NTNU
Norwegian University of
Science and Technology

Flood Frequency analysis using ENKI simulated discharges

Yueyang Chen

Hydropower Development
Submission date: July 2017
Supervisor: Oddbjørn Bruland, IBM

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Faculty of Engineering
Science and Technology
Department of Hydraulic and
Environmental Engineering

M.Sc. THESIS IN
HYDROPOWER DEVELOPMENT

Candidate: Yueyang Chen

Title: Flood Frequency analysis using ENKI simulated discharges.

1 BACKGROUND

Dimensioning floods are traditionally found using either a simplified Precipitation-Runoff model and dimensioning rain events based on nearby precipitation stations or by flood frequency analysis using observed runoff from representative catchment scaled to the actual site.
Both these methods open to a high extent for subjective considerations with significant influence on the resulting dimensioning floods.

The distributed hydrological model ENKI enables simulation of runoff time series at any point within the region it is calibrated for. Time series that in turn can be used in flood frequency analysis at selected points to find for instance the dimensioning flood for a road culvert or other infrastructure constructions.

2 MAIN QUESTIONS FOR THE THESIS

1. Perform a literature review of methods for dimensioning flood estimations in Norway and in China and discuss differences.

2. Set up ENKI model for Gaula Catchment. Collect data for the catchment and perform calibration of the model.

3. Select two locations with different scale of upstream catchment size for dimensioning flood estimations. Calculate dimensioning flood for these sites using traditional methods.

4. Calculate runoff for the sites using ENKI for an as long period as there are data coverage. Evaluate the simulation using split sample analysis (simulation using a

model calibrated with the actual site included in the calibration and one where the site is excluded)

5. Perform flood frequency analysis based on simulated results for the site and calculate dimensioning floods. Compare results with traditional methods for the same site.

3 SUPERVISION, DATA AND INFORMATION INPUT

Professor Oddbjørn Bruland will supervise the thesis work and assist the candidate to make relevant information available.

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, lists of figures and tables, a list of literature and other relevant references and a signed statement where the candidate states that the presented work is his own and that significant outside input is identified.

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 12th of June 2017.

Trondheim 16th of January 2017

____

Oddbjørn Bruland
Professor

FOREWORDS

This Master's thesis titled "Flood Frequency analysis using ENKI simulated discharges" is carried out under the supervision of Professor Oddbjørn Bruland, Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway.

The thesis work started in January 2017 and was completed in July 2017 based on the data collected online and then framework ENKI.

I hereby confirm that all the work carried in this thesis is my own and significant outside efforts have been acknowledged. Any of the others' work or research for degree completion has been stated.

Yueyang Chen
July, 2017
Trondheim, Norway

ACKNOWLEDGEMENTS

First of all, I would like to acknowledge Prof. Oddbjørn Bruland, Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, for his advice, suggestions and support in carrying this thesis work. His support starting from the topic selection to the end of thesis writing is highly appreciable and helpful. He is keen to giving time during discussions and arranged for new people involved and help during the thesis work. His rich experience in this field gives more inside and guides during the study.

I would also like to extend my gratitude to Prof. Knut Alfredsen, NTNU who has helped me a lot. From literature study till many discussions where I have doubts, he is always open and welcome to discuss. Extra help is obtained from him both during my study in NTNU and during the thesis work.

My sincere thanks to Dr. Teklu T. Hailegeorgis from NTNU for his extra ENKI knowledge and help on ENKI model setup. His experience in the model and understanding enriches me a lot.

Similarly, I want to show my special thanks to Prof. Ånund Killingtveit, without him, I cannot finish this program. I would like to thank for his cooperation and support during the Master's Program at NTNU.

Last but not the least, I would like to express my great thanks to my mother Weihong Kang for her love, support and care and in my life and especially during my studies abroad.

ABSTRACT

As climate change topics get heated and more related researches have been undertaken, the facts have been observed and revealed that more and more natural disasters and extremelitie are influencing people's way of life dramatically, for instance the flood.

Floods have always been problems in most countries in the world, this paper firstly gives a glance of the methodologies applied in Norway and China traditionally and modernly in dimensioning floods. A comparison of the traditional methods and modern one (rainfall-runoff model) have been carried out.

A case in Guala Catchment along Goula River which brings the most catastrophic floods in Norway historically has been studied. Literature review gives some ideas on how this river behaves and actually inside this catchment, most of the area are protected, to be specific along some parts of the river, there are some drinking water conservations or natural conservations have been protected, which makes the river less regulated compared to most of the Norwegian rivers for power production. This might be one of the reasons discussed in the paper regarding possible reasons of the catastrophic floods formation.

A distributed hydrological model is set up and implemented for the catchment in order to simulate runoff generation where four discharge gauging stations exist. Daily resolution data has been collected on precipitation, air temperature, runoff, relative humidity, wind speed and global radiation so that the ENKI framework containing different sub-routines (models) can be operated. Setup, calibration and validation have been finished by ENKI and a set of "best-performed" parameters are obtained and listed in the paper. The criteria based on Nash–Sutcliffe model efficiency R^2 is used to terminate the calibration process, Nash–Sutcliffe model efficiency is testified and widely used, but this is not the only criteria to use, since the purpose of the work is to analyze flood, and based on the fact that the annual peak value (AMS) for each year would be picked to proceed with the frequency analysis, the performance of the model in catching the peaks is more important and meaningful than the overall performance in this sense. In addition, manual calibration is taken as well to hit the peaks, finally is it found that PcorrRain,

PcorrSnow, TX, k_2, k_1, k_0 have strong correlations with the flood generation. R^2 of 0.6 have obtained and compared in calibration period. R^2 of 0.42 have been obtained in the validation period.

It seems that there are still big improvements in model calibration due to the time limitation, since the data which has been fixed manually and the ones interpolated by the model must be different, and for such distributed model, data is of crucial importance. So this can be further tested to check which one behaves better. This has been discussed in the conclusion part.

Tradition method—Gumbel Distribution in dimensioning flood has been applied in the analysis both to the whole catchment and also two upstream part of the catchment with different sizes. The comparison between the analysis of observed runoff series and simulated runoff series is carried out.

As for the recent frequent floods happened in Gaula Catchments, one potential topic can also be the relationship between climate change, human activities and floods in such a catchment with an area of 3000 km^2.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AET Actual Evapotranspiration

Avg. Average

AMS Annual Maximum Series

API Antecedent Precipitation Index

DEM Digital Elevation Model

DLL Dynamic Link Library

ESRI Environmental System Research Institute

GIS Geographical Information System

HBV Hydrologiska Byråns Vattenbalansavdelning

km^2 Kilometer square m Meter

m^3/s Cubic Meter Per Second

masl Meter Above Sea Level

mm Millimeter NMI

Norwegian Meteorological Institut

NVE Norges Vassdrags- og Energidirektorat

P Precipitation

PET Potential Evapotranspiration

PDS Partial duration series

POT Peak Over Threshold Approach

R^2 Nash Sutcliffe Efficiency

T Temperature

SINTEF Stiftelsen for industriell og teknisk forskning

Q_{sim} Simulated Runoff

UTM Universal Transverse Mercator

1INTRODUCTION

1.1 WHY FLOOD FREQUENCY ANALYSIS IS IMPORTANT

Flood is an extreme natural hazard that occurs when there are overflow coming that can submerge dry lands where they are supposed to be dry normally. The overflow basically means excessive flowing water than normal conditions which drains to an outlet where it is low. Flood usually occurs in river, stream channels, estuarine areas, coastal areas and urban areas where lots of infrastructures, human properties and lives are threatened. Therefore it is of great value and importance to carry out flood frequency analysis and estimation based on the available hydrological data, and develop a system to evaluate and forecast flood to avoid these losses as much as possible. Overdesign and under estimation of the design will bring waster of construction and damage of built infrastructure respectively. It is more important to analyze in a proper way with the right method than just analyzing. In this paper, a distributed hydrological model is built to help testify the performance of the analysis of flood based on the simulated flood sequence for Gaula Catchment. In central part of Norway, Gaula River is an important water course to breed the Trøndelag people which is protected from regulation. While in recent years, the unpredictable flood causes lots of damages which we could have avoided if proper flood frequency analysis has been done. A historical data of seventeen-year-series has been used and analyzed based on ENKI framework, a simulation of flood runoff was generated and compared with the observed data.

1.2 OBJECTIVE

- Literature study of methods for dimensioning floods;
- Set up ENKI model for Gaula Catchment;
- Collect data for the catchment and perform calibration of the model;
- Runoff calculation for the sites using ENKI with data coverage;
- Flood dimensioning comparison between two upstream catchment with traditional methods;
- Perform flood frequency analysis based on simulated results for the site and calculate dimensioning floods. Compare results with traditional methods for the same site.

1.3 HOW IS THE FLOOD FREQUENCY ANALYSIS DONE TRADITIONALLY

Flood frequency analysis is mainly used for predicting design floods either for design concern or for safety concern. In Norway, flood mapping is made on the basis of 200-year flood, dam safety analysis is done on the basis of 500-year, 1000-year and probable maximum floods depending on the class level. (NVE, 2011) There has been developed good analysis technics of flood in Norway. Widely used methods are Probability Plotting Method, Webull Formula, Hazen Method, California Method and Gumbel Method. These methods are categorized as statistical approach estimating flood quantiles with the help pf probability models. While the prerequisite is that we have observed historical data at hand to carry out these analysis. In contrast, there has been developed rainfall-runoff models for the regions where the data is quite scarce or poorly measured. Rainfall-runoff model method is also used and discussed in the later chapters.

Before carrying out a flood frequency analysis, historical records of peak flow are needed. In a way to proceed the determination of design flood, we usually use two main methods to gain the peak flood data which is annual maximum series (AMS), and partial duration series (PDS) respectively. (NVE, 2011) It is apparent to tell from the name that the annual flood series are generated by picking the highest discharge coming in a year, with one value only most of the time, and it is a special case of the block maximum series with a duration of one year. While in another way to getting the peak for specific value, we also use partial duration series which is also known as the approach of peak over threshold. The main advantage of the later method can be easily found in flood-rich years where a threshold has been set. On the other side, the negative effect of this method is that it neglects the years with low-frequent flood events or non-flood years. (NVE, 2011) Some measures have been taken to balance these two methods in order to have a representative and smooth data of peaks from different periods of a year or different years. Some studies (Madsen et al., 1997; Martins and Stedinger, 2001) have shown that partial duration series approach is more precise that annual maximum series approach. But in the study of Cunnane (1989), a result shows that the annual maximum series outperform than the partial duration series approach when the average peak number of a year is smaller than 1.65. (NVE, 2011) While analyzing flood frequency in this paper, annual maximum series have been selected to proceed.

After we get the annual peak flow data series, we can use the statistical methods analyzing the frequency then. Since it is the statistical method, it is crucial to calculate statistical information like mean value, standard deviation, skewness and recurrence intervals which are used later in constructing a flood frequency duration curve. Frequent used distribution types here are Normal Distribution, Log-Normal Distribution, Gumbel Distribution, Log-Pearson Type III Distribution. (http://streamflow.engr.oregonstate.edu/analysis/floodfreq/)

Plotting a graph of discharge versus probabilities to get a flood frequency curve can be easy and direct. By doing this, a number of peaks should be picked out. Put them in a descending order, start number them from 1 to the end, where the number can be represented by m. We can then find the probability of flood by the equation:

$$P = m/(n+1) \tag{1}$$

Where P denotes probability of flood
m denotes the order of the flood in list
n denotes the total number of years in the record

Thus a flood frequency curve, the bets fitting curve of the data set, is plotted with the probability as x-axis and runoff as y-axis in the graph. It is also common to see graphs with recurrence interval versus runoff. In this case, the objective is to determine the magnitude of the flood for a one time in a given specific period which is the recurrence interval.

$$T = 1/P \tag{2}$$

Where T denotes recurrence interval
(https://www.slideshare.net/vivek6002/flood-frequency-analyses)

But there is one thing to notice here, the recurrence interval is a probability concept which does not necessarily have to mean that for the specific interval from the time being, there must be a flood, rather than a statistical probability.
Gumbel Method is selected to be used later on.

1.4 WHAT IS THE HYPOTHESIS BACKGROUND FOR USING HYDROLOGY AND DISCHARGE

Flood is changeable and unpredictable, the nature of a flood event can be quite different from another even at the same site but for an adjacent period. This brings lots of troubles analyzing the frequency of flood, so some hypothesis has been made in order to make the mechanism easy to understand and the analysis easy to carry out. The number one hypothesis of statistical flood frequency analysis in that the mechanism of the flood formation is the same, in another word, the event should be independent and identically distributed so that we can use one flood frequency distribution to describe the flood event which we have data in. To be specify, in Norway, the mechanism of a flood formation can be extreme rainfall, or considerable snowmelt or the combination of both. Using the distribution described in the last chapter, we can extrapolate the function of distribution in order to get the magnitude of flood for a giver recurrence interval beyond the length of observed data. But there is one thing to note here, the expected length of recurrence interval should not be too far from the existing period. The longer the period is, the more uncertainty it will bring. It is suggested from NVE (2011) report that if needed, to be extrapolated, the preferable length should be only up to twice the record length. Uncertainty in this process is variable as well, which cannot be neglected. These hypothesis and assumptions have to be fulfilled so that he frequency analysis can be carried out, otherwise more complicated statistical methods should have be induced to take into consideration of correlation between observed data and the change over time.
(http://daad.wb.tu-harburg.de/tutorial/flood-probability-assessment/hydrology-of-floods/flood-frequencies-and-design-flood/flood-frequency-analysis/objectives-and-assumptions/)

Sometimes we need a regional analysis to have a thorough idea of the regional flood which is more practical. In here another hypothesis is made, the identification of the region to be analyzed should be a homogeneous regions so that the index flood method can be applied. The law behind the index flood method is the flood inside of the region follows the same frequency distribution (NVE, 2011). The controversy between the hypothesis and reality lies in homogeneity which is nearly impossible in the real world, but approximate homogeneity might be sufficient to ensure the regional analysis is more accurate that an at-site analysis with small scale of data. (Hosking and Wallis, 1997)

For rainfall-runoff model method, there are hypothesis made as well. In the snow subroutine, assumption has been made that the snow pack can retain the melt water as long as the amount does not exceed a certain fraction of the snow (Barbro et al., 2003). The soil of the catchment in the subroutine of the model should be saturated or 80% of moisture depending on the scale of a catchment, so that a conservative estimate can be achieved (NVE, Midttømme et al., 2011). A better representation for the reality is gained under these hypothesis. This will bring more attentions in the later chapter when it comes to the model work.

1.5 STUDY AREA

The study region, Guala Catchment is mainly located in the municipality of Sør-Trondelag with the area of 3086 km^2. Figure shows the location of Gaula Catchment in Norway and based on NVE website statistics, this catchment accounts for ca. 0.95% of the total area of Norway. There are four runoff stations inside of the catchment namely Eggafoss, Lillebudal Bru, Hugdal Bru and Gaulfoss. Gaulfoss is the largest one among the four stations which has been which is the total outlet of the catchment as well.

Guala River, known as one of the longest salmon river in Norway, which crosses the entire study region has a range of 85 km. It starts from Holtålen and drains all the way to the Sokna River in Midtre Gaudal.

2 LITERATURE REVIEW

2.1 FLOOD AS A PROBLEM

Floods can be devastating natural disasters and have influence on economy, environmental and people. Worldwide, flood accounts for 40% of losses of in the total loss of natural hazard. As the development of economic zones where it is getting more populated, the losses caused by flood is increasing. (S.A. Changnon, 1985)

During a flood event, especially during the flash ones, most of the infrastructure are destroyed. Furthermore, emergency people need to take actions to rescue people where urgent and necessary. All these would incur considerable cost and loss. Besides, it would take long time to re-construct the site and replacing people where affected are hard to operate. It is rather hard to bring back the business locally either.

Another issue regarding flood occurrence is the environmental problem. During a flood event, especially a flash one, lots of chemicals and other substances that are light enough to be carried by the flood would be carried. This ends up with bad quality of water and maybe different contamination sources can be brought in the water body locally. Furthermore, the killed body of animals can be taken far away downstream due to the flush stream. In some cases, natural balance of ecosystem can be affected and broken due to the invasion of so insect brought locally by the flood.

