current climate change, it can be statistically proved that global warming will surge the probability of extreme weather events.[1]

Anthropogenic climate change that will make the freshwater system vulnerable is proved from the observational records. Both climatic (precipitation, temperature, sea level rise, CO_2 concentration) and non-climatic drivers (socioeconomic development, land use change, water demand changes) are responsible to change the freshwater ecosystem. In a general global analysis for the period 1948-2004, a significant change in the streamflow was found from several large rivers. Intensifying competition among agriculture, ecosystems, industry, energy production due to reduction and alteration in surface and groundwater could make the situation worse than imagination while already 80% of world's population is suffering from water security (IPCC, 2014b).

Europe is well watered with many permanent rivers, climate change impact in Europe will be different for different parts of it. Annual runoff is projected to increase in the north (15%), decrease in the south (23%) and unchanged in central Europe. The southern part will have a larger negative effect than others, however, the northern part will also have to suffer due to the alteration. Though the northern part is projected to be on beneficial site at the mid of the century, at the end of the century, the effect could be negative for this part as well. In addition to that, summer drought is observed all over Europe and the risk of flood is high in the eastern and northern part of Europe (IPCC, 2008).

In the Arctic, warming is the largest, and precipitation will fall as rain instead of snow which will make the winter a wetting season and summer a drying season from the results of Coupled Model Intercomparison Project phase 5 (CMIP5). Precipitation anomaly will be seen everywhere, and the projection is extreme in higher latitudes. Glacier melting and shrinking will affect the source of water severely (IPCC, 2014b). Changing precipitation and runoff

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[1] https://climate.nasa.gov/effects/

pattern will change energy production as well since consumption, production, etc. are related to climate and water. Water quality is also predicted to be changed due to climate change (IPCC, 2014a). The declining rate of precipitation have resulted in severe degradation in the ecosystem of most delta regions of China, Pakistan, India and Bangladesh and water temperature rise in Rhine river is projected to increase by 1-2.4^{o}C within 2050 (IPCC, 2008).

Climate and weather have a great influence on people's lives. IPCC enforces to meet 2^{o}C rise in mean global temperature, otherwise, there will be a high risk of damage in the earth if the rise in temperature is higher than 2^{0}C. Climate change is already happening and the severity of it depends on how much will be the change and the adaptability.

1.1 Objective

'Klima i Norge2100' has given the climate adaptation policies, however, the gap between the policies and decision makers' choice is needed to be made to cope with this climate change. The report (Klimaprofil Sør-Trøndelag, 2016) is also limited to the information of changes due to an extreme climate (f. ex. flood values, precipitation change, rising temperature) and not in detailed planning for the management. These extreme values will affect the hydrological cycle, river hydraulics, power production, water temperature, stormwater management, vegetation, etc. Since an integrated water resource modelling should be done to avoid/ reduce the impacts and to adapt these changes, this study is done to give an overview of Gaula catchment on how the responses in the catchment will be due to the changing climate. The study is focused on the following points below:

- How will be the future changes (2040-2099 from 1976-2005) for precipitation and temperature for Gaula from the downscaled climate data?

- Is the annual and seasonal runoff increasing or decreasing from the present condition?

- How is the changed runoff going to impact on Lundesokna power plant?

- How are the low (summer) and high (winter) flow affecting the river?

- Is the air temperature increasing water temperature as well?

- Effect of temperature increase in surroundings.

1.2 Study Site

Gaula is a natural 150.6 km long river situated in the south of Trondheim. It starts from a mountainous region (highest elevation-1325 masl) in Sør-Trøndelag and draining in the north through Gauldalen towards the Trondheim fjord (Figure 1-2). Gaula has a large catchment area almost 3635.8 km^2 and specific runoff 27.1l/(s*km^2). Most part of the catchment is snow mountain, forest and marsh area (Figure 1-4). The river is flowing through Holtålen, Os, Midtre Gauldal, Trondheim and Melhus municipalities (Figure 1-3) (nevina.nve.no). Gaula gets its highest peak runoff at spring when the snow is melting, sometimes the rain is also added with the snowmelt in spring (Klimaprofil Sør-Trøndelag, 2016).

Haga bru station (near Støren) is used to measure the discharge in Gaula. In this study, data from Haga bru catchment (area 3069 km^2 and specific runoff 27.6 l/(s*km^2)) (Figure 0-1)was used for HBV model. Sokna river (downstream of Lundesokna hydropower system) is situated at the east side of Gaula (after some distance from Haga bru station). Lundesokna hydropower system used in nMAG for hydropower simulation has a total catchment area (including Burusjøen and Holta) of 395 km^2 and an average annual runoff 12.1 m^3/s (381 Mm^3/yr) (Casas-Mulet et al., 2014).

For hydraulic modelling in HEC-RAS 5.0.6, the river from Støren to the fjord (almost 38km) was used which has the highest elevation of 57 masl.

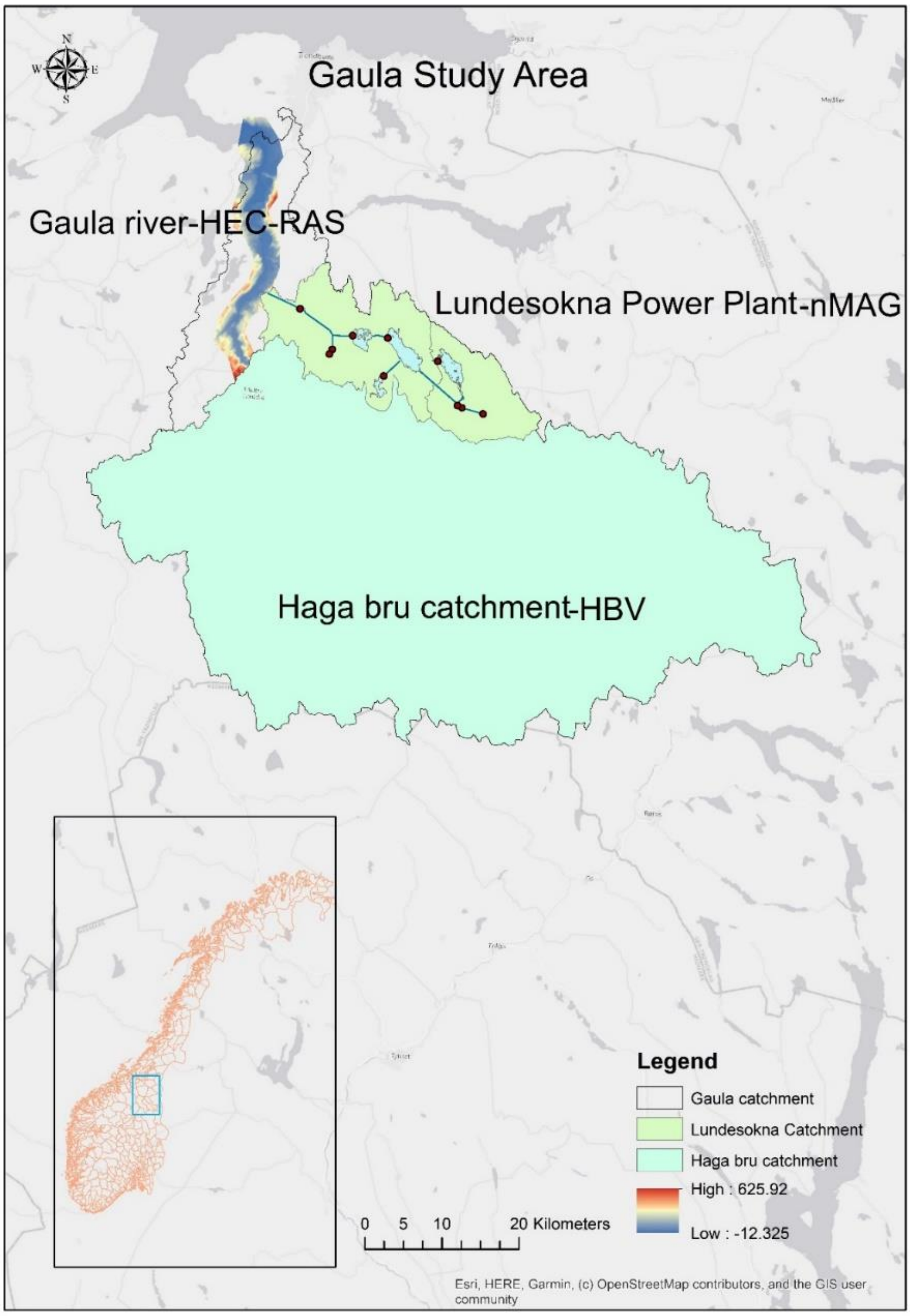

Figure 1-1: Study site

Different parts of the catchment used in different modelling as shown in the figure above.

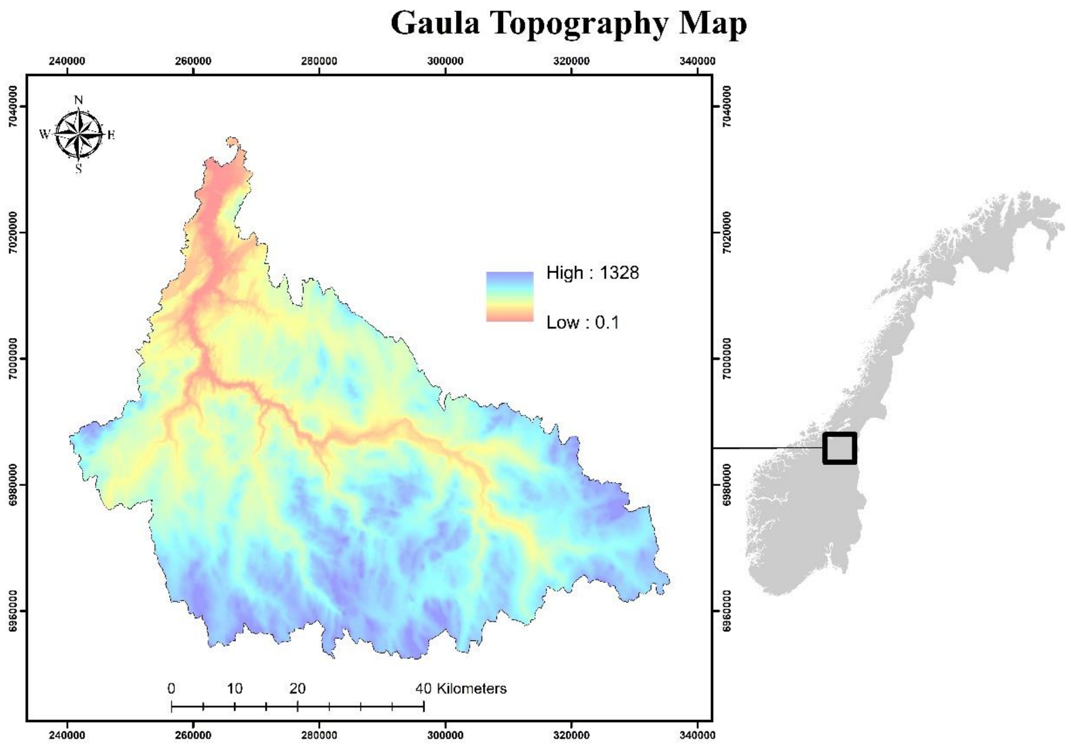

Figure 1-2: Gaula topography map

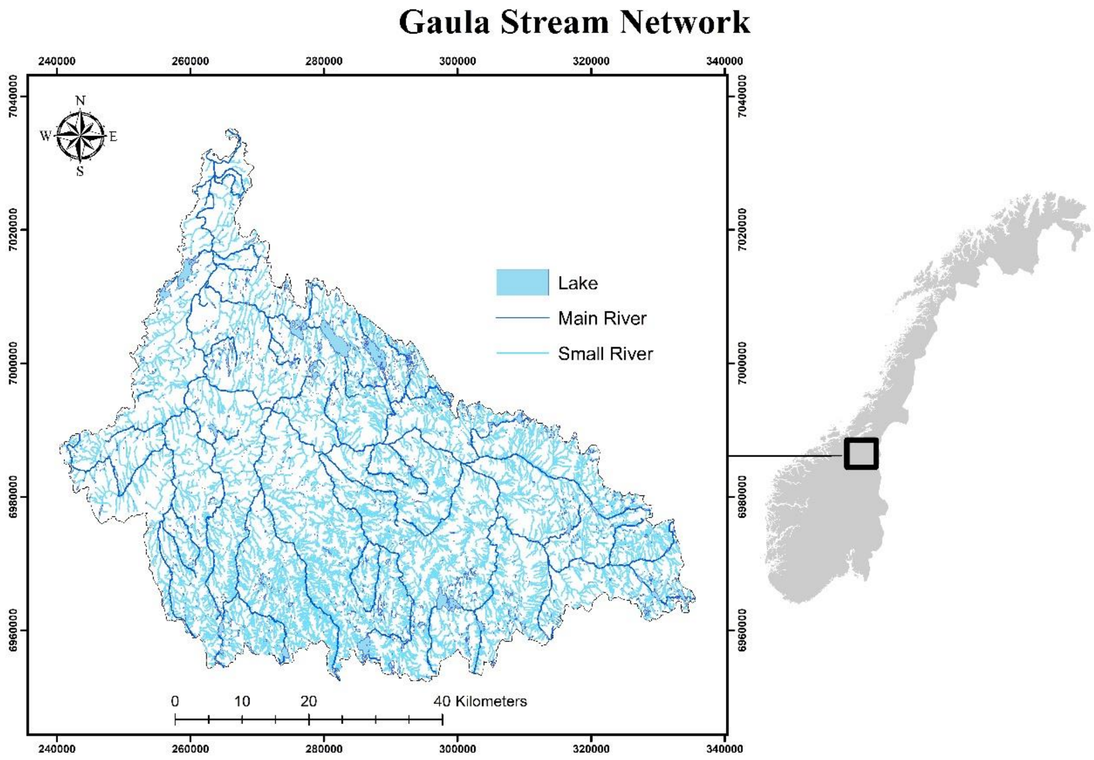

Figure 1-3: Stream networks in Gaula

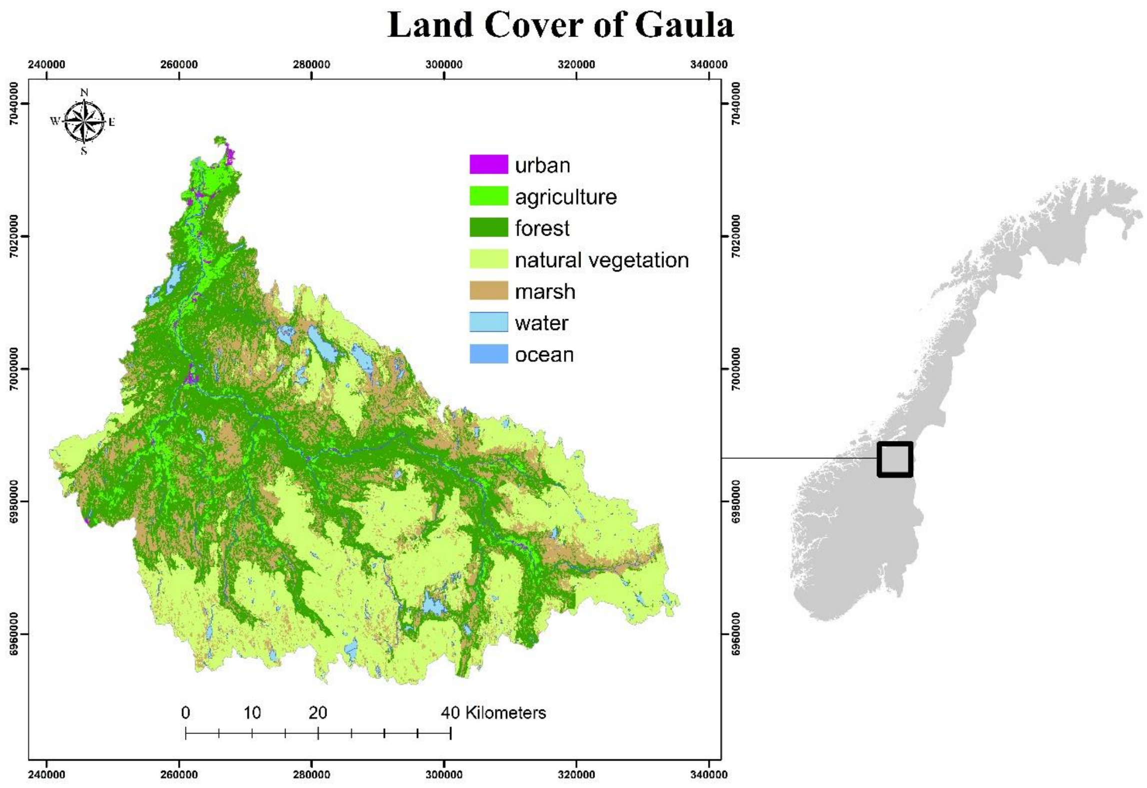

Figure 1-4: Land cover in Gaula

2. LITERATURE REVIEW

This chapter will give a brief on literature review for cold region flow regimes, hydropower and water quality changes due to climate change.

2.1 Flow Regime Change

Anthropogenic changes in the climate will be affecting severely and will lead to unstable regional trends on the flow regime and in the north, the change is strong and significant. According to (Andréasson et al., 2004), in Sweden, an increase in temperature 2.5-4.6^{0}C and in precipitation 7-23% will change the mean annual runoff by 5-24%. However, the changes are different for different regions. Six water basins were studied, and the results showed that in northernmost basin Suorva, snow accumulation is not affected much, and the hydrograph is not so different for future periods compared to the present, while the spring peak is reduced in Kultsjon in the north. The mountainous north-western part has the highest increase in runoff and in the southern part the impact is the opposite. Lule river in Sweden will also have increasing mean annual runoff and earlier spring flood in future climate scenarios (Graham et al., 2007).

Norway has also similar phenomena like the cases in Sweden. An increase in annual precipitation 18% and temperature rising 4.5^{o}C is going to affect severely Norwegian flow regime at the end of this century. The changes are dissimilar from region to region. Increasing trend of precipitation and temperature is seen from all the regions for all future periods (2031-2060 & 2070-2100) and all emission scenarios (RCP45 & RCP85). The study finds that days with extreme precipitation are also higher and severe. Compared to the other seasons, summer precipitation is the dominating one and Finnmarksvidda (north of Norway) is the region where the precipitation and temperature are expected to be the highest. The runoff changes are higher in Nordland, Vestlandet and Østlandet. The change is somehow lower or negative for Trøndelag, Sørlandet, Trøms and Finnmark. A severe reduction for snowpack will happen near the coastal areas and the inland mountain will also lose a large amount of snow in 2100 (Hanssen-Bauer I. et al., 2015).

Northern-Norway's runoff is dependent more on glaciers than other parts of Norway. At the mid of the century, glaciers will be melting and will give a rise in flow throughout the spring and summer period and at the end of the century, the retreat of glaciers will reduce the summer flow and the average flow as well in northern-Norway (Beisland et al., 2015).

Gudbrandsdallågen in east Norway is a glacierised catchment and at the end of the century, flow is going to be reduced than the mid of the century (Beisland, Koestler, et al., 2017).

Flow rising in Westland is comparatively highest (average annual 2-9%) among the other regions in ‘Klima i Norge2100’. A study done on ‘drinking water resources in Bergen’ shows that in future there will be no deficiency for drinking water supply and winter drought extremes will also be gone (Riisnes and Erle Kristvik, 2015) which shows good evidence of rising flow in Bergen. Moreover, a rising pattern of precipitation will increase probable maximum flood 4-15% and design outflow flood 6-29% in future for the dams in Aurland hydropower systems (Chernet et al., 2014). In addition to that, annual runoff is predicted to increase in Aurland catchment approximately by 7% (RCP4540), 8% (RCP4570) 6.7% (RCP8540), 15.6% (RCP8570). The summer flow is decreasing and it is more than 20% for RCP8570 (Graaff, 2019).

For Trøndelag region predicted runoff from ‘Klima i Norge2100’ is negative for all the scenarios and periods. (Klimaprofil Sør-Trøndelag, 2016) indicated a very small increase in runoff for Sør-Trøndelag due to extreme precipitation and melting of snow. (Roald et al., 2006) studied 25 basins in the Norwegian mainland to observe the impact of changing the climate on streamflow. Dynamically downscaled data for Precipitation and temperature based on RegClim from two global climate models HADAM3H and ECHAM4/OPYC3 and emission scenario A2 and B2 were used to do the analysis for the period 2071-2100 compared to 1961-1990. An annual increase of 5-20% (3-25 mm) of precipitation was found for most of the basins with a rising trend in all basins (exceptional: east Norway) for all seasons and all scenarios.

Gridded water balance model (a spatially distributed version of HBV) was used for hydrological simulations. The common trend found from the results is increasing runoff in the West and for Mid, East and North both increasing and decreasing trends. Seasonal streamflow is also varying for regions and models. Higher winter and lower summer flows are common for all the basins. In contrast to that, spring and autumn flows are varying for the basins and the models as well. None of the models are giving a positive change in runoff for Mid-Norway except ECHAM4B2. Rathe and Aursunden in Mid Norway are having an increase in annual, winter and autumn runoff for HADAM3HB2, HADAM3HA2 and ECHAM4B2. Besides, spring runoff is varying and summer runoff in decreasing for all catchments. Jonsvatnet and Benna are two water supplying reservoirs in Trondheim and they were studied to find the future capacity of supplying water and an increase of 0-5% for Benna and 5-10% for Jonsvatnet were found from the study of (Ånund Killingtveit and Knut Alfredsen, 2016). (Graaff, 2019) studied Orkla catchment and found 4.7% (ca) annual increase in runoff for RCP8570. Percent change in spring runoff is negative and in summer the change is small with both negative and positive value.

2.2 Hydropower Changes in Cold Regions

Hydropower is the world's largest (78%) renewable source of energy which can reduce CO_2 emissions and provide secured electricity supply as well. According to (Berga, 2016), climate change will have a small effect on the existing hydropower production and more potential is possible to add in coming future climate. (Hamududu and Killingtveit, 2012) also agreed that in global level hydropower production is going to be increased in a small amount. However, since hydropower is solely dependent on hydrology, change in climate will affect the existing system.

(Lehner et al., 2005) found that, in Europe existing hydropower potential is going to be on the negative side (around 6%) in 2070 while Scandinavia and Russia will produce 15-30% more, southern Europe 25% less and the UK, Germany will produce the same amount of energy as they are producing now. An increase in northern Europe and a decrease in other parts of Europe have been found by (Hamududu and Killingtveit, 2012). Energy sector in Europe will be in a jeopardizing situation due to increasing temperature (Tobin et al., 2018; Vliet, Michelle T. H. van et al., 2012) and southern Europe will be more vulnerable than northern Europe and hydropower sector will also be at risk due to this (Tobin et al., 2018; Vliet, Michelle T. H. van et al., 2012).

Lule, Ume, Ångerman and Indal rivers in northern Sweden are the highest water energy producing rivers in Sweden and an increased runoff will be an advantage both for power companies and ecosystem (RENÖFÄLT et al., 2010). Hydropower production in Sweden will experience alteration depending on the location of the river basin. Almost 50% of energy is produced from Hydropower in Sweden and Lule river basin alone produces 20% of Hydropower energy. (Graham et al., 2007) investigated by using different regional climate models and found hydropower production will increase by 34% (range varies from 18 to 59%) from the existing condition. Manicouagan water system, Canada will face negative plant efficiency due to excess spill with increasing power production (Haguma et al., 2017). Moreover, the Columbia river basin in Pacific Northwest is also going to have increased production in future winter, conversely, decreasing flow in summer will give low energy production (Boehlert et al., 2016). (Schaefli et al., 2007) analysed future hydropower performance for 2070-2099 period compared to 1961-1990 and found a negative impact (36% median decrease) for the increasingly high temperatures in Swiss Alps. In addition to that, for the massive retreat of glaciers, the runoff will decrease at the end of the century in Vispa valley, Switzerland which will make a clear negative impact on hydropower systems (production decrease by one third) (Finger et al., 2012). Great Lakes in the U.S was studied with transient GCM scenarios and the results were found negative for all scenarios for Hydropower potential (Chao, 1999). Norwegian hydropower system will face similar situations as the international cases stated above. A detailed study was tried to do on the Norwegian hydropower system to understand how changing climate will affect it in different regions and different systems.

An overview over whole Norway's energy production responses for the future climate was done in 'Et væravhenging kraftsystem-og et klima i endring' (Beisland et al., 2015). One emission scenario (RCP8.5) and 10 GCM-RCM combinations models for two different time periods as climate projections from 'Klima i Norge2100' (Hanssen-Bauer I. et al., 2015) were used to find the climate change effect on power production. An increase of 8.6% and 14.3% production were reported for 2031-2060 and 2071-2100 respectively compared to 1981-2010 time period for the whole Norway. A regular inflow will give less seasonal variation and the consumption of electricity is supposed to be changed in future climate since temperature in summer and winter will be higher than the present conditions.

	Time period	Mid-Norway	North-Norway	West-Norway	East-Norway	South-Norway
Inflow%	2031-2060	6.5	16	11	3.5	6.5
Inflow%	2071-2100	7.5	14	15.5	7.5	19
Production%	2031-2060	6.5	15.6	10	4.4	7
Production%	2071-2100	8.2	12.4	11.9	9.8	16.2
Spill%	2031-2060	9	35	40	-1	20
Spill%	2071-2100	-1	35	81	-1	71

Table 2-1: approximate change (%) in inflow, production and spill for 2031-2060 and 2071-2100 from 1981-2010 (Beisland et al., 2015)

From this table above, it is seen that increasing spill percentage in Mid-Norway and East-Norway is quite smaller than North, West and South Norway. It is also stated that in Mid and East-Norway, the system is mostly unregulated than other places in Norway and due to a regular flow into the system, utilization will be increased in these places.

Table 2-1 is showing that in Norway, power production will be altered for different regions in a different way. Even in the same system, there are too many things to consider. Two studies found from NVE are presented here:

Glommavassdraget-Glomma river basin has three parts with different topography and geographical conditions Gudbrandsdallågen, Østrerdalen and Nedre del. The first one (regulated) is dependent on glaciers, the second one (variated regulation) on the mountain areas and the last one (unregulated) is dependent on these two and local rivers. However, due to climate change, three of them will experience different scenarios. In Gudbrandsdallågen, production will decrease in 2100 than in 2050 due to the retreat of glaciers. Østerdalen has to handle more spill and unproductive production compared to the other two. Nedre del's dependency on the run-of-river system will increase its efficiency due to flow continuity in the system (Beisland, Koestler, et al., 2017).

BKK Kraftverk- BKK power system has six water basins (Sammangervassdraget, Modalsvassdraget, Matre-og Haugdalsvassdraget, Bergdalsvassdraget, Herlandsfossvassdraget, Eksingedal-og Teigdalsvassdraget) and they are in different altitudes and have a different regulation system. Power production, reservoir volume are not also equal for all of them.

Due to the warming climate, snow volume will be reduced tremendously for Herlandsfoss (300masl). Bergsdalsvassdraget (900masl) will have much better condition than Herlandsfoss and change in inflow to the system is positive in higher altitude and almost no change in lower one and a middle one Matrevassdraget (600 masl) will face a medium positive increase in inflow.

Unregulated/ low regulated systems in BKK will face unproductive spill while the regulated one (Ulvik II) has a prediction of increasing production middle and the end of the century. Large inflow in 2100 is reducing the utilization percentage in the Ulvik II system because that inflow will exceed the limit of the reservoir (Beisland, Birkeland, et al., 2017).

The same models, scenarios and future periods were used in 'Klimaendringer i Glommavassdraget' (Beisland, Koestler et al., 2017) and 'Virkninger av klimaendringer på BKK's kraftproduksjon' (Beisland, Birkeland, et al., 2017) from 'Klima i Norge2100' and a short summary between them is given below (Table 2-2):

Hydropower system	Glomma	BKK
Location	Eastern Norway (Sør-Trøndelag, Oppland, Hedmark, Akershus and Østfold; source:NVE)	Western Norway (Nord-Hordaland)
System	Less regulation	More regulation
Hydropower simulation model	Vannsimtap	Vannsimtap
Total production (average annual)	12TWh (9% of total production in Norway)	6.6TWh (5% of total production in Norway)
Source of runoff in future	Melted glacier	More rain instead of snow
Inflow RCP4540	Increasing 1%(ca)	Increasing 2.5%(ca)
Inflow RCP4570	0%	Increasing 4%(ca)
Inflow RCP8540	Increasing 3.1%(ca)	Increasing 5%(ca)
Inflow RCP8570	Increasing 3%(ca)[2]	Increasing 11%(ca)
Inflow peak	Reduction in peak in a certain amount and shifting of hydrograph backward in a small amount	Moved from spring to autumn
Production change	Increasing for all cases	Increasing for all cases
Seasonal production	Increasing all over the year except summer (JJA)	Increasing all over the year except summer (JJA)
Spill	Decreases (more for RCP8570)	Increases (more for RCP8570)
%of utilization	Increases (almost same for RCP45 and RCP85) due to an even flow throughout the year	Decreases (more for RCP8570) due to high flow than capacity

Table 2-2: Short comparison summary between Glommavassdraget & BKK kraftverk (control period 1981-2010 future period 2031-2100)

Table 2-2 is showing how two large hydropower system in Norway are predicted to behave in the future. It is evident from this table that in future regulation system, location, source of inflow will be influencing hydropower system in different ways.

(Graaff, 2019) studied with the same climate models and emission scenarios for four hydropower systems (simulation in nMAG) in Norway situating north (Alta), south (Mandal), central (Orkla) and west (Aurland) of Norway and the results are given below (reference period 1971-2000, future 2040-2069 &2070-2099):

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[2] Runoff decrease due to melted glacier

	Alta	Orkla	Aurland	Mandal
RCP4540	15	2	8	-3
RCP4570	17	4	8.5	-4
RCP8540	16	3	6	-3
RCP8570	32	7	14	-4

Table 2-3: Annual production change in % (approximately)

Annual production is increasing for three while southern Mandal is different. Seasonal production in Alta is positive for all seasons, Aurland has a negative on summer and Orkla and Mandal have negative both in spring and summer (Graaff, 2019).

Though Mandal has a negative production from (Graaff, 2019), however, (Palou Angles, 2015) did a study using 5 climate models and 9 scenarios (CNRM-RCP45 & RCP85, ICHEC-RCP26, RCP45 & RCP85, IPSL-RCP85, MOHC_HADGEM2-RCP4.5 &RCP8.5, MPI_ESM-RCP85, HADM-A2 & B2 emission scenario) from EURO-CORDEX to see the impacts on hydropower resources in Mandal and found an increase of 4% (by using nMAG) for the period 2071-2100 compared to 1971-2000.

(Chernet et al., 2013) studied Aurland hydropower system for HadAm3HA2, HadAm3HB2 and ECHAM4B2 models and found 11-17% of increasing inflow to the power plant and 9-20% increase for hydropower generation (by using nMAG) for the period 2071-2100 compared to 1961-1990.

Expensive measures are needed for the hydropower systems in cold regions due to the operational constraint (ice jam, frazil ice) created by ice (Gebre et al., 2013). Orkla hydropower was studied by (Timalsina et al., 2015) to observe the effects of climate change on ice regime and it was found that ice period will be shortened in a warming climate and production will be increased in winter. (Harby et al., 2016) used ECHAM4/OPYC3 GSDIO (emission scenario IS92a, domain 2) to study the climate change effects in regulated Orkla river and found increased production, less spill and shortened period of surface ice cover for the period 2020-2049 compared to 1980-2009. However, (Gebre et al., 2014) mentioned that reduction in ice-covered days may bring both positive and negative impacts for future hydropower. Reduction on the duration and static ice loads will be on the positive side and unstable winter will be on the negative side. As mentioned by (Prowse et al., 2009), economic sectors in Northern Canada including hydroelectric sector have been facing great challenges due to changing weather and snow/ice-dependent hydrological regime changes will impose economic and operational problems in a warm climate. Nonetheless, proper modification strategies like building an artificial reservoir and deeper study for adjusting timing and magnitude of snow and ice might improve the situations. Moreover, (Viers, 2011) stated that changing hydrologic regimes should be taken into considerations for relicensing hydropower, otherwise, that will impact natural and human communities. Public trust is a big issue for hydropower since it is related to the ecosystem, agriculture, irrigation, etc. Besides, it is worthy to mention that electricity price and consumption are factors of air temperature and an integrated model can reduce the revenue loss. Production loss due to low flow can be avoided by slightly optimizing water head and balancing turbine schedules is mentioned by (Gaudard et al., 2013). Due to variation in flow, system performance will be hampered and building new plants are costlier than optimizing turbine (Haguma et al., 2017). As, there exists a great uncertainty in electricity price and consumption in future, therefore, the companies should assess a long-term perspective plan and develop specific tools to avoid risk in their investments (Gaudard et al., 2016). The overall system is changing with the climate. While now winter consumption is higher than the summer and the reservoir filling is done in spring, summer and used in winter, in future that would be different and will be challenging to plan the total system (Beisland, Birkeland, et al., 2017).