Damages and injuries would take place for humans and animals during a severe flood. People become homeless and the dead body of animals cause big problems thus a bad circle is created. During a flood event, it is high probable that the electricity and other compulsory daily supply is cut off due to the obstacle of the flood. Diseases are widely spread during a severe and long-last flood which would definitely threaten the safety of human beings.
(http://eschooltoday.com/natural-disasters/floods/effects-of-flooding.html)

2.1.1 CONDITIONS IN NORWAY

Norway is a country located in the north part of Europe which lies between latitudes 57° and 81° N, and longitudes 4° and 32° E, with an area of 385 252 km^2. It is surrounded by Norwegian Sea and North Sea with a total coastline of 25 148 km except the eastern side of the country which has a long border line with Sweden, and Finland, Russia respectively by the corner of northeast. The climate is mainly maritime. Due to the huge embrace by the sea mainly in the western part of the country, higher temperature and more precipitation are expected. In a way, there are higher probabilities that flood occurs frequently due to the frequency of precipitation and the topography. (https://en.wikipedia.org/wiki/Norway)

From the Atlantic by the western part, wind brings lots of warm air and moist, when it blows up and climbs the mountains which there are quite many in Norway, precipitation may occur when there is a drop in air temperature. The warm moist can be an asset as well, since this keeps the temperature comparably stable, in this sense, it means that even in the coldest month in a year, the temperature can still be above 0°c. When there are intensive and heavy rain, this creates many troubles, especially some big flood that has been brought in the western part of Norway close to the coast. (Killingtveit, 1997)

Majority rivers in Norway is categorized as Nival regime whose main character is high runoff in the river during summer time due to the snow melt water, in addition spring flood is common and mainstream for this type of regime. By the western fjords, the dominating regime of river is Pluvio-nival. Under this regime, river behaves similarly as the ones under Nival regime whereas less runoff in summer is expected compared with the former one mentioned. Floods under these river regimes are mainly in spring and autumn, since in spring, much more precipitation can be expected, coupled with snow melt, thus spring flood occurs. When in summer, the precipitation is not much high as precipitation in spring nor in autumn, higher evaporation is expected as well. In fall time, usually there are high precipitation. (Killingtveit, 1997)

Hydrological variables have high variations in Norway due to a great number of mountains. Main different types of rainfall have been identified and listed due to the mechanism of formation in Norway:

- Rain floods--is usually intensive and quick
- Snowmelt flood--contributions are from snow water when temperature starts rising up, usually start from May in Norway
- Combined rain and snowmelt floods
- Ice jam floods
- Landslide induced floods—usually induced by rainfall
- Dam break floods-critical in Norway (Killingtveit, 1997)

Generally speaking, the most common floods are caused by the snowmelt and precipitation together in Norway. As recorded, there were two devastating floods in Norway which occurred in 1345 and 1789 respectively. Similarly, both of the two floods were in late summer which means it was highly probably caused by snow melt and the intensive and heavy rainfall. The damage was huge, there were many people dead during the extreme event as well. Flood can also bring lots of extra troubles, like sedimentation issues, erosion issues as well. At the same time, since Norway is a mountainous country, when a flood occurs, there must be heavy around, this is a potential threat to landslides which have been proved many times. The landslides, debris flow and flood, they coupled each and occurred usually. After the recording system was established, there are more records for what was happening that time, so that the data can be described and reserved. Based on the records, it is said that the flood in 1927, 1966, 1967 and 1995. (Killingtveit, 1997)

The precipitation and runoff show very large variation within different parts of the country, due to topographical and climatic variations. The average annual water balance for the country for the normal period 1931-60, together with maximum and minimum values are given in the table below. The highest precipitation is found along the mountain ridge running parallel to the west coast. The lowest values are found in the interior, behind the mountain ridge, and in the inland in the far north. Water balance components for Svalbard are yet not known, but the average annual precipitation is low, probably below 300 mm.

Table 1 Water balance components for mainland Norway (unit: mm/year)

	Average	Maximum	Minimum
Precipitation	1415	5000	300
Runoff	1180	4800	200
Evapotranspiration	235	450	100

As mentioned, it was practical and traditional to use statistical methods to analyze flood frequency and calculate design flood. It is also applicable in Norway based on the annual maximum floods from observed discharge data. From 1981 onwards, there has been a requirement published, from then on, the Log-Normal, Gumbel and Log-Pearson probability distribution functions are most widely used. (Killingtveit, 1997)

As the development of different techniques especially computer, simulating the process with a rainfall-runoff model become essential and getting more and more important. HBV model for example developed in Sweden is widely used in Norway as well. It is a practical model which can simulate the process of runoff formation under the mechanism of snowmelt and rainfall. In addition, there are some shortages of the traditional statistical analysis method. Due to the capacity of the precipitable water in the air and soil moisture difference in different seasons, and snow cover of land, it has highly uncertain to analyze floods nor have a thorough picture of the process with the help of traditional analysis method. Then the advantage of model work is obviously important and essential. (Killingtveit, 1997)

In 1995, there was a devastating flood occurred in Norway which lasted for about two-week time with a damage around 225 to 300 Mill. USD. It was a 100-year return flood. While for the time it occurred, that was triggered by snowmelt and rainfall, it was neither extreme snow melt nor extreme rainfall but abnormal whether. It was not as warm as usual in the early May that year, which was very cold instead. The temperature in most of the catchment was below zero that time, so this caused a time lad in melting process. Up until the end of the month, there was a rise in temperature which incurred dramatic increase in releasing melt water, coupled with the normal rainfall, the flood was then on the way. The snowmelt in the same period in one catchment called Glomma has a snow melt water accumulation of 100 mm which is equivalent to 4000 Mill.m^3 across the whole catchment compared to 10mm rainfall per day across the whole catchment. The damages were huge that ruined farm land, buildings, factories, shops and roads and so on. Associated problems brought was the shut down of water supply and wastewater treatment plants due to the severe flood. But hopefully Norway was the best country that has developed enough hydropower projects with some having a reservoir, due to the operational strategy, usually the reservoirs are emptied before the flood season for the sake of storage and energy generation. This helps to dampen the negative influence that a devastating flood can bring. This clearly reveals that the hydraulic structure in a way can be a good protection against floods. In other sense, the forecasting work of flood can be closely linked to hydropower development where reservoir behaves as a link. Model work makes it possible since the integration of the rainfall-runoff model has been developed to link the routine models and reservoir operation models by some power companies. (Killingtveit, 1997)

After the strike, the Norwegian Water Resources and Energy Administration (NVE) started revising their forecasting method in a more efficient way and tried to develop more measures against flood.

2.1.2 CONDITIONS IN CHINA

Since ancient time, China is among a few countries that holds the most severe floods disasters in the world, and it still is. The feature of floods in China is high frequency, long duration and wide range due to the vast territories. In 1991, the massive flood caused a loss of 10.6 billion USD in which 4.4 billion was lost only in June and July the same year. It is crucial to pay great attention to flood in China.

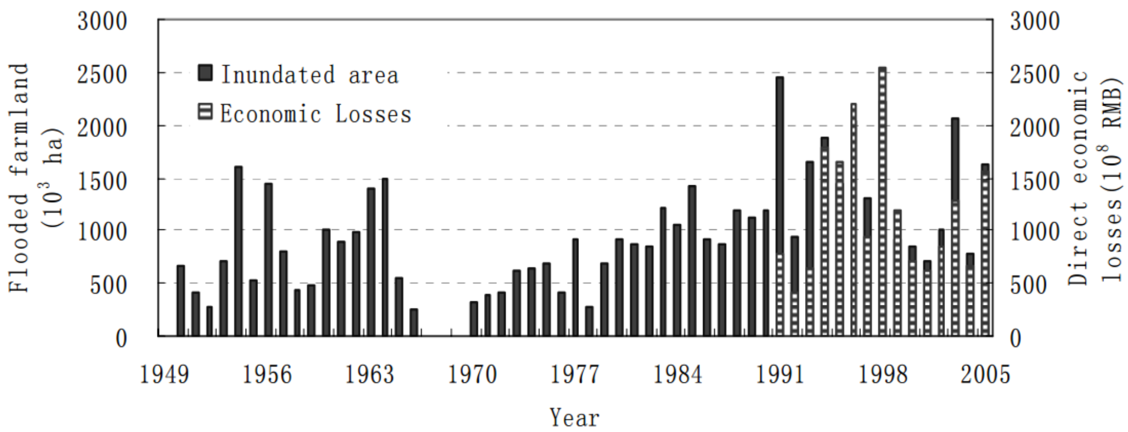


Figure 1 Damage due to flood in China since 1949 (Zhang, 2006)

Soil erosion and sedimentation transportation:
With the occurrence of floods, soil erosion can be created which is followed by more natural hazards like debris flow, landslides and rock burst.

The erosion of soil and loss of water have a direct effect on soil capacity in holding water, permeability, organic matter content in the soil which in a way causes the loss of investment and production of agricultural cultivation. But it is reported in China that the indirect loss of agriculture caused by flood is almost twice of the direct loss of agriculture. Not only this, flood has a profound effect on the sediment transportation, the flushing water can bring more and further the sedimentation during an event, in parallel deadweight on the riverbed and in reservoirs downstream can be increased, which dramatically influence the function in a negative way. Xuan River, a tributary of Yellower River in China, is formed by this force whose river bed and banks are much higher than the territory on both sides. The reason behind it is due to the cumulative coming sediments, then local people start building higher banks so that the river can be still functional. For a long period of doing so, Xuan River is formed. The problems lie similarly in reservoirs as well. It is reported that the due to the heavy sedimentation caused by flood, the active storage capacity of reservoir in China has been reduced by 10%-43%.

The damage and losses caused by debris flow and landslides is related to the formation of any kind of floods, and they all similar in consequence. So it is logical to consider debris flow and landslides as a flood associated hazard. There has been several heavy rain in Chengdu Province of China in the summer of year 1981. It was observed that there have been many debris flow happened in the wester Sichuan and Northern Sichuan Basin. As a matter of fact, more 700 landslides were observed in Longquan Mountain Area which is east to Chengdu, the capital city of Sichuan Province.

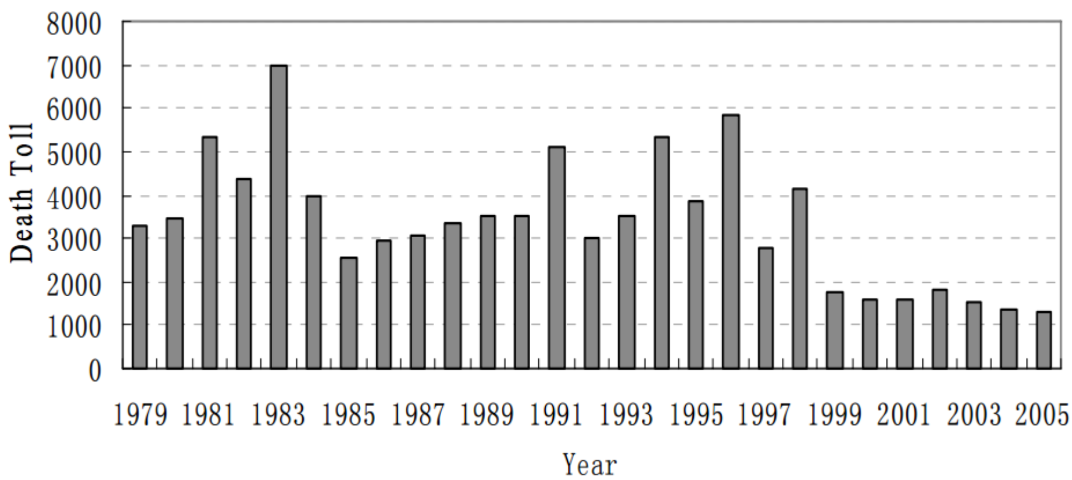


Figure 2 Life losses due to flood in China since 1979 (Zhang, 2006)

Changes in hydrological conditions:
Floods is featured as ferocious and sudden. This type of flood is quite easy to see in China, especially for the summer flood which is large in water quantity, high in the peak, increase in flow and drastic in water level change. Under this circumstance would the discharge reaches or exceed the hydraulic capacity of the river. As the case in Sichuan Province again, in July 1981, the change in water level of mainstream of Tuo River reaches as high as 10.7m – 15m during a massive flood during which most of the town streets were flooded along the river.

As the big change of soil condition during a flood event occurs, there is a rapid change in the sediment concentration of flow as well. As the example showed above, the flood occurred in 1981 along Tuo River, the maximum observed 7-day sediment concentration in Sanhuangmiao Station, Dengyunyan Station and Lijiawan Station are 2.05 kg/m^3, 4.74 kg/km^3, and 5.84 kg/m^3 respectively whose concentrations are 2.6 times, 5 times and 6 times more that multi-year average respectively. As similar of Luan River, the multi-year sediment concentration is 2 320 000 t, from which there are 90% comes from the flood period. The notable flood along Luan River in 1959 created a sediment concentration of 87 900 000 t.

Water quality:
Floods have huge consequences not only on water quantity, but also water quality. The water quality analysis of Tuo River suggested that the severity of water quality is much worse during a flood period that a plain period. The effects brought by flood of water quality is as follows:

1. During a flood period, the turbidity of water and the concentration of suspended solids increase. As for Min River flood in 1986 in Sichuan Province, this has caused severe crisis of water supply in Chengdu. At the same time, sedimentation has a strong adsorption capacity of heavy metal which can cause the transportation and concentration of heavy metal and toxic substances as the sediments flow. A formation of a secondary pollution sources is activated by the deposition of these pollutes, such as arsenic and cadmium with a concentration of up to 5000 to 50 000.

2. Storm flood is the main way to cause diffused pollution, such as Sichuan 1981 flood, coli concentration in Tuo River rose a few dozen to hundreds of times. On the one hand flooding from

agricultural areas carried large amount of organic matter and pesticide residues; on the other hand flooding from the city. The flood coming from city flushed trough urban ground deposits, open mining pits, construction sites, industrial waste, confluence of sewers and street debris to the mainstream which eventually resulted in the accumulation of pollutants concentration.

3. Flooding turbulence may cause the release of sediment contaminants, thus formatting secondary pollution such as in Tuo River. There are quite often flash floods which usually brings lots of sediments, this causes a sharp drop in dissolved oxygen, followed by dead fish in the river. For some stratified lakes and reservoirs, damage may happen to the layer and the turbulence may form water quality pulsation. Occasional water quality pulsating caused by flood is more unpredictable than seasonal one which as a consequence followed by de-oxidation discharge.

4. During a flood, inflow increase, flow rate rises, flow rate increase, river runoff ratio may increase as well which has a potential to purify water. On the other hand, in some areas due to backwater effect of flood of the mainstream, the tributary cannot flow smoothly. Some lakes or tributaries have their own peak of water contamination during this kind of period. As for the new harbor in Ezhoucheng, due to the long-term backwater effect of flood, it is obvious to observe that the peak moment of water pollution during the floods.

5. Siltation can be found in rivers, lakes and puddles after flood. Not only the capacity of the water body is reduced, but also the environmental capacity, to some degree, this increases the degree of water pollution.

Impact on wild animals and plants:

1. Affect the habitat of animals and plants thus affect the growth and reproduction. Reshaping the bank slope, deterioration of water quality caused by flood all have effect on the growth and reproduction of animals and plants.

2. Due to submergence, wave pounding, and direct cover, animals and plants face death or survival threat. For example, flood can destroy plants by flushing easily, but long time immersion could cause slow growth of plants or death, flood can drown animals as well. On the other hand, floods may destroy the growth of animals that are harmful to humans, such as rodents and insects, which can inhibit the growth of weeds.

So the occurrence of floods may affect the number of animals and plants and the diversity of species in a way, such impacts are more serious to rare or endangered animals and plants species.

2.2 FLOOD FREQUENCY ANALYSIS METHODS DEVELOPMENT

As mentioned, the history of flood can date back to ancient times when the civilizations began, and it has be a problem since then. As the advancement of the society, people want to know much about this mysterious phenomenon in order to reduce the damage and prevent it if possible. The understanding of mechanism behind the flood process thus became fundamental to solve the corresponding problems. As the development of demand to interpret this phenomenon, in addition, techniques in field measurement and data processing provide a unique platform to carry the research. As a matter of fact, the research is at full strength after computer era came, the modelling working is thriving and provides much more possibilities to make the simulation more realistic like the physically distributed hydrological model does. Good combination of statistical probabilities analysis and hydrological modeling is widely used at the current stage and it shown that it works well. More research is going on with regionalization method to expand more into the ungauged area for flood estimation.

In the previous chapter, the hazard and damage that a flood brings have been stated. Recognition and mitigation of flood was intended at the initial stage of the analysis since too much losses can be caused during such an event. Actually at the beginning, due to lack of the knowledge of natural science and the incomplete understanding of the mechanism that the earth works, not a lot of theories were found nor raised up, but some engineering protection against flood were invented. Like as early as in Qin Dynasty in China around 250 B.C., flood protection structures were constructed. More attention were put in this field after the Renaissance time in Europe (R. Giuseppe, 1994). Besides improving the capacity of a river course, diverting the excessive flood can be useful as well. Then floodways towards another river was constructed, usually taking the temporary storage of a reservoir upstream (R. Giuseppe, 1994). Gradually much more strict rules had to be applied when designing an anti-flood structure. The method of determining design flood for hydraulic structures were noticed. After then, there was a booming age for developing flood analysis methods. Listed are the milestones in the evolution of flood analysis methods.

From 1750 to 1850, this is the age that regular observation of precipitation and river stages were initiated, during which large Empirical Formulae were used. From 1850 to 1900, precipitation data and discharge flow were collected more systematically when the Rational Method was developed (Mulvaney, 1851). Electrical Counter Meters and Venturi Meter were evented in 1860 and 1898 respectively, this caused a development of Flood Envelope Curves (Dickens, 1863) and Isochrone Lines (Imbeaux, 1989). During 1900 and 1945, Channel Storage Method (Fantoli, 1904; Puppini, 1923), Flood Frequency Analysis (Fuller, 1913; Foster, 1924; Hazen, 1930), Unit Hydrograph (Sherman, 1932), Probable Maximum Precipitation (NWS, 1937) and Extreme Value Theory (Gumbel, 1941) were developed as the advancement of computers with punched cards in 1900, differential calculus applications, applications of statistical methods and the first generation of digital computer in 1943. Followed with the model years between 1945 and 1970. Tons of models were nicely developed during this stage. To name a few, the Conceptual Models (Nash, 1957; Dooge, 1959), Stanford Watershed Model (Linsley Crawford, 1960), Regional Flood Analysis (Dalrymple, 1960), Kinematic wave on a titled V-shaped catchment (Wooding, 1965) and Overland flow model compared with experimental results in 1970 by Kibler and Woolhiser are the classical ones. For this period, techniques of data and processing had much help for the model work like Analog Models for flood routing in 1948, the second generation of digital computers in 1949, systems analysis applications in 1956, long distance transmission of data (radio and telephone) evented and developed in 1958, Remote sensing application in the early 1960s, and the flood warning system through remote monitoring of precipitation and river stages at the same time. From 1970 onwards, more development of computer boosted flood analysis as well. In 1970, Box and Jenkins developed time series analysis and forecasting methods, which is used in flood analysis and estimation. Later on in 1973, Natale and Todini created constrained linear system. In 1975, WMO comparison of streamflow models came into use. NERC finalized the UK flood studies report in 1975. Geomorphologic Unit Hydrograph (Rodriguez-Iturbe, Valdas) and System Hydrologique Europeen (Beven et al.) were finalized respectively in 1979 and 1980. Techniques boomed out in this stage are Satellite based data transmission system in 1972, Weather Radar and real-time hydrological forecasting in 1975, solid state memory module for data collection in 1979, ultrasonic and electromagnetic methods in streamflow gauging in the late 1970s, microcomputers and personal computer in data processing in early 1980s, geographic information system in distributed hydrological models in later 1980s.

2.3 GENERAL FLOOD FREQUENCY ANALYSIS

As mentioned above, flood frequency analysis is a way to achieve the goal of predicting the magnitude of a flood for a given period of time or predicting the recurrence time of a flood when a specific magnitude of flood is given based on existing data. Firstly this problem was solved by Gumbel with the help of statistical frequency curves.

The key of flood frequency analysis is historical data, we need to have observed discharge at hand so that the analysis can be carried out. Picking up the peaks of a year throughout many, based on the statistical parameter such as mean, standard deviation and skewness, one can construct a frequency distribution graph. Based on the statistical distribution, we can find the most suitable one from the frequent used distributions like Normal Distribution, Log-normal Distribution, Weibull Distribution, Exponential Distribution, Gumbel Distribution, Pearson Distribution and Log-Pearson III Distribution etc. Since one has determined on one probability distribution, the flood frequency curve can be plotted. One can use the graphs to estimate design flow for a recurrence interval for planning, design and safety concerns.

The importance of flood frequency analysis is obviously huge. Behaving as the guideline in designing infrastructures like bridges, dams, culverts, sewage disposal plant and waterway etc., it is crucial to make sure that the design has reached the optimum point, since over design or under design would bring different problems. Flood frequency analysis is as importantly as required in flood insurance and flood mapping as in hydraulic designing. Precise estimation is beneficial for both safety design and the protection of human life and property losses.

In order to carry out a comprehensive analysis, a good understanding of the analysis and terminology is essential.

Recurrence interval (return period) is defined as the inverse of the probability that an event would be exceeded in a giver year which provides a more straightforward way to show the probability of the occurrence of an event. As for a 50-year return flood, the probability of exceedance is 0.02 in a year, so the flow that can exceed in a year is 2%. But return period is just a statistical concept which does not necessarily mean that the event has to occur for a specific period nor anything fixed. Usually the curve is drawn with either a linear scale or a logarithmic scale by discharge versus probability. We can then estimate the magnitude of a flood with a given period, or estimate the return period with a given threshold by fitting the distribution plotted with a theoretical one. (https://serc.carleton.edu/hydromodules/steps/168500.html)

2.4 FLOOD FREQUENCY ANALYSIS METHODS APPLIED IN NORWAY

In Norway, flood dimensioning has been dealt in a proper way. This nation has a history to fight with these kind of natural disasters so some achievements have been obtained. Recently in Norway, the flood dimensioning is of crucial importance for designing and assessing safety especially for hydraulic structures like dams. Norwegian Water Resources and Energy Directorate (NVE) currently has recommended methods to do flood analysis and estimations.
As mentioned, there are two main categories in dealing with this:

1. The traditional method: statistical flood frequency analysis based on the existing observed data;
2. Rainfall-runoff models: model work based on some direct causes data rather than the output data.

2.4.1 STATISTICAL FLOOD FREQUENCY ANALYSIS

The key behind this method is qualitative data, the principle of this method is the choosing right mathematical function to describe the distribution of events, the function can extrapolate the series to give values corresponding to return periods beyond the length of the observed record. (Midttømme et al., 2011) It always starts from picking up the highest flow data observed from each of the year or unit period by either AMS or POT and analyze based on this. This method can be straightforward if the intended period to analyze does not exceed much over the observation period under the assumption that the event is generated with the same mechanism. (Midttømme et al., 2011) Extrapolation can be done as long as possible while suggested to be done not more than twice of the observation length due to the increasing uncertainties.
NNE has developed a database called Hydra II holding historical daily observation of water level prior to the installation of the recording devices. While data need to be double-checked before using even not there are hydrometrist controlling the quality before storing. (Midttømme et al., 2011)
For the statistical distribution selection, there are many different types available and widely used for flood frequency analysis, the theoretical correct limit distribution are as listed:

Generalized Extreme Value (GEV) distribution mainly for AMS
Generalized Pareto (GP) distribution mainly for PDS.
Actually many distributions can be adjusted and utilized, but parameters are the key things to decide further on which distribution is more suitable. As mentioned, in NVE people have developed a series of software dealing with this analysis, it is listed below. The best distribution found can be representative is either the Gumbel (EV1) 2-parameter distribution, or the Generalized Extreme Value (GEV) 3-parameter distribution (Midttømme et al., 2011). Number of parameters and understanding of properties of the catchment is more important than finding a suitable distribution to describe the data, since the physical description of a catchment or a region is the criteria in assessing a fitting degree of a distribution rather than simply in. Lots of applications have indicated that 3-parameter distributions are more sensitive to outlying the events (Cunnane, 1985, Sælthun and Anderson, 1986). Flexibility of distribution increased as the number of parameters increase. In a way, NVE has specified the minimum length of record for 3-parameter distribution and comparisons are highly recommended, concerning the influence of other factors (Midttømme et al., 2011).

Table 2 The statistical distribution available for use in Ekstrem, Dagut and Finut from NVE

Software	**Distribution**
Ekstrem, Dagut/Finut	Log-normal (2 parameter)
Ekstrem	Log-normal (3 parameter)
Ekstrem, Dagut/Finut	Gumbel (EV1) (2 parameter)
Ekstrem, Dagut/Finut	GEV (3 parameter)
Ekstrem, Dagut/Finut	Gamma (2 parameter)
Ekstrem	Gamma (3 parameter)
Ekstrem	Log-Pearson (3 parameter)
Dagut/Finu	Gaussian Normal
Dagut/Finut	Pareto (2 parameter)

Once a fitting process is finished, there might be several distributions can represent the data distribution, then visual inspection would be needed where topper part should be noticed particularly which has a potential advantage of emphasizing more on peak flood than all records. L-moments is recommended by Hosking and Wallis (1997) in differentiating the best among the fittable distributions. But the selection varies from people as well, below it shows several flood frequency distributions from NVE that fits to flood event data from Krinsvatn in central Norway. The range in flood frequency estimates with different distributions is illustrated below as well:

- 200-year return flood: 260-340m³/s (301 m³/s ± 14%)
- 1000-year return flood: 234-502m³/s (368 m³/s ± 36%)

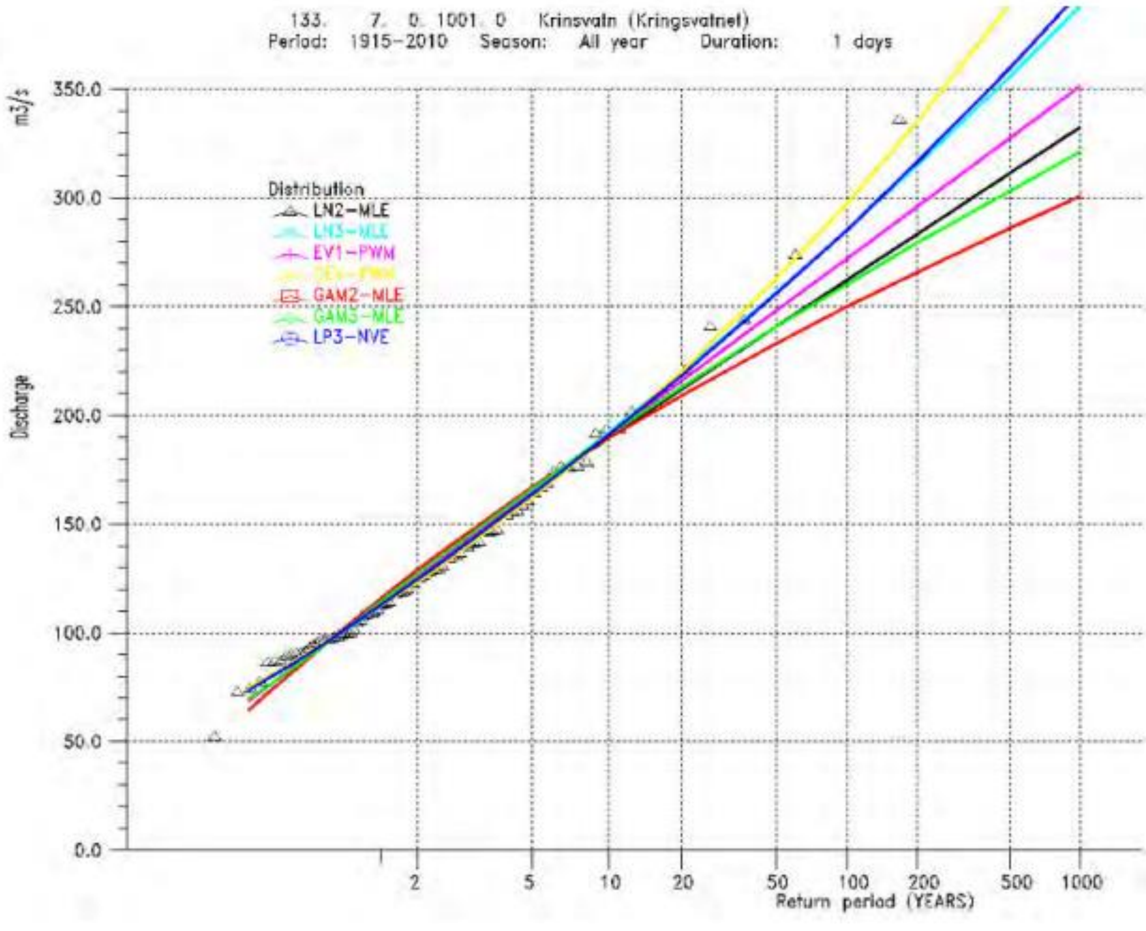


Figure 3 Various flood frequency distributions fitted to flood data for Krinsvatn (Central Norway) from NVE

Parameter estimation has great influence on the fit of different distribution. Different methods have been applied in NVE to carry out the analysis of parameter estimation. Utilized methods are the method of moments (MOM), the probability weighted moments method (PWM, equivalent to L – moments) and the maximum likelihood estimation method (MLE). All the methods have been evaluated by NVE which is listed below:

Table 3 Parameter estimation methods available in the NVE's Ekstrem, Dagut and Finut software

Software	Distribution	Parameter Estimation Method
Ekstrem	Log-normal (2 parameter)	MLE
Dagut/Finut		Not specified
Ekstrem	Log-normal (3 parameter)	MLE
Ekstrem	Gumbel (EV1) (2 parameter)	PWM
Dagut/Finut		PWM or MLE
Ekstrem	GEV (3 parameter)	PWM
Dagut/Finut		PWM or MLE
Ekstrem	Gamma (2 parameter)	MLE
Dagut/Finut		MOM or MLE
Ekstrem	Gamma (3 parameter)	MLE
Ekstrem	Log-Pearson (3 parameter)	NVE Procedure
Dagut/Finu	Gaussian Normal	Not specified
Dagut/Finut	Pareto (2 parameter)	PWM or MLE

Index flood is widely used to express the average or median value of flood internationally, in Norway mean flood is most often used while sometimes median flood is also used. NVE has developed a calculation procedure for obtaining index flood. But one has to bear in mind, this is obtained from existing data, what if data is scares in the target region, scaling from the nearby sites can be applied with the help of regional regression formula. This is summarized in the following table (This is only valid for the catchments larger than 20-50 km^2 and special care should be given for the catchment smaller than 100 km^2 whereas no upper limits have been set):

Table 4 Regional formulas for derivation of the index flood (QM in l / s km2)

Spring flood regions	
1	$\ln Q_M = 0.2722 \bullet \ln S_T - 0.1406 \bullet \ln A_{SE} + 0.1006 \bullet \ln A_{SF} + 0.6172 \bullet \ln Q_N + 2.11$
2	$\ln Q_M = 0.0930 \bullet \ln S_T - 0.0816 \bullet \ln A_{SE} + 0.0281 \bullet \ln A_{SF} + 0.5076 \bullet \ln Q_N + 3.59$
3	$\ln Q_M = 0.3066 \bullet \ln S_T - 0.0220 \bullet \ln A_{SE} + 0.0939 \bullet \ln A_{SF} + 0.3252 \bullet \ln Q_N + 3.09$
4	$\ln Q_M = 0.1848 \bullet \ln S_T - 0.0137 \bullet \ln A_{SE} + 0.0873 \bullet \ln A_{SF} + 0.5143 \bullet \ln Q_N + 2.77$
Autumn flood regions	
1	$\ln Q_M = 1.2805 \bullet \ln Q_N - 0.2267 \bullet \ln(A/L_F) + 0.0664 \bullet A_{SE} + 0.0053 \bullet S_T + 1.00$
2	$\ln Q_M = 1.2910 \bullet \ln Q_N - 0.1602 \bullet \ln(A/L_F) + 0.0508 \bullet A_{SE} + 0.0065 \bullet S_T + 0.65$
3	$\ln Q_M = 1.2014 \bullet \ln Q_N - 0.0819 \bullet \ln(A/L_F) + 0.0268 \bullet A_{SE} + 0.0013 \bullet S_T + 1.07$
Glacier and annual flood regions	
BRE	$\ln Q_M = 0.0119 \bullet Q_N - 0.0848 \bullet A_{SE} + 0.0165 \bullet L_F + 5.81$
K1	$\ln Q_M = 1.5212 \bullet \ln Q_N - 1.1516 \bullet \ln P_N - 0.0569 \bullet A_{SE} - 0.0093 \bullet L_F + 8.80$
K2	$\ln Q_M = 1.1524 \bullet \ln Q_N - 0.0463 \bullet A_{SE} + 1.57$

Where A = catchment area (km^2)
Q_N= mean specific annual runoff ($l/s\ km^2$)
P_N = mean annual precipitation (mm)
A_{SE} = effective lake (%)
A_{SF} = exposed bedrock (%)
L_F = catchment length (km)
S_T = gradient of the main river (m/km)

In the table shown above, the new catchments and climate features are not involved while NVE is considering to include these information later on. But as one may know, it is nearly impossible to represent the real world entirely by the formula, especially for small catchments which are more sensitive to intensive and heavy rainfall than big catchments. Thus underestimation incurred more often to small catchments than to large catchments. So it is suggested that one can verify the catchments' characters and reviewing the equations before application, especially for small catchments. Due to the scarcity of data or wide range of ungauged areas, most commonly, index from

is estimated from the nearby sites, though index flood has a rather strong correlation with catchment areas where not linear.
Followed by index flood, growth curve has to be derived from close stations' data, or from a fixed regional growth curve. NVE has suggested that a set of curves can be used below to Norwegian flood regions, it is obtained by applying different distributions various sites separately and averaging what is currently existing. It shows the regional growth curve in the following contents:

	Q_5/Q_M	Q_{10}/Q_M	Q_{20}/Q_M	Q_{50}/Q_M	Q_{100}/Q_M	Q_{200}/Q_M	Q_{500}/Q_M	Q_{1000}/Q_M
H1	1,3	1,6	1,8	2,2	2,5	2,8	3,2	3,5
H2	1,3	1,6	2,0	2,4	2,7	3,0	3,6	3,9
H3	1,3	1,7	2,0	2,6	3,0	3,4	4,2	4,7
K2/ bre	1,2	1,4	1,6	1,9	2,1	2,3	2,5	2,7
K1	1,2	1,4	1,7	2,0	2,2	2,4	2,7	3,0
V1	1,2	1,4	1,6	1,9	2,1	2,3	2,5	2,7
V2	1,2	1,4	1,5	1,7	1,9	2,0	2,2	2,3
V3	1,2	1,4	1,6	1,8	2,0	2,2	2,4	2,5
V4	1,3	1,5	1,8	2,1	2,3	2,6	2,9	3,1

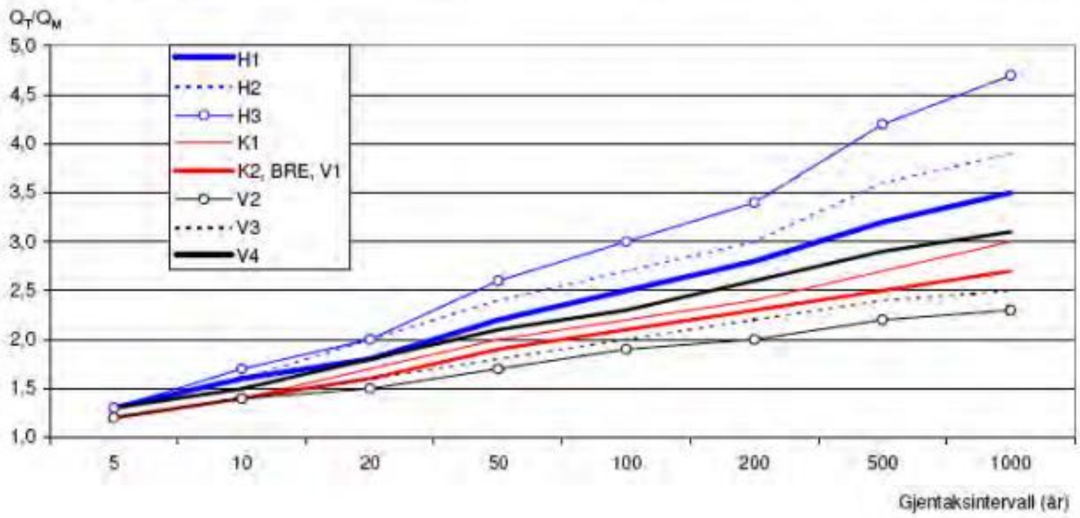


Figure 4 Regional growth curves from NVE

Assessing performance of methods applied in flood analysis and estimation are essential. There are guidelines (Midttømme et al., 2011) suggesting that several analysis of different stations within a region should be carried out. In a way to check the extremities, on the other hand, the pattern should be studies since it is in the same region, mechanism behind it should be same or similar which is the assumptions mentioned in previous chapter. Still, uncertainties is unavoidable under any circumstances, unfortunately the uncertainties cannot be assessed nor reduced by applying this method. But operations in the NVE software Dagut/Finut, there is a function called bootstrap can estimated and plot the confidence period in order to check the fittability of the distribution.