2.3 Water Quality

Changed flow regime will affect the quality of water and this will not only be changed for climate but also for land use change, deforestation, urbanization, etc. A long-term study on the aquatic ecosystem on North-America showed that climate change has an effect on water quality (Murdoch et al., 2000). Extreme meteorological events have the possibility to degrade the quality of water. Water quality parameters are a) temperature, p^H, dissolved oxygen, dissolved organic matter and nutrients, b) organic and inorganic micropollutants, c) biological parameters and water quality indicators are fish, green algae and diatoms (Delpla et al., 2009).

Frequent floods will make the water polluted, whereas, droughts and floods have relatively uniform impacts on aquatic biota. Hydrologic diversifications affect the functional organization of streams and rivers and lead to an adaptation of the biota within these ecosystems. By 2070, water stress is predicted to increase in entire Europe. Decreased flow leads to an exposure to UV, rising water temperature, increased concentration on nutrients and pollutants, growing of non-native species, accumulation of organic matter and siltation of sediments, (Sabater and Tockner, 2010) and this sediments result to riparian vegetation. Shortened ice-regime has also an impact on the ecosystem since ice is a major factor for many species nearby and alteration in ice regime might have negative or positive effects on them (Prowse and Beltaos, 2002). A study done on Fennoscandia (Sweden, Finland, Norway) showed that the winter duration in these regions would decrease for the period 2041-2070 and 2071-2100 compared to 1961-2010 period and that will impact the ecosystem obviously (Gebre and Alfredsen, 2014). The aquatic ecosystem has a variable resistance capacity to cope up with the water quality stress during snowmelt, storm, high temperature and in drought. However, there is a threshold limit to sustain with this changing climate and if this is exceeded, a small shift in stress can exacerbate an unequal alteration in the water quality (Murdoch et al., 2000). High winter flow will increase the concentration of nitrogen load and the losses of nitrogen in the river and in the arable root zone, increase the amount of organic and inorganic micropollutants (Arheimer et al., 2005). A study done on the western USA for climate change effects showed that increased winter flood would cause decline the habitat of brook trout (Salvelinus Fontinals) and brown trout (Salmo trutta) habitat by 77% and 48% respectively since they are sensitive to high flows after spawning (Wenger et al., 2011). A study done on Norwegian hydropower system by (Graaff, 2019) shown that increasing environmental flow in winter will give a positive effect on salmon.

Water temperature is a vital factor for the freshwater ecosystem since it is a critical determinant of metabolic and physical processes (Wenger et al., 2011). River water has a direct relation with air temperature (Isaak et al., 2012; van Vliet et al., 2013; WHITEHEAD et al., 2009) more than discharge or precipitation, augmentation in the surface temperature will definitely attack the water temperature and chemical, bacteriological processes run faster in higher temperatures. Oxygen concentration fall and this results in fish mortality (WHITEHEAD et al., 2009). Continuous warming in the northwest U.S in the coming century will stress the salmon and trout population and recovering these species would be difficult (Isaak et al., 2012). Due to increasing temperature cutthroat trout (Oncorhynchus clarkii) will lose its habitat by 58% (Wenger et al., 2011). In addition, a study done on the Mediterranean Sea on multiyear droughts showed that the sensitive species might extinct or their number may decline, and replacement of resistant species may appear (MAGALHÃES et al., 2007). However, (Wenger et al., 2011) found that flow regime change will benefit rainbow trout (Oncorhynchus mykiss) habitat in the western USA since this species is sensitive to negative temperature.

A study done by (Vliet, M. T. H. van et al., 2011) on 157 river temperature stations for the 1980-1999 period showed that during heat waves and droughts thermal regime rise is very high and a decrease in discharge from 20-40% exacerbates the water temperature by 0.3-

0.8^{o}C in average. Global mean and high (95th percentile) river water temperatures are projected to increase on average by 0.8-1.6 (1-2.2)^{o}C for emission scenario B1 and A2 for one-third of the global land surface in period 2071-2100 compared to 1971-2000. The projections are high in the U.S, Europe, Eastern China, Southern Africa and Australia. The water quality and fish habitat can be affected potentially in these places (van Vliet et al., 2013). Water temperature is projected to increase for B1-A2 scenario for 2040 and 2080 by 0.7-0.9, 1.4-2.4^{o}C for the US and 0.8-1.0, 1.4-2.3^{o}C for Europe in summer. For cooling water use, low flow and high river temperature are not acceptable. Due to rising water temperature, thermoelectric power plants in Europe and the U.S were forced to reduce production in summer (Vliet, Michelle T. H. van et al., 2012).

Water quality is directly related to the economic sectors because of agriculture, fishing, tourism, energy and another sectors’ dependency on it. Few studies have been done on water quality for climate change effects. Monitoring of water temperature data and change in water management system are necessary to reduce the negative impacts of water quality change effects since this is related to both human and aquatic life.

3. MATERIALS

3.1 Gridded Precipitation and Temperature Data from seNorge2

Met.no provides gridded(1km*1km) and daily updated precipitation and temperature data for whole Norway. seNorge2 has a historical database from 1957 to 2015 and from 2015 to present climate data. According to (Lussana et al., 2018), a spatial interpolation method is used to obtain the precipitation and temperature in dense station areas, data provided by seNorge2 has a better quality due to higher effective resolution. Abebe Adera at NTNU used a R script to get the average gridded precipitation and temperature time series for the reference period (1976-2005) from Norwegian Meteorological Institute by clipping the Haga bru catchment area. Figure 3-1 is showing the gridded points for precipitation and temperature for Haga Bru catchment.

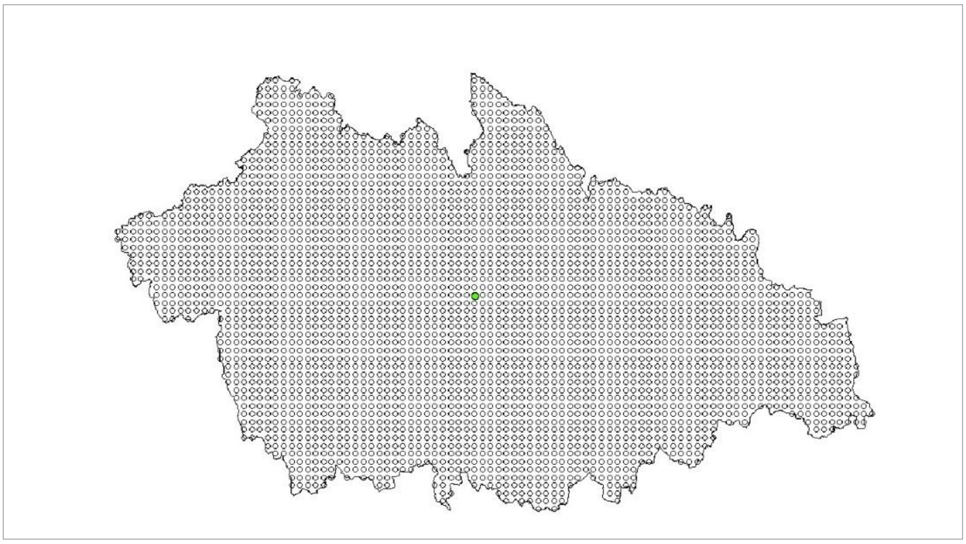


Figure 3-1: Gridded precipitation and temperature data points for Haga bru catchment

3.2 Climate Models and Scenarios

To understand the Earth's climate system, climate models are used widely, and they are able to reproduce the past climate as well as the future. The climate community uses various types of climate models while the models are different in terms of simplicity, equations, components, etc. For instance, the basis of Energy- Balance Models (EBM) are simple energy balance equations and the model is zero or one dimensional, while Global Circulation Models (GCM) have the most complex and detailed representation of the Earth's system. There are also other types of climate models Radiative-Convective Model, Statistical- Dynamic Models, Earth Models of Intermediate Complexity and Regional Climate Models. RCMs have a similar structure like GCMs but in a finer resolution (Abiodun and Adedoyin, 2015). Global Circulation Models (Global climate models) present most of the Earth's system process (sea, air, land) and to simulate the human-induced climate change they are used, and they have grid size varying 100-500 kilometres. Horizontal and vertical areas on the Earth's surface are represented by many grid cells in GCM (Upton-Cosulich, 2014). Since GCMs have coarse resolution they are unable to produce the local features, therefore, downscaling is necessary, and two processes are used Empirical Statistical downscaling and Dynamic downscaling or Regional Climate Modelling. Regional climate models have finer resolution varies from 50*50 to 12*12 km^2 and they are used for the basis of climate projections of atmospheric, hydrologic and oceanographic variables (Hanssen-Bauer I. et al., 2015).

Emission scenarios are used to explore how the future climate will be changed by the influence of human activity and Representative Concentration Pathways (RCP) is the latest scenarios used in the Fifth Assessment Report on IPCC. Greenhouse gases and aerosols are included in RCP. In this study, two RCPs were considered, RCP4.5 and RCP8.5. RCP4.5 considers stabilization to radiative force 4.5 W/m^2, it assumes climate gases will increase up to 2040, and a decrease of greenhouse gases after 2040. RCP8.5 has the continuous emission of greenhouse gases and this is the worst scenario. Temperature rise is expected to be more than 4^{o}C in this scenario (Christian Bjørnes, 2015).

The climate data used in this study comes from an ensemble of the EURO-CORDEX project. Norwegian Climate Service Centre (kss) downscaled the data from EUR-11 ensembles (grid size 12*12 km^2) and provides 1*1 km^2 gridded data for whole Norway. Five different GCM (Global Climate Model) and four different RCM (Regional Climate Model) were used in this study as climate projections (Wong et al., 2016). Norwegian climate adaptation policies are made from these models. Precipitation and temperature downscaled data from kss were taken as climate input for this study and simulated in HBV (Hydrological Model).

Used process

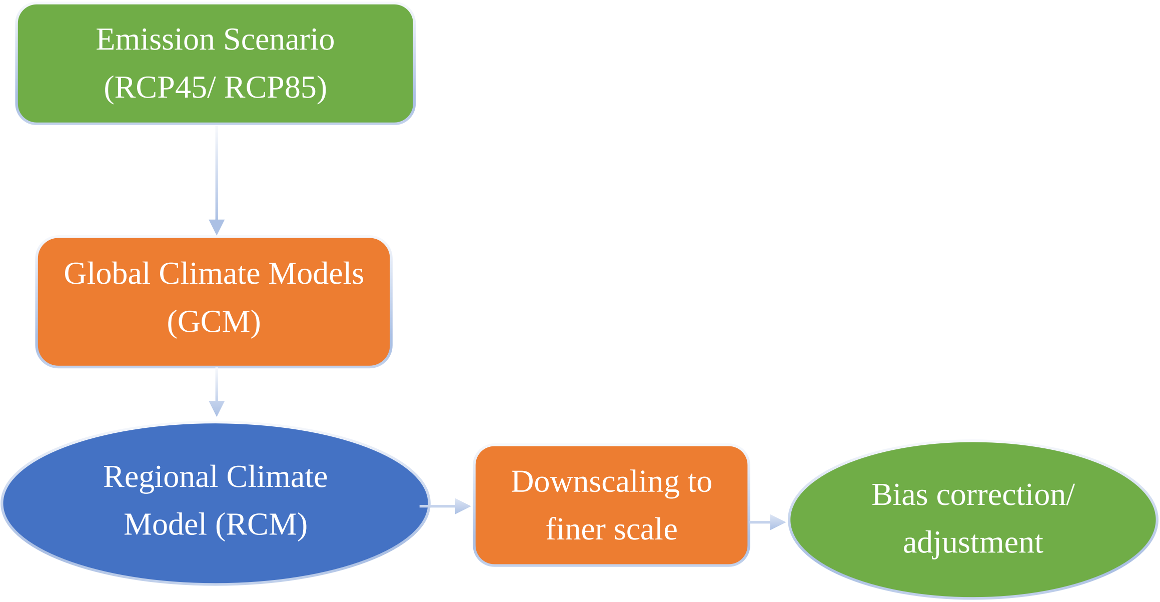


Figure 3-2: Selection of data from climate models

Global Climate Model	Regional climate model	Time period	Institution
CNRM	CCLM	1976-2005; 2040-2069; 2070-2099	Climate Limited-area Modelling Community
CNRM	RCA	1976-2005; 2040-2069; 2070-2099	Swedish Meteorological and Hydrological Institute
EC-EARTH	CCLM	1976-2005; 2040-2069; 2070-2099	Climate Limited-area Modelling Community
EC-EARTH	HIRHAM	1976-2005; 2040-2069; 2070-2099	Danish Meteorological Institute
EC-EARTH	RACMO	1976-2005; 2040-2069; 2070-2099	Royal Netherlands Meteorological Institute
EC-EARTH	RCA	1976-2005; 2040-2069; 2070-2099	Swedish Meteorological and Hydrological Institute
HADGEM	RCA	1976-2005;	Swedish Meteorological

		2040-2069; 2070-2099	and Hydrological Institute
IPSL	RCA	1976-2005; 2040-2069; 2070-2099	Swedish Meteorological and Hydrological Institute
MPI	CCLM	1976-2005; 2040-2069; 2070-2099	Climate Limited-area Modelling Community
MPI	RCA	1976-2005; 2040-2069; 2070-2099	Swedish Meteorological and Hydrological Institute

Table 3-1: Climate models used in this study

3.3 Digital Terrain Model and Depth Data from Høydedata

For hydraulic modelling, depth data (dybdedata-NVE Gaula2016) for the river and a digital terrain model (DTM-1) surrounding it were taken and it was processed in Arcmap10.6. Cell size was chosen 1m by 1m for the mosaic raster since it can provide a better quality for the analysis. For practical purposes and for better analysis, the study area for HEC-RAS was divided into five parts as the reach was quite long (approximately 38 km). The depth data map is available on Høydedata which has cell size 0.25m by 0.25m. Though it was possible to make the combined DTM and depth data raster to make cell size of 0.25m by 0.25m which would give more accurate results, however, it would make a costly computational step, therefore it was avoided, and cell size was chosen 1m*1m to make the terrain model for hydraulic simulations. Flood calculations are also possible from the terrains even though in this study it was only used for flows less than 70 m^3/s. The name of the parts and the tributaries might not be correct since they were taken randomly from the nearest places.

4. METHODS

This chapter is describing the procedures used in this study.

Methodology

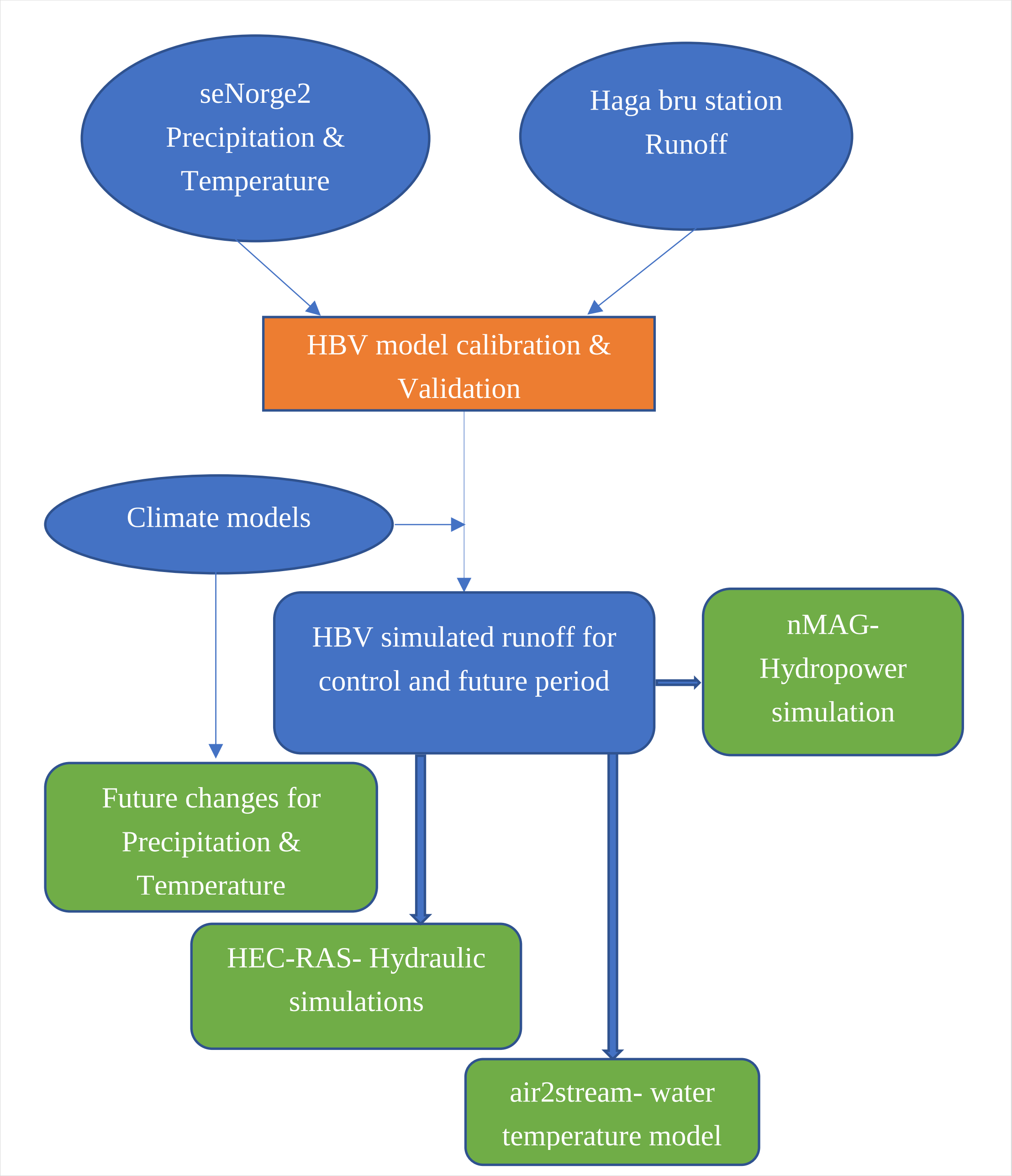


Figure 4-1: Methods used in this study

4.1 HBV-Hydrological Modelling

HBV is a conceptual lumped model and is widely used in Scandinavia. Basically, it is a Rainfall-runoff model which can be used for various purposes like forecasting runoff and floods, filling up missing data and studying climate change effects. The HBV model has four modules; Snow, Soil moisture, Upper Zone and Lower Zone and the model is linear for all modules except the soil moisture routine. Input data for HBV are catchment characteristics, time series of precipitation, temperature, runoff and potential evapotranspiration. The model needs to be calibrated before going for execution. A certain period of time is needed to be calibrated and further, it can be taken to validate a certain period. The parameters used in hydrological responses in HBV can be classified in confined (unchanged and found from maps, surveys, etc.) and free parameters (should be determined by calibration). HBV model efficiency is determined by the Nash-Sutcliffe value (-∞ to +1) and a higher value represents a better fit of the model (Killingveit and Sælthun, 1995).

Observed data (1976-2005) from seNorge2 (precipitation & Temperature daily time series) and Haga bru (discharge daily time series) were given as input to the HBV model. Catchment characteristics (area, hypsography, lake percentage) were found from nevina.nve.no (Appendix A). First, the model was calibrated for the period 1976-1990 against the observed data and then it was proceeded to validate the period 1991-2005. The Nash-Sutcliffe criterion (R^2) found from calibration and validation were satisfactory. Therefore, the model was trusted to simulate for future climate scenarios to find the runoff and snowpack.

4.2 Downscaling and Quantile Mapping

Downscaled and bias-corrected data were downloaded from https://nedlasting.nve.no/klimadata/kss. The data was tried to use directly for the analysis, but it was found that the provided precipitation data from the climate models did not correspond with the measured data. The climate data for the reference period for these 10 GCM-RCM combinations were giving higher values (annual precipitation-1190.33mm) than the observation (annual precipitation- 805.29mm). Post-processing is needed to adjust the model data with the local scale because of systematic biases presence in the regional climate data. Statistical transformations are considered as a popular approach for post-processing since it tries to adjust the distribution of model data with the local one. Even though the statistical process performed well to remove biases from precipitation data, but it was also found assumptions underlying the data affects the performance significantly to the output of the data (Gudmundsson et al., 2012). Abebe Adera at NTNU used 'qmap' package in R to do the correction and adjustment. The present values were corrected and as they are true values and the future values were adjusted as they are unseen (Wong et al., 2016). Afterward, it was found that after correcting the data, the precipitation values from the models corresponded reasonably (Figure 5-4) to the observed data from seNorge2. The pattern of the temperature data from kss (https://nedlasting.nve.no/klimadata/kss) was found well corresponded with the observed data.

4.3 nMAG-Hydropower Simulation Model

nMAG is a Hydropower simulation model developed at NTNU to find the average annual energy production, firm energy and average annual income from a project. Operation strategy on nMAG depends on the hydrology, production system, consumer system and the reservoir operation. It has four modules; reservoir, power plants, inter-basin transfers and control points. Timestep used in this model is monthly, weekly or daily. Compulsory data needed to be given on nMAG are module number, name, reservoir volume, highest and lowest water level, gross head, head loss, maximum discharge and energy equivalent. Usually, in Norway, a minimum of 30 years inflow data is taken as input due to the variation in hydrology as it is possible to observe both dry and wet period in order to avoid over and underestimation of power production (Killingtveit, 2005).

A well calibrated and validated model for Lundesokna hydropower system was taken from (Casas-Mulet et al., 2014). There are three reservoirs Holtsjøen (7 Mm^3), Samsjøen (113 Mm^3) and Håen (25 Mm^3), Burusjøen, Hukla-Holta and Skjellbreia-Bubekken are three inter-basin transfers, three power plants are Sama, Håen and Sokna. Total catchment area for Lundesokna system is 395 km^2. A detailed figure is shown the reservoirs, intakes, waterways and power plants in the Lundesokna system (Figure 4-2). From this study, total production was found 305.255 GWh (period 1986-2009), compared to the baseline (290 GWh, reference period), the deviation is 4.6% which is negligible. However, average annual production now is 330 GWh was found from www.trønderenergi.no. Further, the daily time series of scaled runoff for the future projections were given as input to the nMAG model to find the future inflow (m^3/s), production (GWh), reservoir volume (Mm^3) and spill (m^3/s). Results of the production and the changes are shown in chapter 5.4. The reservoir level can also be found in the thesis draft.

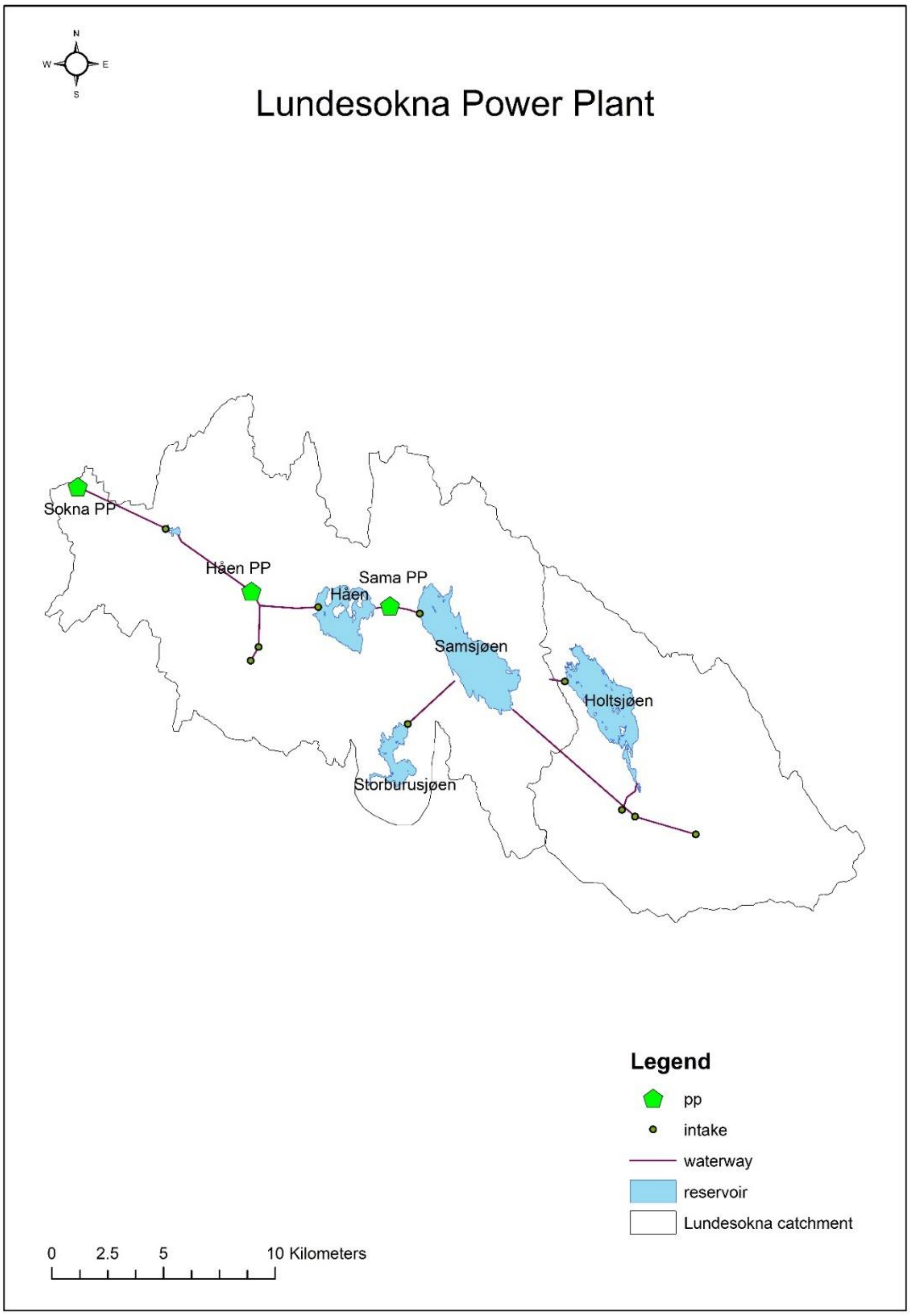


Figure 4-2: Lundesokna hydropower system (reservoir, power plant, intake and waterway data from NVE)

4.4 HEC-RAS 5.0.6-Hydraulic Modelling

To find the effect of decreasing summer/ increasing winter flow changes in future periods, HEC-RAS 5.0.6 (The Hydrologic Engineering Centre's River Analysis System) was used to simulate the river flow. HEC-RAS 5.0.6 was developed by the U.S Army Corps of Engineers

Model calibration-For calibrating the model, an aerial photo captured on 7th June 2016 was taken from norge i bilder (www.norgeibilder.no) to simulate a small part (>1km) close to Haga bru station. The discharge was found on average 68.8 m^3/s (source: NVE) on that day the picture was taken. A visual observation was done by comparing wetted areas and water edge between the simulation depth and the photo. A mesh size of 3m by 3m was chosen and Manning’s number was manually set to 0.03. The computation time interval was chosen 1 minute, mapping interval 10 minutes and the time step was controlled by the courant condition (Maximum courant 3, minimum 0.5). Courant number is a condition of numerical stability based on velocity, distance and time-step. At the upstream of the river a flow hydrograph (30 minutes interval) and at the downstream of the river normal depth with a friction slope 0.01 were put as boundary conditions. The diffusion wave form of equation was used to simulate the scenarios. The sample model was simulated for 24 hours for 68.8m^3/s constant discharge by using a 30-minute hydrograph and the normal depth was set to 0.01.

This calibrated model was used to conduct further simulations for the Gaula river. However, for the part close to the sea normal depth was chosen for the lower boundary condition assuming low tide on that part unlike the previous parts on the simulations.

The same model setup was used to simulate for July twenty-five percentile and January five percentile flows. The simulation period for summer was 24 hours and for winter was 48 hours. Mean annual discharges for the tributaries were calculated from NEVINA. Data input and output were processed in ArcMap 10.6.

Mesh size	3mX3m
Manning’s n (set manually)	0.03
Computational time interval	1 minute
Mapping output interval	10 minutes

Table 4-1: Gaula set-up

Five different discharges were simulated for each part of the river (the baseline, RCP4540, RCP4570, RCP8540 and RCP8570). For the most upstream section, 25 percentiles for July and 5 percentile of January modelled flow data were given as input. The output of the previous section was used as the input in the next section. A steady flow simulation was done to find the wetted areas due to observe the changing flow situations in Gaula. The wetted areas were calculated, and the maps were processed in Arcmap10.6. All the RCPs were compared with the control period/ baseline. Useful information can be found in Appendix D.

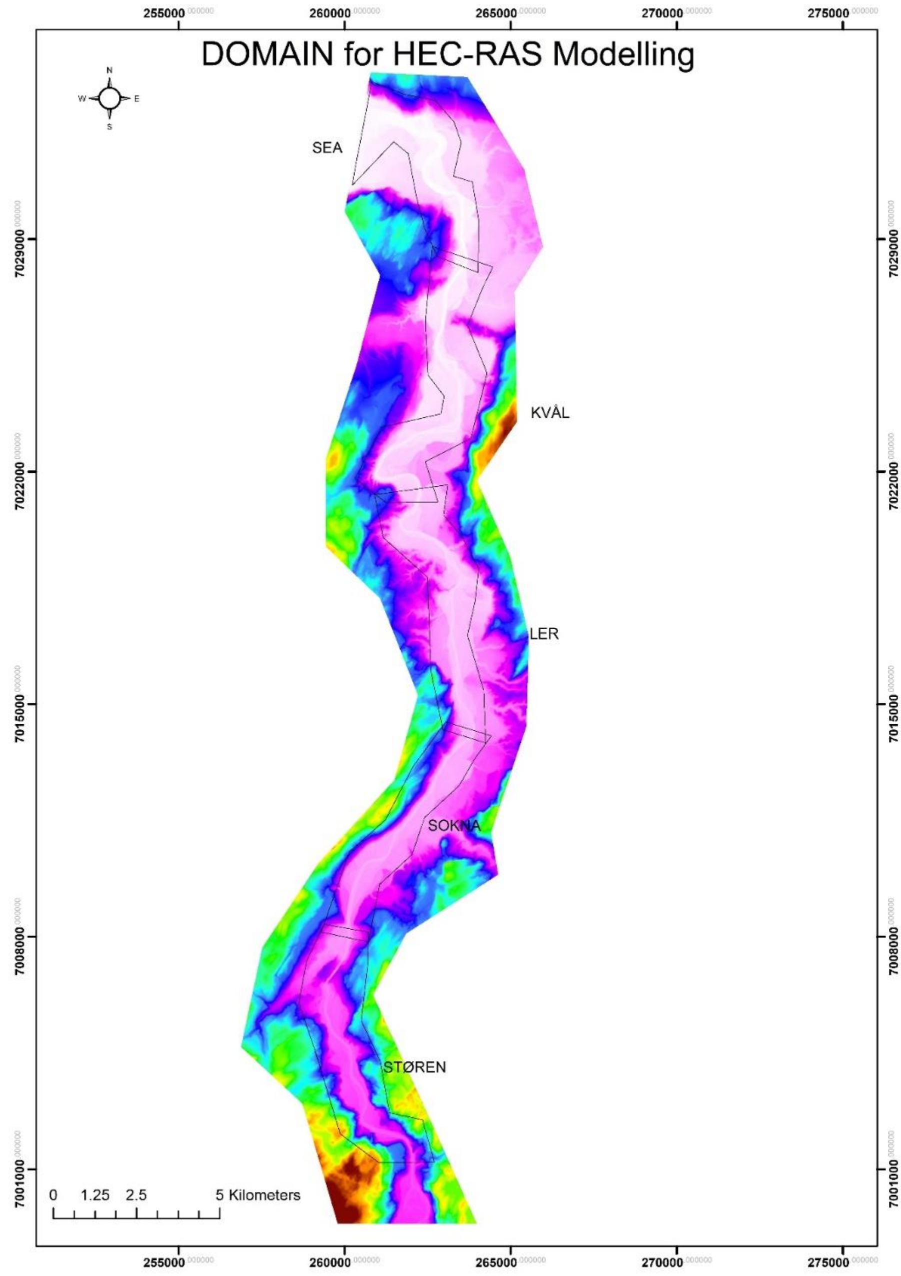


Figure 4-3: Domain for hydraulic simulations in HEC-RAS 2D modelling

4.5 ‘air2stream’-Water Temperature Modelling

‘air2stream’ is a hybrid model that measures the water temperature from the water discharge and water temperature. A daily time series is used as inputs to find the output as water temperature and an intermediate approach is assumed in this model. A single simple differential equation is the final structure of the model. Location of the river does not affect the formulation and Root Mean Square Error and Nash- Sutcliffe Efficiency are used as an objective function for calibration in this model. This model can be an effective tool to depict long and medium-term behaviour artificially. A detail description can be found in (Toffolon and Piccolroaz, 2015).