2.4.2 RAINFALL-RUNOFF MEDEL METHOD

Rainfall-runoff model method is not an independent way compared with the traditional statistical one. Since even after the runoff series are generated by rainfall-runoff model, specific statistical methods have to be applied for the final analysis. The strength of model is that, one can easily simulate or generate with proper help from models where there are not observed runoff data but precipitation data and sometimes with snow information for the corresponding region. There are some dominating reasons applying this method in Norway (Killingveit and Sælthun, 1995):

1. Data series of precipitation are often longer than runoff series
2. Climate station network is in some locations more dense than the gauging station network
3. Precipitation shows stronger regional consistency than runoff (Killingveit and Sælthun, 1995)

Furthermore, dam safety analysis in Norway uses PMF (probable maximum flood) which cannot be implemented in the traditional statistical method. Under this circumstance has a rainfall-runoff model to be used in order finish this task.

In Norway, an event-based lumped model called PQRUT is developed specifically to deal with the safety concern of dam. It behaves well when analyzing low frequency events and PMF. Initially when this model was designed, there were three parameters which can be adjusted based on the catchment features. It is also regarded as a simpler version of HBV model (Bergström, 1976; Sælthun, 1996). While there are still differences between the two models. PQRUT emphasizes more on short-term storm water rather than a longer-term which HBV model focuses. The other apparent difference from a PQRUT model to HBV model is the number of parameter which HBV model has as many as 15 at least. It is then rather obvious that the simple while practical PQRUT model is more suitable for small catchments and for the ones with a fast response. The three-parameter model is like a linear bucket, with simple mechanism of inflow-outflow. Outflow can occur at either a slow rate or a fast rate depending on the relationship between water accumulation (precipitation or snowmelt) and the threshold of the "bucket". The flow chart of the model is shown below:

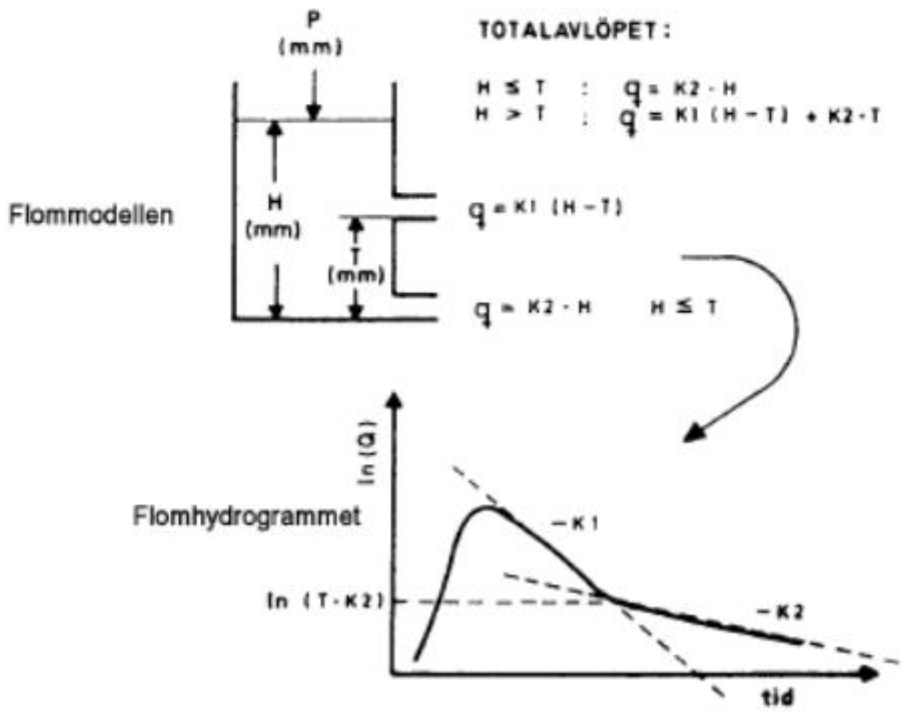


Figure 5 The three-parameter precipitation-runoff model used in PQRUT from NVE

After selecting the right model, parameter estimation becomes the most question to solve. As most of the models' calibration, the parameters can be calibrated on the base of observed data like precipitation or snow related data. But it is sometimes hard as well to find these data with the target time resolution, three empirical equations have been developed to estimate parameters based on catchments' features from 20 catchments (Andersen et al., 1983). It is given as below:

$$K_1 = 0.0135 + 0.00269 * HL - 0.01665 * \ln(A_{SE}) \quad (3)$$

$$K_2 = 0.009 + 0.21 * K_1 - 0.00021 * H_L \quad (4)$$

$$T = -9.0 + 4.4 * {K_1}^{-0.6} + 0.282 * Q_N \quad (5)$$

Where H_L is a measure of catchment relief

A_{SE} Is the effective lake percentage

Q_N is the normal specific runoff ($l/s*km^2$)

A_{SE} is defined as $100 * \sum(A_i * a_i)/A^2$
a_i is the surface area of lake i
A_i is the upstream catchment area contributing to lake i
A is the total catchment area

These estimation methods is developed for relatively small catchments typically smaller than 500 km^2. As one can see that a great emphasis has been placed on these formulas here. Thus the parameters estimated in this way would be rather sensitive to the lake area in the target region generally. It is suggested that avoiding bigger areas than 500 km^2 or the ones with a big percentage value of lake. At the same time, one has to bear in mind that lakes or manmade reservoirs have a positive effect in dampening the peak of a flood events. But in our case of Gaula Catchment, there are not many lakes nor reservoirs to attenuate the effect of the floods. This is one of the reasons why there are so many historical floods along this river, and it is also the reason why the response time of this river is short and fast so that less time is left for the people to prepare.

A nice and proper procedure has been developed by NVE based on a set of different empirical equations or curves like rainfall depth and duration, storm profile and so forth. Areal reduction factors should be applied in order to differentiate variability of events temporally and spatially. A factor is utilized here to reduce the magnitude for example of point rainfall to areal rainfall, this factor is called areal reduction factors. The factor scale descends as the rainfall duration increases basically. The factor is a regional concept rather than a fixed value. So it varies much in regions from one to another. In Norway, this work is much harder due to the mountains and varied features of catchment (Sælthun and Anderson, 1986). Other issues regarding rainfall-runoff model applications in Norway including snow, snowmelt, soil moisture, runoff response etc.. These concerns would not be discussed here, the detailed while related descriptions, operation, parameter calibration, and model performance assessments are mentioned in detail where used in the later chapter for model work.

Either going through the traditional statistical analysis or the rainfall-runoff model process method to dimension or estimate flood, Q_{1000} should be estimated as a guideline in Norway. Any differences between the two results derived from both methods should be discussed and studied. While as a matter of fact, for both of the methods, pre-agreement have been reached due to the applicability and performance of different methods. For example, the statistical analysis method is better for large catchment which is typically bigger than 1000 km^2, but a return period up to 1000 year. However, the rainfall-runoff model is tested that it behaves better when it comes to small catchments or calculating PMF. As mentioned above, PMF is a good case to be implemented by the model than statistical way. There might be deviations between the two methods, but NVE suggests that when there is a big difference in the performance of the two methods, statistical method is chosen to proceed further. (NVE, 2011)

2.5 FLOOD FREQUENCY ANALYSIS METHODS APPLIED IN CHINA

China is among the most severe countries that suffer from natural hazard like flood since long ago. So this nation has a history in fighting with these disasters while some methods of analysis and forecasting has either been developed or adjusted from the methods developed abroad.
In China, the most commonly used methods in flood frequency analysis are empirical correlation methods, catchment hydrological modeling methods. The current skill of China's hydrological forecasting techniques is assessed objectively.

As data scarce time is rather a long period, in addition, with the limitation of computational tools, Chinese way of analyzing floods stays in a rather empirical stage. Late until 1960s was the mathematical simulation concept introduced into hydrology, then a new era—hydrological modeling began. By then, on one hand, China was learning the method from foreign countries, on the other side, the hydrologists and related experts started working on developing a Chinese-tailored hydrological model. So far, there are been two main ways that is commonly used in China which is correlation graph scheme method and hydrological modelling.

2.5.1 CORRELATION GRAPH SCHEME METHOD

This is rather a practical while empirical method widely used in China, summary, trial and error was piled up as an accumulation, massive measurement data is used as a base. Usually for this kind of method, the accuracy is high, especially for the parts where the water level and discharge relations is complicated, and the river courses where a lot of construction works have great impacts on. Since this is more or less like a empirical method, in a way it has specific parameters and standards for different river course. There are seven main big watersheds in China including some hundreds of gauging stations, more than thousands of schemes have been raised, while it can be summarized to several kinds, it is shown as below:

1. API Method (Antecedent Precipitation Index)

This method is based on the rainfall-runoff generation mechanism physically, taking the main factors into consideration and building the quantitative relations between precipitation and runoff based on the parameters mentioned like the soil moisture before the rainfall event P_a, rainfall duration T, and the season S when the rainfall event happens which can be expressed as:

$$R = f\,(P, P_a, T, S) \tag{6}$$

But practically speaking, the four parameter relationship is more used than the five-parameter one like

$$R = f\,(P, Pa, T) \tag{7}$$

Or the more often used three-parameter graph,

P - R relation chart for 3-parameters P - R relation chart for 3-parameters.

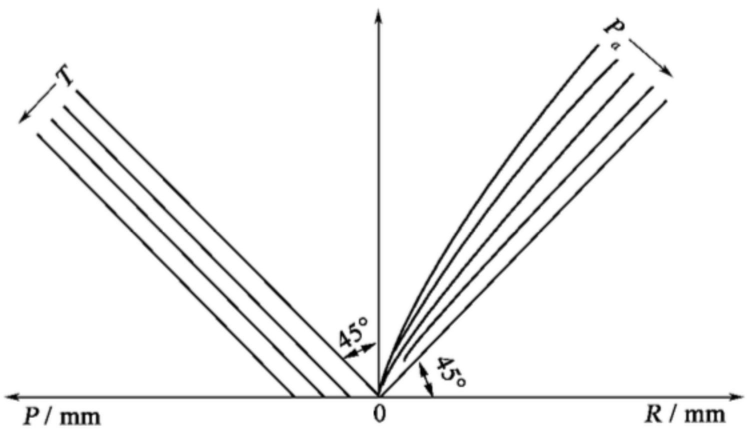


Figure 6 P - R relation chart for 3-parameters

2. Corresponding Water Level Method

The key for this method is to build a relationship between the water level upstream and downstream of a specific gauging station. And then develop the relationship of both. In order to increase the accuracy, some more parameters need to be added here, like the total discharge for this section in river and the average precipitation of this section as well. The relationship is shown as below:

$$Z_{down,\ t+1} = f(Z_{up,\ t}) \quad (8)$$

$$Z_{down,\ t+1} = f(Z_{down,\ t},\ Z_{up,\ t}) \quad (9)$$

$$Z_{down,\ t+1} = f(Z_{up,t}, \sum Q_{sec}) \quad (10)$$

$$Z_{down,\ t+1} = f(Z_{up,t}, Psec) \quad (11)$$

3. Synthetic Stream Generation Flow

Build up the relationship between the peak water levels in order to have an overview of the water level and discharge

$$Q_{down,\ t+1} = f\ (\sum Q_{up,t}) \quad (12)$$

$$Z_m = f_1(\sum Q_{up}) \quad (13)$$

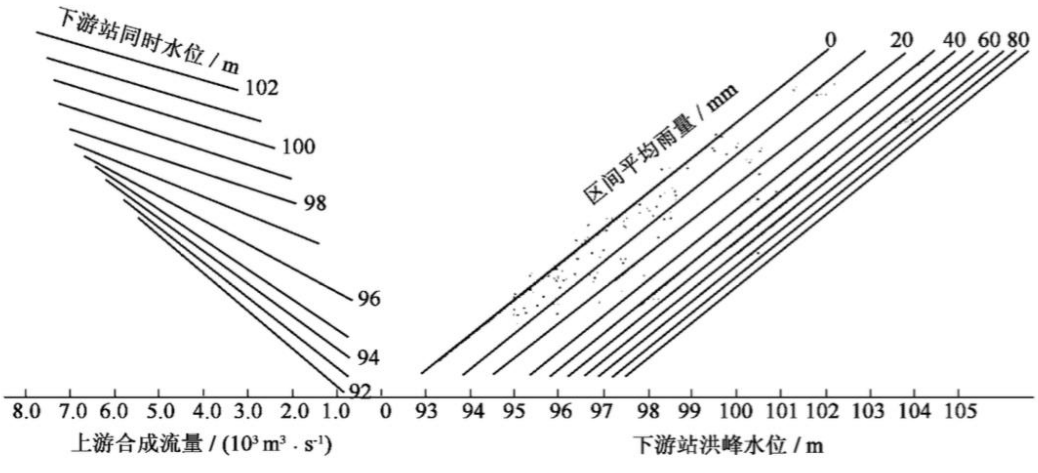


Figure 7 Relation chart between downstream water level and composing flows of upstream

4. Water Level Difference Method

Difference between upstream and downstream has been developed for a specific section of a river course:

$$Z_t = f(Z_{t-1},K) \tag{14}$$

$$Z_{t+1} = f\,(Z_t, \sum Q_{t-t}) \tag{15}$$

Where K is the water difference ratio

$\sum Q_{t-t}$ is the synthetic discharge within a short time T

5. Multi - Parameter Correlation Method

As the name indicated, this method considers much of the parameters for a rainfall –runoff generations processes including total amount of precipitation, duration o precipitation, intensity of precipitation and water level difference shown as bellow:

$$Z_m = f(P,Z_{ini},P_c) \tag{16}$$

$$Z_m = f(P,Z_{ini},T) \tag{17}$$

Where P is the average rainfall

Z_m is the water level related to the peak

Z_{ini} is the water level increase

P_c is the storm center distribution

T is net rain duration

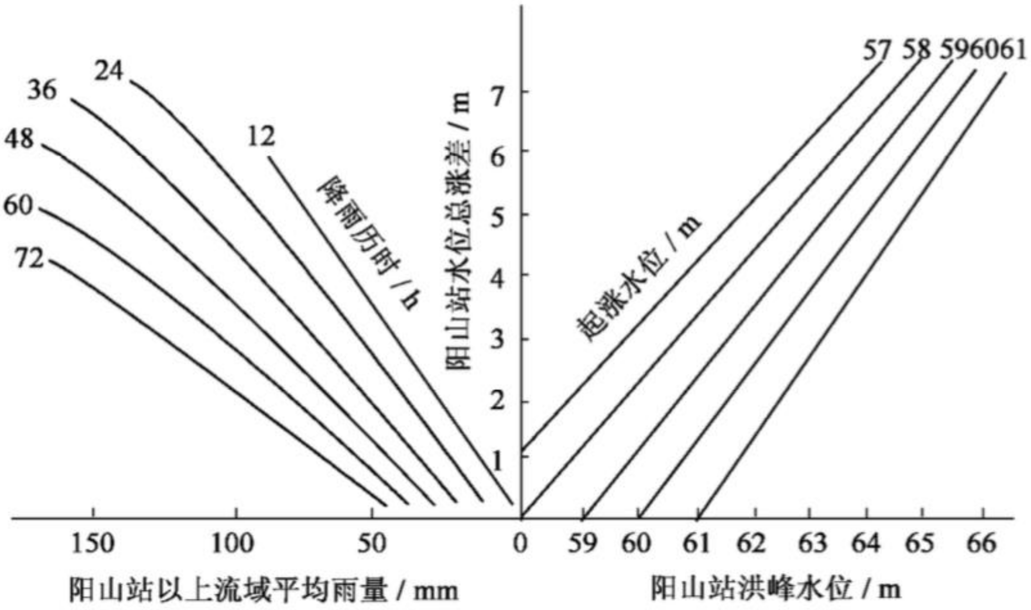


Figure 8 Peak-forecasted by precipitation with multi-parameters

6. Rainfall-Runoff Process Method

This method uses the antecedent water contents in soil, increase of discharge during flood as the reference to establish a relationship as shown below:

$$Q_m = f((P+P_a),Q) \tag{18}$$

$$Q_m = f(P, P_a) \tag{19}$$

Where Q_m is peak discharge

P is the average precipitation

P_a is the antecedent water contents in soil before the rainfall

Q is the maximum increase of discharge per hour

All these methods mentioned here is applicable to specific regions in China only which is rather limited since all the curves correspond to specific region only, one can also develop the corresponding curves in other regions with the same principle. But still limitations and uncertainties is still big. As the computer technology and information system develops, more emphasis has been moved to hydrological modelling.

2.5.2 HYDROLOGICAL MODELLING

Like most of countries, there are different hydrological models applied in China in analyzing discharge thus flood as well. But China starts quite late and due to some politician reasons, the process stopped somehow for about 20 years in the middle of the 20th century.

Some mostly used methods and models domestically and from abroad has been listed below that has been utilized in China.

Table 5 Hydrological models used in flood analysis in China (Zhang, 2006)

1	Xin'anjiang Model	10	SMAR Model
2	API Model	11	NAM Model
3	Jaingwan Runoff Model	12	Tank Model
4	Hebei Storm Flood Model	13	Sacramento Model
5	Shanbei Model	14	SCLS Model
6	Xin'anjiang Model for Semiarid Areas	15	Index Recession Method
7	Liaoning Model	16	Recession Curve Method
8	Double Attenuation Curve Model	17	Unit Hydrograph Method
9	Double Excess Runoff Yield Model		

Take the Xin'anjiang Model as an example to illustrate the principle that has been applied.

The structure is shown below:

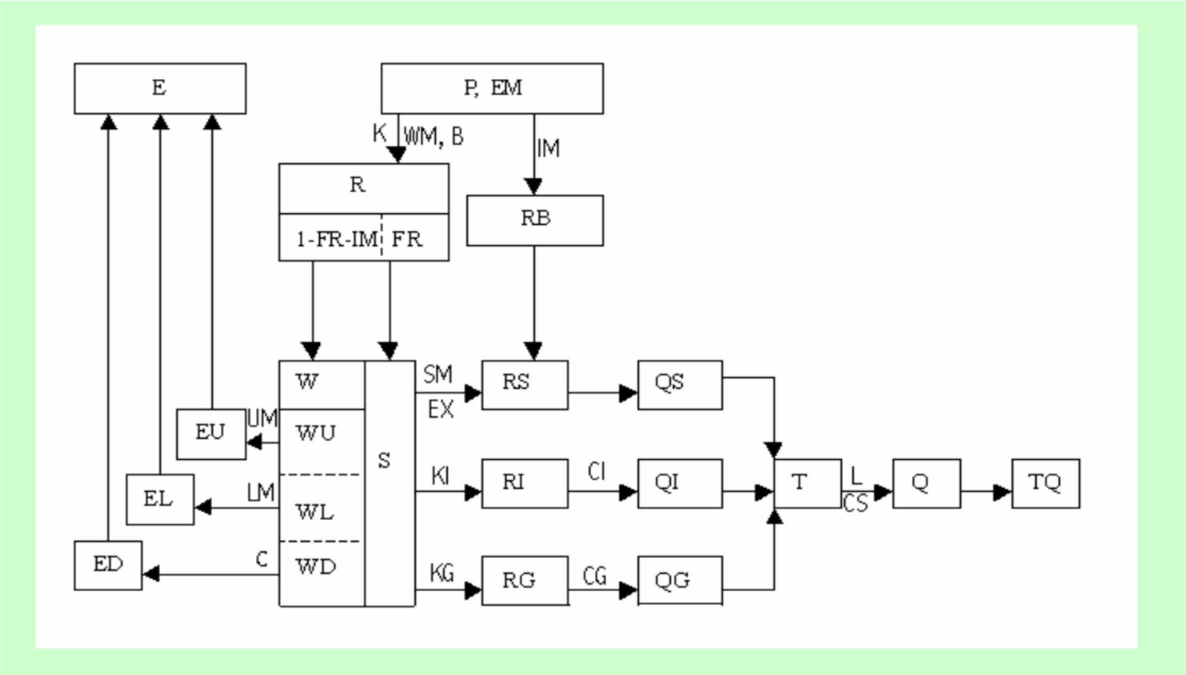


Figure 9 Flowchart of the Xin'anjiang model (after Zhao & Liu, 1995)

This model was developed in Nanjing, China in the 1960s. Different adjustments have been made accordingly, there are three main components contained in the model.

1. Three different runoff generation layers have been identified, the RS (surface runoff), RI (sub-surface runoff) and RG (underground water) due to the catchment feature and the soil capacity
2. According to the three different layers, the runoff generation is conceived with the consideration of the previous status of the catchment and the impermeability of the area thus including the field capacity (this model is built up for wet and semi-wet areas)
3. In the model, it also contains specific routine parts especially for the surface runoff into the river with the help of unit hydrograph or Nash routing model, while as the other two parts sub-surface runoff and underground water can only be routed into discharge using the Nash Linear Reservoirs model or other methods.

2.6 TOOLS AND METHODS APPLIED

In my thesis work, I am going to analyze the runoff data from the four gauging stations namely Eggafoss, Gaulfoss, Hugdal Bru and Lillebudal inside Gaula Catchment. Gumble's Method would be used in analyzing the flood frequency.

Hydrological data like precipitation, temperature, relative humidity, wind speed, and radiation would be collected within or close to the catchment. If there are no measurement stations inside the catchment, one can only use the data from stations as close as possible. These are the input data to ENKI, which is a framework of hydrological model, in which most subroutines are simulated and implemented by HBV model. Regarding the model work, it will be described in later chapters. This is the main task before doing the flood frequency analysis, since flood analysis is based on the existing runoff data. In the task, as described, we will use the hydrological data as the input to feed the model, the output of the model is runoff, which we have observed (reference) data series already to compare and adjust. Until we get a good simulation series against the observed data from warm up, calibration to validation, we can say that generally this model is applicable to the whole region or even the similar characterized catchments.

Before implementing the model, we need data of the catchment as well, like the name of the main stations, latitude, longitude and elevation to generate the shape of the catchment by ArcGIS.

2.7 SPECIFICATION OF CATCHMENT

The study catchment, Guala Catchment is mainly located in the municipality of Sør-Trondelag with the total area of 3086 km^2. Gaula Catchment is composed by four sub-catchments, which are Eggafoss Catchment, Gaulfoss Catchment, Hugdal Bru Catchmetn and Lillebudal Catchment with the area of 655.4 km^2, 1716.8 km^2, 545.5km^2 and 168.3 km^2 respectively. There is one thing to notice here, as for Gaulfoss Catchment, actually Gaulfoss is the name of runoff gauging station of this catchment by the outlet, at same time, it is also the outlet of the whole Gaula Catchment, so in principle, we can say Gaulfoss Catchment and Gaula Catchment are the same in this sense. In ENKI model, in order to make the model understand which the sub-catchments are, we subtract the so-called Gaulfoss local from the total Gaulfoss by excluding Eggafoss, Hugdal Bru and Lillebudal. Then total Gaulfoss Catchment is called Gaulfoss original.

3 THEORY REVIEW

3.1 METHODOLOGY USED IN THE STUDY

1. Data collection of precipitation, temperature, radiation, wind speed, relative humidity and runoff. Analysis of flood frequency based on the historical observed data of runoff.
2. Set up and calibrate subroutines models (mainly HBV models) in ENKI framework based on the collected daily data, after satisfactory calibration, validation would be carried out to "testify" the performance of model and parameter set. Manual calibration would be needed where necessary. Once the calibration is finished, we can say this model is fair enough to proceed, if the validation period also performs well, this model with the parameter set is generally good to simulate the runoff series in the whole catchment at any point with a good input data serie.
3. Flood frequency analysis is carried out with Gumbel Method, both simulated and observed data are analyzed. The comparison of the two group is done.
4. Runoff is calculated for the sites with ENKI for an as long period as there are data coverage. Based on different output at different sites, the corresponding flood frequency analysis is done as well.

3.2 ENKI

3.2.1 ENKI INTRODUCTION

Unlike most hydrological models, ENKI is actually a modular framework containing various hydrological models and other environmental models which is user friendly than a single hydrological model. ENKI provides a platform where people can assemble different routines and implement with different models inside to achieve a certain goal of simulation. The model can be either lumped or distributed. The original purpose of ENKI was to build and evaluate a distributed rainfall-runoff model, while it ends up with different processes which can be divided into subroutines and simulated by different hydrological models and environmental models in the corresponding routines if that can be well defined and parameterized in a proper way. It has been now developed as an open source under GNU LGPL. (Kolberg, 2012)

Usually the subroutines are pre-defined in a library stored, now it is possible to add more modules as desired and all the modules connect with a user specific order. The model has to run in a defined geographical region within a specific period. GIS data is needed here to construct the region, form can be raster, point-vector, even values only. If one intends to obtain good results after preparing the input variables, make sure that the model setup is complete and consistent, distributed maps overlaps spatially where necessary, the potential input time series should exist, initial stage of the parameters are set in a right state, the last but not the least is the GIS data prepared for input should also have a static map data in parallel. (Kolberg, 2012)

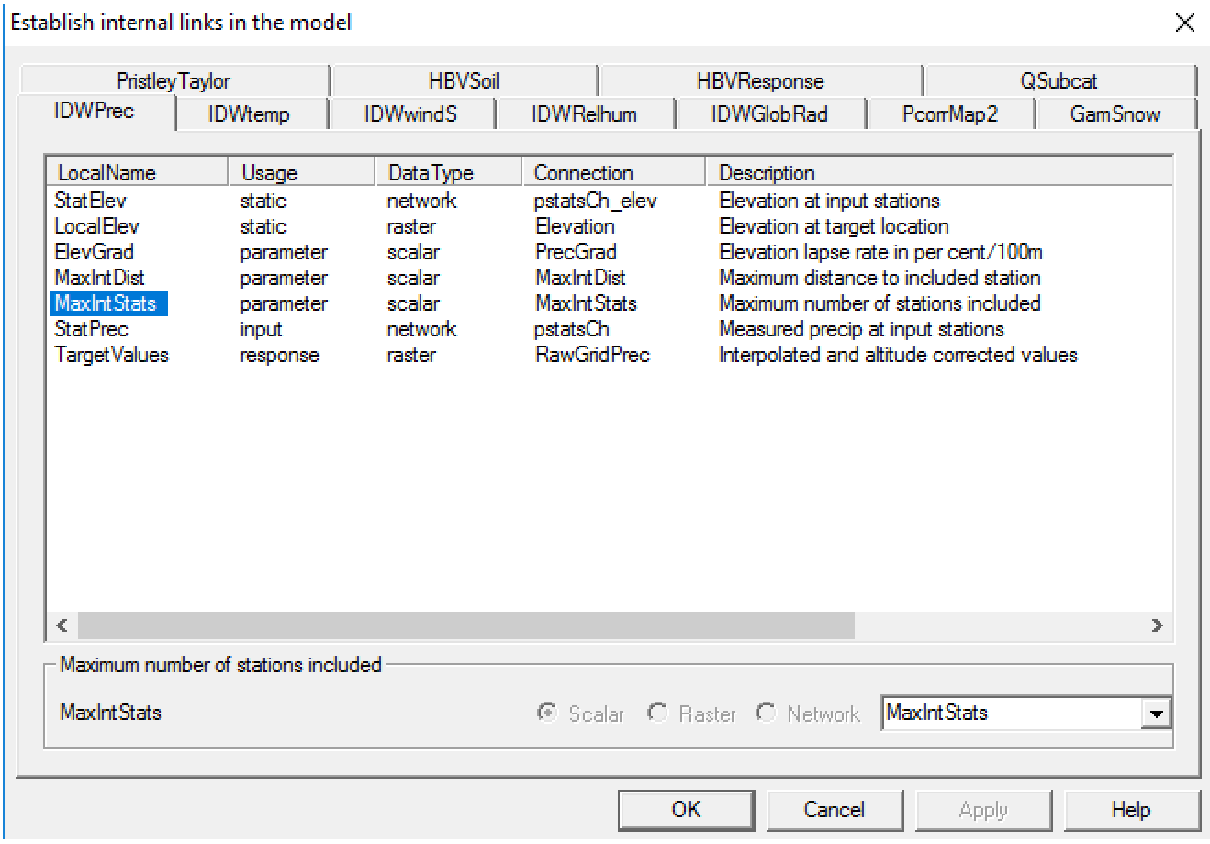


Figure 10 Open source under GNU LGPL

When operating models in ENKI, initial parameters should be set, followed by model warm up, calibration and validation. For calibration, meeting standard or reaching pre-defined running times could be the sign to stop, but most of the cases, R^2 (Narsh-Sutcliffe value) is the criteria to refer. Automatic calibration is included in ENKI, but manual calibration could be carried out where necessary. Uncertainty estimation is also involved in ENKI.

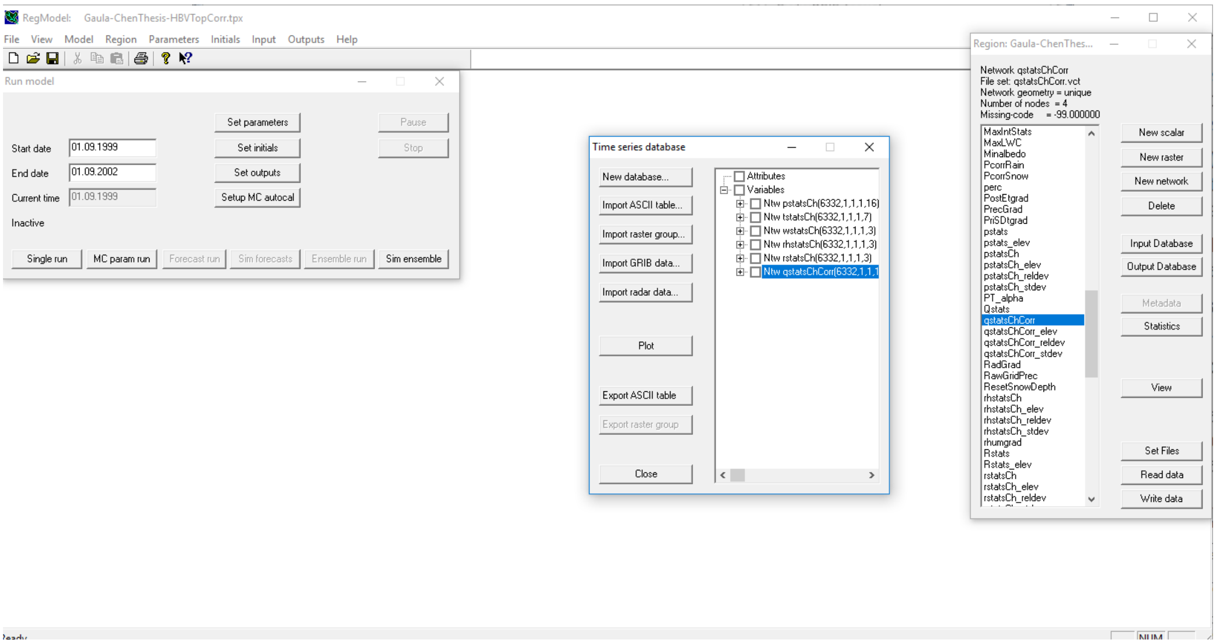


Figure 11 Input data set

All maps, prepared for ENKI should be converted to *IDRISI* format. There are many programs available for converting. *SAGA GIS* is open source program, containing tools for converting to IDRISI format. Within the region there are input and output time series. Input database is responsible for determining the time step within the model and the period of calibration. (SINTEF, 2003)

The mechanism of the work and reason in choosing ENKI to go with is the flexibility and applicability of the model especially for the choice of distributed model. Since it is more practical in ungauged areas which is more often met and better representability in the real world. Due to the fact that some countries especially Norway is changing in topography, it brings tremendous real challenges for model workers to simulate the real-world process. Especially when dealing the gradients in meteorology, land surface properties etc. distributed models give a fair way to solve these problems in a proper way. A non-linear process for example, the use of catchment average in model equations lead to a biased results sometimes, but if a distributed model is applied within a certain size of catchment, the errors can be reduced than depending thoroughly on the equations, because the errors depend more on heterogeneity and the uncertainties on input data than the equations under this circumstance. In a way, interpolation and downscaling of input is more emphasized. (Kolberg, 2012)

3.2.2 DIFFERENT TYPES OF VARIABLES IN ENKI ROUTINES

Table 6 Variable types in ENKI routines

Name	Description
Raster	Rectangular grid, usually representing the simulation domain
Network	Irregular point set, may extend outside the domain
Scalar	Spatially constant quantity, located or not
Static	Time-invariant quantity not subject to calibration e.g. Elevation model, lake map, forest map, gauge station map etc.
Parameter	Time-invariant quantity,available for calibration e.g. can be spatially distributed (raster,network), or calibrated (scalar)
Input	Dynamic variable which is read, but not written e.g. Must either be in input database, or also be a response/state in earlier routine
Response	Dynamic variable which is written, but not read e.g. Output variable, available for storage and evaluation
State	Dynamic variable which is both read and written e.g. Need initialisation values

3.2.3 FUNCTION OF ENKI

In model construction processes, ENKI is applied and offers three main functionalities in different levels.

1 Model Application

Running and evaluating a target model by calibrating regionally against existing data is realized with the help of several objective functions. Quite a few algorithms like PEST (multi-surface gradient search using Jacobian matrix), SCE-UA (global shuffled complex evolution), Random MC (GLUE), DREAM MCMC (adaptive metropolis sampler) and Conditional Univariate etc. are applied accordingly for calibration, uncertainty analysis for input errors and parameters.