A well calibrated and validated model for air2stream done for Eggafoss was found from Professor Knut Alfredsen at NTNU. A rudimentary study was done due to lack of time and only RCP8570 was used. Discharges and air temperatures for all ten models were averaged and taken as input in the model. Though this is not a better way to average the discharges, however, to get a full overview of Gaula for future climate, water temperature model was necessary to observe the warming atmosphere on the river. For the baseline, simulated runoff from the station was taken as inflow input and observed temperature from seNorge2 was used.

5. RESULTS AND DISCUSSIONS

This chapter gives the results and discussion on hydrological modelling, climate change, hydropower production, hydraulic modelling and water temperature change for the assessments done in chapter four.

5.1 HBV Model Calibration and Validation

Calibration

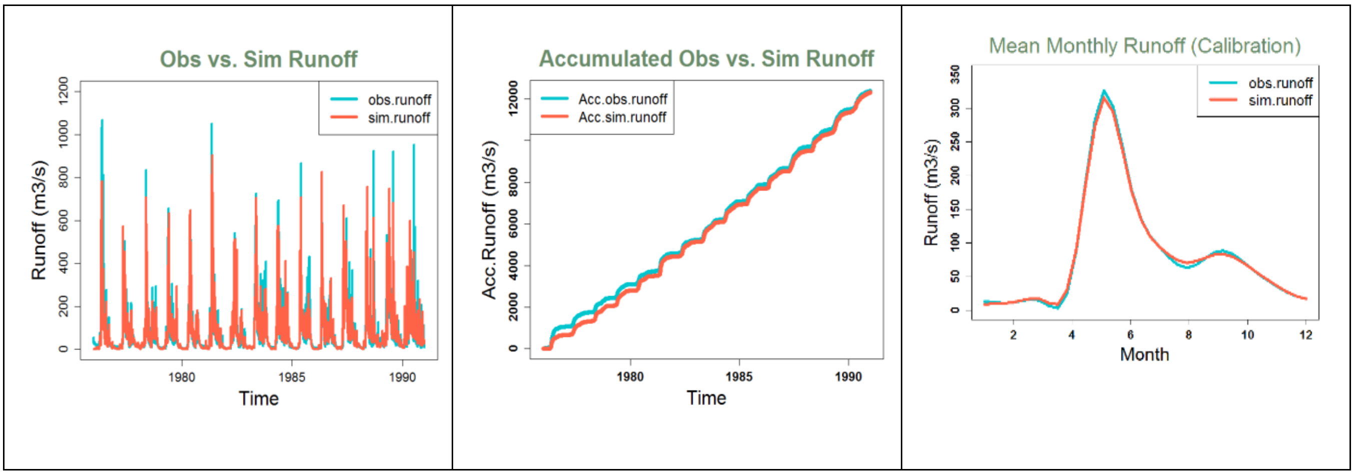


Figure 5-1: (left) Observed vs Simulated runoff; (middle) Accumulated Obs. Vs Sim. Runoff; (right) Mean monthly runoff for calibration period 1976-1990.

The simulated runoff for the calibration period (1976-1990) fitted better with the observed runoff and R^2 value came 0.866. As the NSE value defines the goodness of fit, and a higher value is a sign of a better model, the value 0.866 represents a better fit calibrated model for Gaula. Afterward, the model was validated with the same confined and free parameters for the period 1991-2005, and the NSE value came 0.830.

Validation

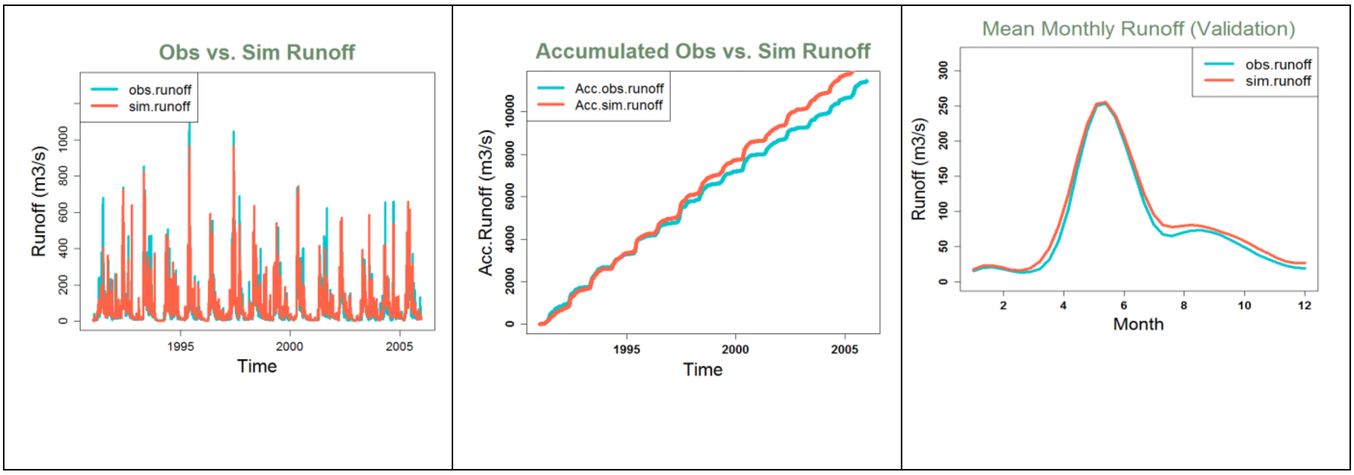


Figure 5-2: (left) Observed vs Simulated runoff; (middle) Accumulated Obs. Vs Sim. Runoff ;(right) Mean monthly runoff for Obs and sim runoff for the validation period (1991-2005)

Nash-Sutcliffe value

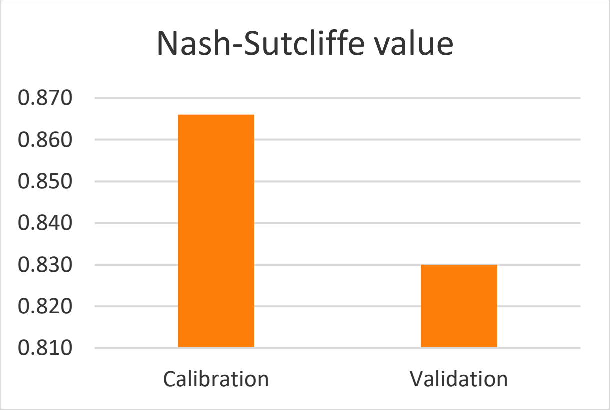


Figure 5-3: Nash-Sutcliffe value for calibration and validation period

From the Nash-Sutcliffe value, it is seen that the calibrated model well validates the period 1991-2005. Therefore, the model was trusted to simulate for analysing the precipitation and temperature data from present and future climate projections.

5.2 Bias-Corrected Climate Data

For the control period, observed data was checked with the climate model's data. Blue line here (P & T) is from observed data and orange is the ensemble mean of the models, shaded lines are the models.

Control period precipitation and temperature

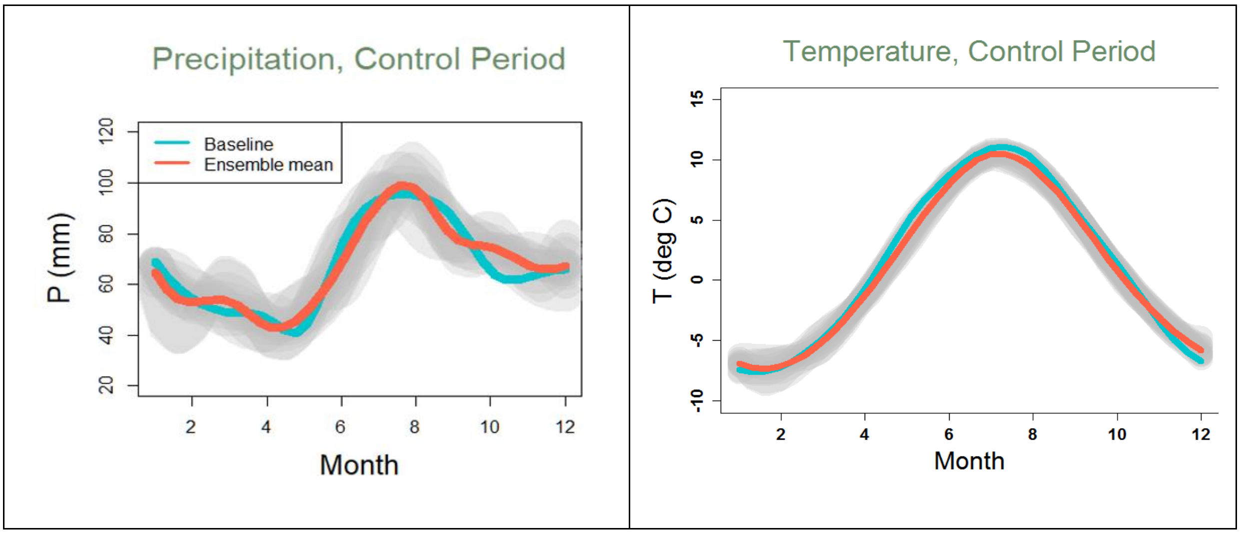


Figure 5-4: Mean monthly Precipitation and Temperature for Control period (Observed vs 10 climate models), Blue line is the observed from seNorge2 data and the orange line is the ensemble mean of ten climate models and the shaded lines are showing the mean monthly of the models.

Figure 5-4 shows that the ensemble mean of all models corresponded in an acceptable limit with the baseline of precipitation and temperature (observed data). The annual precipitation of the baseline was found 805.29 mm and annual precipitation for the ensemble mean is 809.74 mm. EC-EARTH_HIRHAM model gives a value of 806.43 mm and MPI_CCLM and MPI_RCA give the highest 813.3mm as annual precipitation. Moreover, it is clear that the temperature data from NVE has a good correspondence with the observed temperature from Met.no. Model MPI_CCLM has an average higher temperature value (0.81^{o}C) than other models. HADGEM_RCA has also an average higher value of 0.77^{o}C where the ensemble mean is 0.69^{o}C.

Since both precipitation (after correction) and temperature were showing a good correspondence with the observed data, therefore, the data was taken to the HBV model as input to simulate runoff and snowpack.

Simulated runoff and snowpack from Haga bru station are the blue lines in the figure below. Orange is the ensemble mean of the climate models and shaded line are the model values.

Control period runoff and snowpack

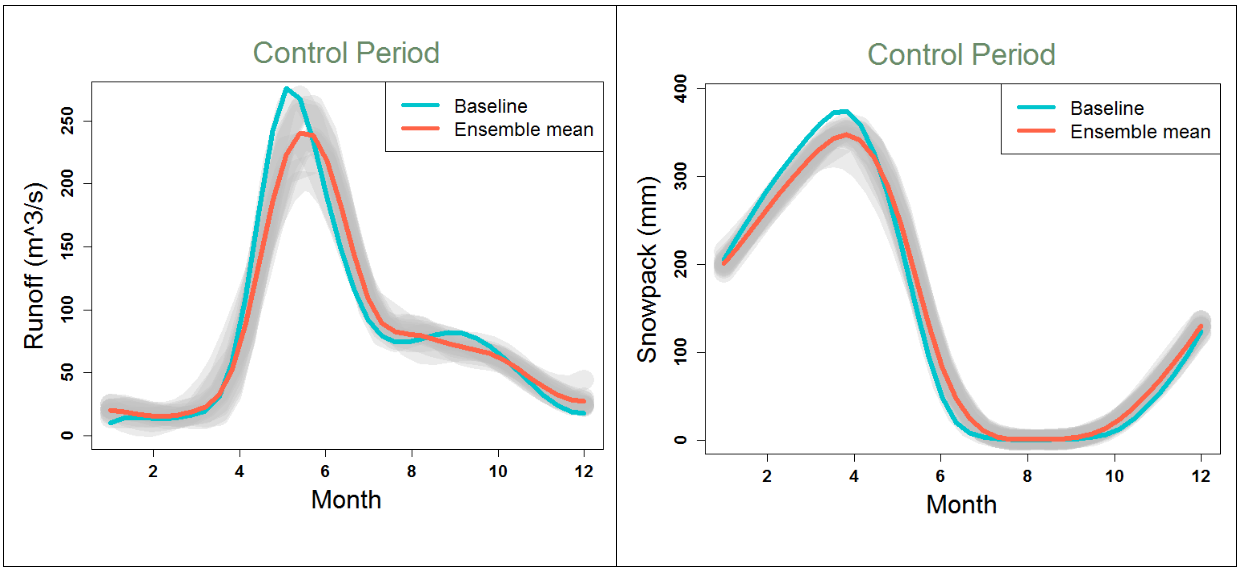


Figure 5-5: Results from HBV model-Mean monthly runoff and snowpack for control period for 10models and baseline (blue line baseline, orange line ensemble mean of the models and the shaded lines are climate models)

Figure above is showing that the ensemble mean of the models is deviating in a small percentage from the baseline even though the inputs are bias corrected. Due to downscaling, the climate data loses some precision because of high non-linearity in the hydrological process and temporal, spatial biases in the inputs (Wong et al., 2016). MPI_CCLM model has a good correspondence with the baseline and the deviation is larger between baseline and IPSL_RCA though the average annual runoff for baseline, IPSL_RCA and MPI_CCLM are 79.6 m^3/s, 79 m^3/s and 78.6 m^3/s respectively.

As the downscaling effect is very small, bias-corrected and adjusted data was taken for further analysis.

5.3 Climate Scenarios in the Future

In this section, bias-corrected (modelled data 1976-2005) data was compared with the bias-adjusted (modelled 2040-2099) data. This section will give an overview of a changed hydrological regime for Gaula. For analysing the data, mean monthly values are plotted in the figures, the blue line is the control period/ reference period, orange is the ensemble mean of the future models and the shaded lines are the mean monthly values of the models.

Future precipitation Gaula

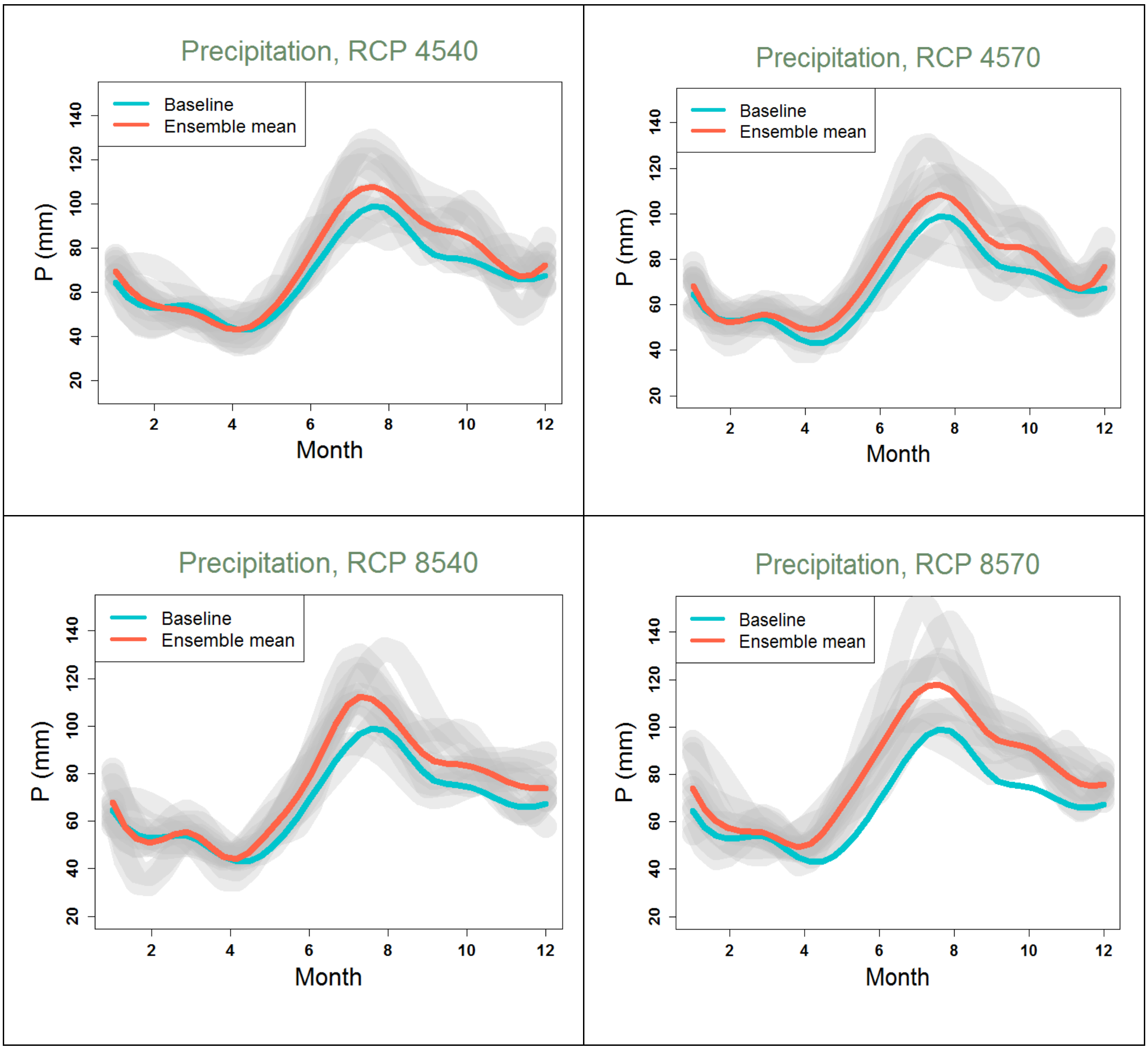


Figure 5-6: Mean monthly precipitation for different climate scenarios with all models

The Figure above shows how the precipitation is projected to change for future climate scenarios. It is clearly seen that; precipitation increment is almost for all months for all scenarios. The increment is not seen in all the models from the reference period in RCP4540, RCP4570 and RCP8540. RCP8570 is showing increase almost for all the models although, MPI_RCA, MPI_CCLM and CNRM_CCLM have some lower values compared to the baseline for the winter period. HADGEM_RCA and IPSL_RCA models have higher projections for precipitation among others.

Future Temperature Gaula

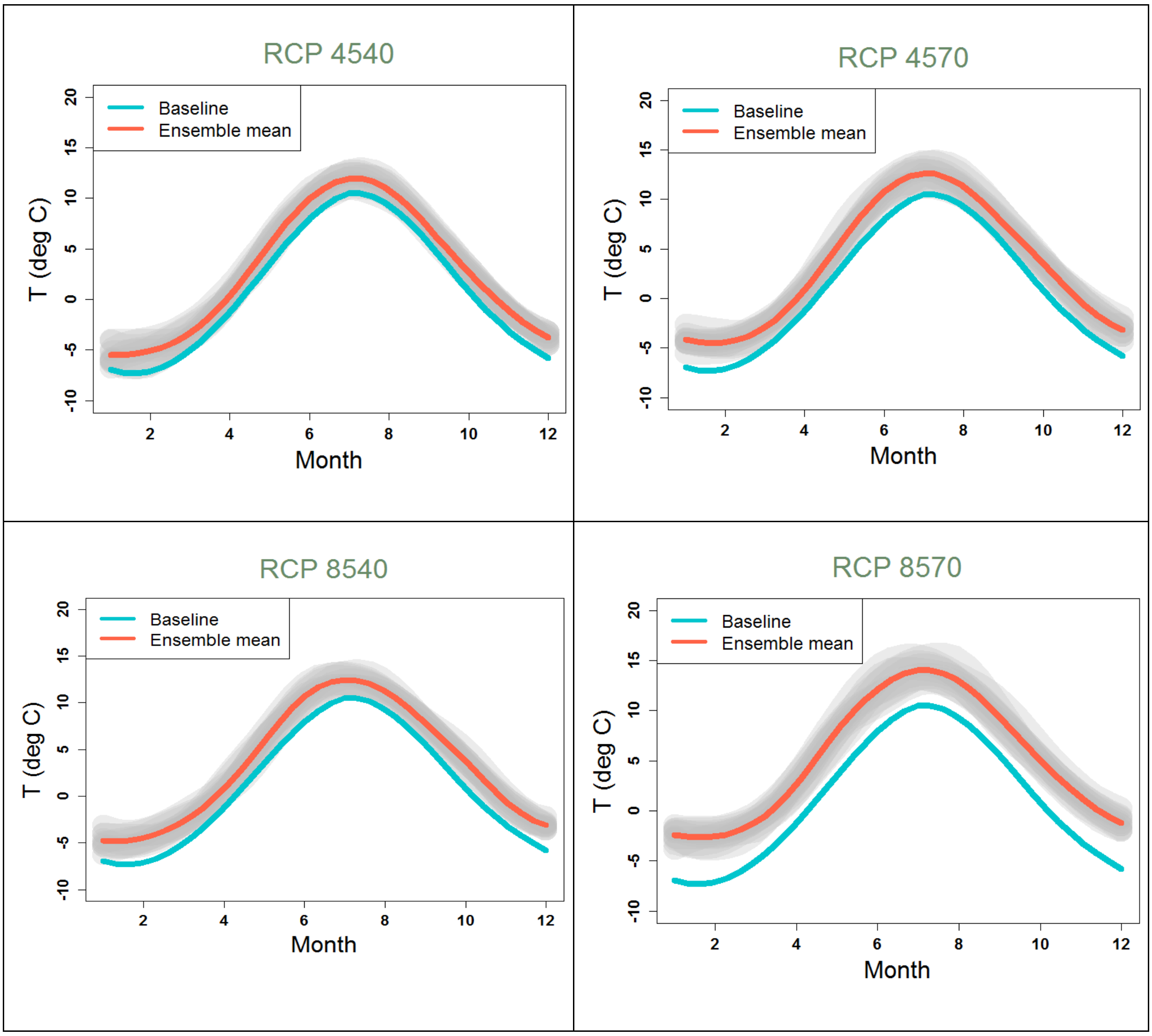


Figure 5-7: Mean monthly temperature for different climate scenarios with all models

A clear evidence of rising in temperature is distinct in Figure 5-7, all models agreed on increasing temperatures on future climate. HADGEM_RCA is the warmest and MPI_RCA is the coldest model. For RCP4540, the upper curve of temperature is for HADGEM_RCA combined with IPSL_RCA and the lower one is MPI_CCLM with MPI_RCA. For the rest of the scenarios, the patterns were found almost the same. HADGEM_RCA has a higher prediction of average annual increase than other models 2.55^{0}C for RCP4540, 3.3^{0}C for RCP4570, 3.13^{0}C for RCP8540 and 5.34^{0}C for RCP8570.

Future Runoff Gaula

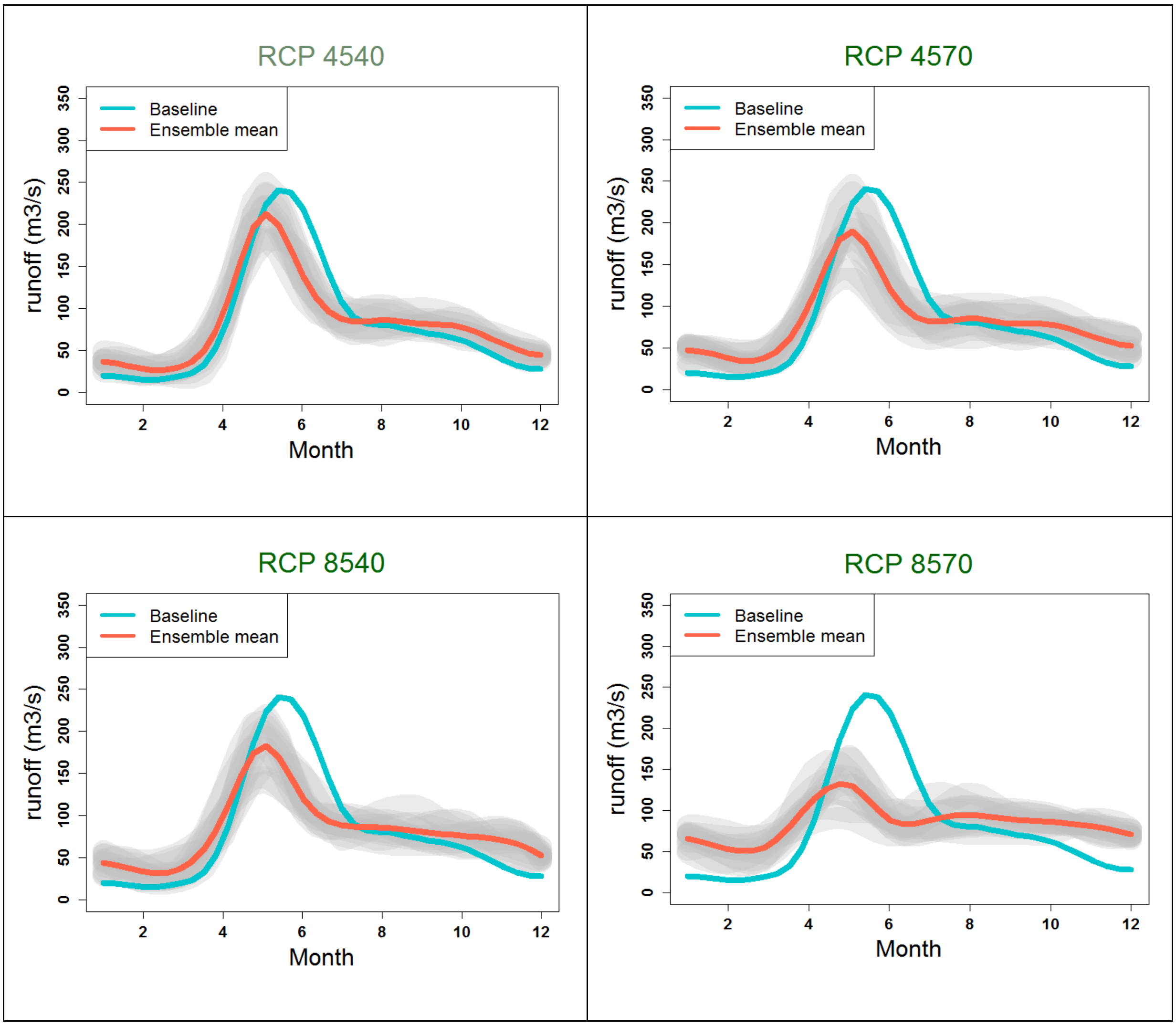


Figure 5-8: Mean monthly runoff for different climate scenarios with all models

For the emission scenario RCP45, EC-EARTH_HIRHAM and MPI_CCLM are predicting higher peaks than the baseline. The peak of the hydrographs has moved mid of May to mid of April. For RCP8570, most of the models are showing the hydrograph peak between mid of April to May, EC-EARTH_HIRHAM has a peak in April and the flattest one is EC-EARTH_RACMO. It has the lowest spring runoff values than other models, and this model has the second lowest annual average precipitation change (12.64%) for RCP8570.

Snowpack Gaula

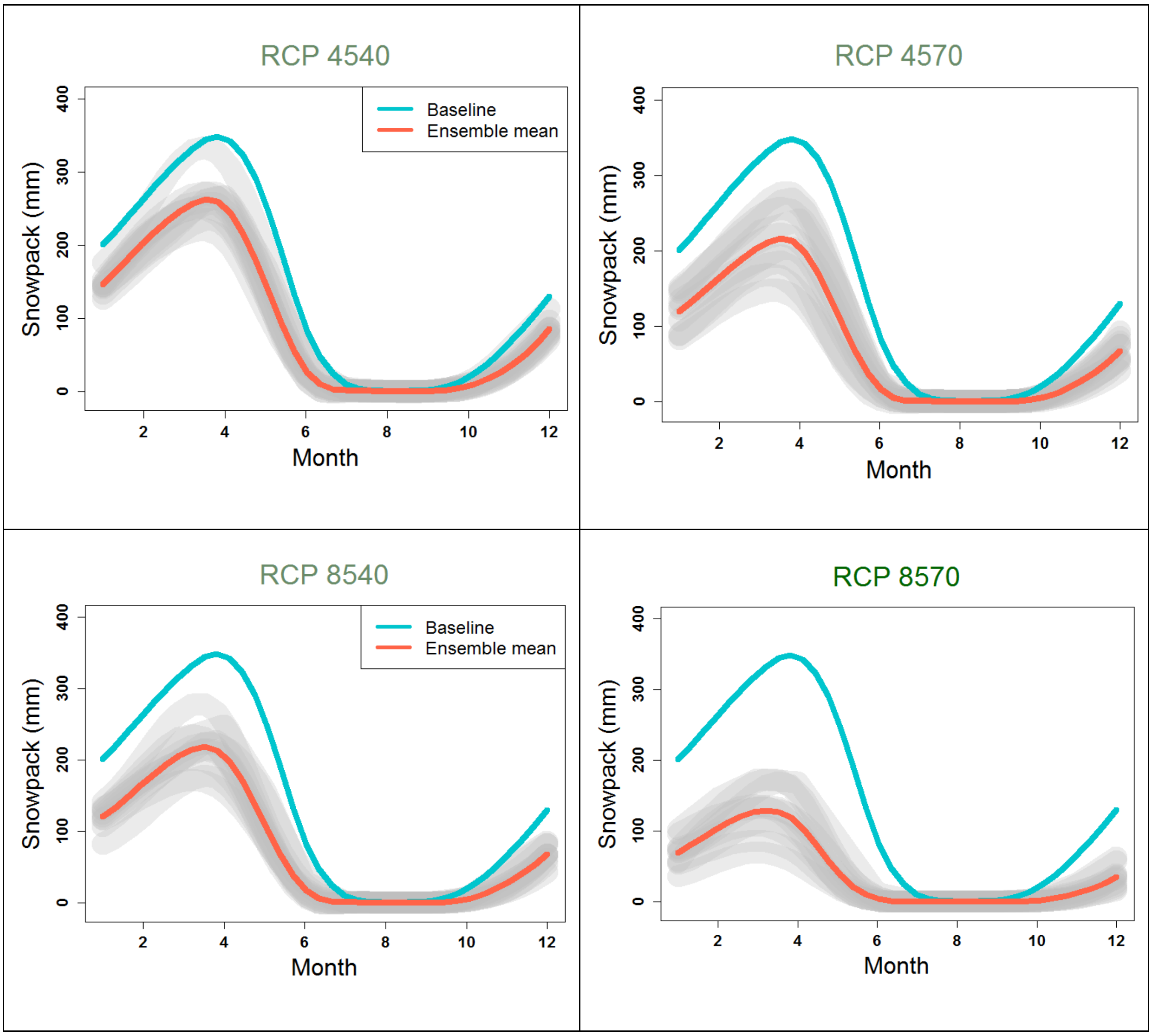


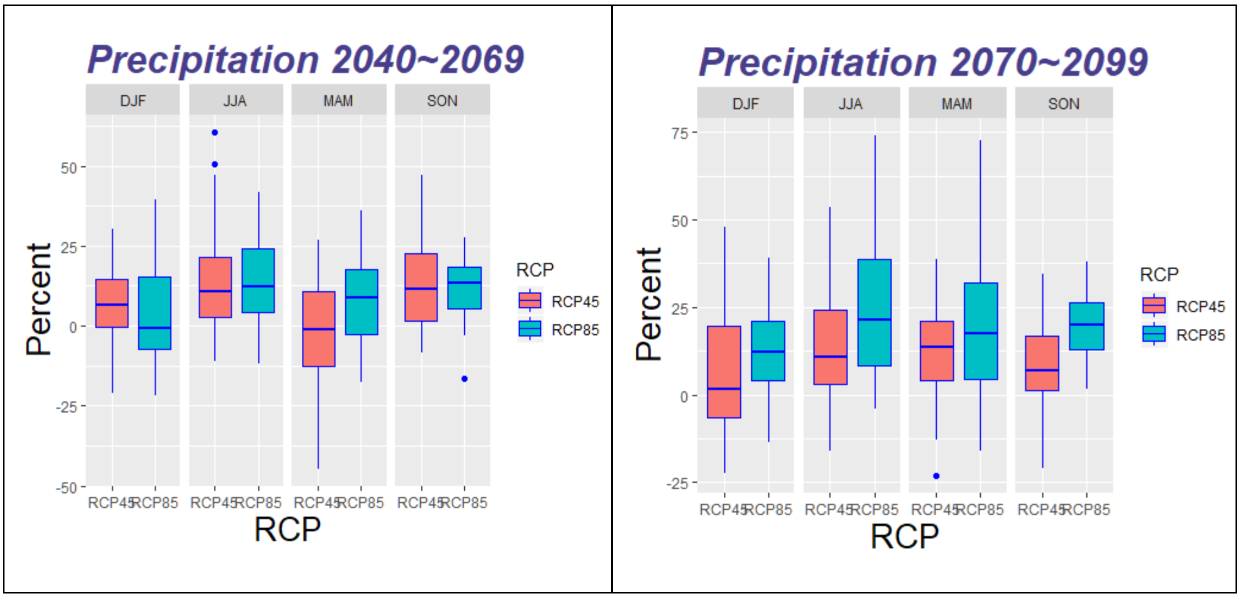
Figure 5-9: Mean monthly snowpack for different climate scenarios with all models

EC-EARTH_RACMO model has the highest snowpack reduction (85%) for RCP8570 compared to the control period. As mentioned in the literature, a warming climate will reduce snowpack in a certain amount. None of the models has disagreed on the reduction of snow amount in the future. The figure above shows that, in Gaula the snowpack will be reduced at a high rate. In the coastal areas, there might be no snow in future periods but in high mountainous areas still, there will be some snow left in Gaula.