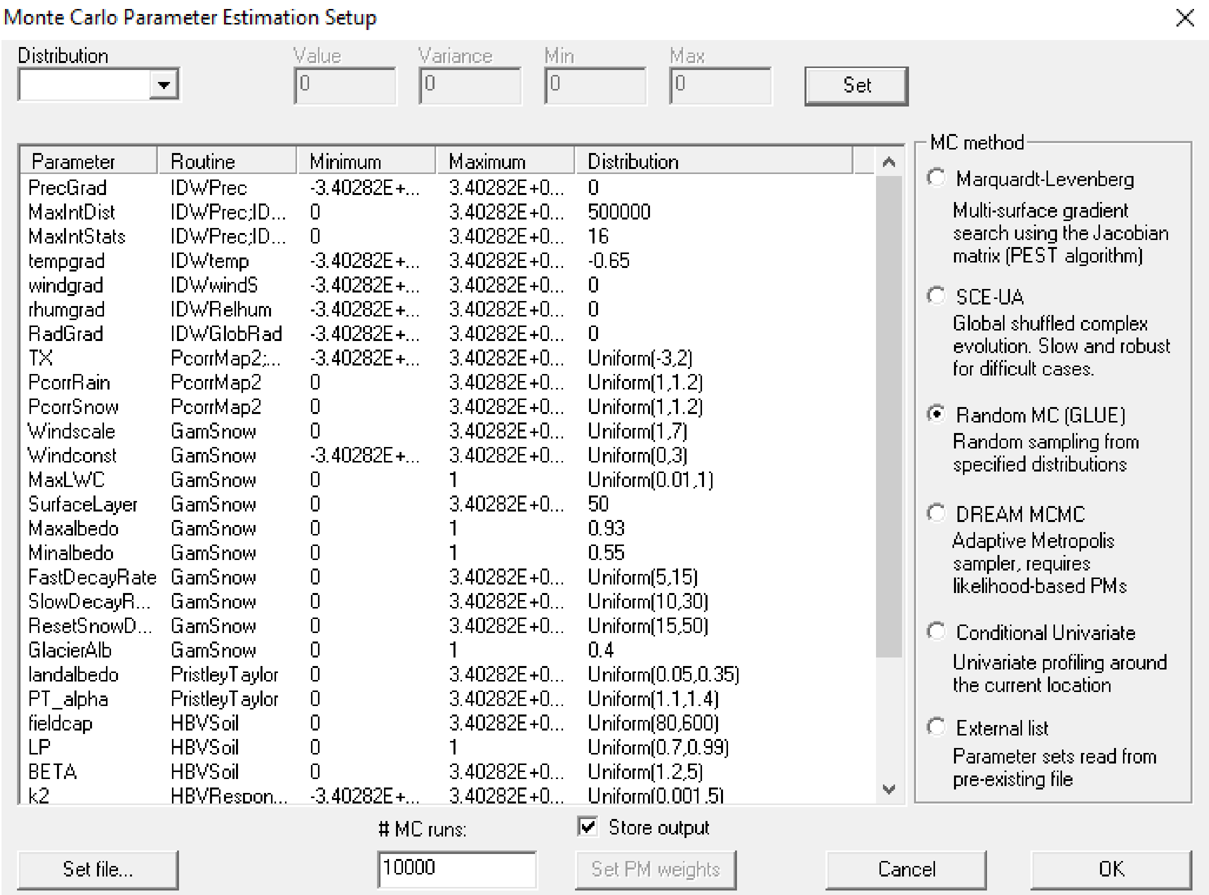


Figure 12 Calibration setting interface

2 Model Analysis

ENKI offers great convenience in ensembling different sub-routines without writing much codes. For the purpose of this kind of operation, one can easily add or replace routines, run multi-model arrangements in solving same task or testify different schemes by shifting parameters.

3 Routine Implementation and Testing

Basically this is to add more routines into the existing framework, meaning either the new process is lumped or distributed new routing, ENKI can testify and go through the quality control of the routines. In addition, this remains to port the application to other companies and computer platforms. (Kolberg, 2012)

3.2.4 STRUCTURE OF ENKI

As mentioned, the structure of ENKI is like a multi-layer cake, it is piled up with different subroutines but not simply vertically. It is composed my different subroutines and connected by some certain links which is called region. For different subroutines, there are models correspond to them which contains equations. It can be found in the ENKI software when setting up, followed is the interface for setting up, which shows different options of methods and subroutines to choose.

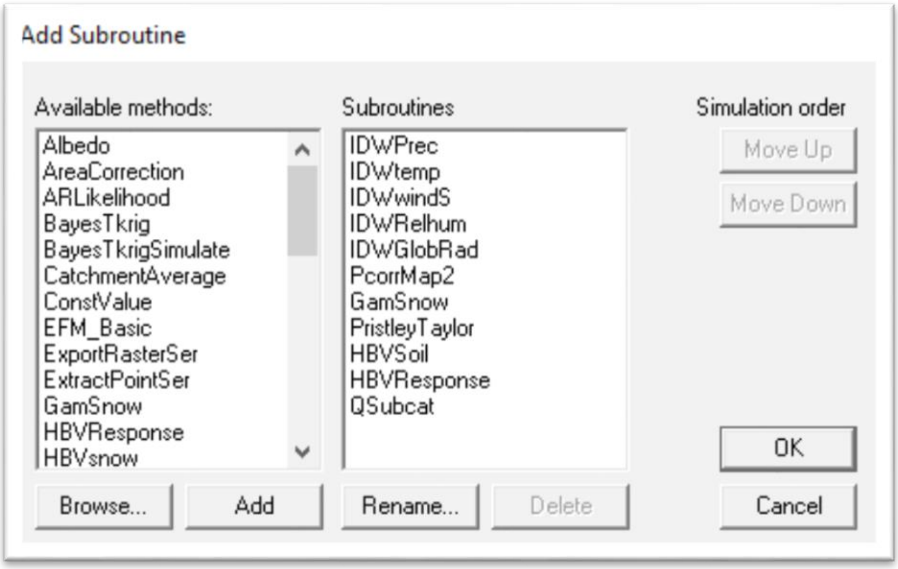


Figure 13 ENKI Structure

There are existing subroutines to choose from in the library. Simply click on “add”, the available methods from the left side can be added to the subroutines on the right which will be used later in model work.

In my simulation of the rainfall-runoff process, I chose the combination of IDWPrec, IDWtemp, IDWwindS, IDWRelhum, IDWGlobRd, PcorrMap2, CamSnow, PristleyTaylor, HBVSoil, HBVResponse and QSubcat.

3.2.5 SUBROUTINES

1. Precipitation and Temperature Routine

As mentioned in the input counterpart, precipitation and air temperature plays vital role in the whole process. As the first part of the whole process, this uses IDWPrec, IDWtemp respectively to calculate the corresponding data of precipitation and temperature for each cell for each time step which is daily in the case. The methods are actually interpolation to all the cells inside of the catchment from the input stations either inside or rather close while outside. Always a raster map is generated after the process by the framework itself.

2. Snow Routine

GamSnow is the name of this routine. The function of this process is to calculate snow accumulation and outflow from a snowpack at the stage of snow area to snow water equivalent for each of the cell in the catchment. Energy balance is needed here to calculate, thus precipitation, air temperature, relative humidity, wind speed and radiation are as the input to this routine.

3. Evapotranspiration Routine

Penman equation in principle is regarded as the most suitable method to represent evapotranspiration in real world, while due to much coefficient and complication, Priestley-Taylor (PriestleyTaylor) is chosen to be used as a simplification version in simulation.

4. Soil Routine

Soil, is discussed to be the most complex matter in most of the routines. Accordingly, in the model, more time and efforts need putting in this routine as well. The main task in this routine is to compute storage of water in upper soil, evaporation from soil and vegetation, runoff generation and net precipitation (Rinde, 2016). In this routine, HBVSoil is used, as simplified as a bucket. The principle is like pouring water into a bucket with an outlet, the volume of the bucket, the contribution of the pouring water and the “escaping” water from the water body inside of the bucket matters. These are customized as FC, BETA and LP respectively.

5. Response Function

If there are not many lakes inside the catchment, this routine should be the last one that water can reach. Excess water from the last routine—soil routine comes to this part which can be divided into two parts—upper zone and lower zone.

Upper zone describes storage in surface water and in the active part of groundwater, runoff delay and timing. It is equivalent to the Unit Hydrograph method transferring runoff generation to a runoff hydrograph by accounting for transport delay and attenuation. Upper zone mainly computes quick runoff or described as storm runoff sometimes. (Rinde, 2016)

Lower zone (lake part) describes storage in deep groundwater and lakes, runoff delay and timing. Lower Zone computes slow runoff which sometimes is described as base flow from groundwater reservoir and lakes. This flow will continue a long time after rainfall and snowmelt have stopped.

3.2.5 MODEL CALIBRATION

Calibration is like a machine learning process but more physical meanings have been entitled into this process. The parameters set of a model before calibration has been set for a specific range or a constant number due to the property of the parameter, many tests, researches carried out before have been applied accordingly. As for the input data, quality is of crucial importance. For more accuracy, gauged areas' data is taken as sample representing the area, also making it possible to estimate uncertainties for the ungauged part. Based on the experience, in the Norwegian mountainous regional calibration, the R^2 value can be reduced by 0.05 to 0.07 compared to catchment specific calibration. (Kolberg et al., 2012)

In an operational point of view, it is much easier to maintain one common model for several routines instead of calibrating, feeding, updating different ones for this phase. (Kolberg et al., 2012)

The principles for ENKI calibration requires operators have good understandings of the model structure and how different parameters influence the process and different responses can be brought up due to this. Trial and errors is applied in this process, thus large uncertainties and flexibilities are brought by the combination of sets of parameters. In ENKI, it is easy to differentiate between the confined and unconfined parameters. Constant parameter are set at the initial stage, whereas the free parameters need to be calibrated and recorded when the process is finished. The calibration can be run for several iterations to several thousand iterations. In this case, it is hard to say that the parameter set is good enough since there are always room to improve. But in another way, there are also limitations caused by the model setup and the quality of data as input, when these limitations function, most of the time it seems that the calibration has reached an equilibrium so that no matter how many more iterations is added, the result does not change much. In ENKI, auto calibration is possible so that the model can run itself after some certain sets. The Monte Carlo parameter auto calibration is used in ENKI framework. The most important parameters for ENKI and HBV model is listed below.

Table 7 ENKI Parameter and Calibration Interval Values

Parameter	Description	Value	Calibration Interval	
PrecGrad	Elevation lapse rate (percent/100 m)	0	0	10
MaxIntDist	Maximum distance to included station	500000		
MaxIntStats	Maximum number of stations included	23		
Tempgrad	Elevation lapse rate (units/100 m)	-0.65		
Radgrad	Elevation lapse rate (units/100 m)	0		
Humgrad	Elevation lapse rate (units/100 m)	0		
CX	Degree-day factor	4	3	6
CRF	Refreezing coefficient	0.01	0	0.01
TS	Zero-melt temp treshold	0.5	-1	2
TX	Precip type temp treshold	1	-1	2
LW	Maximum liquid content (frac)	0.1	0	1
s00	Snow distribution low limit	2.3		
s25	Snow distribution 25% quartile	1		
s50	Snow distribution median	0.9		
s75	Snow distribution 75% quartile	0.8		
s100	Snow distribution high limit	0.3		
LandAlbedo	Albedo of snow free surface	0.1		
PTalpha	Prisley-Taylor alpha parameter	1.26		
FC	Field capacity	200	50	600
LP	Treshold for minimum SM/FC	0.9	0.7	0.99
BETA	Nonlinearity in unsaturated storage	2	1	5
K2	Outlet coefficient quick outflow upper tank	0.3	0.1	0.6
K1	Outlet coefficient slow outflow upper tank	0.1	0.01	0.15
K0	Outlet coefficient outflow lower tank	0.05	0.01	0.1
Perc	Percolation rate from upper to lower tank	0.6	0.5	5
tresh	Treshold height for fast outflow in upper tank	20	10	60

Lakep	Lake portion of catchment (0 - 1)	0.02		
Rcorr	Bias correction factor for rain	1.05	1.05	1.2
Scorr	Bias correction factor for snow	1.2	1.15	1.5

SOURCE. Hydrological models. (Killingtveit and Sælthun, 1995)
SINTEF (Lena Tøfte-10.2014)

A criteria has to be set to stop the calibration process. There are usually two different ways to terminate the process which are subjective method and objective method respectively.
Subjective methods utilize the plotted hydrography between observed data series and simulated data series, cumulative difference is also used in most cases as well.

Objective methods has to set a function which can be derived from the data difference which is the observation and simulation. The function then contains Q_{obs} and Q_{sim}. It can be calculated as follows:

$$R^2 = \frac{\sum(Q_O - Q_0)^2 - \sum(Q_S - Q_0)^2}{\sum(Q_O - Q_0)^2} \qquad (20)$$

Where Q_o is observe runoff
Q_0 is the average runoff
Q_s is the simulated runoff

Cumulative difference is expressed as $\sum(Q_O - Q_S)$

4 DATA ACQUISITION AND QUALITY CONTROL

4.1 DATA ACQUISITION

In Norway, it is easy to find and acquire hydro-meteorological data than most of the countries I know. This offers a good platform and atmosphere for the student and researchers to carry out the corresponding study in related field. I have collected data from different fields: precipitation, air temperature, discharge, wind speed, relative humidity and radiation. The data's sources range from NVE, eKlima, to NIBIO. The detailed information for each type of data is listed below:

Table 8 Data Collection

Type	Duration	Resolution
Precipitation	1999-2015	Daily
Air temperature	1999-2015	Daily
Discharge	1999-2015	Daily
Wind speed	1999-2015	Daily
Relative humidity	1999-2015	Daily
Radiation	1999-2015	Daily

After data acquisition, the quality of data need to be checked. To find errors and correct the errors before feeding them to the hydrological model is essential. Because the input quality is the foundation that you can expect a model to present you a good output. First rule to remember is be skeptical to data.

4.2 DATA QUALITY CONTROL

There are few steps to follow in controlling data quality. It is shown as follows:

4.2.1 VISUAL INSPECTION

- Check the completion of data series (whether it is covers the whole range that one wants for the model)
- Check the unphysical values like spikes, negatives where is it not supposed to be
- Check the flat regions where sensor or transfer system may fall out
- Check unphysical variation patterns which may be caused by sensor malfunctioning (Rinde, 2016)

4.2.2 FILLING GAPS

- Calculate correlations between the temperature series for periods where they all have data (if there are too many data missing or the correlation is too bad while the data is broken, for the data from these stations can be abandoned)
- There are two main categories to fill the gap of missing, but the main principle goes the same. Fill gaps in "target-series" with data from the series with the strongest correlations based on the findings from previous procedure, then shift the values according to the absolute different in average temperature over the correlation periods

  Periods with overlapping => establish correlation shown as below for air temperature.

$$T_3 = T_2 + (avg.T_3 - avg.T_2) \tag{21}$$

  For precipitation and runoff corrections, relative difference in average precipitation and runoff over the corrected period is applied as follows:

$$P_3 = \frac{Avg.P_3}{Avg.P_2} \times P_2 \tag{22}$$

$$Q_3 = \frac{Avg.Q_3}{Avg.Q_2} \times Q_2 \tag{23}$$

However, one thing has to be kept in mind is that, runoff in Norway is strongly influenced by snowmelt which has been mentioned the mechanism of flood formation in Norway part. The catchments hypsography is then in a vital position when selecting correlation series, sometimes it is more important than proximity.

- When it comes to filling the gap for runoff, the proximity has to be cared, which means that the catchment to be filled has to share high similarity from the one that has a complete data series. Reasonable distance should be considered, sot that the precipitation and temperature forcing from both catchments should be similar. To show the similarity in snow melt variations, similar hypsographic distribution is needed. Some other important components is the size of the lake percentage inside the each catchments should be in a comparable stage so the effect of runoff dampening are similar as well.

  These are the principles to follow while filling up the gaps for runoff data series, but it is rather ideal which is difficult to find in real world. Then the requirements is adjustable according the that, if the mechanism of the runoff formation is similar which means both of the catchments are in similar weather region then, the differences of the size of catchments and the lake percentage are also acceptable in a way. (Rinde, 2016)

4.2.2 ACCUMULATION PLOT

- This is to verify if the correct scaling has been applied to fix the data gap. If the scaling is done properly, the accumulation plot should continue with same gradient when observed over a long period
- But if the data series last for a long period, the climate change may cause a gradual non-linear development in the accumulated observed values in a gentle way. (Rinde, 2016)

4.2.3 DOUBLE MASS CURVE

- After checking the inhomogeneity of the filled data, the next step is to detect consistency in the filled data series
- Plot the accumulated development of a time series against the corresponding developments of other time series in the same climatic region

- Double mass curve is plotted as the accumulated values at each station against the accumulated values of another station. In principle the corrected data series should show a linear development in accumulated values over time regardless of climate change effects
- In double mass curve plot true irregularities like exceptionally hot and wet years or climate change, are removed from the graphs based on the foundation that the stations are all from same meteorological regions. The graph only gives an idea of the cumulative observed values relative to the cumulative values at other stations. (Rinde, 2016)

4.2.4 SOURCES OF ERROR IN RUNOFF MEASUREMENT

- Sensor malfunctioning or transfer error
- Inaccurate rating curve (especially for large flows)
- Ice build-up during cold winter periods
- Change of cross section due to erosion/sedimentation (especially after large flood events)
- Regulations (reservoirs or diversions established upstream in catchment). (Rinde, 2016)

4.2.5 TYPICAL CAUSES TO SYSTEMATIC MEASUREMENT ERRORS IN OBSERVATION

- Sensor malfunctioning or errors in data storage / transfer / conversion.