5.3.1 SEASONAL AND ANNUAL CHANGE AND FUTURE CLIMATE IN TRØNDELAG (KLIMA I NORGE2100)

Figure 5-10 is showing the spread of ten climate models in a seasonal change distribution pattern. Models' behaviours are different from each other. Precipitation spread is large for all seasons in the models. For far future, summer and spring precipitation change is quite high in some models. For DJF precipitation, all the conditions have model values spreading from negative to positive, whereas, for JJA most of the values have positive changes. Significant increase in runoff on winter is seen from some models. The spread is quite large for spring runoff in the models. Even though all the models agreed to have positive changes in winter streamflow, the spread is quite large while the summer and autumn runoff have a lower spread.

Seasonal change for all climate models



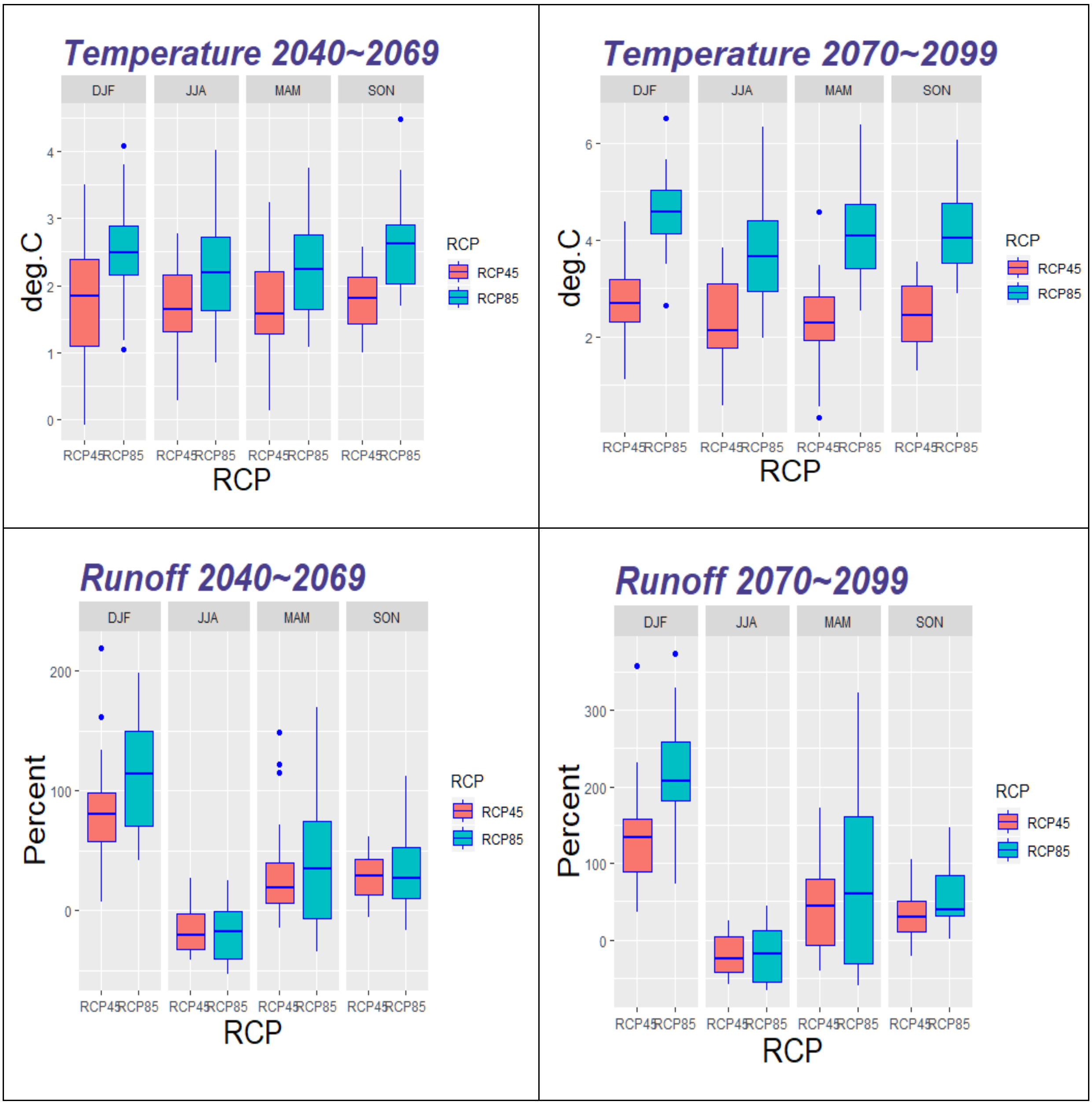


Figure 5-10: Seasonal changes for all climate models (the middle line is the median value and upper and lower are 75 and 25 percentiles respectively)[3]

Figure 5-11 and Figure 5-12 were compared to Figure 5-13, though data found from ‘Klima i Norge2100’ has future periods 2031-2060; 2071-2100 compared to 1971-2000. Albeit, data used in this study has future periods 2040-2069; 2070-2099 compared to 1976-2005 since they are not so different the comparison made in this study is reasonable.

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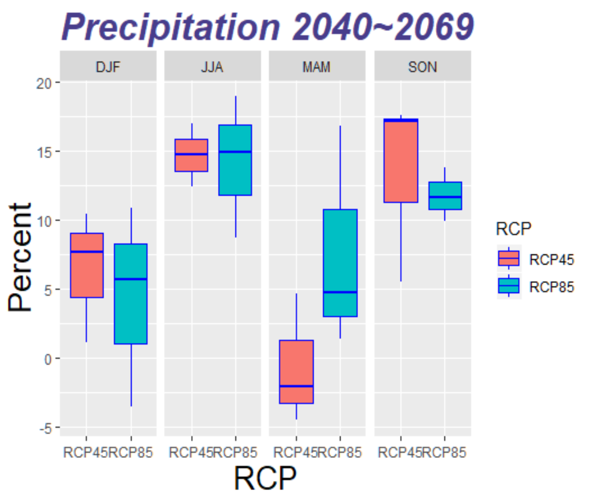
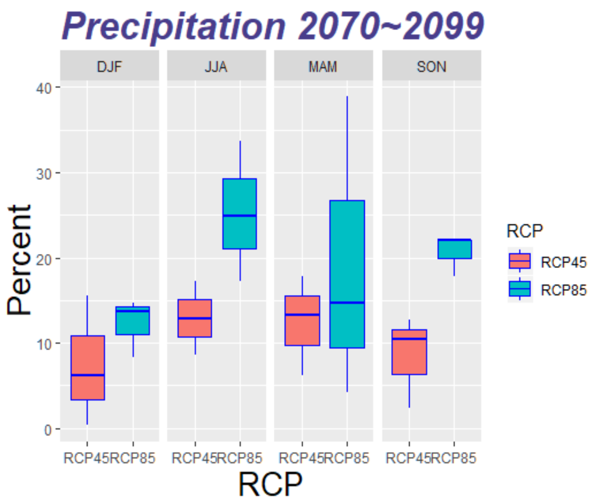
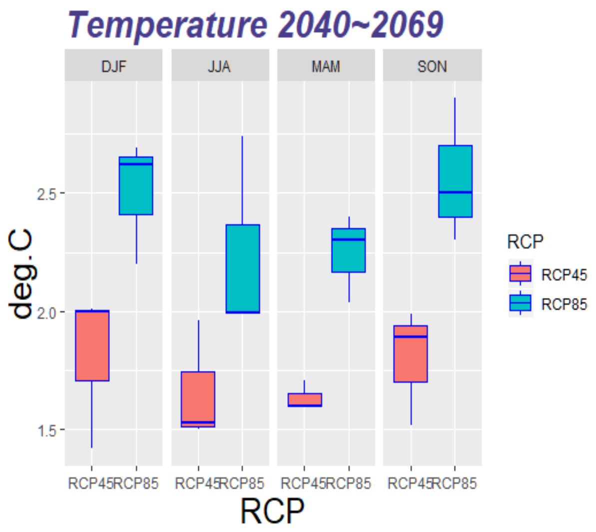
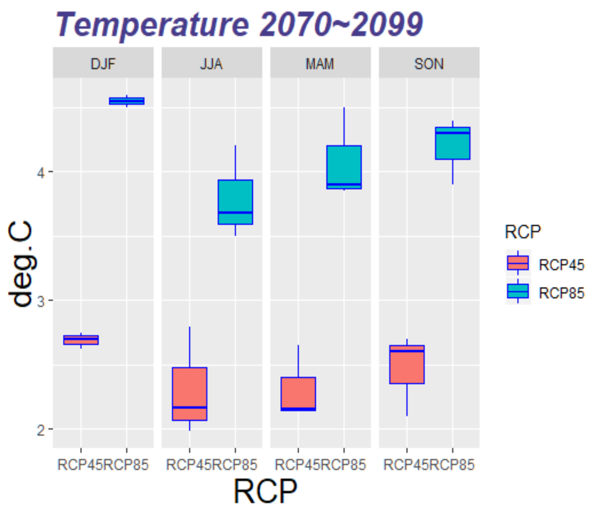
[3] JJA (summer) came before MAM (spring) in the figure

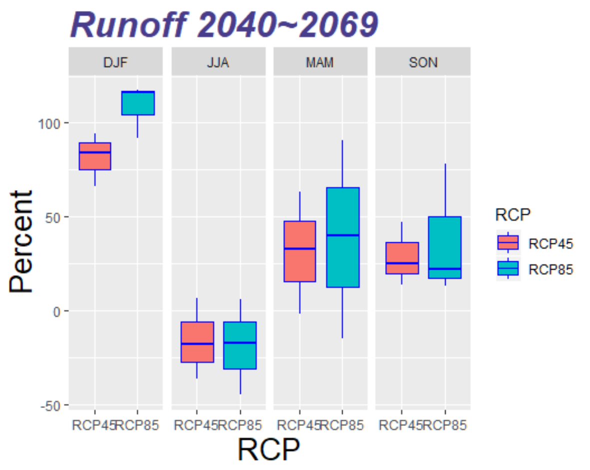
Seasonal change











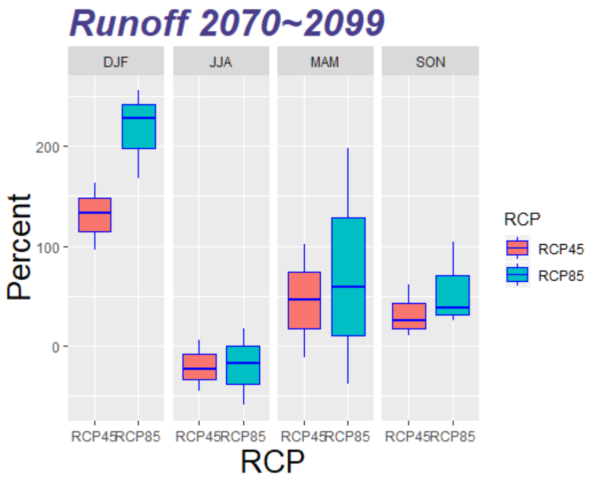
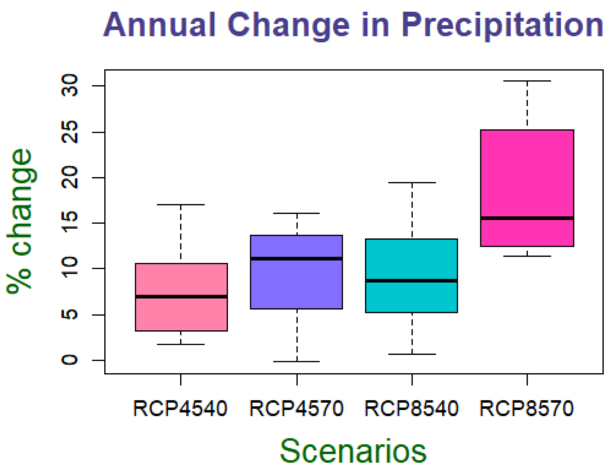
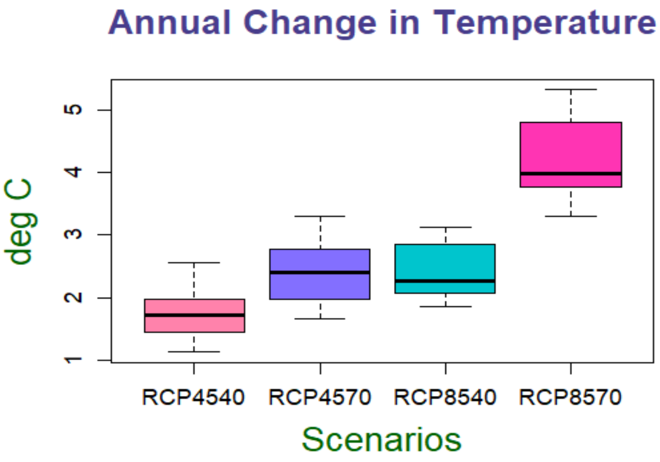


Figure 5-11: Seasonal changes from the ensemble means of all ten models (middle, upper and lower lines are representing the median, 75 percentile and 25percentile respectively)[4]

Seasonal precipitation increasing is highest in summer (JJA), although, a large spread is found on the 75 percentiles for the precipitation increase in spring for RCP8570. These high rises in precipitation in summer (JJA) and spring (MAM) will lead to frequent floods and the increasing temperature will lead the river on drying. Except the seasonal runoff, seasonal temperature and precipitation are in line with the results found in 'Klima i Norge2100'.

Annual change





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[4] Summer (JJA) came before spring (MAM)

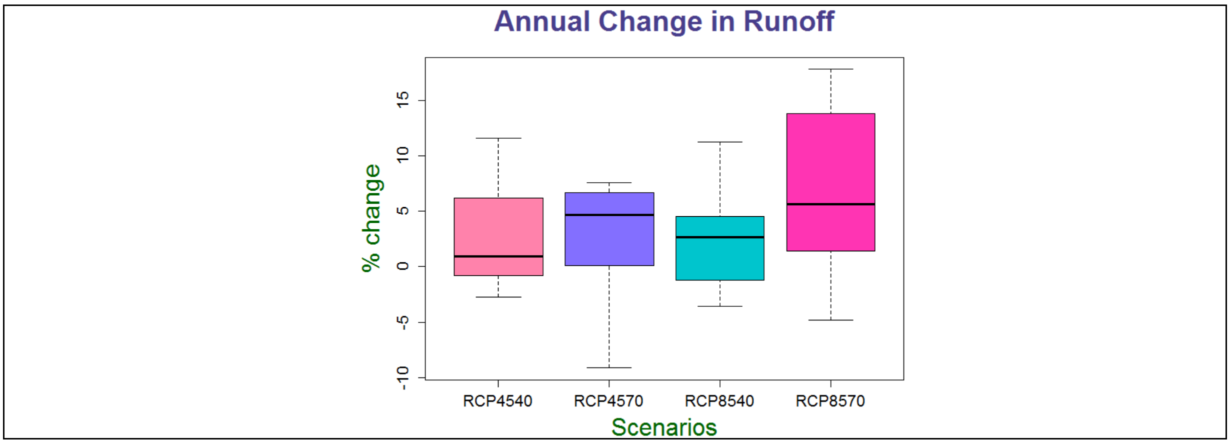
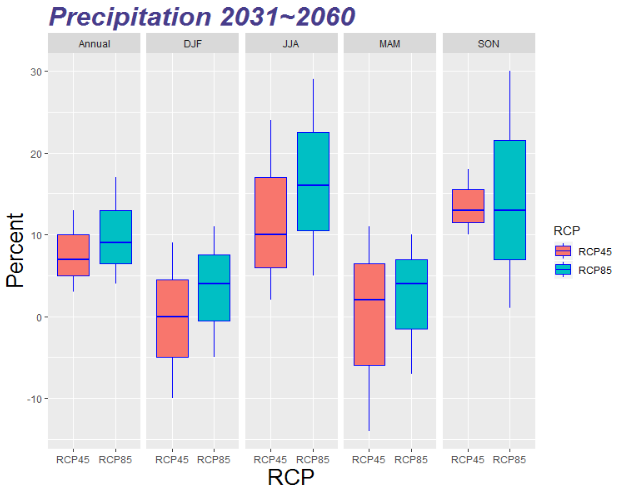
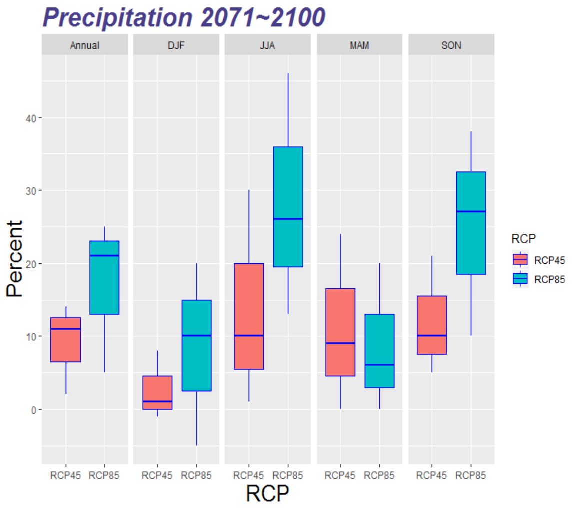


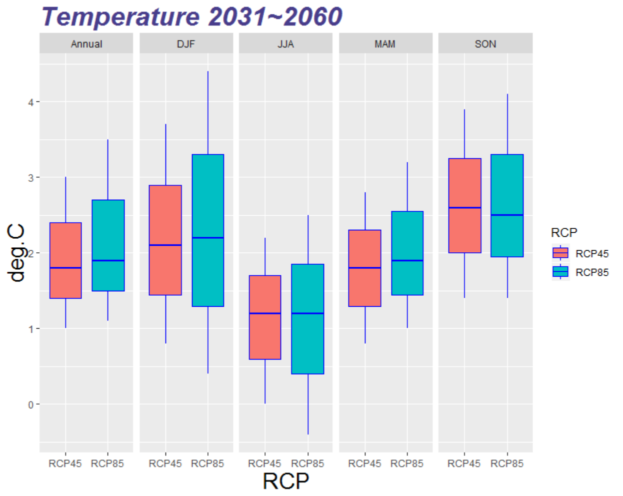
Figure 5-12: Annual change for different scenarios and periods (middle, upper and lower lines are median, 75 and 25 percentiles)

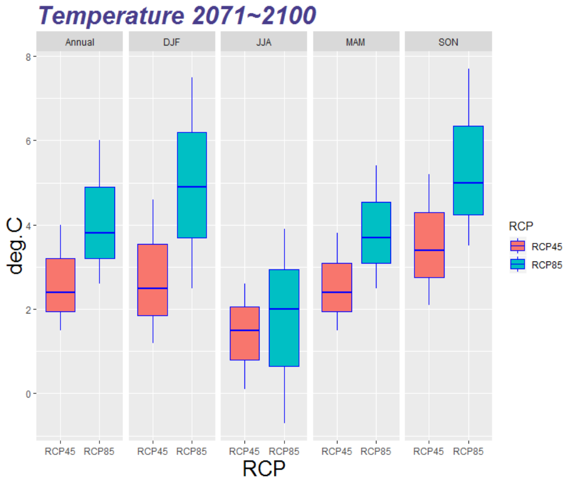
Annual precipitation in Gaula is increasing by 6.9, 11.1, 9.5 and 15.62 % (median) for RCP4540, 4570, 8540 and 8570 respectively. Annual increase in temperature for RCP4540 is 1.76°C, RCP4570 is 2.44°C, RCP8540 is 2.39°C and RCP8570 is 4.15°C. Annual changes in precipitation and temperature are in line with the data in Trøndelag. However, the annual change for runoff is showing small increase (highest median increase 5.6% for RCP8570, 0.9, 4.7, 2.7% for RCP4540, 4570, 8540) for the future climate (the spread has both positive and negative values) though Figure 5-13 is showing a very small decrease for runoff in Trøndelag. The simulations done for Trøndelag was done for a large scale and this study on a local scale. The HBV parameters were calibrated for a local scale and due to that, the results differed slightly. (Graaff, 2019) studied nearest Orkla catchment with the same models and found an increase of 4.7% for RCP8570 (highest of all scenarios). In addition to that, (Ånund Killingtveit and Knut Alfredsen, 2016) also found an increase for Benna and Jonsvatnet in Trøndelag. Therefore, values observed from Gaula with a small increase in runoff for future is acceptable and reliable.

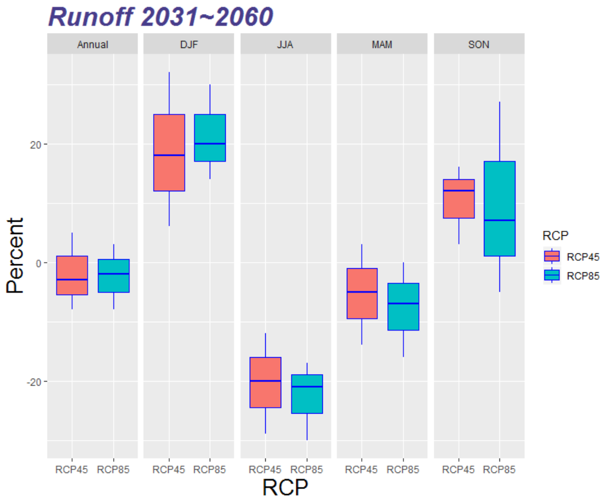
Climate scenarios inTrøndelag (Klima i Norge2100)











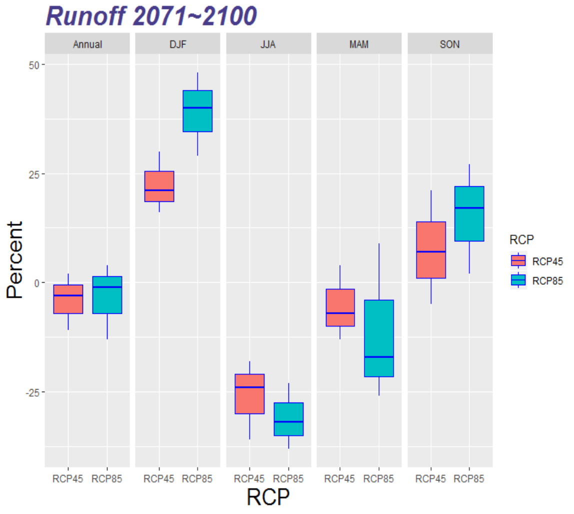


Figure 5-13: Climate projections for Trøndelag (data from Klima I Norge2100(Hanssen-Bauer I. et al., 2015))

5.3.2 SUMMARY OF CHANGED HYDROLOGICAL REGIME IN GAULA

Ensemble means of all scenarios are put here with the baseline to get the summary of the results above.

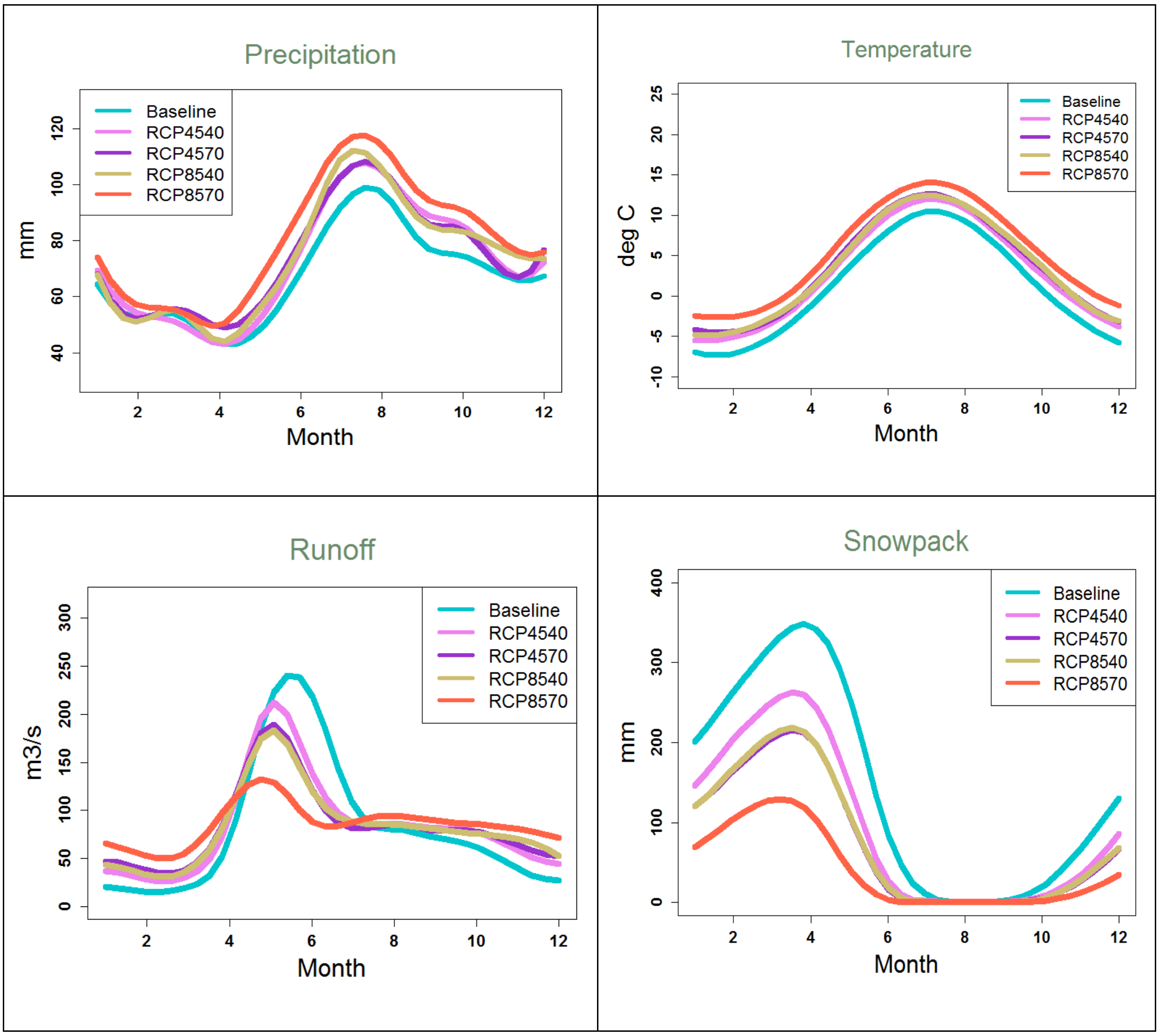


Figure 5-14: Baseline and ensemble means from different periods and emission scenarios (Mean monthly of precipitation, temperature, runoff and snowpack)

A clear evidence of global warming is distinct in this figure. Temperature rising is much higher for the extreme scenario RCP8570 than the other scenarios. For RCP8540 and RCP4570, winter precipitation is not so different from the baseline while in RCP8570 the change is everywhere.

Precipitation and temperature rising are properly evident from the control period with RCP4540, 4570, 8540 and 8570. Moreover, the figures also say that RCP8570 is going to be the extreme case amongst others. The temporal shift of seasonal runoff is clearly seen from the figure. RCP8570 is the most extreme case where precipitation and temperature are expected to be the highest. Runoff is changing for all scenarios and the peak of spring flood is shifting backward since Gaula is a snowmelt-dominated river. (Ånund Killingtveit and Knut Alfredsen, 2016), (Beisland, Koestler et al., 2017) and (Graaff, 2019) have similar findings for Benna, Jonsvatnet, Glomma and Orkla. The curve for runoff is getting flattered as it is going for the extreme case RCP8570 and in spring the runoff has lost its peak. (Beisland, Birkeland et al., 2017) also stated that the higher the temperature the flatter the hydrograph.

Snow is important for Norwegian hydropower and tourism industry. Unhappily, the snowpack is also reducing simultaneously with the increased runoff and for the worst case (RCP8570) the percentage is 70 % reduction of snowpack from the present condition while 46%, 52% and 50% of reduction are seen for RCP4540, RCP4570 and RCP8540 respectively from the baseline (Appendix C). Flow regime change is certain from the above results and will have an influence in Gaula.

Including the hydrology, there remains uncertainty regarding climate change and emissions. To get a possible outcome different scenarios and models are used. The models are from different geographical locations and different regional climate models therefore, they are not behaving similarly. In this study, HADGEM_RCA and IPSL_RCA models have higher projections and MPI_RCA has comparatively lower projections than others. However, since the models used in this research did not spread much, the results from the ensemble mean are acceptable.

5.4 Lundesokna Power Production

Control period simulated runoff for the observed Haga bru station was used as the baseline in this part to avoid many other calculations and bias-adjusted data was used for the future to see the effect of climate change in Lundesokna power plant. Since simulated Q (for the observed runoff from gauging station) and the ensemble mean of the bias-corrected data (Figure 5-5) corresponded in a reasonable limit, the comparison between the control period and the future periods with these data would not be so much different with the bias-corrected and adjusted data. Mean monthly values are plotted in the figures, the blue line is from the reference period and the orange line is the ensemble mean of the models, shaded lines are the models mean monthly values.

Inflow to the reservoirs

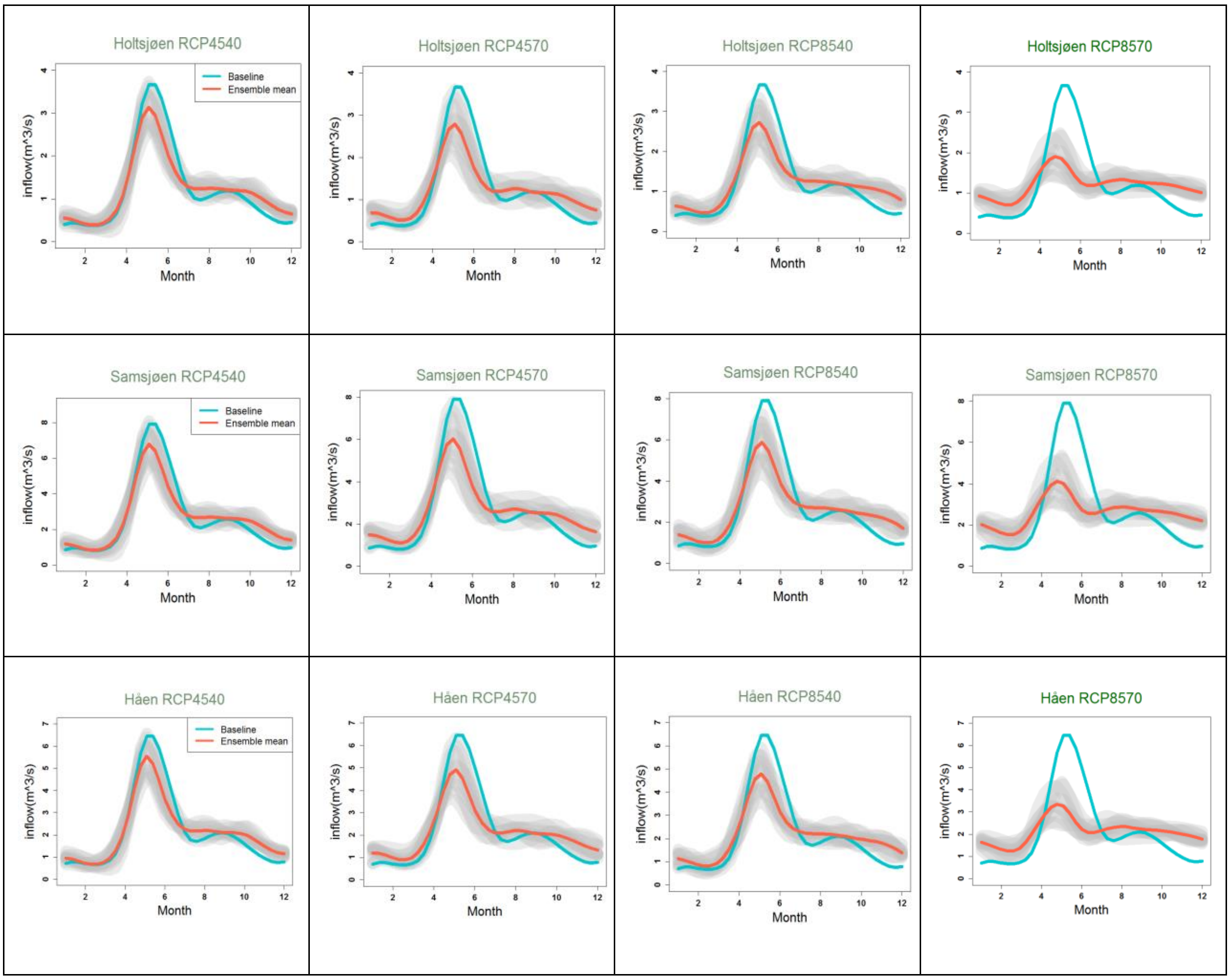
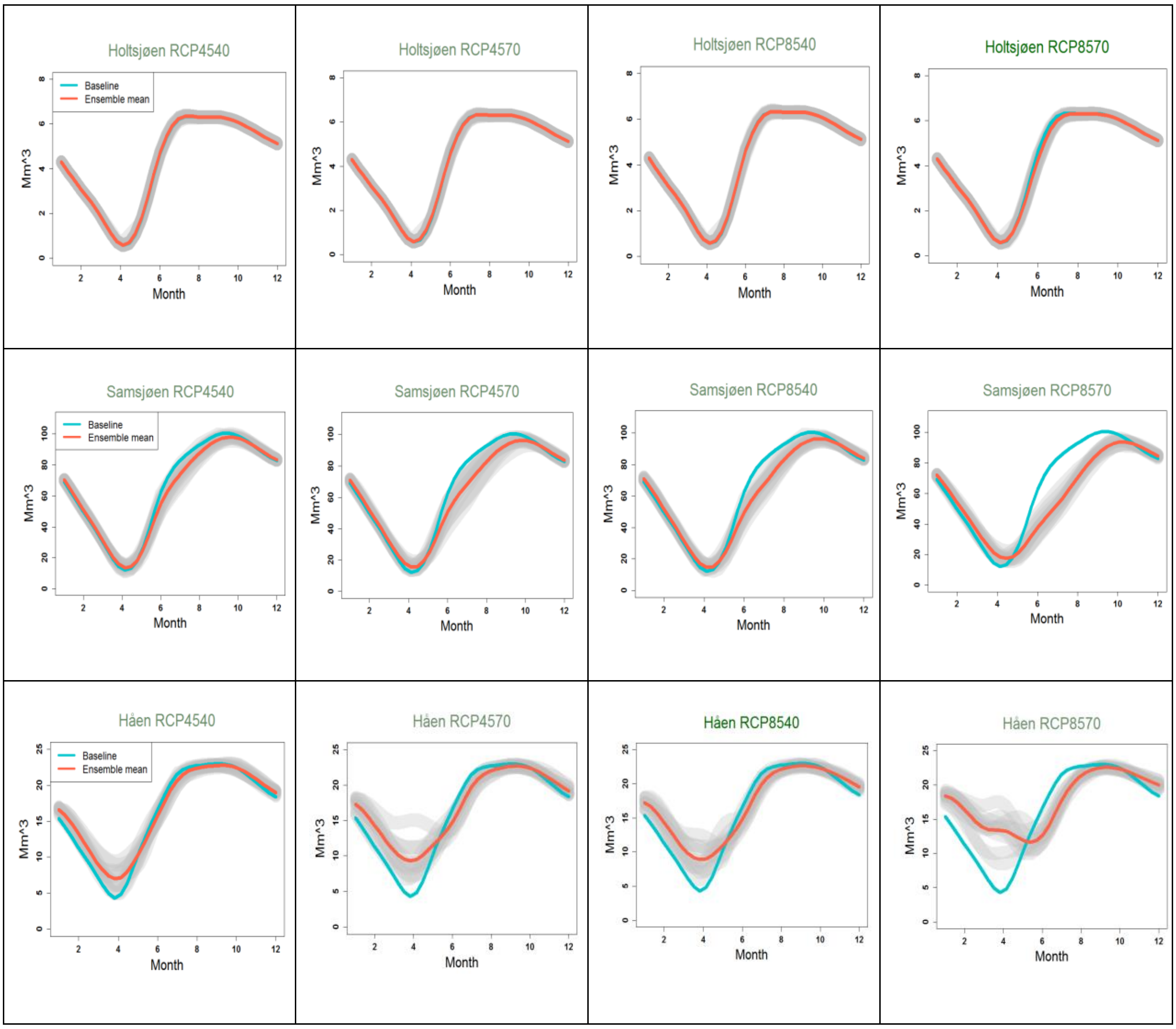


Figure 5-15: Mean monthly inflow to the reservoirs (Blue line is the mean monthly of the baseline, orange is the ensemble of all models and shaded lines are the mean monthly inflow of the future projections)

Changes in inflow for the three reservoirs are shown in the above figure. In 2070-2099, almost all models have increasing winter and autumn inflow than the 2040-2069 period. Summer inflow is decreasing in all models for all scenarios except MPI_CCLM has a higher peak on RCP4540 than the baseline. Models’ behaviours are not so different for different scenarios and the spread is not so large.

Reservoir volume


Holtsjøen RCP4540

Holtsjøen RCP4570

Holtsjøen RCP8540

Holtsjøen RCP8570

Samsjøen RCP4540

Samsjøen RCP4570

Samsjøen RCP8540

Samsjøen RCP8570

Håen RCP4540

Håen RCP4570

Håen RCP8540

Håen RCP8570

Figure 5-16: Mean monthly reservoir volume (Blue line is the baseline and orange line is the ensemble mean of models, shaded lines are the models)

Reservoir volume for the three reservoirs (Holtsjøen, Samsjøen, Håen) is shown here. HADGEM_RCA and IPSL_RCA have a large summer volume reduction in Samsjøen than other models. For reservoir Håen, models have different behaviour for different scenarios. The spread is also small here.

Power Production

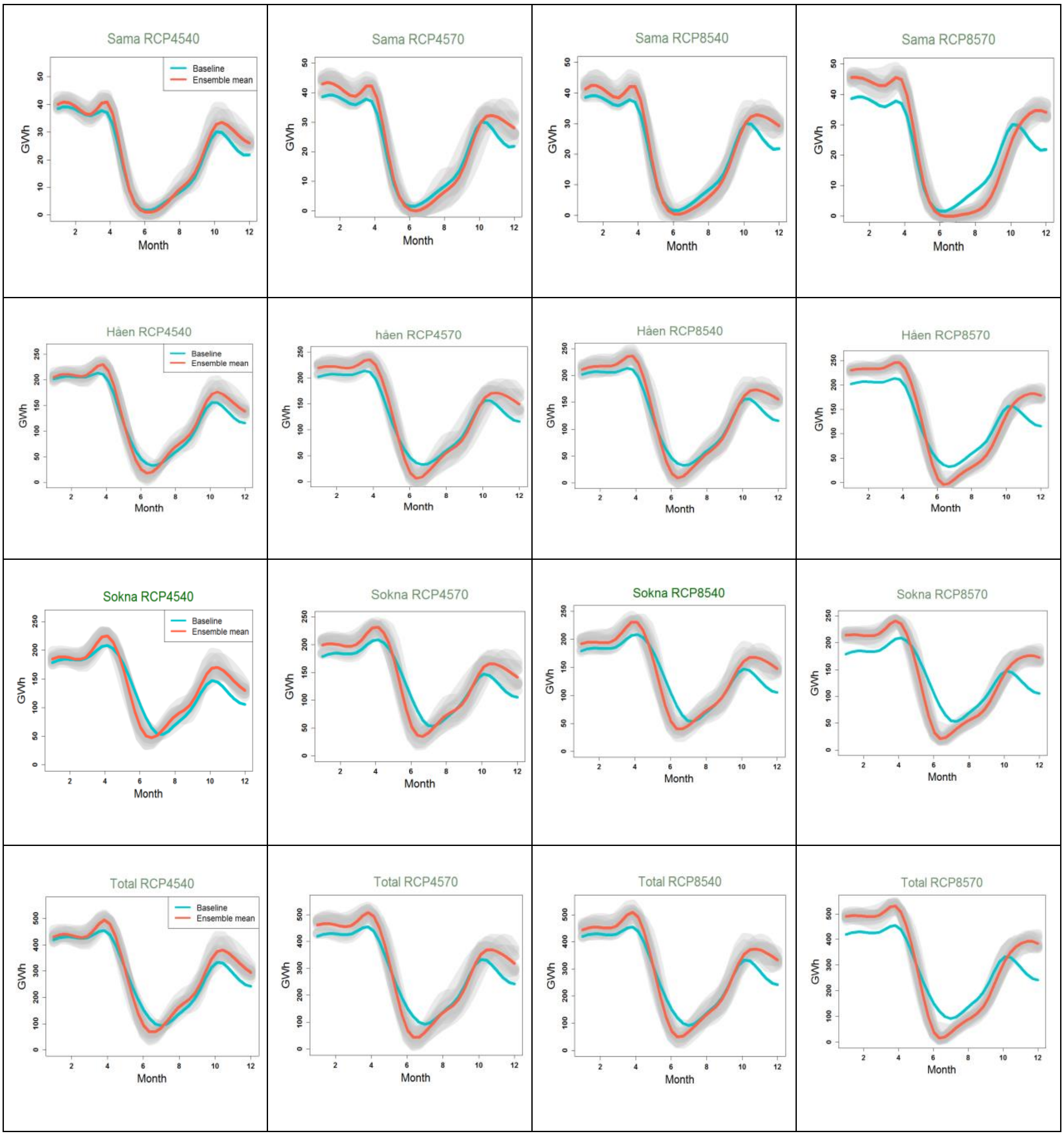


Figure 5-17: Mean monthly power production

Productions for Sama, Håen, Sokna and the total are presented above with all models. IPSL_RCA and HADGEM_RCA have higher winter productions than others. Sama power plant has an average annual power production of 21.99 GWh for baseline. For RCP8570, in July Sama power plant has no power production from most of the models. Sokna power plant has the better condition than other power plants in July. The spread of the models is also small here.

Spill

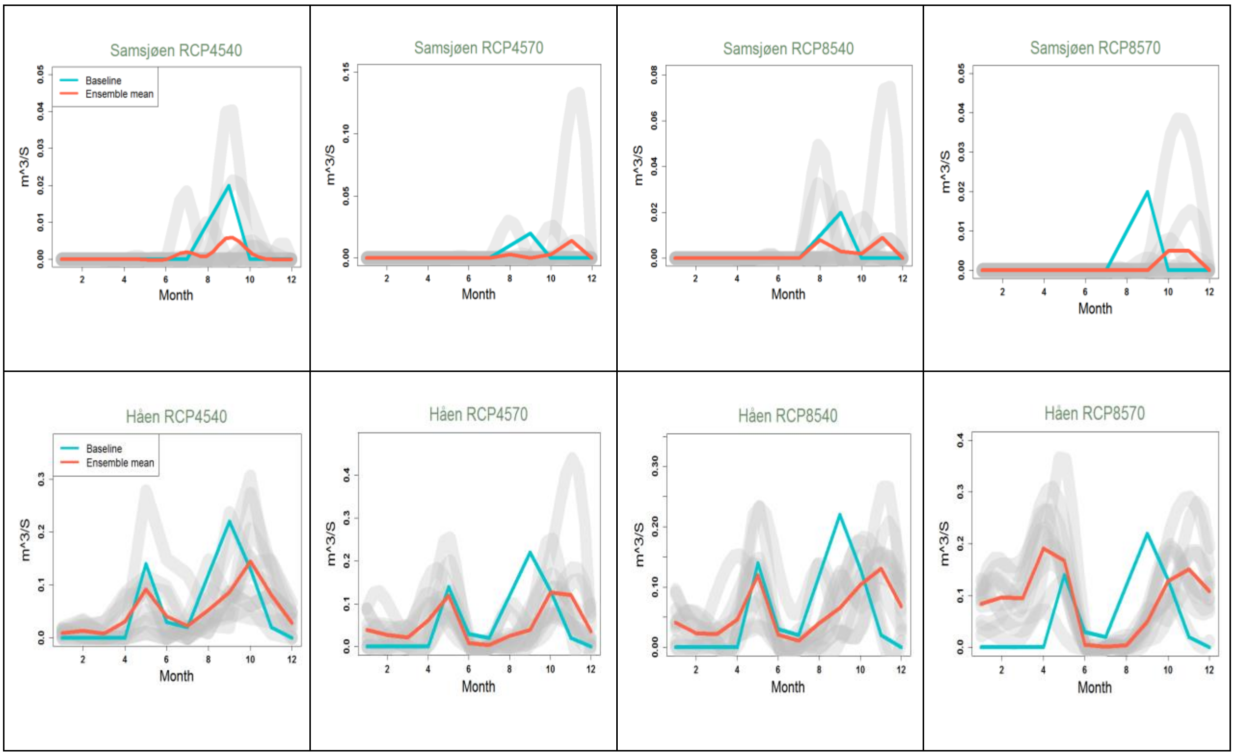


Figure 5-18: Mean monthly spill for Samsjøen and Håen reservoir

Models are behaving differently for spill, especially for Håen. The spread is large for spill in Håen. In Samsjøen, spill is zero for most of the models in future and it is reduced than the baseline. Reservoir Holtsjøen is a small reservoir and no spill was observed from that. This figure is a signal for the power companies since it is showing the spill is changing its timing and magnitude. The spill has moved its period which is clearly seen from the figures. Especially, for Håen the spill is moving back from May to April and moving forward from August-September to October-November. It is visible that the spill is not increasing with the production increase in Samsjøen. This is the reason for the regular inflow (due to earlier snowmelt) in the reservoirs and therefore, utilization of the system is getting better (Beisland, Koestler, et al., 2017).

5.4.1 ANNUAL AND SEASONAL CHANGES

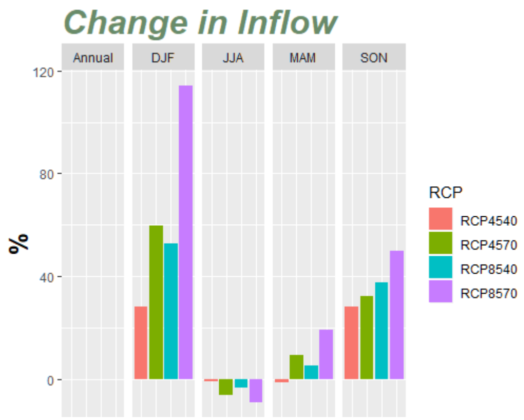
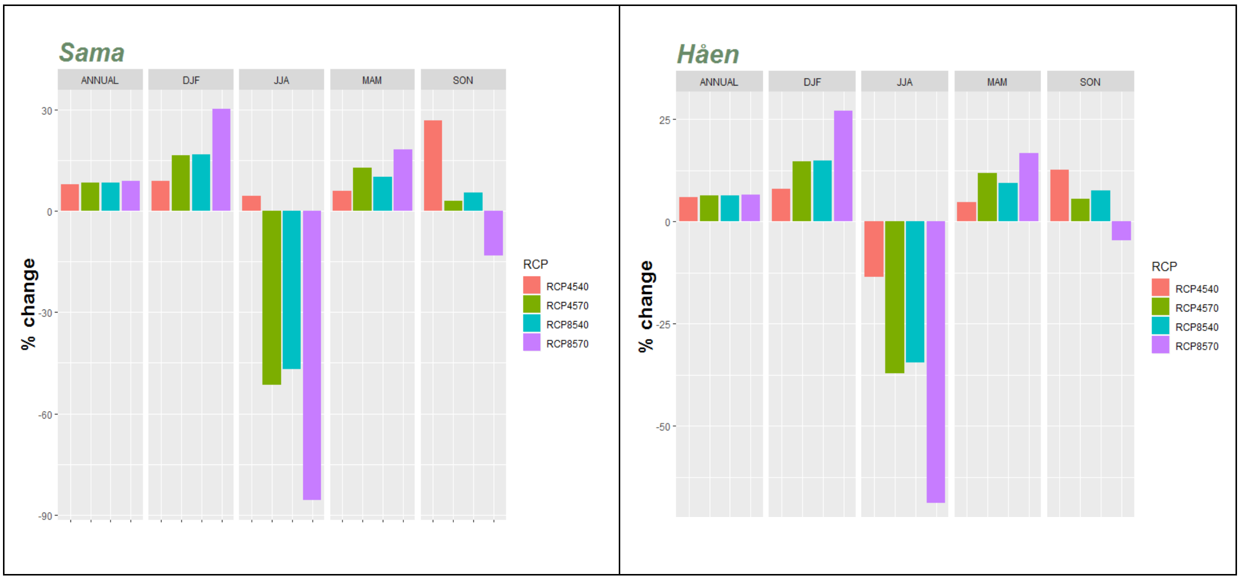


Figure 5-19: Change in the inflow

Annual change in inflow is zero for Lundesokna. The increase is positive for winter, autumn and spring except RCP4540 spring. In summer, the change is negative for all scenarios.

Seasonal Change Production



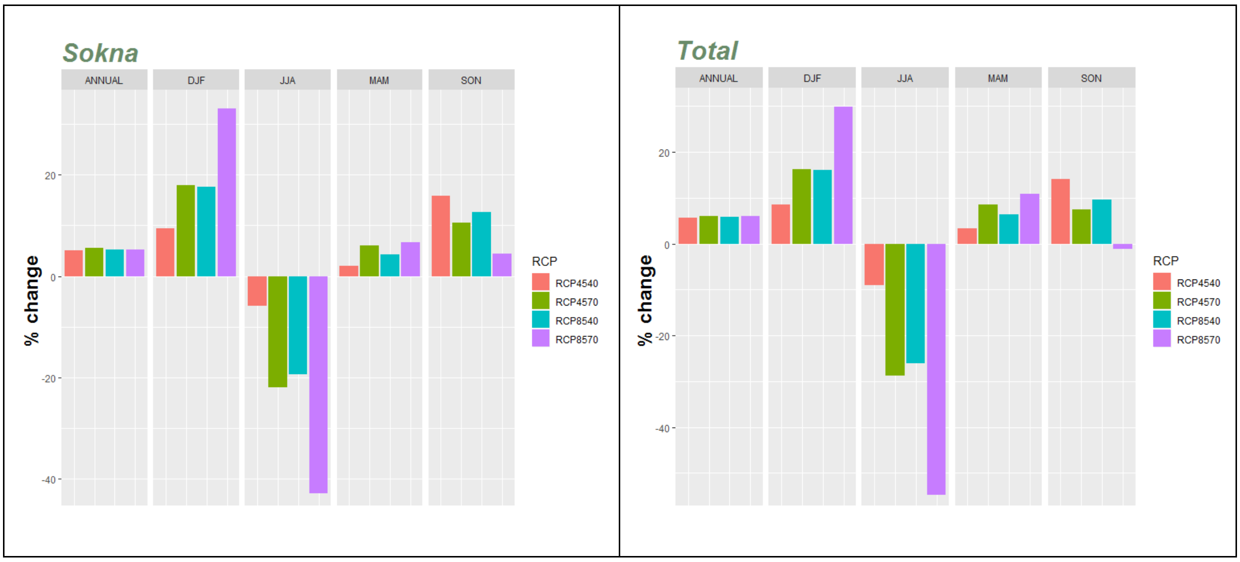


Figure 5-20: Seasonal and annual change in production for all three(including total) power plants[5]

The figure above is showing the percentage change of production for all three power plants and all together. It is clearly seen that, due to an increase in runoff, the production is increasing for all three power plants and all scenarios compared to the control period to near and far future. Since the summer runoff is moving to winter and autumn, the production is highest in winter and lowest (negative for all except Sama in RCP4540) in summer. Summer production reduction in RCP8570 is 85.62%, 68.80%, 42.82% for Sama, Håen and Sokna respectively. For the baseline, annual average power production is 21.99 GWh, 131.22 GWh, 136.93 GWh and 290.14 GWh for Sama, Håen, Sokna power plants and in total respectively. Annual increase in total power production is increasing by 5.64%, 6.13%, 5.92% and 6.08% respectively for RCP4540, RCP4570, RCP8540 and RCP8570. In total summer production is decreasing by 9.11%, 28.69%, 26.16% and 54.79% for RCP4540, RCP4570, RCP8540 and RCP8570 respectively. Findings from (Beisland et al., 2015) has shown an increase in production of 6.5% for the near future and 8.2% for far future in mid-Norway. Moreover, (Graaff, 2019) studied Orkla catchment and found small positive increase by using the same climate models and emission scenario and Orkla was studied previously with another scenarios by (Timalsina et al. 2015), (Harby et al., 2016) and the result was positive, therefore the increase in production from Lundesokna can be said reliable.

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[5] JJA came before MAM

5.4.2 SUMMARY OF THE EFFECT OF CLIMATE CHANGE ON LUNDESOKNA POWER PLANT

Ensemble means of all scenarios (RCP4540, RCP4570, RCP8540 and RCP8570) are presented here with the baseline.

Summary of Inflow to the reservoirs

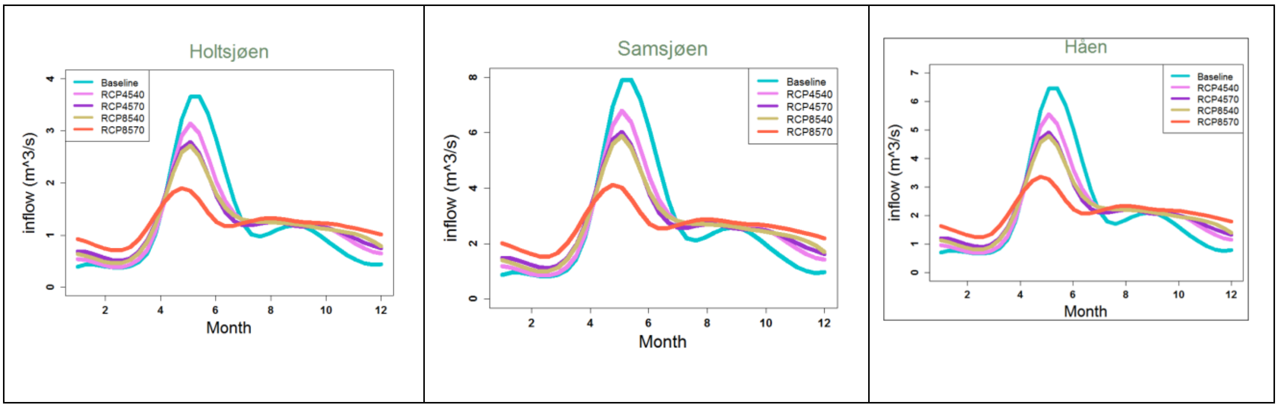


Figure 5-21: Summary of inflow to the reservoirs (mean monthly)

Inflow coming to the reservoirs for all climate scenarios are shown in the figure. For RCP8570 the inflow is more regular than it is used to be in the control period since in winter instead of snow it will be raining, and the snow will be melted by a large amount. Winter and autumn runoff are increasing with the following decrease in summer and spring. Average inflow coming to the reservoirs are 1.2 m^3/s, 2.59 m^3/s and 2.11 m^3/s for Holtsjøen, Samsjøen and Håen respectively. This inflow in future scenarios would be similar to the hydrograph of Gaula (Figure 5-14), as it was described at the beginning of this chapter, the comparisons were done in this chapter with the simulated runoff from the gauging station and the bias adjusted future data, therefore, this figure has a small difference with Figure 5-14.

Reservoir Volume Summary

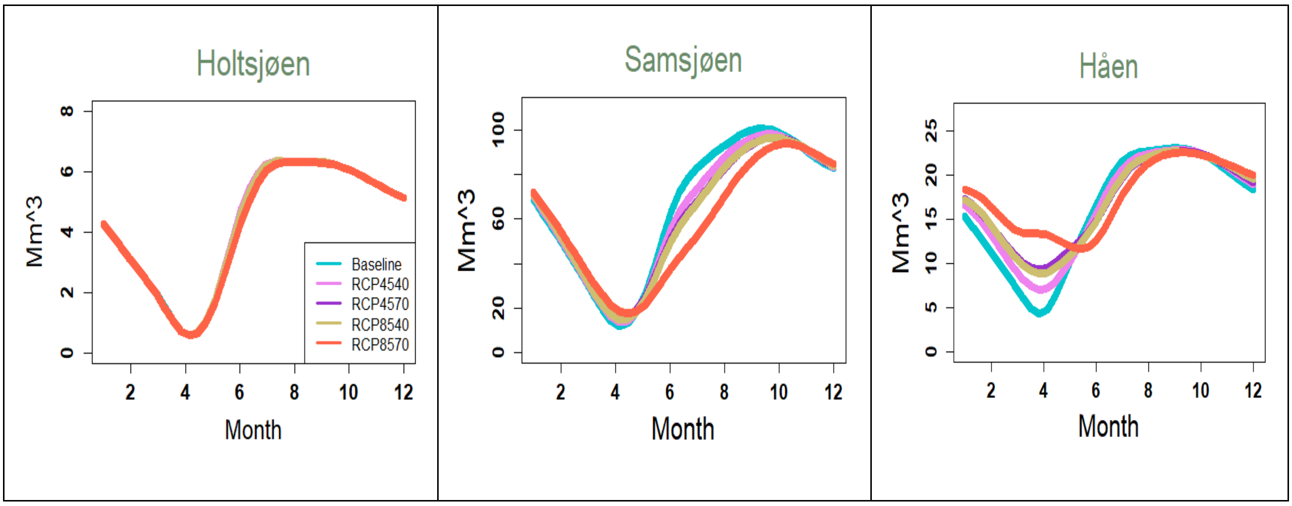


Figure 5-22: Summary of reservoir volume for three reservoirs

Holtsjøen has a capacity of 7 Mm^3 and it has negligible changes with the control period. Samsjøen reservoir with a capacity of 113 Mm^3 will face significant changes for the summer period and it does not show a markable increase in winter. The reduction of volume in July is significant compared to the control period and it is worsening with the worst climatic conditions (Table 5-1).

	Decrease (Mm^3)
RCP4540	9.07
RCP4570	15.01
RCP8540	15.73
RCP8570	30.32

Table 5-1: Reduction of reservoir volume in July for Samsjøen

Reservoir volume is decreasing in Samsjøen simultaneously with the increasing temperature. This is a warning that, if the temperature rise is more than the predictions or if the evaporation is too high, the reservoir might be drying at a high rate in the future. Reservoir Håen with a capacity of 25 Mm^3 is getting the advantage of increasing flow in winter and early spring. The highest volume increase will happen in April and the value is 8.89 Mm^3 for RCP8570. In addition to that, the summer volume decrease is not so high compared to Samsjøen for Håen.

Summary Production

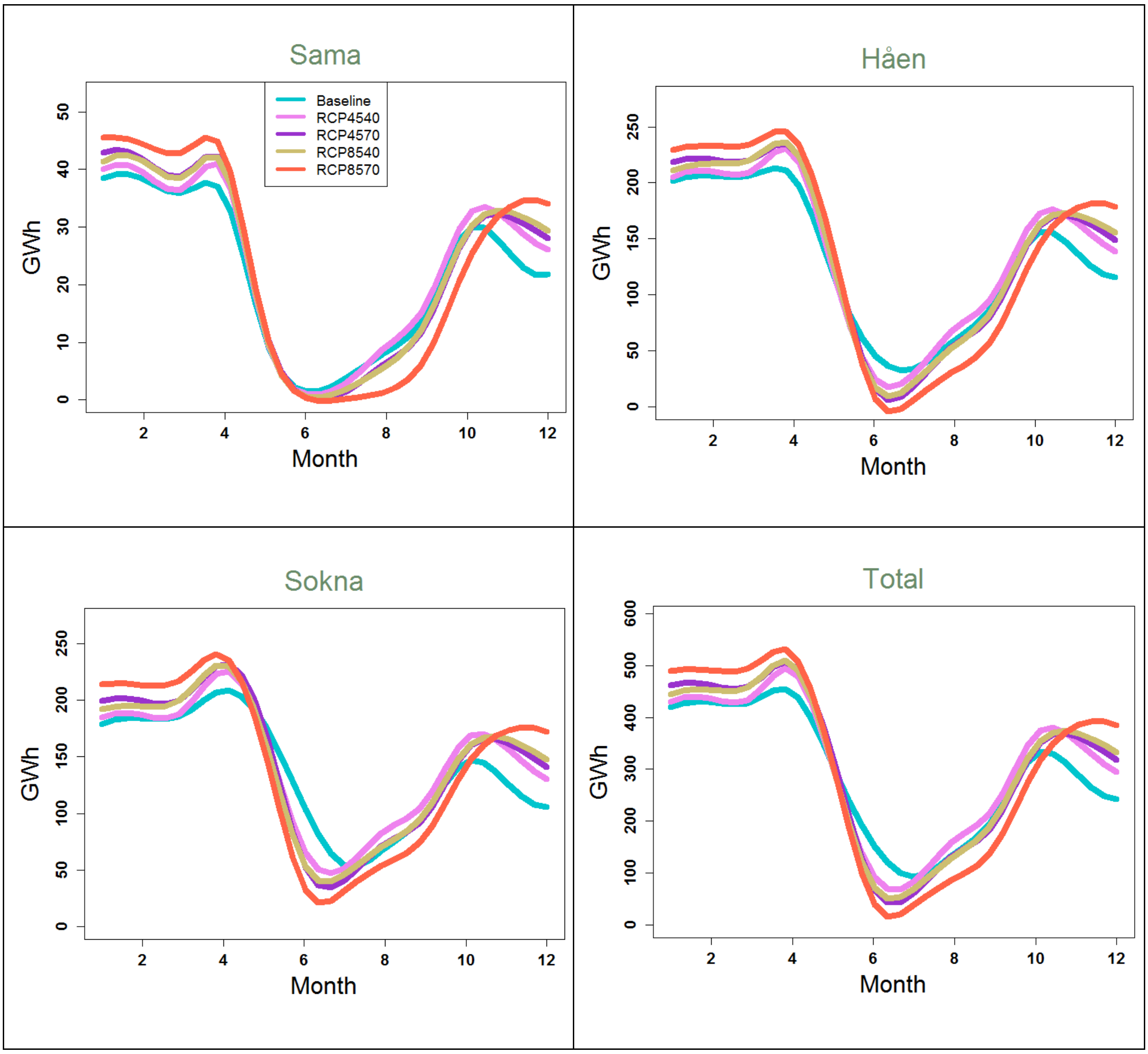


Figure 5-23: Power production summary (mean monthly production)

It is distinct from the above figure (Figure 5-23) that, power production is changing almost all over the year for future projections. Increasing runoff in winter is increasing production and simultaneously decreasing production in summer and spring with low flow conditions. The power production curve is changing with the altering runoff. Average annual production will be 23.94 GWh, 139.78 GWh, 144.07 GWh and 307.79 GWh for Sama, Håen, Sokna and in total respectively for RCP8570.

The reservoirs height should be increased, or new reservoir could be added to store the high precipitation in summer and high flow in winter which might help in the drying periods (Prowse et al., 2009). The additional spill water can be used for producing more energy in the future. To save this spilled water in winter, the power company can increase the reservoir level to be benefited in the drying seasons. Optimizing the hydraulic head and turbine schedule in summer also could prevent the problems with the low flow as recommended by Gaudard et al. (2013).

The analysis was done following the planning strategy for the current period. The regulation system which is followed now might no longer exist in the future. Since winter is getting warmer and summer is getting drier, the consumption will change. A heating system like the present conditions will be replaced by summer air coolers and the price for electricity would not be the same. In addition to that, nMAG does not consider temperature effect, the input it takes is runoff, since the future is unknown, summer production might decrease more than it is predicted in this study. The power companies need to change their strategies for the future to avoid losses and to provide a secure supply of electricity. Long-term assessment should be done to understand the future market. Otherwise, the system might fail, and hydropower system can lose its reliability and that could be a negative impact on the environment.

5.5 HEC-RAS Hydraulic Simulations

5.5.1 MODEL CALIBRATION

The hydraulic model was calibrated for a constant discharge of 68.8 m^3/s by observing visually from Figure 5-24. Top left (a) is the air photo from norge i bilder on 7th June 2016. Top right (b) is the model response for this flow in HEC-RAS5.0.6. Bottom left (c) is in Arcmap10.6, from the photo of norge i bilder with the wetted area from the hydraulic simulation. Bottom right (d) is the transparent photo of (c) to show the rivers wetted area clearly. Observing visually the wetted areas in this figure, it is seen that the geometry of the river section is produced in a better way and is similar to the photo from norge i bilder, therefore, it can be said that the set up for Gaula described in 4.4 is reliable to do further simulations.