  The data are not registered as they should, or errors are introduced when data is stored, transferred or converted from raw-units till actual temperature values.
- Faulty sensor re-calibration / replacement
- Censor registrations shift systematically to a higher or lower level after re-calibration or replacement of sensor.
- Moving of gauging station

  Censor registrations shift systematically to a higher or lower level because gauging station is moved, for some reason, to a new location.
- Change in surroundings like

(1) Vegetation growth / removal (precip /temperatur
(2) Buildings / urbanization (precip /temperature)
(3) River profile changes (runoff)
floods may cause erosion / sedimentation in the river bed and thereby change the cross section profile for which the discharge curve is constructed.
(4) Regulations upstream in catchment (runoff)
Reservoir regulations will alter seasonal runoff profile. Diversions in or out of catchment will increase or decrease total volume. (Rinde, 2016)

4.3 RUNOFF DATA

As mentioned, it is crucial to find most suitable data within the catchment or rather close to the catchment, as listed in the appendix, I have located 25 runoff gauging stations either inside the catchment or close by. It is found that the four ones listed below are the best ones, since they are located at the outlet of each sub-catchment. Detailed information is as followed:

Table 9 Runoff gauging stations information

FID	Object-ID	Shape*	St_NAME	X_LONG	Y_LAT	ELEV (HOH)	SOURCE
2	3	Point	**Eggafoss**	610834.619	6975429.81	330	NVE
5	6	Point	**Gaulfoss**	561752.595	6999015.571	45	NVE
7	8	Point	**Hugdal bru**	562678.638	6986117.108	135	NVE
13	14	Point	**Lillebudal bru**	578844.025	6967073.083	515	NVE

It is also shown below the exact location compared to the whole catchment. Data is collected as daily resolution. There are some errors with the data, the fixing procedure has been shown, and techniques have been applied to correct data in order to achieve the best quality ones for the model and analysis.

Figure 14 Catchment with runoff gauging stations

Visual inspection: there are rare negative data found, after consulting the other stations' data and the same period of the same gauging station in different years, the negative ones have been replaced by absolute value where the error is regarded as error in transfer.

Runoff data's correlation before and after the correction is shown as follows:

Table 10 Correlation of runoff gauging stations before data fixing

	Gaulfoss	*Lillebudal Bru*	*Hugdal Bru*	*Eggafoss*
Gaulfoss	1			
Lillebudal Bru	0.35	1		
Hugdal Bru	0.43	0.09	1	
Eggafoss	0.94	0.35	0.39	1

Table 11 Correlation of runoff gauging stations after data fixing

	Gaulfoss	Lillebudal Bru	Hugdal Bru	Eggafoss
Gaulfoss	1			
Lillebudal Bru	0.92	1		
Hugdal Bru	0.88	0.79	1	
Eggafoss	0.94	0.89	0.76	1

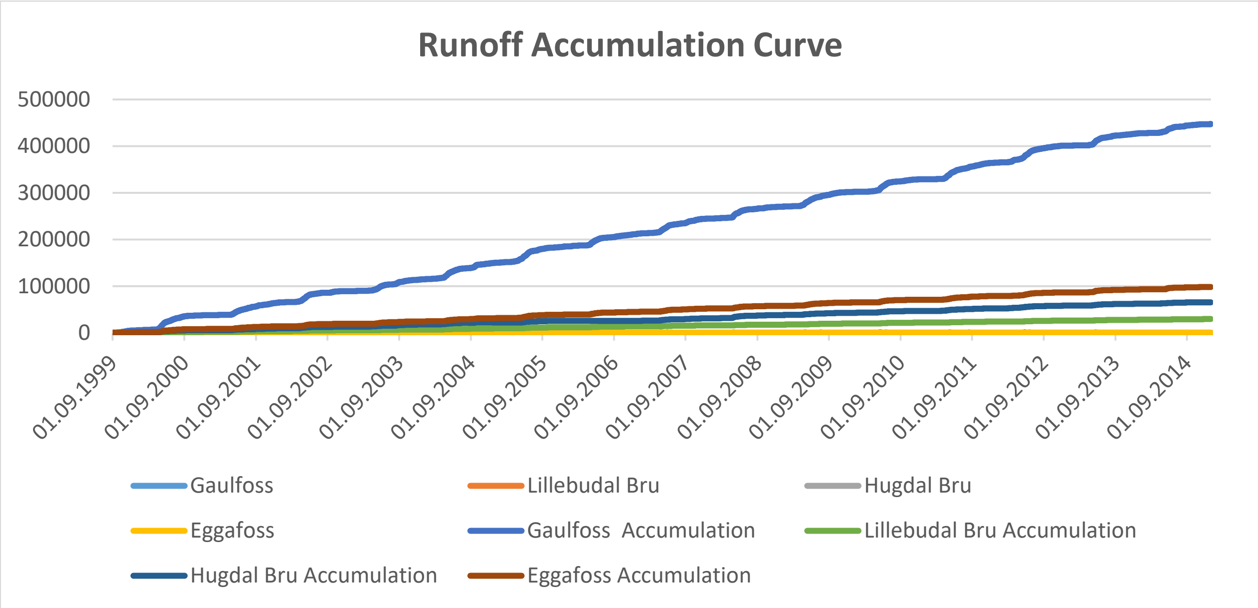


Figure 15 Accumulation curve plot of runoff after data fixing

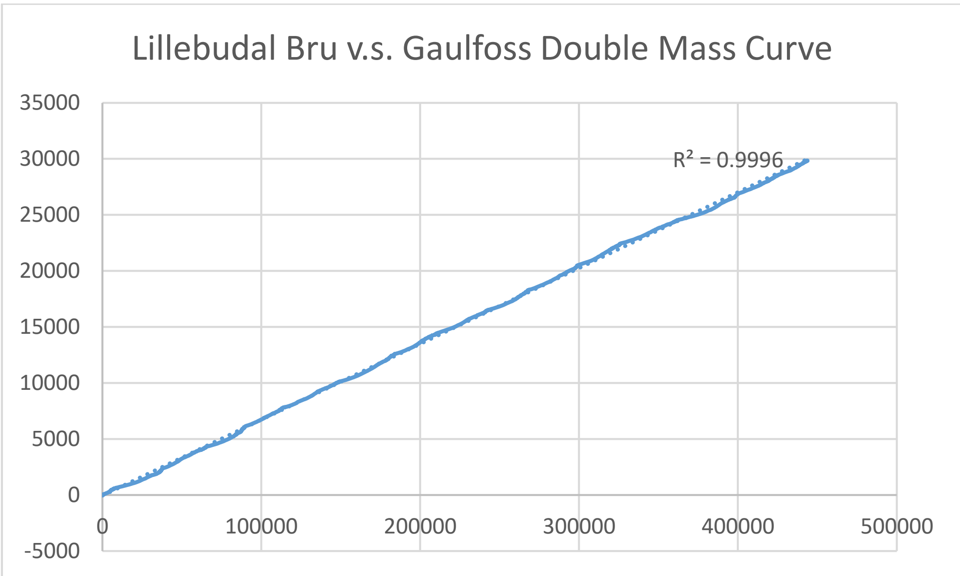


Figure 16 Double mass Curve—Lillebudal Bru v.s. Gaulfoss for example

Average daily runoff is shown below:

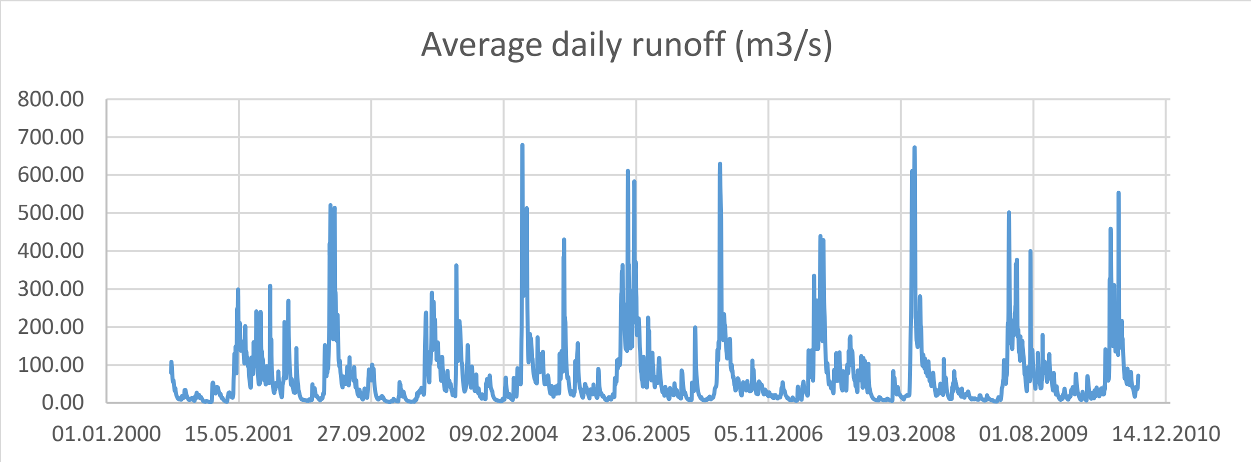


Figure 17 Average daily runoff

4.4 PRECIPITATION DATA

Precipitation data is one of the other key elements as the input to ENKI besides runoff. The role of the data quality is as important as the runoff data. Initially 49 precipitation gauging stations were identified from different sources around Gaula Catchment, while there are some really far from the region which were abandoned along the way. Finally there are 16 precipitation gauging stations selected around Gaula catchment to proceed. Detailed information of the gauging stations are as follows:

Table 12 Precipitation Gaging Station Information

FID	Object-ID	Shape*	St_NAME	X_LONG	Y_LAT	ELEV (HOH)	SOURCE
25	26	Point	AURSUND	625633.78	6951624.84	685	eKlima
30	31	Point	LØKSMYR	572201.21	7012191.08	173	NIBIO
31	32	Point	AUNET	629747.12	6994375.53	302	eKlima
32	33	Point	STUGUDAL	645482.15	6977148.89	730	eKlima
37	38	Point	RØROS	622503	6939642	628	eKlima
38	39	Point	KVIKNE	565288	6941299	550	eKlima
39	40	Point	BREKKEN	647595	6949354	710	eKlima
40	41	Point	BERKÅK - LYNGHOLT	551844	6965643	475	eKlima
41	42	Point	ENDALSVOLL	574095	6966449	606	eKlima
42	43	Point	RENNEBU - RAMSTAD	542492	6971403	234	eKlima
43	44	Point	HALTDALEN III	610400	6976400	290	eKlima
44	45	Point	RØSBJØRGEN	577143	6985667	330	eKlima
45	46	Point	STØREN - VÅRVOLL	565373	6991316	65	eKlima
46	47	Point	HØLONDA	551394	6998865	360	eKlima
47	48	Point	SOKNEDAL	62.9535	10.1788	299	NIBIO
48	49	Point	KOTSØY	62.9763	10.5608	127	NIBIO

It is also shown as below that the relative location to the catchment of the precipitation gauging stations.

Figure 18 Catchment with the relative locations of Precipitation gauging stations used

The precipitation series are much worse than runoff data, where much fixing work need to be done. In addition, there are much uncertainties have been brought up due to the quality of data. The best we can make up is using the techniques discussed above to fill and correct the data to make it representable.

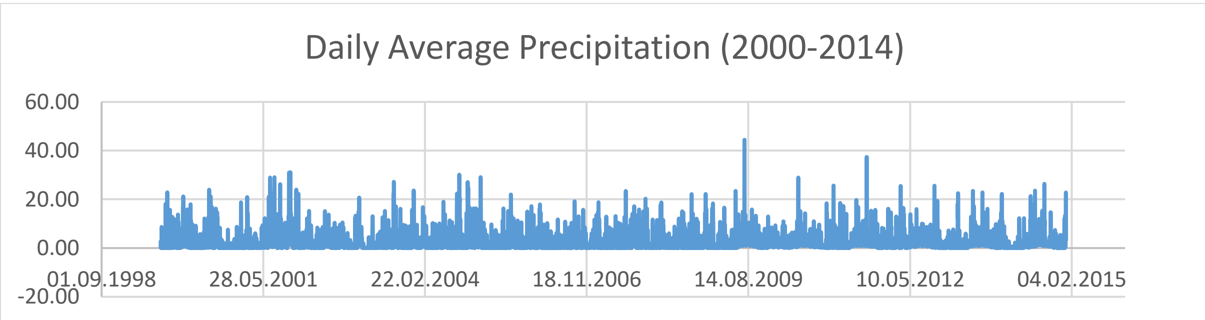


Figure 19 Average daily precipitation of the region

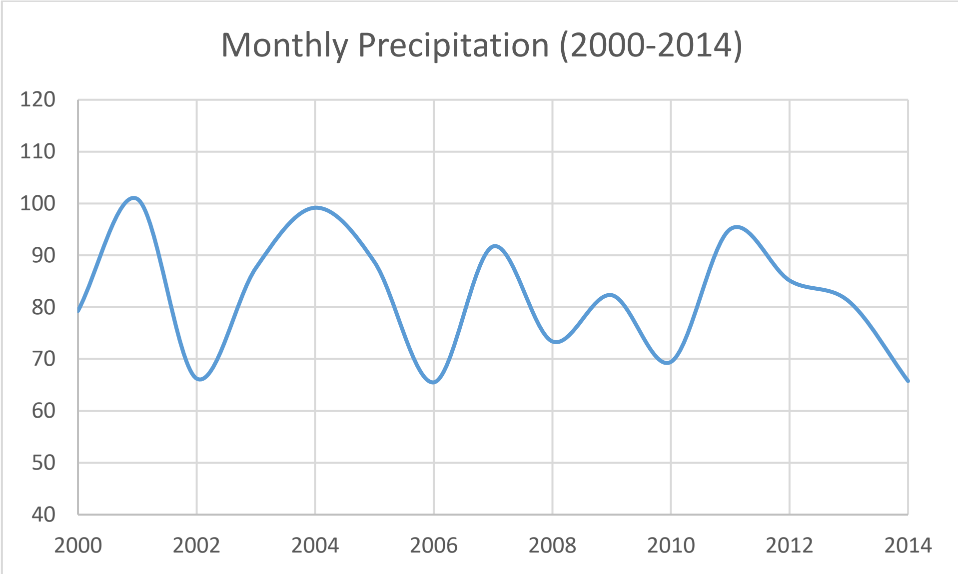


Figure 20 Monthly precipitation

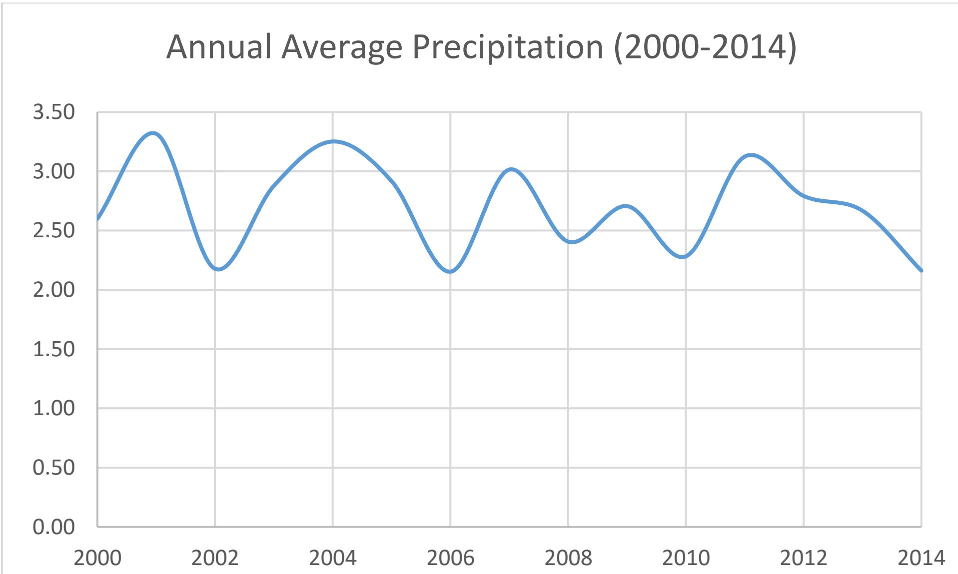


Figure 21 Annual average precipitation

Below it shows the double mass curve after data fixing, example is for Støren and Vårvoll station:

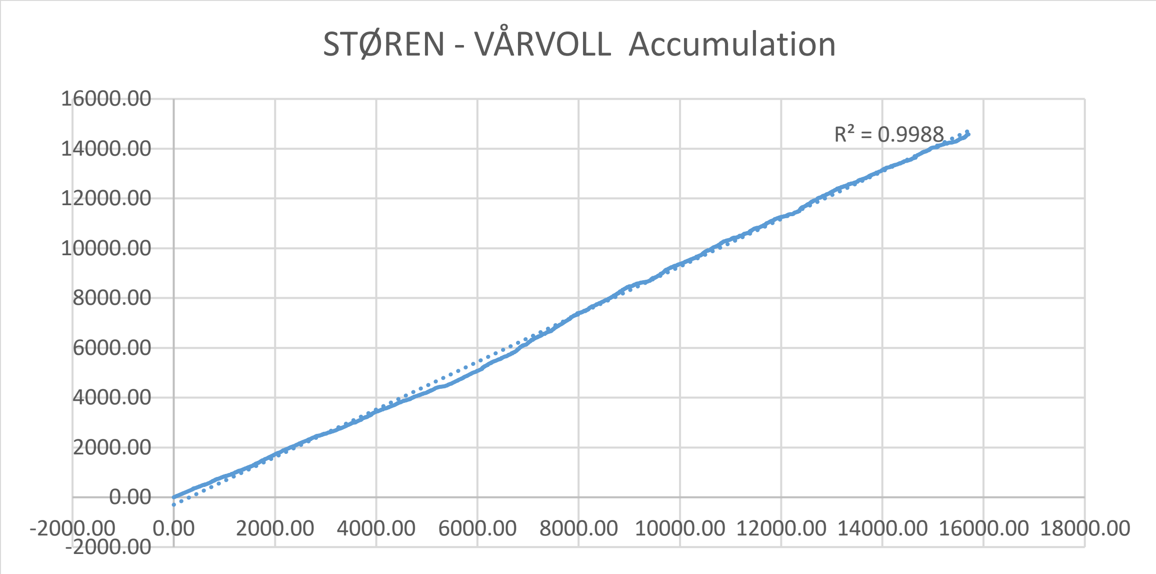


Figure 22 Double mass Curve—Støren v.s. Vårvoll for example

4.5 TEMPERATURE DATA

Compared with precipitation data, the stations for measuring air temperature are much less in number. Corrections have been applied where necessary. While actually the model can also interpolate the missing data when it starts running. There are 22 temperature gauging stations have been identified around the catchment, while 7 has been selected to proceed.