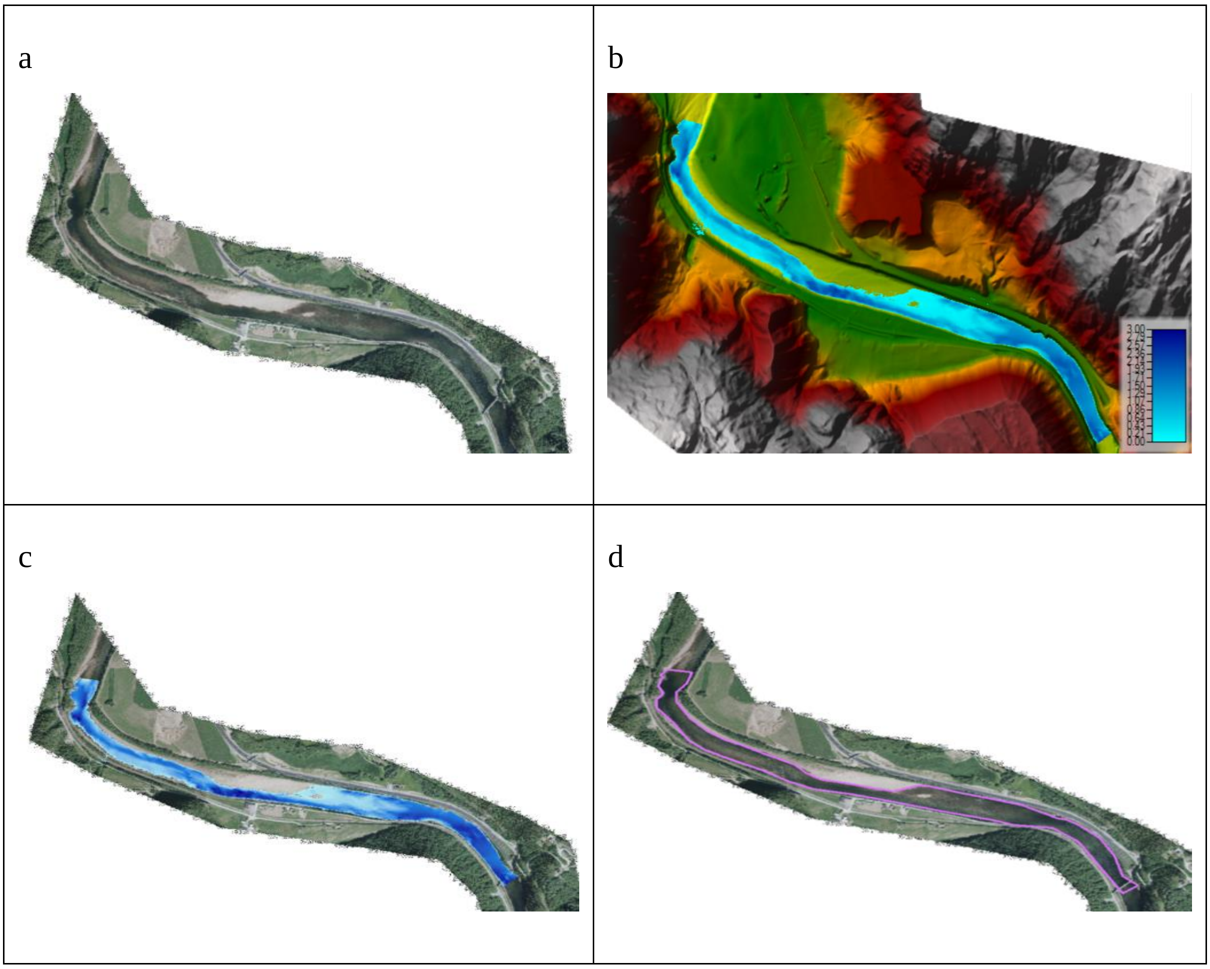


Figure 5-24: Visual Calibration for Gaula; (a)Air photo of Haga bru station on 7th June, 2016 (www.norgeibilder.no), (b)simulation on HEC-RAS, (c)Depth on ArcMap10.6 for the same discharge on b, (d)transparent picture of depth on c(highest depth 2.8m lowest 0.05m)

5.5.2 SIMULATIONS FOR JULY

The calibrated model was simulated for July (25 percentile flow) to see the effect of the flow in future periods since from the HBV simulations, it was observed that in future climate summer drought will appear more frequently from the present conditions. Significant changes for the places drying more are indicated in the figures. Discharges for the simulations are given in Table 5-2.

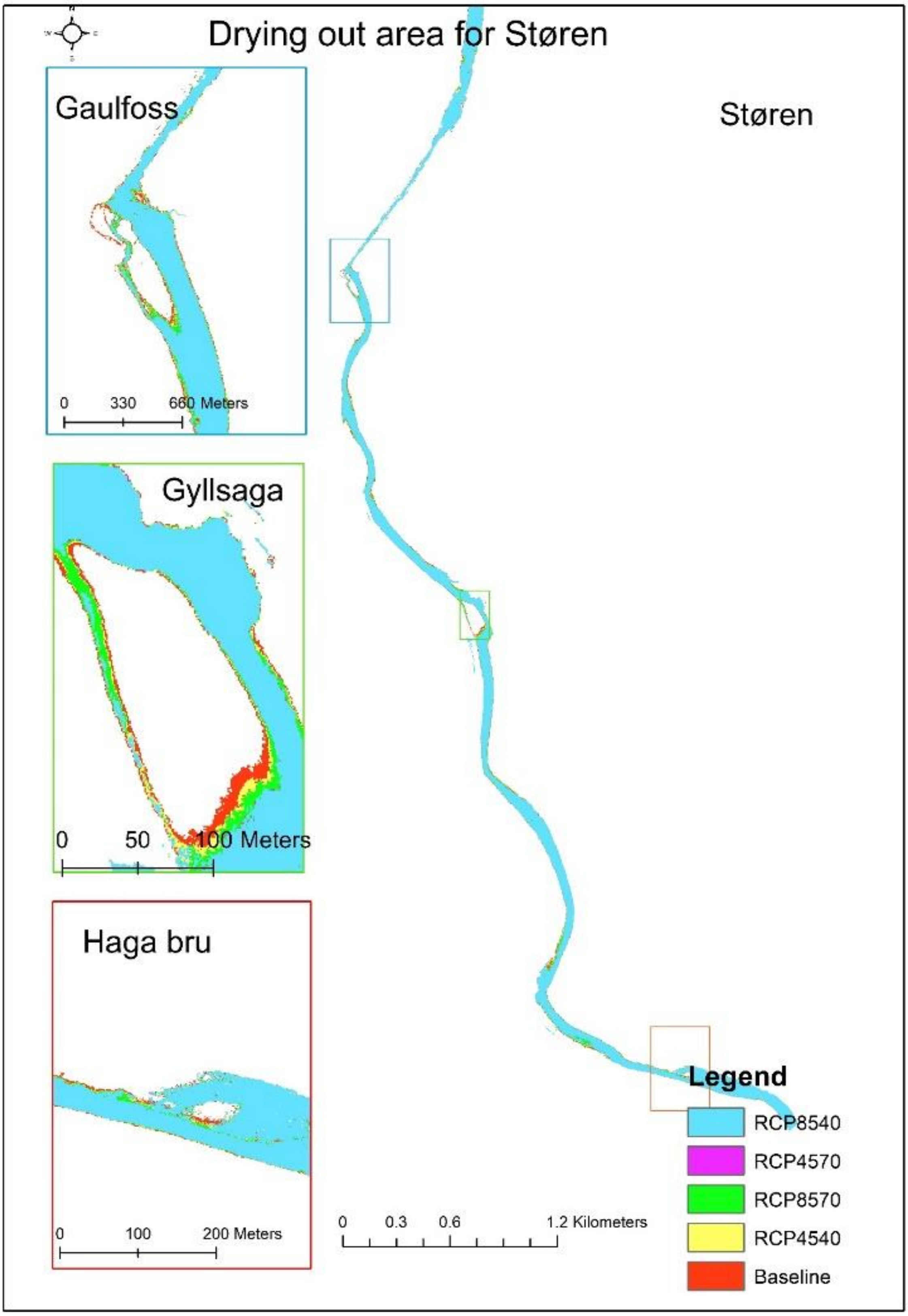
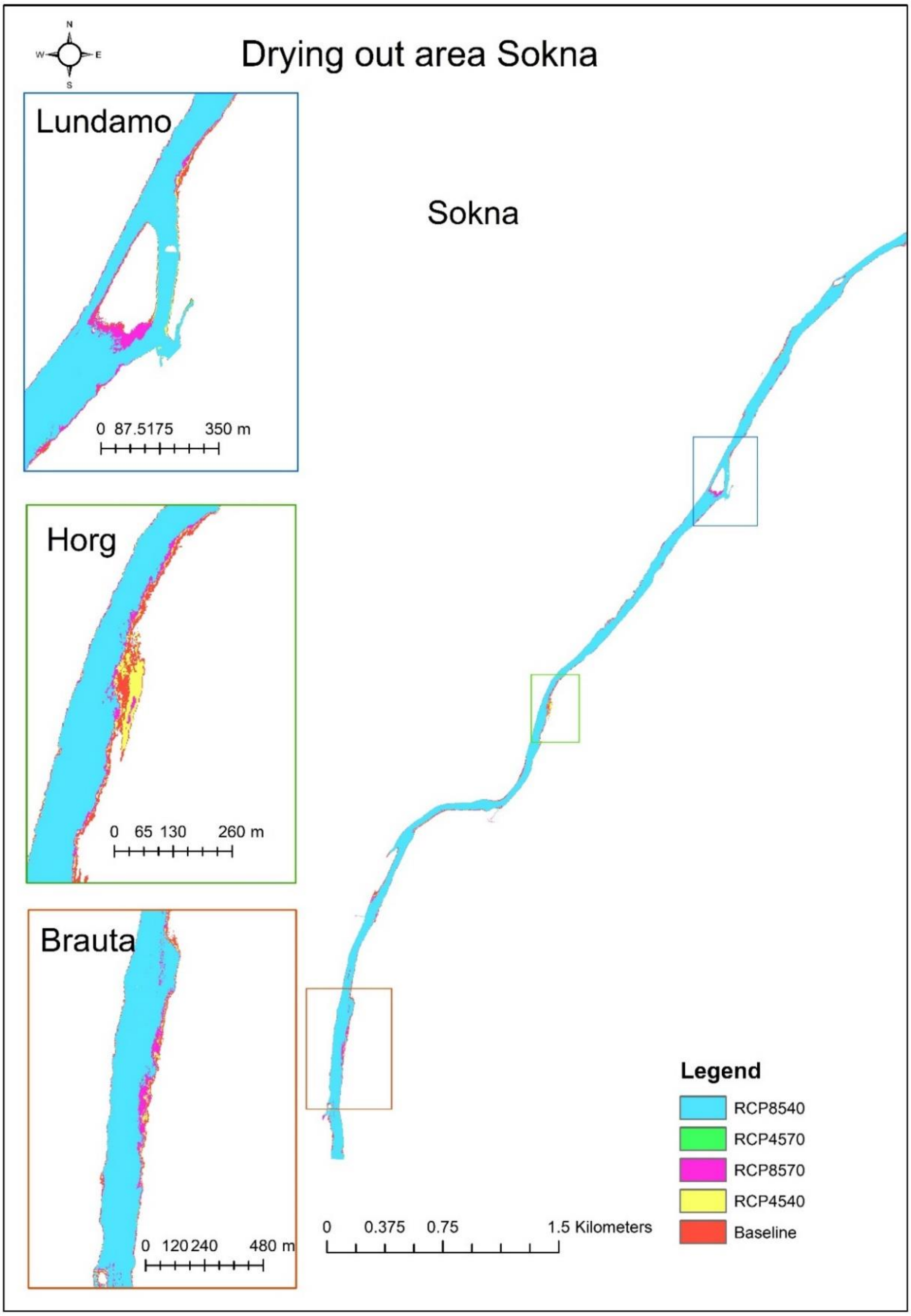


Figure 5-25: Wetted area for different climate scenarios (Støren part) (discharge values in Table 5-2)

This is the starting of Gaula from Haga bru station. Selected places are showing how decreasing runoff drying these areas.

Figure 5-26: Wetted area for different climate scenarios (Sokna part) (discharge values in Table 5-2)



Output of Støren part was given as input here and the selected figures are showing drying effects of low summer flow in the future. Lundamo is the outlet of Lundesokna power plant.

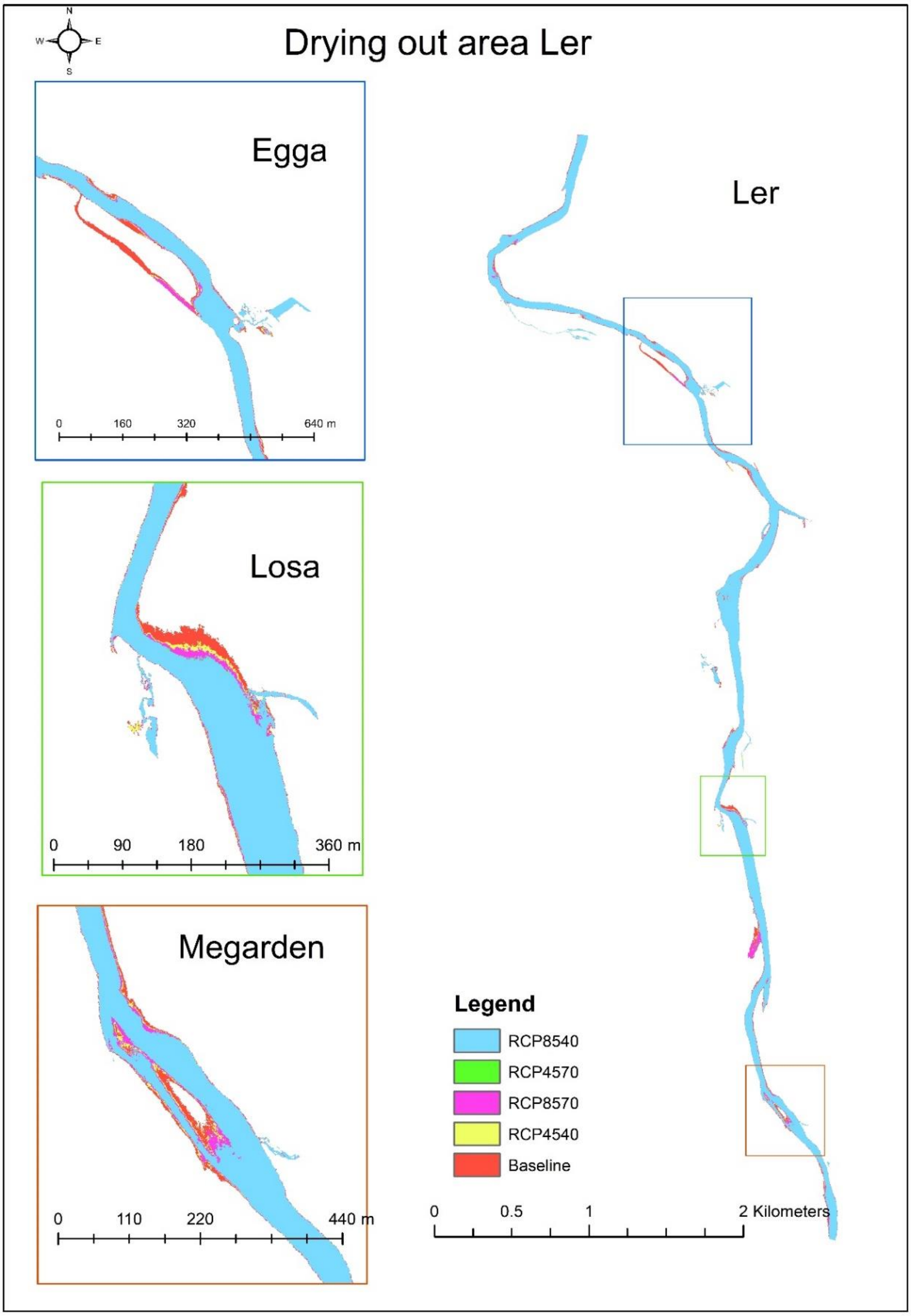


Figure 5-27: Wetted area for different climate scenarios (Ler part) (discharge values in Table 5-2)

Drying percentage is comparatively higher than other parts in this part. The upper part of the river here has a milder slope than the lower part in this section.

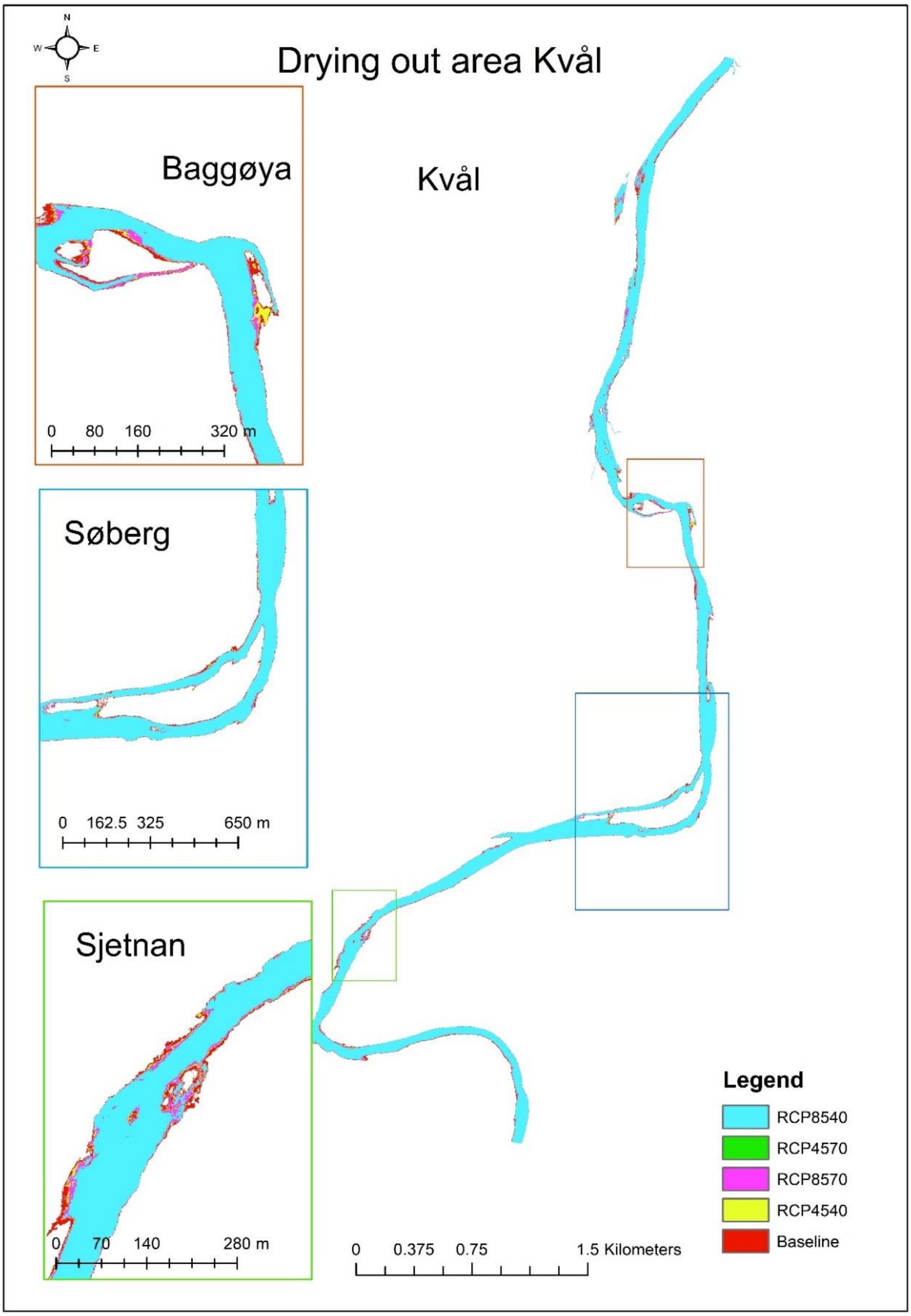


Figure 5-28: Wetted area for different climate scenarios (Kvål part) (discharge values in Table 5-2)

This part is the longest (9.9km) among others and it is clear that the gravel bars are appearing in a high amount due to low flow in the future.

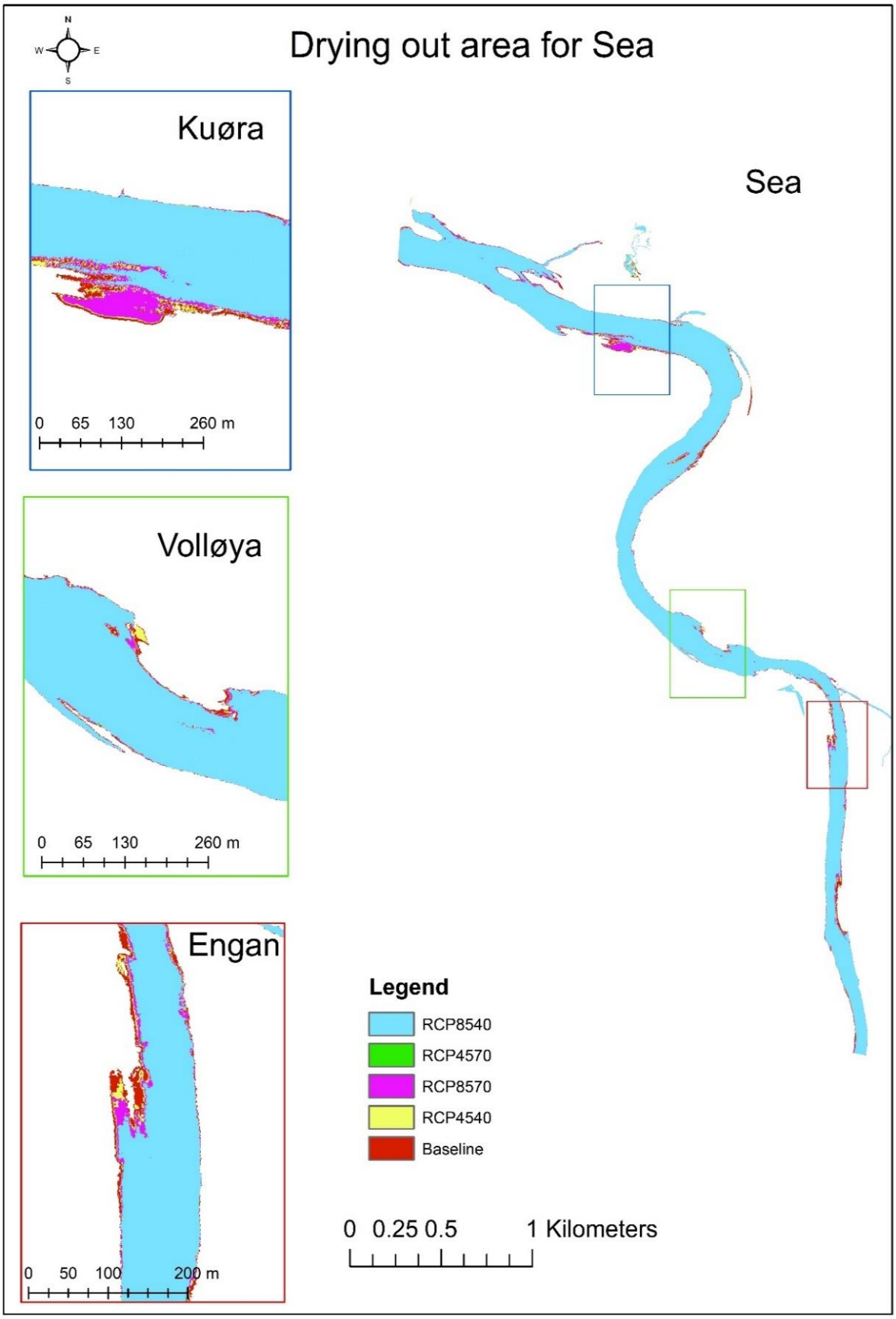


Figure 5-29: Wetted area for different climate scenarios (sea part) (discharge values in Table 5-2)

This part is draining toward the sea and low tide was assumed during its calculation since the target was focused on finding the stranding areas. This is the smallest part and has a length of 6.8km. Affected areas due to drying are indicated in this figure.

Drying in summer

		Wetted area(m^2)	discharge(m^3/s)	dried out area(m^2)	drying%
Støren-7.8km	baseline	430763	56.12		
	RCP4540	411378	42.27	19385	4.5
	RCP8570	401520	36.64	29243	6.79
	RCP4570	382747	28.21	48016	11.15
	RCP8540	381799	27.79	48964	11.37
Sokna-7.4km	baseline	474269	56.47		
	RCP4540	453041	42.43	21228	4.48
	RCP8570	439288	36.78	34981	7.38
	RCP4570	422405	28.32	51864	10.94
	RCP8540	421290	27.9	52979	11.17
Ler-7.8km	baseline	549496	63.05		
	RCP4540	515776	47.36	33720	6.14
	RCP8570	502252	41.05	47244	8.6
	RCP4570	475812	31.62	73684	13.41
	RCP8540	474663	31.15	74833	13.62
Kvål-9.9km	baseline	812899	64.31		
	RCP4540	772107	48.32	40792	5.02
	RCP8570	752646	41.86	60253	7.41
	RCP4570	718037	32.25	94862	11.67
	RCP8540	716224	31.78	96675	11.89
Sea-6.8km	baseline	876132	64.79		
	RCP4540	845815	48.69	30317	3.46
	RCP8570	832320	42.17	43812	5
	RCP4570	805816	32.48	70316	8.03
	RCP8540	805036	32.02	71096	8.11

Table 5-2: Drying out area for Gaula river in summer (all RCPs are compared with baseline)

Summer flow (25 percentile) for RCP8570 was found 36.64 m^3/s, which was greater than RCP4570 (28.21 m^3/s) and RCP8540 (27.79 m^3/s). Even though it was surprising since RCP8570 is the worst scenario and expected to be mostly dry in summer rather than other scenarios, from the future climate projections it was also found that increasing percentage of annual flow for RCP8570 is higher than other scenarios in Gaula. Moreover, the hydrograph is showing a small increase in July for RCP8570 on Gaula (Figure 5-14). (Graaff, 2019) has also similar findings for Orkla (visual observation).

Drying areas for different parts are shown in Table 5-2. Reduction of a discharge 13.85-16.1 m^3/s (from baseline to RCP4540) is drying the river from 3.46-6.14% (different for each part due to river profile, length) and from baseline to RCP8570 the amount of drying is also almost similar. However, RCP4570 and RCP8540 has higher effects of drying than the other two scenarios. The shape of the river affects the drying percentage and it can be seen from the table 5-4 that, Gaula in the upper part is quite steep for all parts except Ler part since it has high drying percentage. Downstream of Lundesokna (Figure 5-26) was considered as a natural stream in this calculation though the Lundesokna hydropower system is functioning there and no environmental restriction (only a bypass in Sokna) is existing (Casas-Mulet et al., 2014) in the system. Obviously, if it was considered, the impact of flow would be more in the downstream of Gaula after Lundamo.

Low flow can be harmful to the ecological system as stated in the literature review part (2.3). It leads the habitat characteristics from lotic to lentic. High drying percentage in Gaula will bring its gravel islands more visible and will bring harm for the species close to it since a tiny change in flow can bring large changes in the ecosystem. In drying areas, sediments will be deposited, and small trees will appear there. Drought in a river channel could be the cause of increasing river temperature, decrease oxygen availability in the river and higher metabolic rates will affect the lives of the species (f.ex. fish). Low flow decreases the efficiency of nutrient processing and increases the nutrient in the river. On fish production and communities, the fluctuating flow has a severe impact as well (Sabater and Tockner, 2010). Since Gaula is a popular salmon river, therefore, these drying places will impact the salmon communities on migration and production. As recommended by (Isaak et al., 2012), to reduce the fish stress in summer, recreational fishing might need to be stopped since this period might become a barrier for the species. Surrounding the Gaula river, there are some farming lands and the effect of water scarcity will also attack agriculture. Therefore, not only the aquatic system but also agricultural activity will have to adapt with this long growing seasons with drying suited crops in a future warming climate (WHITEHEAD et al., 2009).

5.5.3 SIMULATIONS FOR JANUARY

Since the model was calibrated for 68.8m^3/s, and it was found that it is reproducing Gaula river in a proper way, further it was taken to simulate for future winter flow. January 5 percentile flow (from baseline, RCP4540, RCP4570, RCP8540 and RCP8570) were taken to simulate the model and compared the flow effect for different climate scenarios with the reference period.

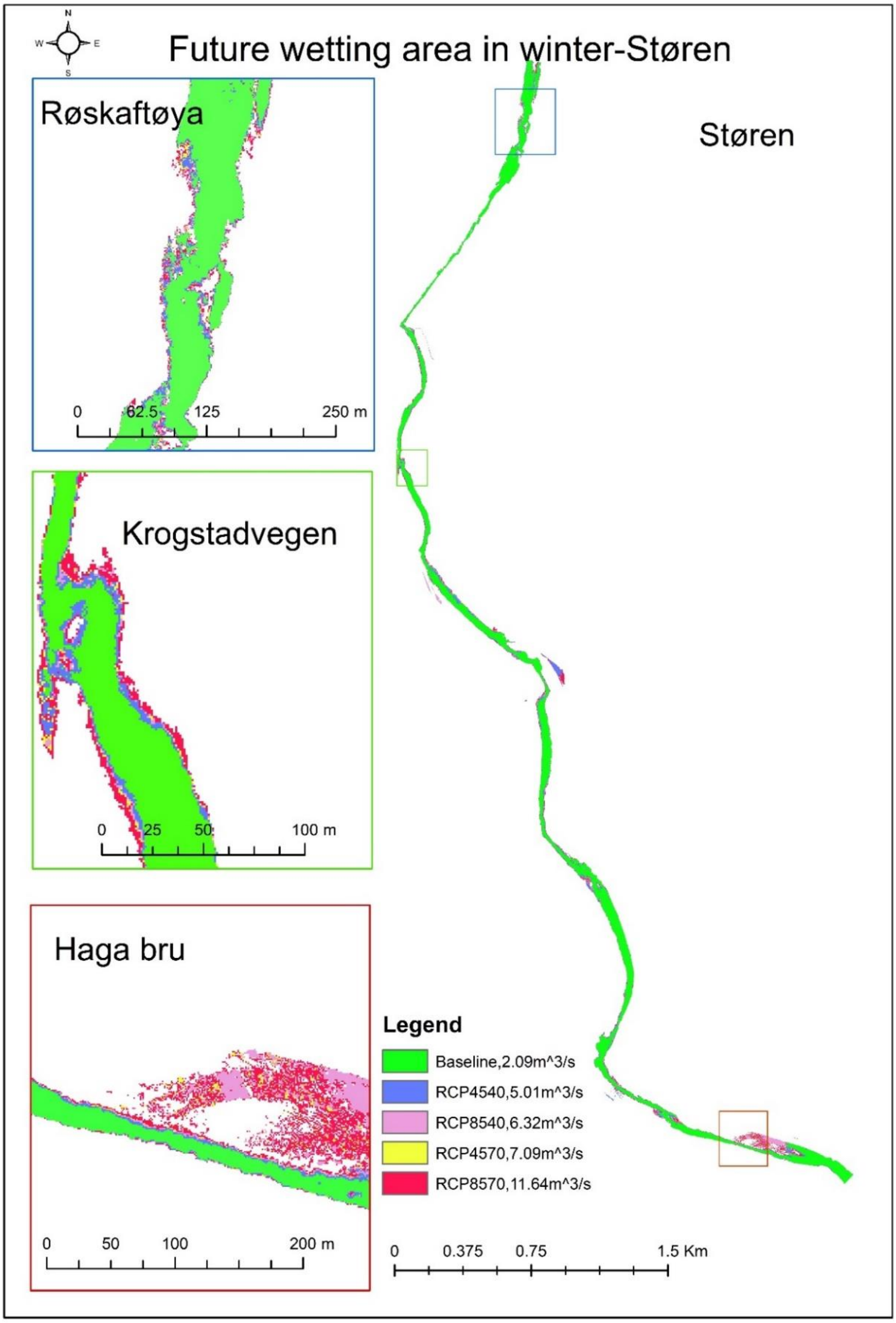


Figure 5-30: Wetted area for different climate scenarios for winter (Støren part)

Future winter flow effect is very clear in this figure.

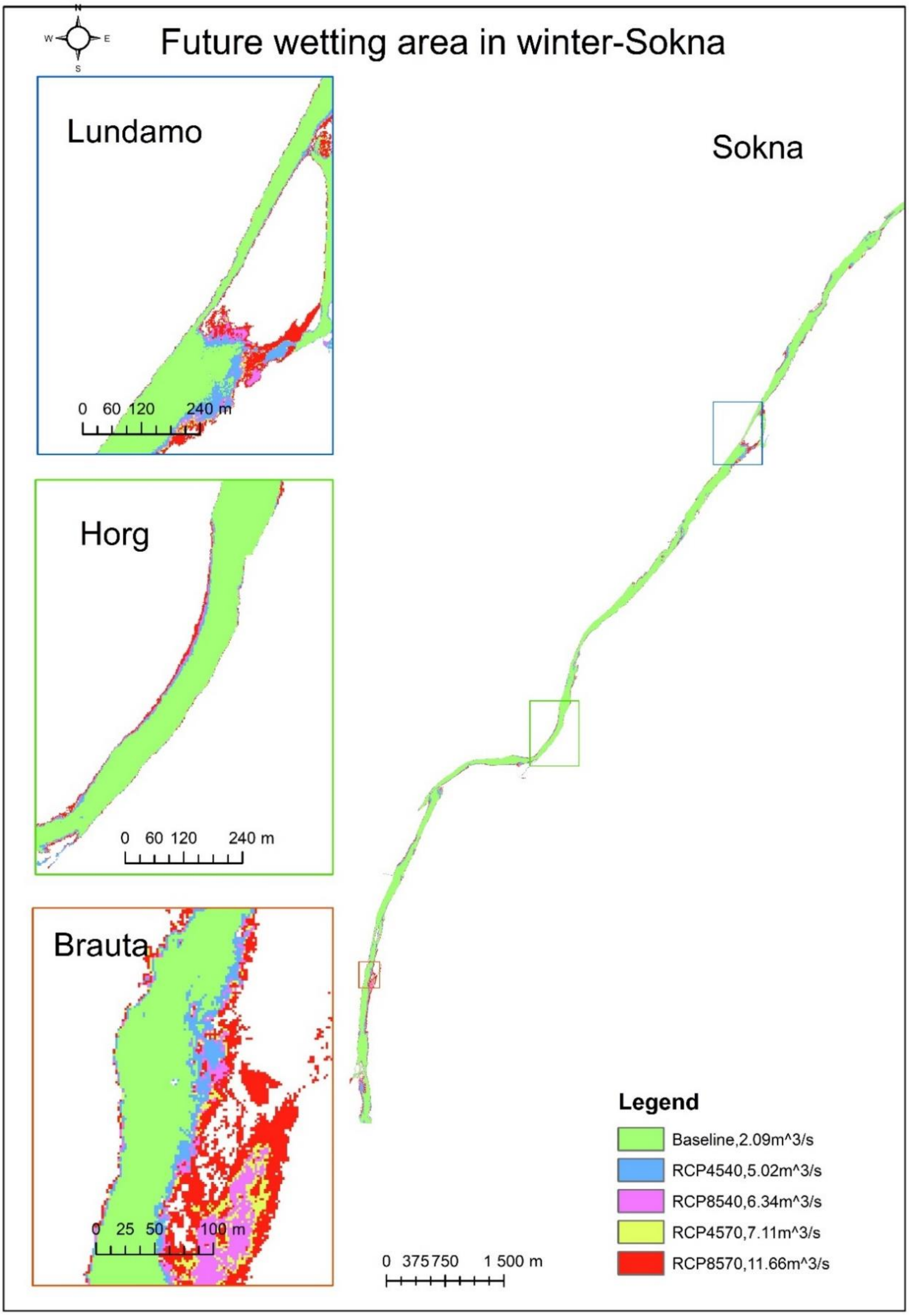


Figure 5-31: Wetted area for different climate scenarios in winter (Sokna part)

Unlike Figure 5-30, it is also seen water appearance is very clear in some places where it used to be dry now.

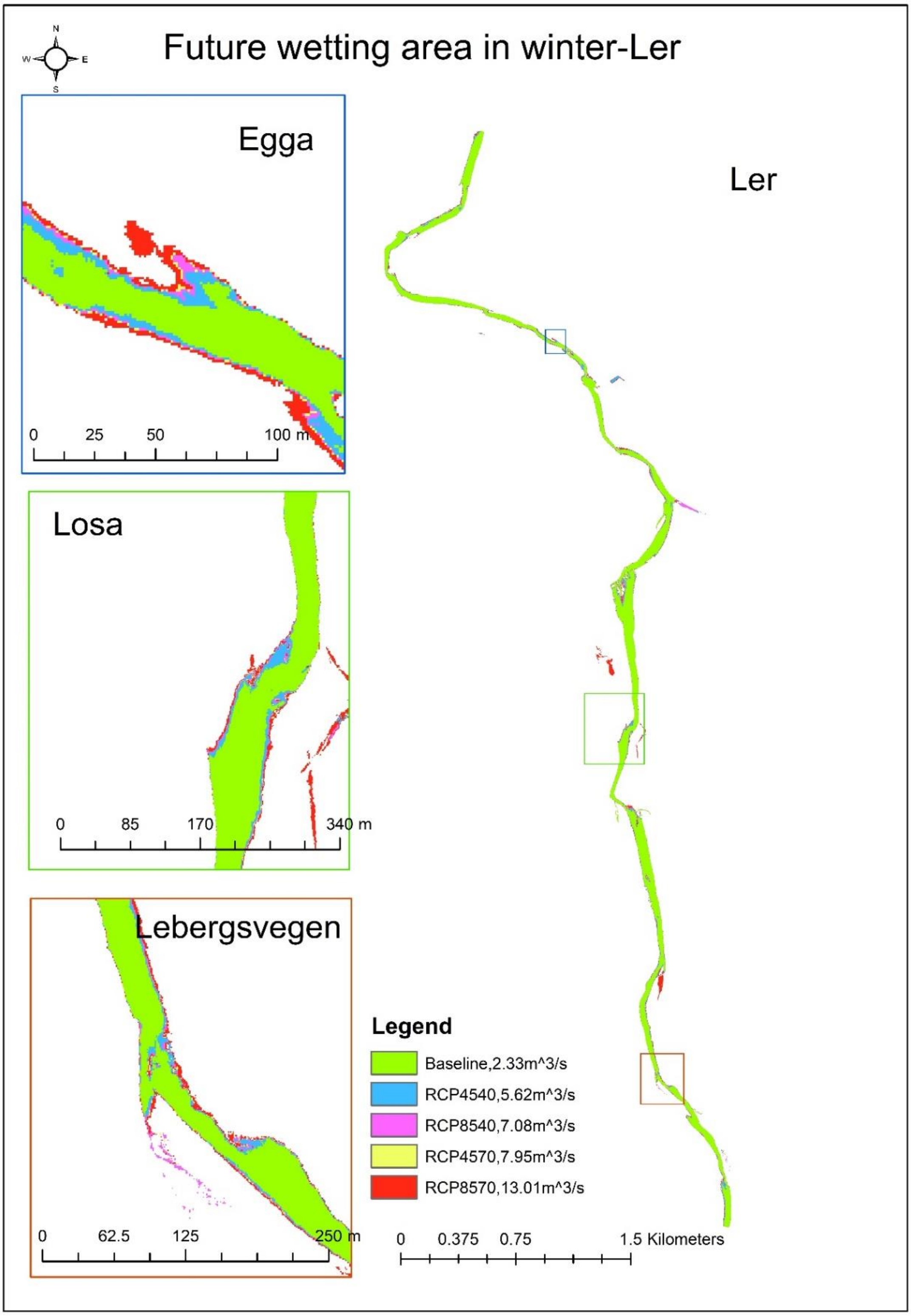


Figure 5-32: Wetted area for different climate scenarios in winter (Ler part)

Wetting is comparatively less in this part due to its geometry. Tributaries numbers are highest here.

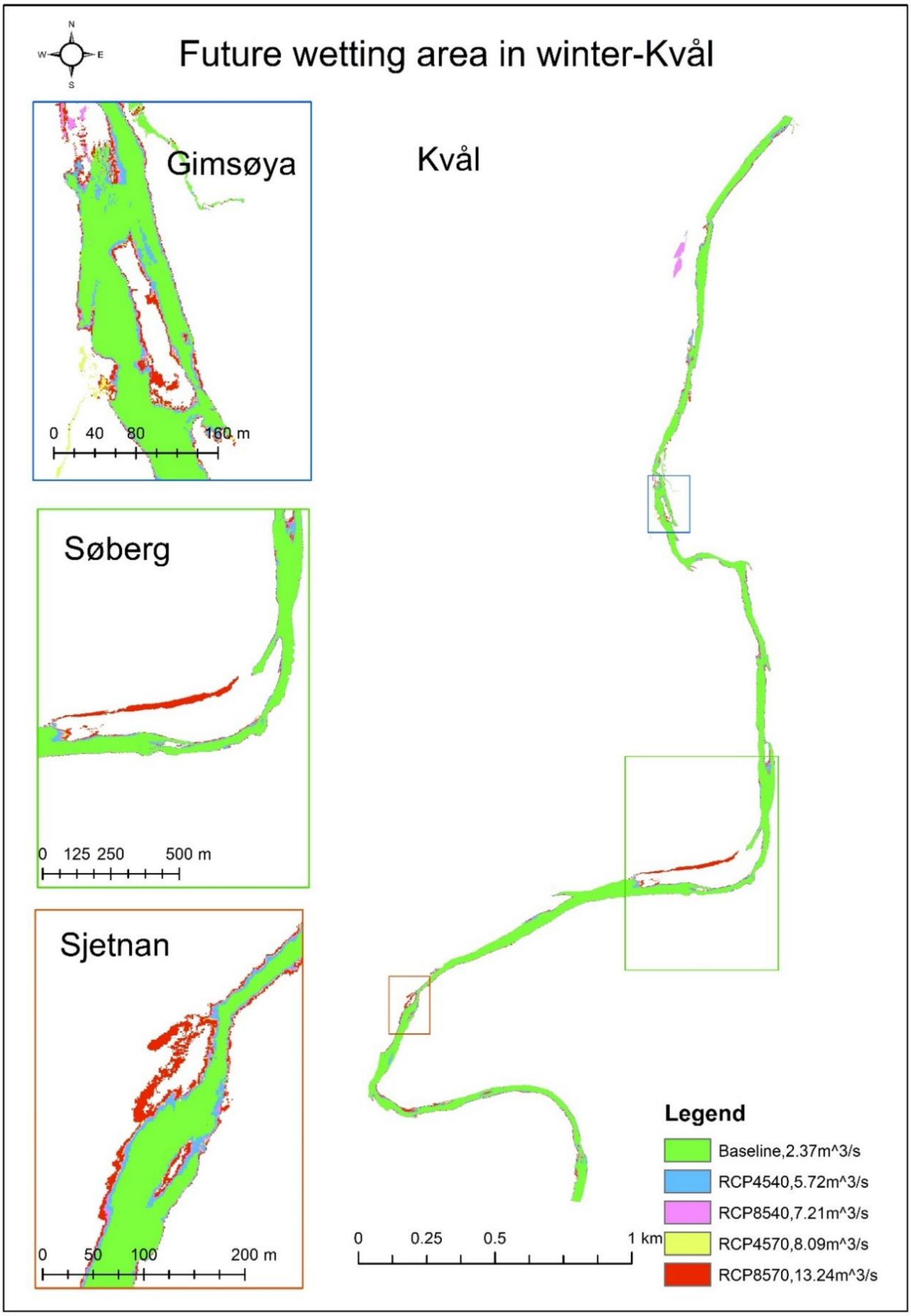


Figure 5-33: Wetted area for different climate scenarios (Kvål part)

Indicated place Søberg shows, increasing flow is building waterway in another side of Kvål winter way (in control period on winter flow only takes the green road).

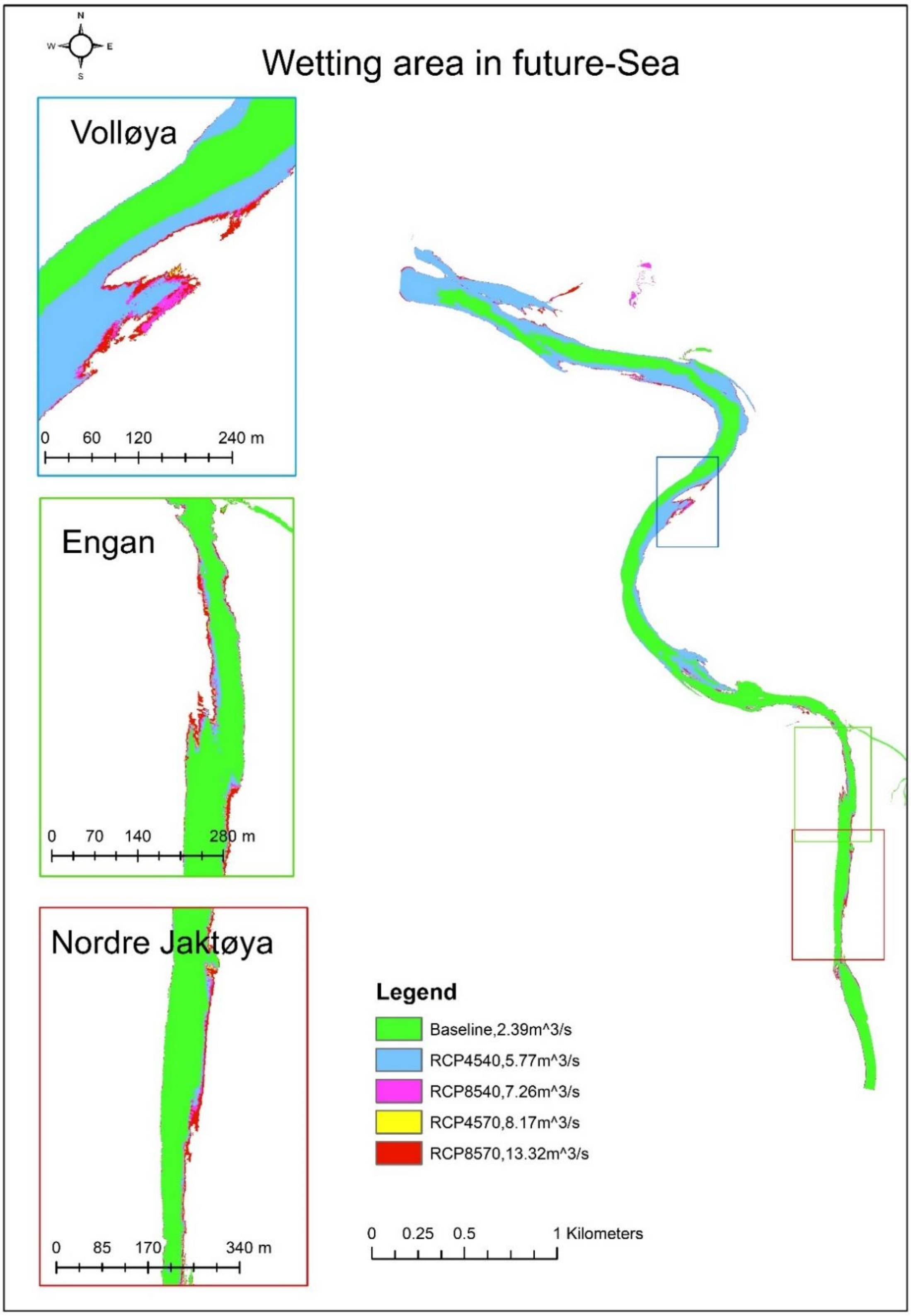


Figure 5-34: Wetted area for different climate scenarios in winter (Sea part)

This part calculation was done assuming low tide and the baseline flow was too low that it could not reach at the downstream end since the time was not enough (48 hrs) for this kind of low flow (2.39 m^3/s) in Gaula. Therefore, the wetted area in this section has significant differences for the baseline with the future scenarios (shown in the table below). Still, for other cases, the model worked properly well.

Wetting in winter

		wetted area(m^2)	Discharge(m^3/s)	changed area(m^2)	%wetting
Støren-7.8km	baseline	245767	2.09		
	RCP4540	275504	5.01	29737	12.1
	RCP8540	289520	6.32	43753	17.8
	RCP4570	294090	7.09	48323	19.66
	RCP8570	320374	11.64	74607	30.36
Sokna-7.4km	baseline	286626	2.1		
	RCP4540	319784	5.02	33158	11.57
	RCP8540	330992	6.34	44366	15.48
	RCP4570	336466	7.11	49840	17.39
	RCP8570	360381	11.66	73755	25.73
Ler-7.8km	baseline	341099	2.33		
	RCP4540	370405	5.62	29306	8.59
	RCP8540	381519	7.08	40420	11.85
	RCP4570	385098	7.95	43999	12.9
	RCP8570	415648	13.01	74549	21.86
Kvål-9.9km	baseline	482349	2.37		
	RCP4540	529866	5.72	47517	9.85
	RCP8540	552869	7.21	70520	13.31
	RCP4570	560583	8.09	78234	14.15
	RCP8570	611864	13.24	129515	23.1
Sea-6.8km	baseline	415027	2.39		
	RCP4540	701765	5.77	286738	69.09
	RCP8540	718165	7.26	303138	73.04
	RCP4570	720418	8.17	305391	73.58
	RCP8570	747283	13.32	332256	80.06

Table 5-3: Wetting area in future for Gaula in winter (all RCPs are compared with the baseline)

Wetting percentages for winter flow show that Gaula in the lower part is flatter than the upper part. Typical cross sections (Figure 5-35) of Støren part in Gaula is also proving that. The table above is showing the percentage of wetting due to high flow in winter. The data is showing a large percentage of wetting for the last part (Sea) which happened because of low flow and low simulation time, otherwise, wetting percentages are higher in Støren part than other three (Sokna, Ler, Kvål). This Sea part needs to simulate again with more simulation time to get better output. Since all simulations took a long time (approximately continuous 80 hours) and five computers were used at the same time from the computer lab at Vassbygget, that was avoided.

Unlike the summer simulation, in Sokna part Lundesokna was considered as a natural stream in winter simulations. Increasing water due to snow melt indicates that in winter, the situations might improve in Lundesokna downstream. However, since the downstream is controlled by the hydropower system, there remains uncertainty how the power company will regulate the system and the consumption as well. It is noticeable from the figures and the table that high winter flow is affecting the river since the wetting percentages are higher than drying percentage. Especially for the scenario RCP8570, the wetting percentage is quite high and that might improve the condition of fishing in Gaula since due to low flow in winter young salmon mortality is high in the cold regions. Therefore, high winter flow could be advantageous for the fishes in Gaula. In contrast, apparently though it seems this is good for the salmons but there could be negative impacts also on other winter sensitive species as well and in the arable land such as increasing cyanobacteria and nitrogen load in the sea (Arheimer et al., 2005) as mentioned in the literature review part (2.3). Brook trout and brown trout habitat might be declining due to high flow (Wenger et al., 2011). The chemical inputs a water body receives from the surroundings, quality of water is the reflection of it and these inputs will be transformed within the water body by biogeochemical processes (Murdoch et al., 2000), therefore, these changes happening in Gaula should be given concentration to avoid further problems associated with water quality.

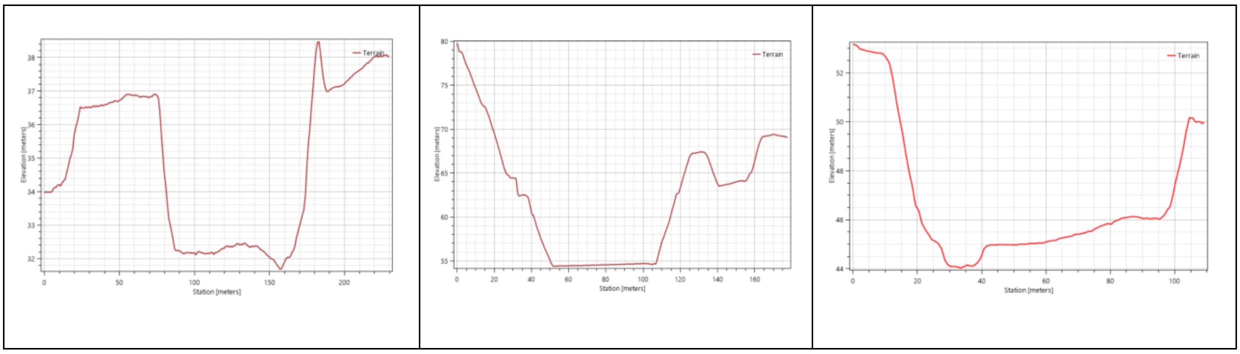


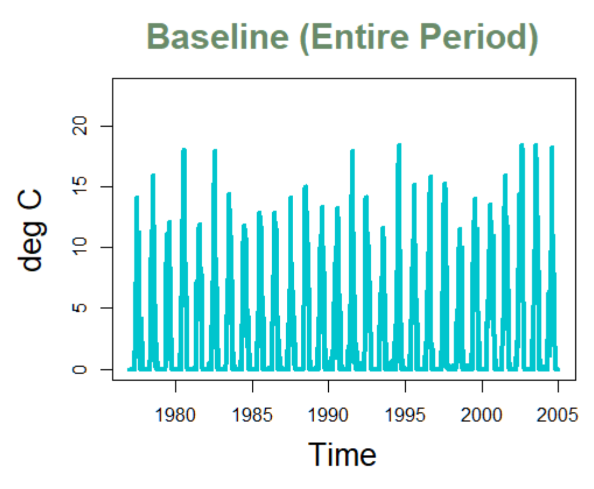
Figure 5-35: Cross-sections of Gaula in downstream (left figure), upstream (middle figure) and middle (right figure) of Støren part

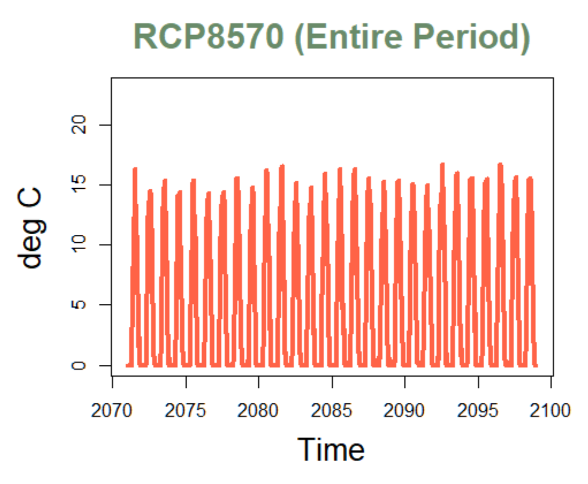
The simulation results were found quite similar to the field observations in Gaula and visually from norge i bilder. Still, there could be some discrepancies since reality is always somewhat different from the computer models.

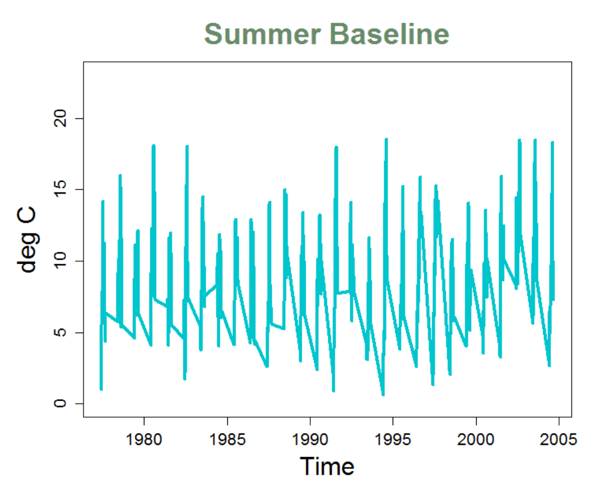
5.6 Toffolon 'air2stream' Model

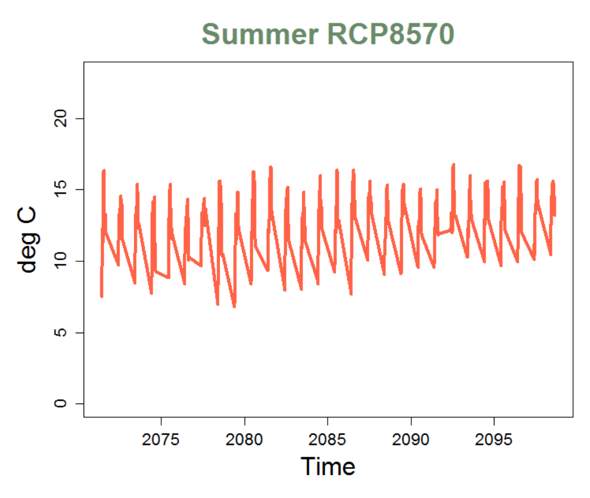
Due to lack of time, Toffolon air2stream model was run only for RCP8570 to compare with the baseline. The average of climate models discharge and air temperature were taken to give input in the model for RCP8570.

Water temperature









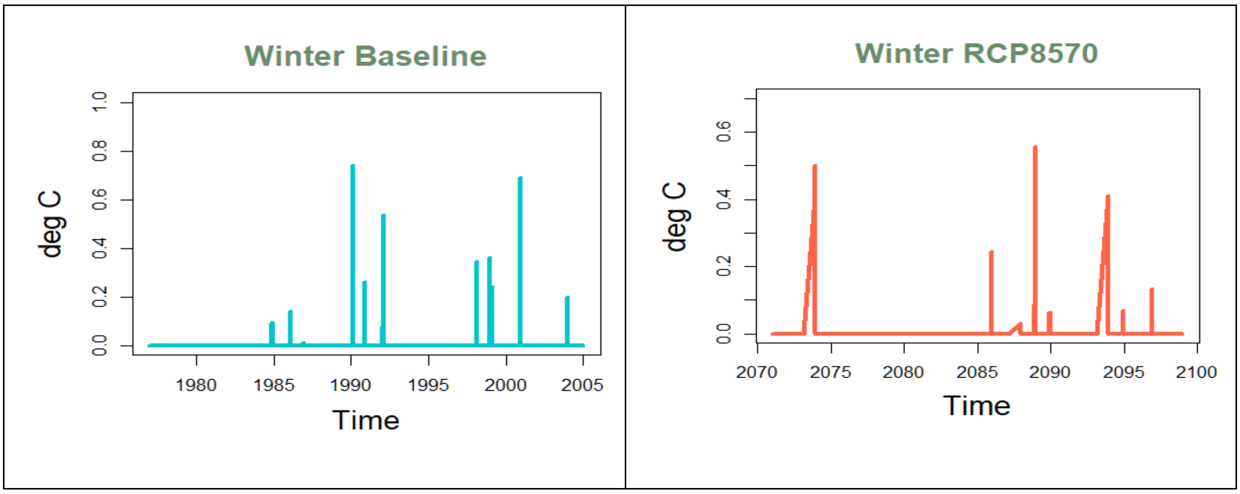


Figure 5-36: Water temperatures (deg C) for the entire period (whole year), summer (June, July, August) and winter (December, January, February) for control period (baseline) and RCP8570

This figure is showing how the water temperature is supposed to be in a warming climate. For the entire period, compared to the baseline the temperature in RCP8570 has an equal trend of higher temperature though Table 5-4 below is showing maximum entire period temperature baseline is higher than the RCP8570 which is a clear indication of influencing water temperature by the air temperature. However, average temperature (Table 5-4) for the whole period and summer period is showing unambiguously evidence of future warming water temperature since RCP8570 (5.06^{0}C, 13.11^{o}C) has a higher value than the control period (3.09^{0}C, 9.15^{o}C). The summer period in the future has a minimum temperature of 6.8^{o}C where in the control period it is 0.6^{o}C. This might be the snow cooling effect since water warming is usually delayed in cold regions due to the effect of snow melting. As winter period is shortening in future and snow will be reduced in a future warming climate (snow reduction is 70% for Gaula for RCP8570), it is obvious that the water temperature would be warming faster.

Mean monthly water temperature

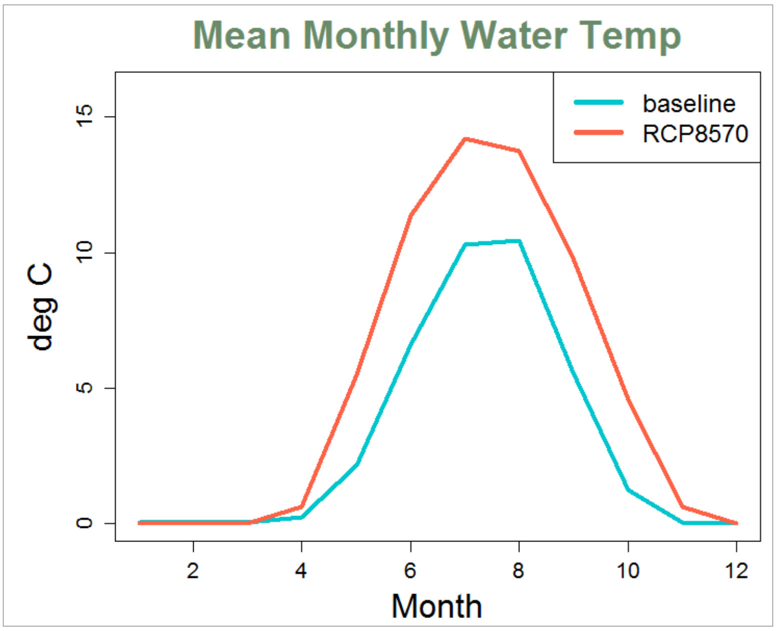


Figure 5-37: Mean monthly water temperature (^{0}C) for the control period and RCP8570

Mean monthly temperature for future is higher than the baseline period in the whole year except the winter period. The results found from this water temperature modelling is the evidence that water temperature will increase because of the air temperature.

Water temperature Gaula

		Baseline	RCP8570
Entire period	Max	18.53	16.77
	Min	0	0
	Average	3.09	5.06
Summer	Max	18.53	16.77
	Min	0.6	6.8
	Average	9.15	13.11
Winter	Max	0.74	0.56
	Min	0	0
	Average	0.003	0.002

Table 5-4: Water temperature (^{o}C) for baseline and RCP8570 in Gaula river

Since river temperature has a major consequence on the biophysical process in lotic environments, this rising would worsen the water quality and the ecosystems in Gaula. The solubility of gases might reduce in this river (especially oxygen). As, water temperature alone is sufficient to reduce the amount of surface waters due to high evapotranspiration (Murdoch et al., 2000), a possibility relies on high drying of the river. Moreover, warming summer temperature could be a danger for salmon mortality (Crossin et al., 2008), other species sensitive to high temperature and invasion of alien species adapting to high temperatures might appear in this river.

Drawbacks- The model ‘air2stream’ was calibrated and validated for ‘Eggafoss’ and different periods were used for calibration and validation period than the simulations for Haga bru in Gaula. Moreover, colder contribution in Eggafoss is higher than Haga bru catchment. For snow melting rivers ‘air2stream’ has a drawback that it cannot reproduce the proper dynamics depending on the air temperature only even though the 5-parameters version used in this study has a good performance without considering the discharges in the simulations (Toffolon and Piccolroaz, 2015). These could be the reasons that the model could not produce the peak for the future periods and therefore, the peak in summer, winter and the whole year are higher in Baseline than RCP8570. This model only depends on discharge and air temperature and measured discharge and air temperature are available almost everywhere. This model does not need the location information, shortwave solar radiation, longwave radiation, etc which are difficult to measure. A statistical approach to measure water temperature has been used in several studies. Therefore, this model is reliable to measure water temperature without much difficulties.

Added value to the study

Hydrological regime change for Gaula was compared with other literature. Since in ‘Klima i Norge2100’, hydrological modelling was done on a regional scale, observed annual runoff change is negative for Trøndelag region. Yet, other studies done on a local scale for Trøndelag has shown that annual runoff is increasing in a small amount. Therefore, the results found in this study is trustworthy. However, precipitation, temperature and snowpack changes are following the pattern found in ‘Klima i Norge2100’.

Hydropower changes in Lundesokna power plant cannot be found in other literature. Orkla power plant in Central Norway was studied several times and the result found from those is positive (small percentage). Nevertheless, Lundesokna study will give an overview of how the strategies should be altered in the future.

Flow effect (both summer and winter) on Gaula will give a better idea for the ecological system change. This study was not done before and the fisheries system will be able to get advantage from this since drying in summer and wetting in winter have several effects on the species in the river. The set up can be used for further studies in the future.

Water temperature change study is not very common around the world and Norway is not an exception. For the aquatic systems, the water temperature has a big role, therefore, the changes in water temperature will give a general idea on the probable alteration happening on the ecosystem in Gaula. Since water temperature is also important for thermal power production this study is giving a general idea of how the temperature will increase in freshwater. It is expected that other rivers, lakes might have similar responses as Gaula in Norway or other cold regions.

6. CONCLUSION AND RECOMMENDATION

The goal of this study was to find out the climate change impacts on the Gaula river. From the findings, it can be concluded that in future in a warming climate, precipitation will increase, and the highest increase would be in summer which will lead to flash floods and problems to the surroundings. Precautionary measures should be taken to have reduced impacts from this. Runoff pattern would be different and due to snow melting in the mountain, a small increase will be seen in Gaula. Climate models have uncertainty including the emission in the future. Downscaling and bias-correction/ adjustment procedure have uncertainty as well. Since, results obtained for changing hydrological regime have similarity with other studies done by (Graaff, 2019) and (Ånund Killingtveit and Knut Alfredsen, 2016) in closest places, the results are reliable.

Hydropower potential in Lundesokna will be increased following the increasing runoff. Energy production will not follow the same pattern as it is now. In summer large decrement in power production will occur due to earlier snowmelt and high temperature. Severe reduction in Samsjøen reservoir during summer is a warning for the system. The spill magnitude and timing will be changed, and further study is recommended to use this additional spill in a productive way and to take adaptive strategy for the power plant since there will be changes in temperature during the whole year. The current strategy is to store the snow melted water for producing energy in high consumption period (winter due to low temperature) which will no longer exist in the future because of climate change. Air cooler demand in summer will increase instead of heater in winter. A modification will be needed to adjust the weather, electricity demand, price, etc. Turbine schedule in the power system might need to be changed due to the change of flow. Increasing precipitation in summer and high flow in winter should be utilized by building new reservoirs to reduce the effects of drying in summer periods. That could benefit both the Lundesokna hydropower system to store water for summer and for the Gaula river to get rid of low flow problems.

Water quality is a vital factor for the ecosystem, and in Gaula water temperature is changing with problems lying with drying flow in summer and wetting flow in winter, therefore, further study is needed to find the ecosystem changes, its effects and adaptive measures. Economic sectors will be affected since the deterioration of water quality will influence the fisheries and recreation industry in Gaula. Regarding the salmon population, further study is necessary since much things are unknown. Fish adjustability with warm water, spawning habitat in reduced summer flow is yet to be studied to reduce the negative impacts. Conversely, negative impacts related to high winter flow is also necessary to take care of.

The water temperature calculation was done roughly only for RCP8570. It is needed to be done for other scenarios and each climate model separately to obtain better results and to have better ideas on the changing happening in water temperature. Vegetation, evapotranspiration increase due to low flow and high water temperature are recommended for further studies. Moreover, Water temperature data is scarce and proper monitoring should be introduced before it is too late.

Figure 6-1: Gaula near Gaulfoss gauge

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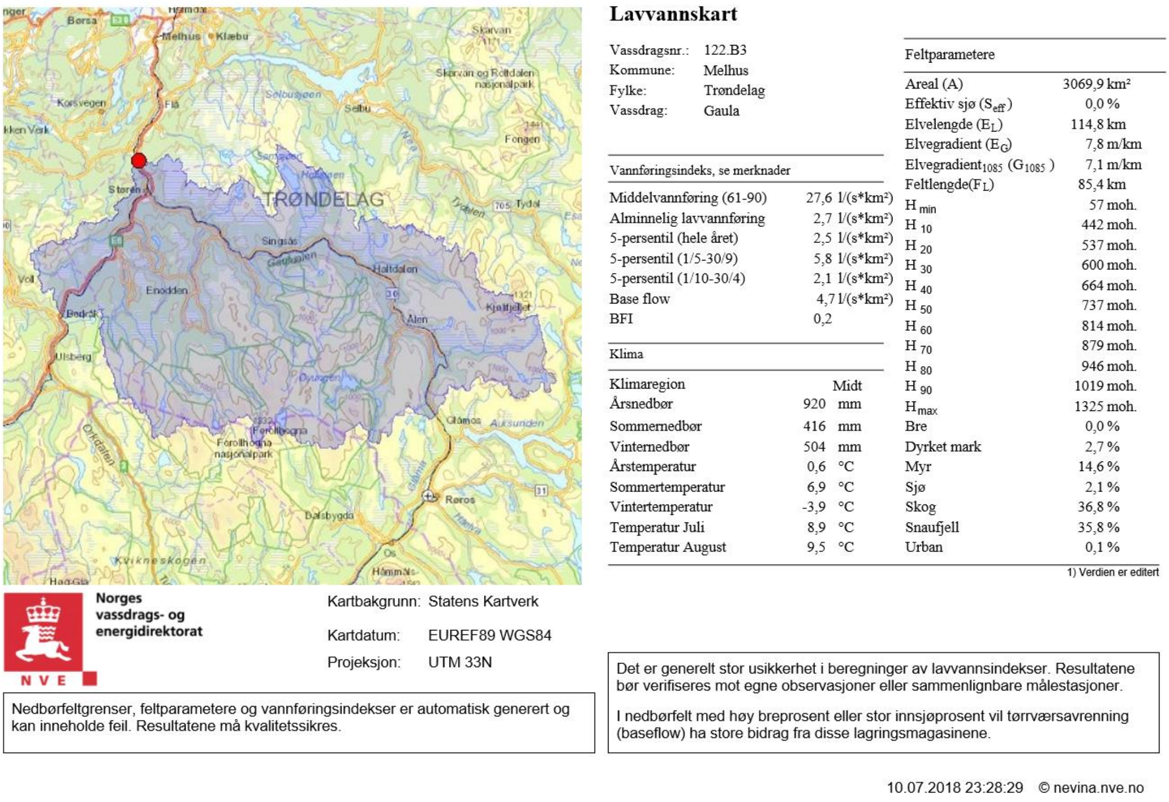
APPENDICES

I. Appendix A

Haga bru catchment



Lavvannskart

Vassdragsnr.:	122.B3
Kommune:	Melhus
Fylke:	Trøndelag
Vassdrag:	Gaula

Vannføringsindeks, se merknader	
Middelvannføring (61-90)	27,6 l/(s*km²)
Alminnelig lavvannføring	2,7 l/(s*km²)
5-persentil (hele året)	2,5 l/(s*km²)
5-persentil (1/5-30/9)	5,8 l/(s*km²)
5-persentil (1/10-30/4)	2,1 l/(s*km²)
Base flow	4,7 l/(s*km²)
BFI	0,2

Klima		
Klimaregion	Midt	
Årsnedbør	920	mm
Sommernedbør	416	mm
Vinternedbør	504	mm
Årstemperatur	0,6	°C
Sommertemperatur	6,9	°C
Vintertemperatur	-3,9	°C
Temperatur Juli	8,9	°C
Temperatur August	9,5	°C

Feltparametere	
Areal (A)	3069,9 km²
Effektiv sjø (S_{eff})	0,0 %
Elvelengde (E_L)	114,8 km
Elvegradient (E_G)	7,8 m/km
Elvegradient$_{1085}$ (G_{1085})	7,1 m/km
Feltlengde(F_L)	85,4 km
H_{min}	57 moh.
H_{10}	442 moh.
H_{20}	537 moh.
H_{30}	600 moh.
H_{40}	664 moh.
H_{50}	737 moh.
H_{60}	814 moh.
H_{70}	879 moh.
H_{80}	946 moh.
H_{90}	1019 moh.
H_{max}	1325 moh.
Bre	0,0 %
Dyrket mark	2,7 %
Myr	14,6 %
Sjø	2,1 %
Skog	36,8 %
Snaufjell	35,8 %
Urban	0,1 %

1) Verdien er editert

Kartbakgrunn: Statens Kartverk
Kartdatum: EUREF89 WGS84
Projeksjon: UTM 33N

Nedbørfeltgrenser, feltparametere og vannføringsindekser er automatisk generert og kan inneholde feil. Resultatene må kvalitetssikres.

Det er generelt stor usikkerhet i beregninger av lavvannsindekser. Resultatene bør verifiseres mot egne observasjoner eller sammenlignbare målestasjoner.

I nedbørfelt med høy breprosent eller stor innsjøprosent vil tørrværsavrenning (baseflow) ha store bidrag fra disse lagringsmagasinene.

10.07.2018 23:28:29 © nevina.nve.no

Figure 0-1: Haga bru catchment

II. Appendix B

Gridded precipitation and temperature data and runoff from the gauging station

Month	Average of P_738masl(mm)	Average of T_738masl(°C)	Average of Q_Haga bru(m³/s)
jan	68.82	-7.44	13.92
feb	54.32	-7.2	14.52
mar	48.98	-4.81	13.56
apr	46.5	-0.76	66.6
mai	42.78	4.8	282.86
jun	75.3	8.7	192.59
jul	93.62	10.98	86.27
aug	94.86	10.05	66.75
sep	86.1	5.8	78.89

okt	65.41	1.37	57.47
nov	62.7	-3.45	31.66
des	66.03	-6.72	18.35
Mean	67.11	0.94	76.95

Table 0-1: Mean monthly of observed Precipitation, Temperature and Runoff

III. Appendix C

Snowpack change

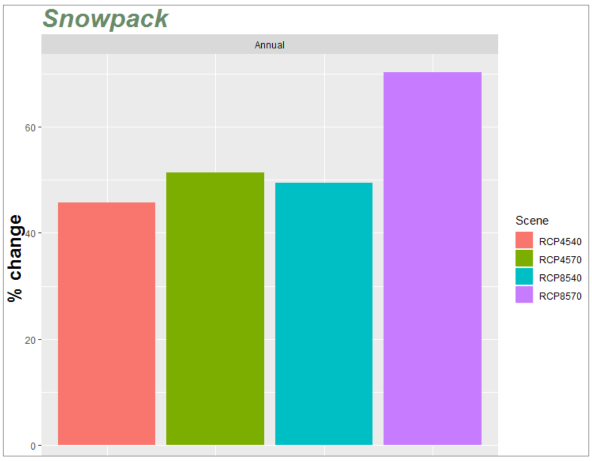


Figure 0-2: Percent change for snowpack

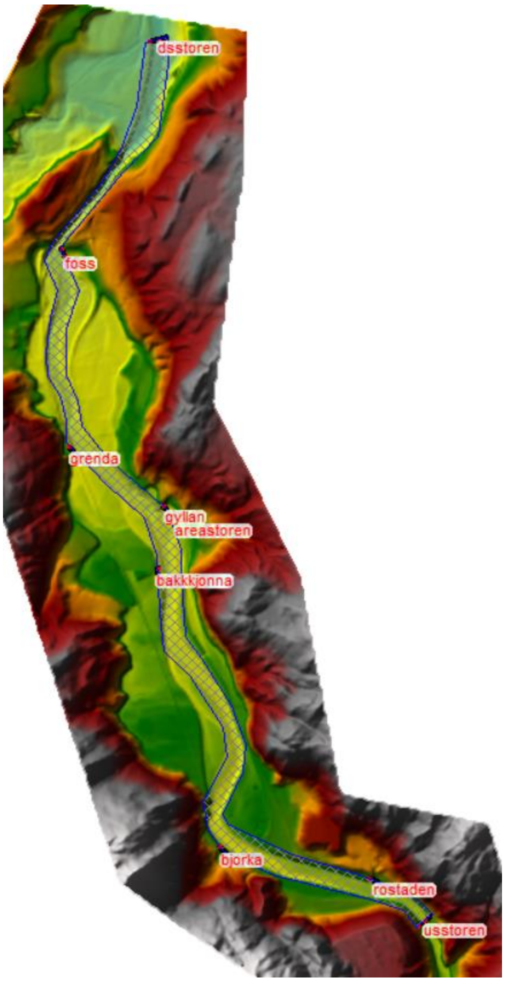
IV. Appendix D

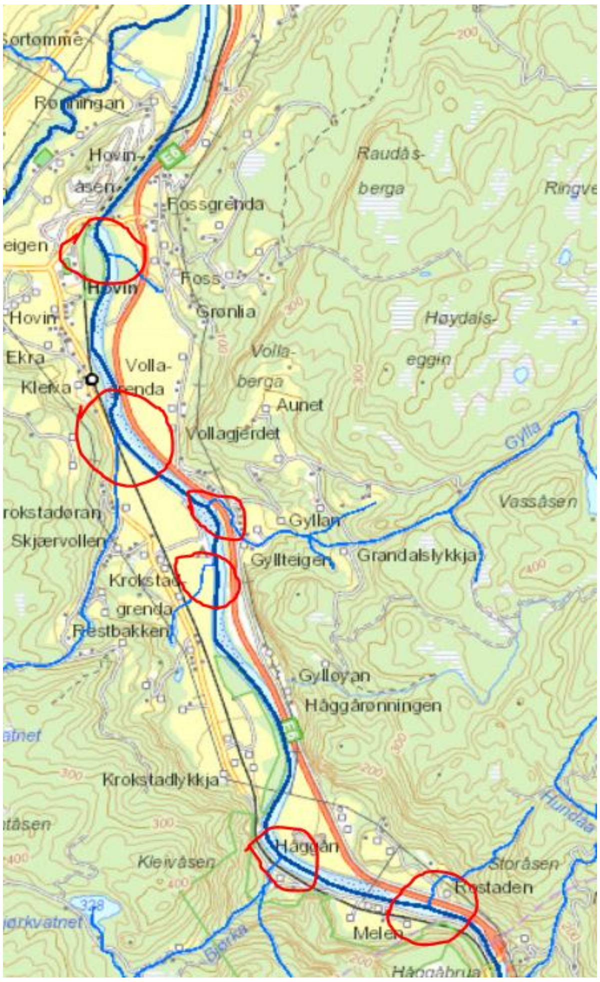
River length

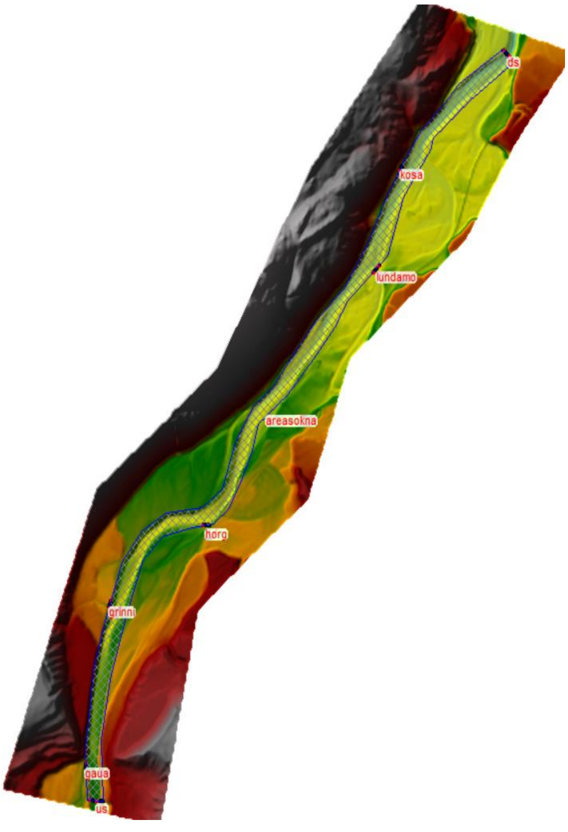
	Length (km)
Støren-first part	7.8
Sokna-second part	7.4
Ler-third part	7.8
Kvål-fourth part	9.9
Sea-fifth part	6.8

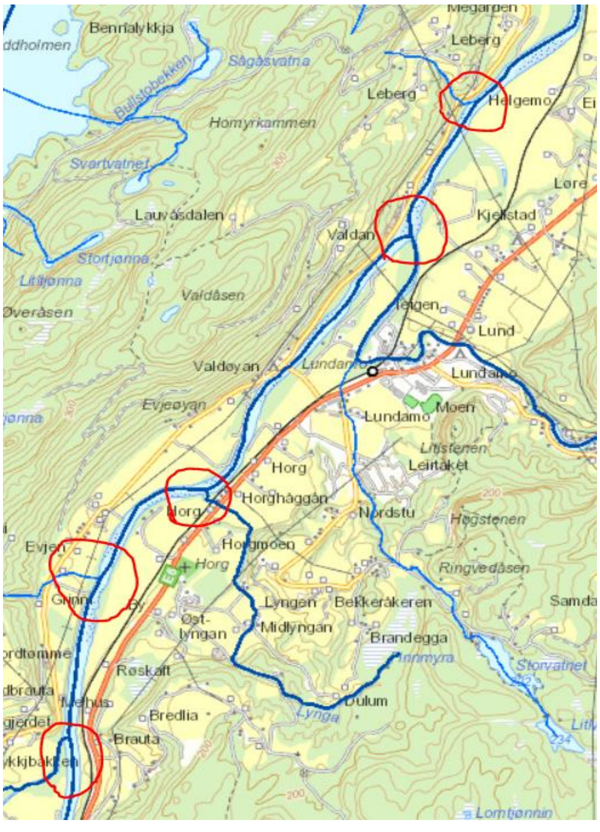
Table 0-2 : Length (approx) of the parts used in simulations for Gaula (measured from www.norgeskart.no)

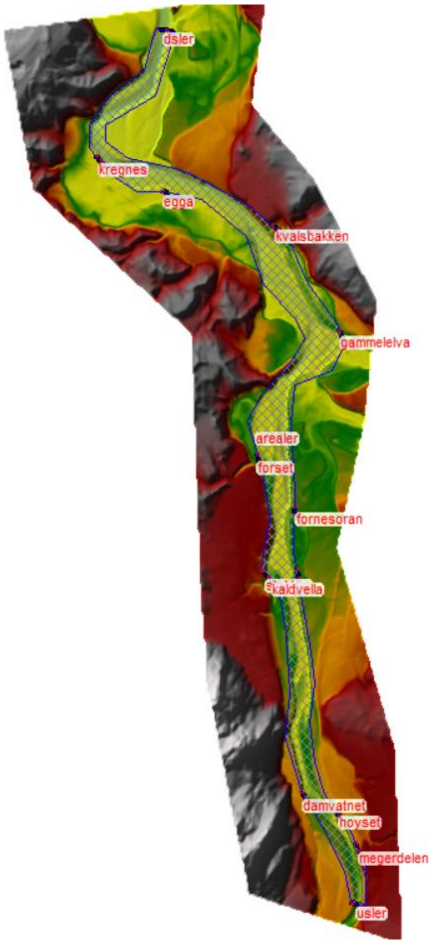
Gaula from upstream to downstream

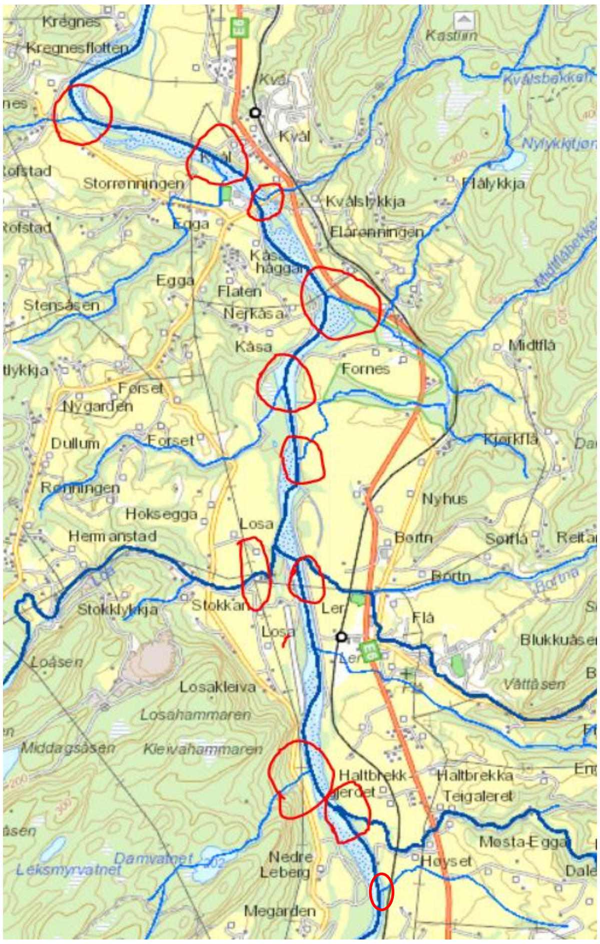

dsstoren
foss
grenda
gyllan
areastoren
bakkkjonna
bjorka
rostaden
usstoren

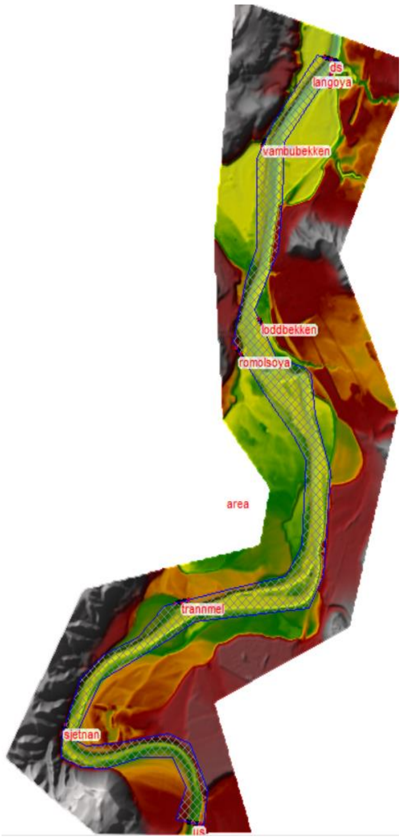

Sørtomme
Romingan
Hovin-
åsen
Fossgrenda
Raudås-
berga
Ringve
eigen
Hovin
Foss
Grønlia
Høydals-
eggin
Hovin
Ekra
Volla-
grenda
Volla-
berga
Klerka
Aunet
Vollagjerdet
Gylla
Vassåsen
rokstadøran
Skjærvollen
Gyllan
Gyllteigen
Grandalslykkja
Krokstad
grenda
Restbakken
Gylløyan
Håggårønningen
Krokstadlykkja
Kleivåsen
Håggån
Storåsen
Rostaden
Melen
Bjørka
Håggåbrua

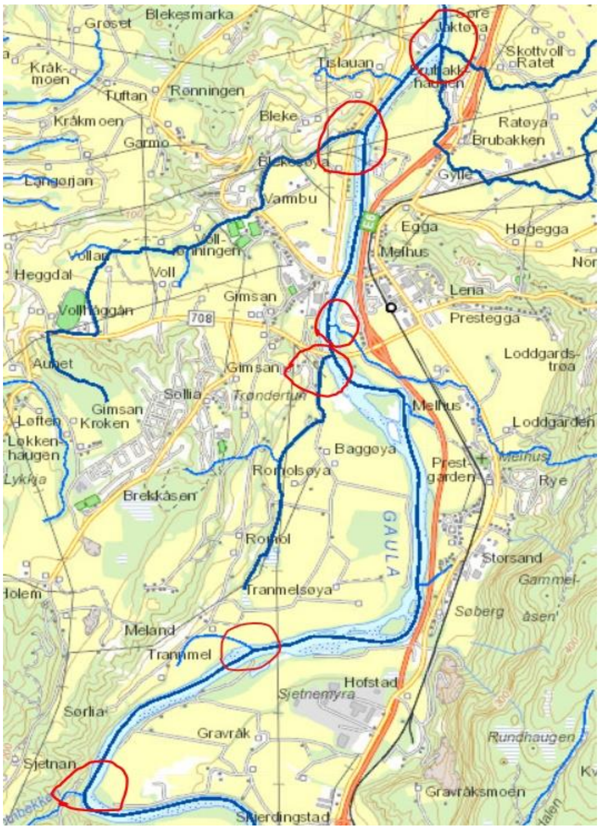

ds
kosa
lundamo
areasokna
horg
grinni
gaua
us


Megarden
Benrialykkja
Leberg
Sågåsvatna
Leberg
Helgemo
Homyrkammen
Svartvatnet
Løre
Lauvåsdalen
Valdan
Kjelstad
Stortjønna
Litltjønna
Valdåsen
Overåsen
Teigen
Lund
Valdøyan
Lundamo
Lundamo
Evjeøyan
Moen
Lundamo
Litlsteinen
Horg
Leirtaket
Horghåggån
Nordstu
Horg
Høgsteinen
Horgmoen
Evjen
Horg
Ringvedåsen
Grinni
Lyngen
Bekkeråkeren
Samda
Øst-
lyngan
Midlyngan
Brandegga
Røskaft
Storvatnet
Melhus
Dulum
Lyngå
Bredlia
Brauta
Lomtjønnin


dsler
kregnes
egga
kvalsbakken
gammelelva
arealer
forset
fornesoran
skaldvella
damvatnet
hoyset
megerdelen
usler


Kregnes
Kregnesflotten
Kvål
Kvål
Kastlin
Kvålsbakken
Nylykkjtjørn
Storrønningen
Kvålslykkja
Flålykkja
Egga
Flårønningen
Kåsa
Egga
Flaten
Stensåsen
Nerkåsa
Kåsa
Fornes
Midtflå
Forset
Nygarden
Dullum
Forset
Kjørkflå
Rønningen
Nyhus
Hoksegga
Losa
Hermanstad
Bortn
Søflå
Bortn
Stokklykkja
Stokkan
Ler
Flå
Blukkuåsen
Losa
Ler
Loåsen
Losakleiva
Våttåsen
Losahammaren
Middagsåsen
Kleivahammaren
Haltbrekk-
gjerdet
Haltbrekka
Teigaleret
Mosta-Egga
Damvatnet
Nedre
Leberg
Høyset
Leksmyrvatnet
Megarden


ds
langoya
vambubekken
loddbekken
romolsoya
area
trannmel
sjetnan
us


Blekesmarka
Groset
Kråk-
moen
Tuftan
Rønningen
Tislauan
Jaktøya
Skottvoll
Ratet
Krukakk-
haugen
Kråkmoen
Bleke
Ratøya
Brubakken
Garmo
Blekesøya
Gylle
Langørjan
Vambu
Egga
Høgegga
Voll-
rønningen
Vollan
Melhus
Heggdal
Voll
Lena
Gimsan
Prestegga
Vollhaggån
708
Loddgards-
trøa
Aunet
Gimsan
Søllia
Tronderun
Melhus
Gimsan
Kroken
Loddgarden
Løften
Løkken-
haugen
Baggøya
Prest-
garden
Melhus
Rye
Lykkja
Romolsøya
Brekkåsen
GAULA
Romol
Storsand
Gammel-
åsen
Tranmelsøya
Holem
Søberg
Meland
Tranmel
Hofstad
Sjetnemyra
Sørlia
Gravråk
Rundhaugen
Sjetnan
Gravråksmoen
Skjerdingstad

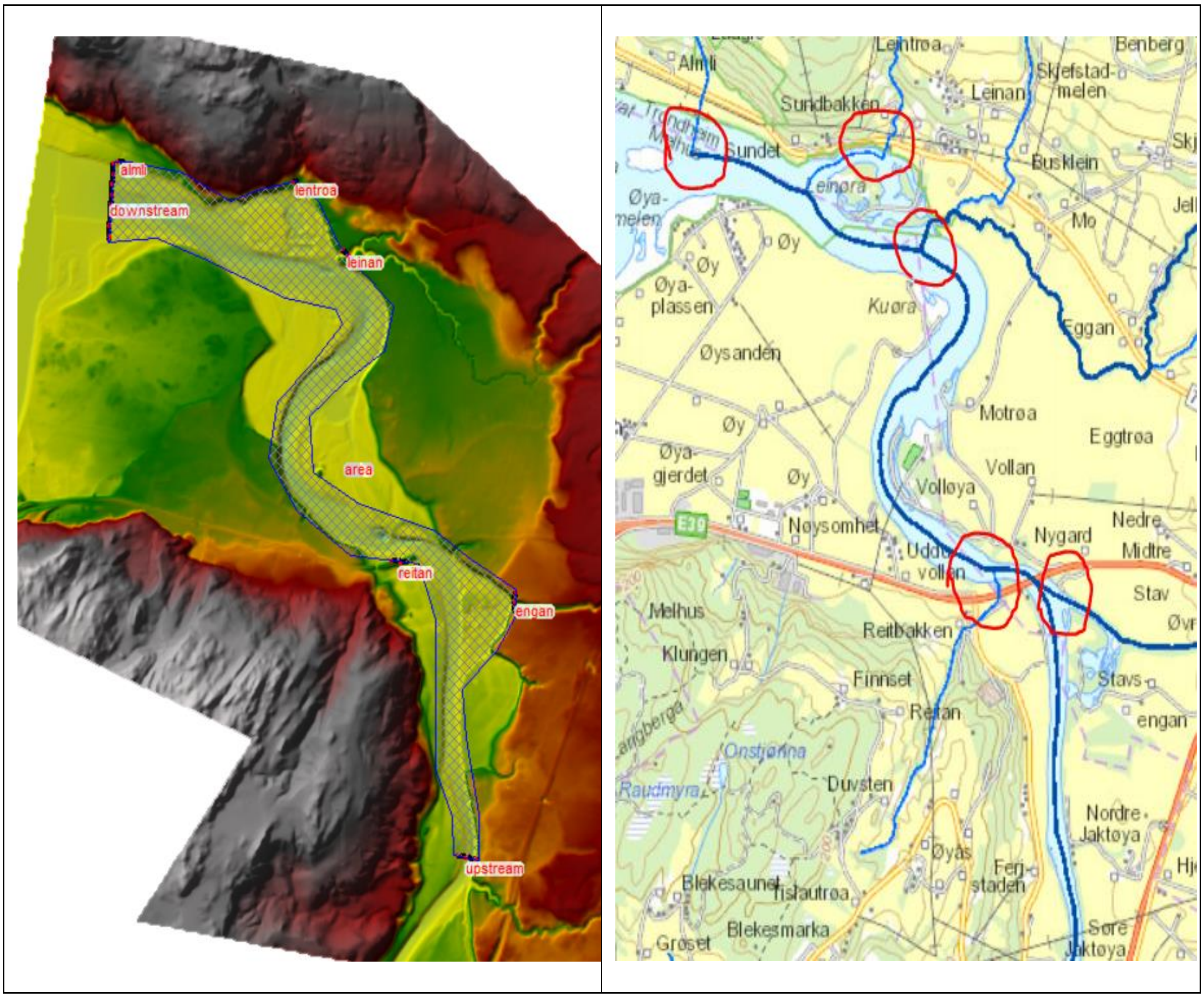


Figure 0-3: Gaula river (top to bottom- Støren, Sokna, Ler, Kvål and Sea part) (left figures are the terrains on right are from NEVINA)

Tributaries

	tributary	area(km^2)	sp.runoff(l/s*km^2)	Avg annual runoff(m^3/s)
Støren	rostaden(storåsen)	0.2	19.5	0.0039
	bjørka	3.4	25.5	0.0867
	bakktjønna	1	17.7	0.0177
	gyllan	5.4	22.8	0.12312
	grenda	4.1	17.9	0.07339
	foss	1.3	19.2	0.02496
Sokna	gaua	81.8	24.3	1.98774
	kverhusdalen/grinni	4	19.4	0.0776
	horg/lynga	5.8	18.6	0.10788
	lundamo	247.7	31.1	7.70347
	kosa/leberg	0.6	16.2	0.00972
Ler	megerden	1.7	15.8	0.02686
	høyset(skotta)	16.7	22	0.3674
	damvatnet/damlokkja	0.9	17.6	0.01584

	ler(kaldvella)	29.4	20.8	0.61152
	stokkan/benna(loa)	26.8	17.1	0.45828
	fornesøran	2	16.7	0.0334
	forset	2.6	17.2	0.04472
	gammelelva	3.6	18.8	0.06768
	kvålsbekken	7.1	24.2	0.17182
	egga/rosmelen	1.9	16.1	0.03059
Kvål	skjerva/kregnes	5.9	21.1	0.12449
	sjetnbekken	4	19.5	0.078
	trannmel	0.3	15.6	0.00468
	romolsøya	4	14.7	0.0588
	loddbekken	7.9	24.1	0.19039
	varmbubekken	4.8	14.8	0.07104
langøya	langbekken	10.8	18.1	0.19548
langøya	stokkbekken	10.3	19.3	0.19879
Sea	søra/engan	14.9	10.9	0.16241
	reitan	1	15.9	0.0159
	eggan/leinan	17.5	15.1	0.26425
	lentrøa	4.4	17.2	0.07568
	almli/kystfelt	0.7	15.6	0.01092

Table 0-3: Tributaries in Gaula used in the HEC-RAS simulations (source: NEVINA)

Procedure for hydraulic simulations

There are five parts of the river Støren, Sokna, Ler, Kvål and Sea. HEC-RAS projects name are following these names. Input terrain files (.tif) are inside the project folder including the projection files (.prj). Missing terrain files can be found in the terrain folders. Maximum courant is 3 and minimum is 0.5 (if the model shows minimum courant zero, the model will be unstable). Hydrograph output and detailed output interval are set to 15 minutes. Summer simulations are named July (f. ex. July baseline, July 4540 etc) and winter simulations are named January (January baseline, January 4540 etc) and the results are also in the same folders.