The air temperature station data is shown as below, detailed information regarding stations can be found in the table, the relative location of the stations to the catchment is shown in appendix.

Table 13 Air Temperature Station Information

FID	Object-ID	Shape*	St_NAME	X_LONG	Y_LAT	ELEV (HOH)	SOURCE
14	15	Point	RØROS	622218.5	6940402	628	Ekima
16	17	Point	BERKÅK	551843.9	6965643	475	Ekima
17	18	Point	OPPDAL-MAURHA	542091	6948222	668	NIBIO
18	19	Point	VINJEOERA 2	550141	7009098	47	NIBIO
19	20	Point	SELBU-STUBBE	606487	7010276	242	NIBIO
20	21	Point	KOTSØY	629763	105608	127	NIBIO
21	22	Point	SOKNEDAL	629535	101788	299	NIBIO

Double mass curve is shown below after data fixing, example is from Vinjeoera2 and Berkåk-Lyngho Stations. The consistence of the data seems good.

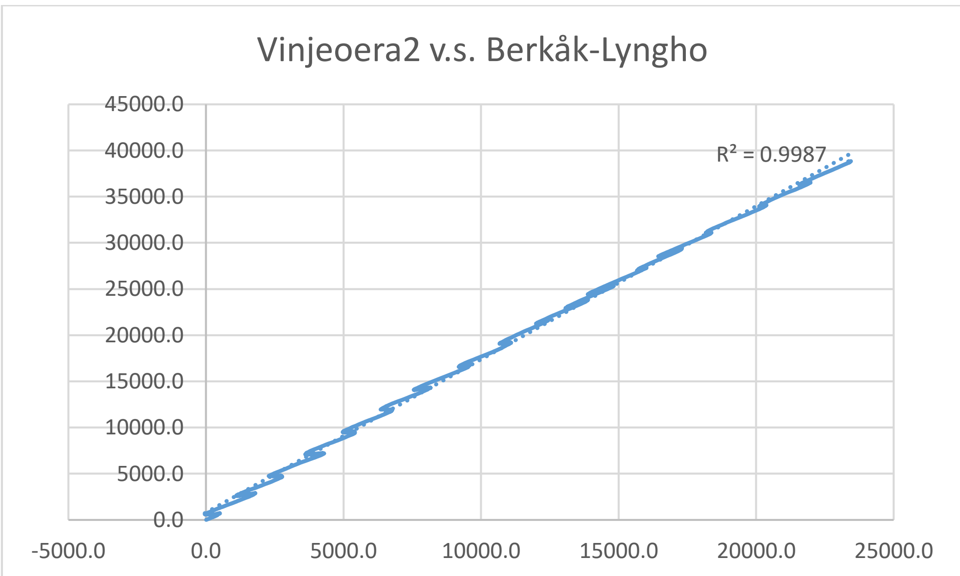


Figure 23 Double mass Curve— Vinjeoera2 v.s. Berkåk-Lyngho for example

4.6 RELATIVE HUMIDITY, GLOBAL RADIATION AND WIND SPEED DATA

In the rainfall-runoff process, as the simplest version, water balance is composed by precipitation, evaporation, runoff and snow melt where applicable. As for the model these are the key factors as well, including air temperature. We have discussed precipitation, air temperature and runoff data previously, there is one remaining parameter to be discussed—evaporation. As one my know that it is really hard to measure evaporation on site, the best and most practical way to get the evaporation data is to calculate it indirectly. Data needed for evaporation calculation can be relative humidity, global radiation and wind speed. It is also possible to get the data from corresponding meteorological stations though scarce.
Relative humidity, global radiation and wind speed shares the same meteorological stations, there are 4 stations found close by, after plotting them on them map to check the relative locations, 3 would be proceeded and implemented in the model. Detailed information regarding stations can be found as follows, the relative location if the meteorological stations to the catchment is shown in the appendix.

Table 14 Meteorological Stations Information

FID	Object-ID	Shape*	St_NAME	X_LONG	Y_LAT	ELEV	SOURCE
0	1	point	SKJETLEIN	565141	7024177	75	Bioforsk
1	2	point	SOKNEDAL	629535	101788	299	NIBIO
2	3	point	RENNEBU - RAMSTAD	542492	6971403	234	NIBIO

4.7 CATCHMENT AREA

There has been described the information regarding Gaula catchment, below it shows the location of the catchment and also the four sub-catchment which contained in the main one -- Gaulfoss, the relationship between the four sub-catchment, the relative locations of the runoff gauging stations, air temperature measurement stations, precipitation gauging stations and corresponding meteorological stations for measuring wind speed, relative humidity and global radiation etc.

Figure 24 Catchment area, location and the other sub-catchments

Raster map generated by ARC map tools shown below:

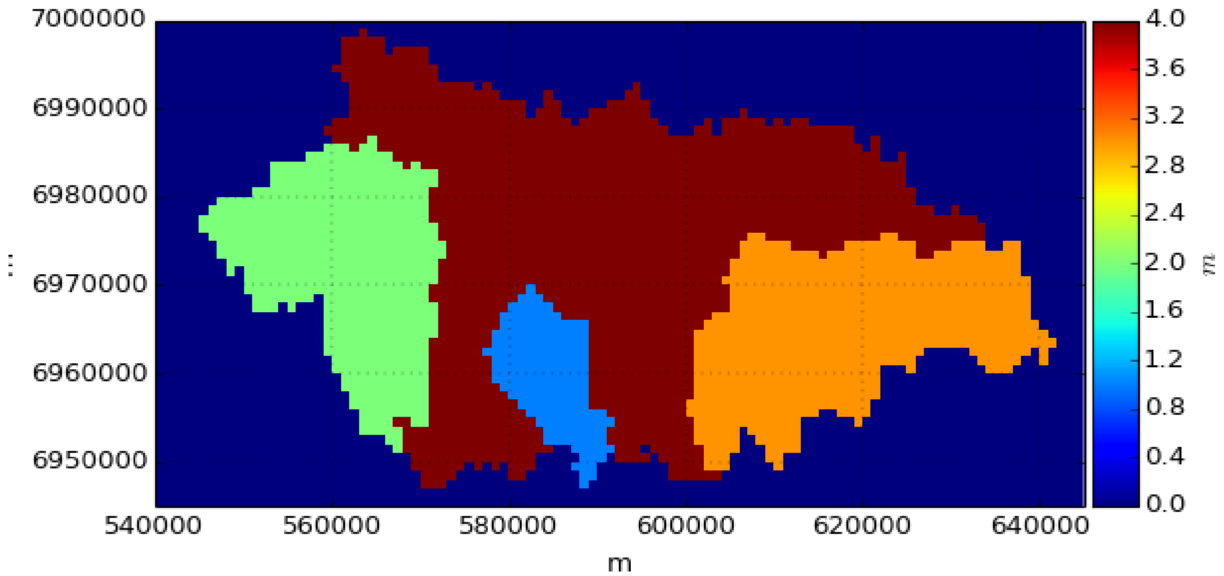


Figure 25 Catchment area in raster form for ENKI use

4.8 BASIC CATCHMENT INFORMATION

4.8.1 AREA ABD RELATIVE RELATIONSHIP

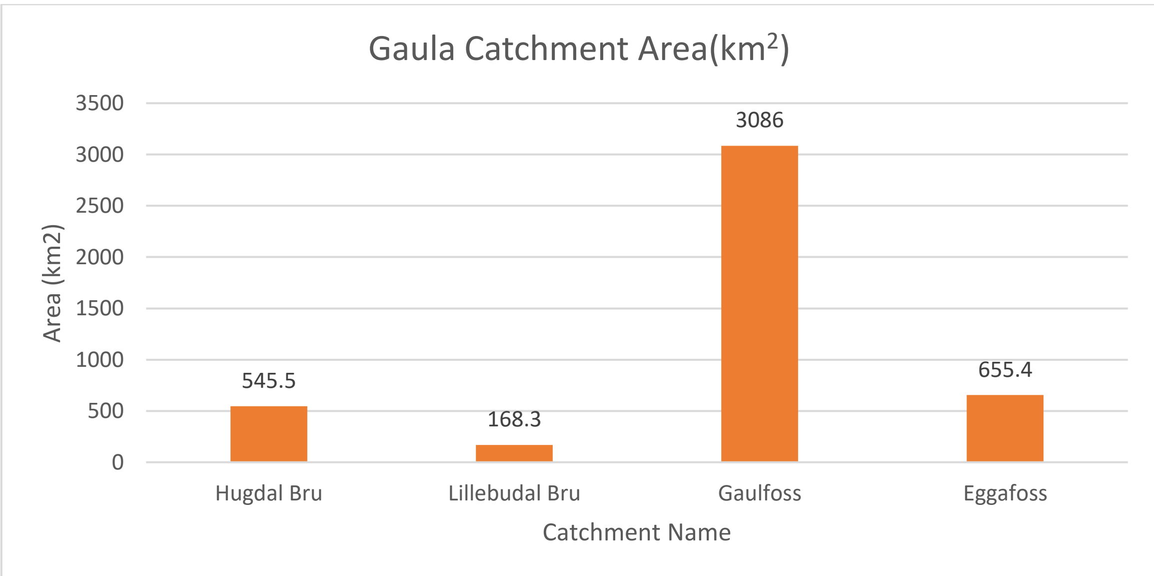


Figure 26 Catchment area

As mentioned in the previous chapters, Gaulfoss actually acts as the whole catchment where there are three sub-catchments locating inside of it. The relationship of the area for the four catchments is shown above. Gaulfoss local as noticed should equal to the subtraction of Eggafoss, Lillebudal Bru and Hugdal Bru from Gaulfoss, which is 1712.3 km^2.

4.8.2 CATCHMENT SPECIFIC RUNOFF INFORMATION

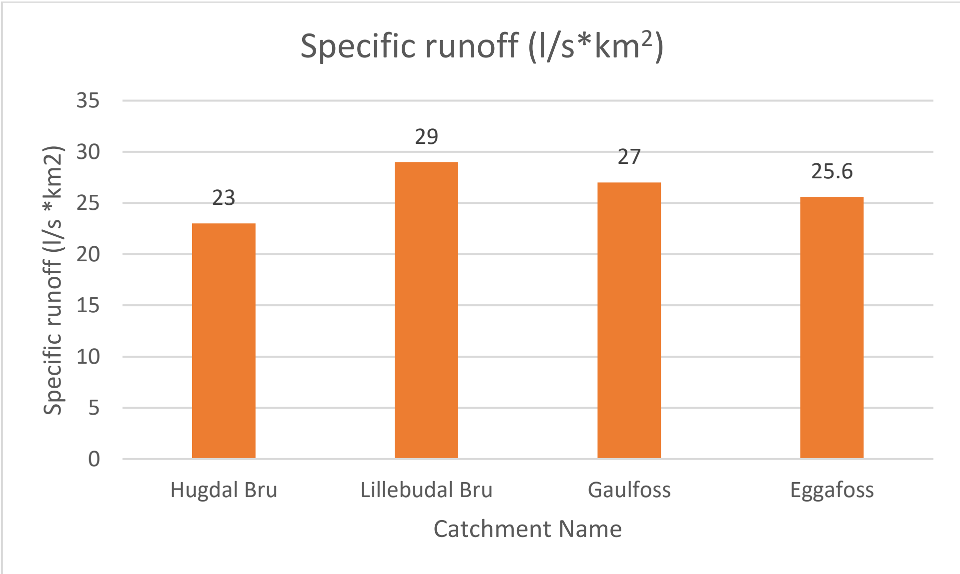


Figure 27 Catchment Specific Runoff

In the above graph, it gives a basic idea of the specific runoff value in this region, being 28.65 l/s*km^2 as the average specific runoff, which is close to the specific runoff of Gaulfoss and Lillebudal Bru.

4.8.3 CATCHMENT HYPOSGRAPHIC INFORMATION

Table 15 Catchment Hyposgraphic Information

Name	Hugdal Bru (moh)	Lillebudal Bru (moh)	Gaulfoss (moh)	Eggafoss (moh)
0 %	132	516	51	285
10 %	443	675	436	623
20 %	503	769	534	717
30 %	543	847	597	775
40 %	583	907	662	811
50 %	623	948	735	844
60 %	663	983	813	878
70 %	717	1016	878	918
80 %	816	1046	945	964
90 %	933	1088	1019	1021
100%	1254	1303	1325	1284

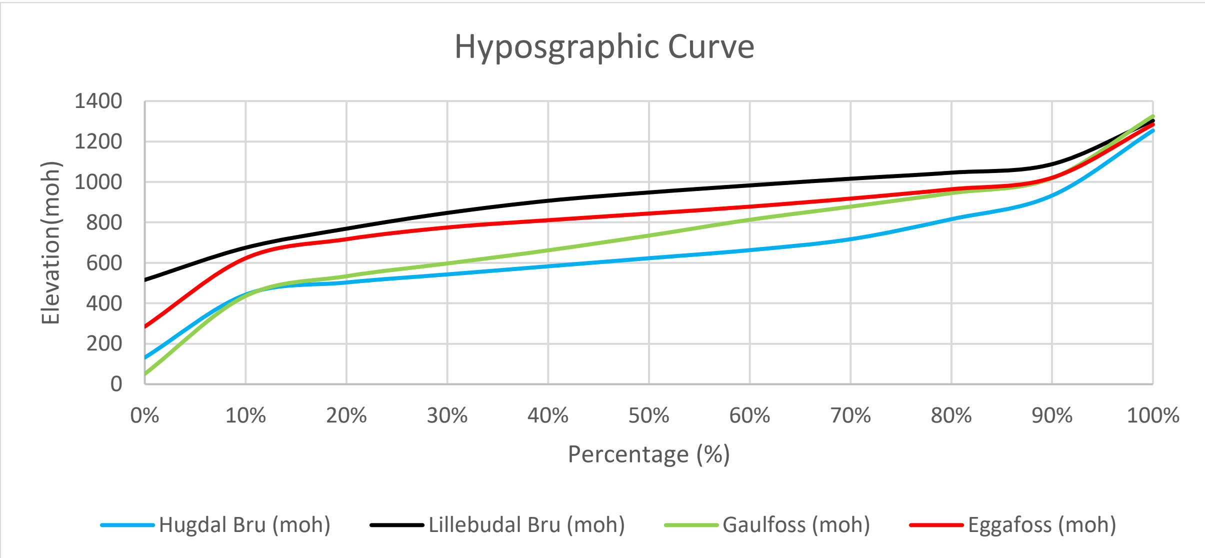


Figure 28 Catchment Hyposgraphic Curve

One can notice that the elevation goes down from Lillebudal Bru (as the highest) and Eggafoss to Gaulfoss and Hugdal Bru which is also the draining direction. The elevations distribution is then shown in figure in the table.

5 RESULT OF ENKI CALIBRATION AND VALIDATION, RESULT AND COMPARISON OF FLOOD FREQUENCY ANALYSIS

5.1 RESULT OF RUNOFF SIMULATION FROM ENKI

After feeding the model with data, warm-up has been finished with the data from 01.09.1999 to 01.09.2010, afterwards the long run of calibration with data from 01.09.2000 to 01.09.2010 gives an acceptable result of R^2 for each of the individual sub catchment ranges from 0.6 to 0.77. The rest of the data prepared is to validate the parameter just got from the calibrations to check the variability. Since the work focuses mainly on flood where annual maximum value is picked out when carrying out flood frequency analysis. So the more the behavior of the simulation tends to "catch" or "hit" the peaks, the better the result would be given by the simulation. But it does not necessarily have to be higher with R^2 as explained. The R^2 might be litter lower than the best performed ones but can give better result in the flood frequency analysis.

5.2 RESULT AND COMPARISON OF CALIBRATION AND VALIDATION

As for the Gaula case, it has been clarified that there are four "so-called" sub-catchments inside the big one, while for Gaulfoss being as the total one, Gaulfoss local is the subtraction from the whole and three others. The total R^2 value is the average of the four sub-catchments' specific performance. It has been found that the average R^2 for calibration is 0.6 while for Gaulfoss local, Eggafoss and Hugdal Bru has the R^2 value of 0.61, 0.77 and 0.64 respectively, so the performance evaluation value has been dropped 0.01, 0.17 and 0.04 respectively, which has a bigger drop in the latter one. On the other hand, Lillebudal Bru behaves fairly around the average in this process, giving a local performance of 0.6. This performance is a bit strange and would be described and discussed in the later part.

After running the calibration for more than 20 separate times, the average iteration times for each run range from 5000 iteration times to

30 000 iteration times, still R^2 seems to be stable around a certain figure where Gaufoss is 0.5, Lillebudal Bru is 0.57, Hugdal Bru is 0.61 and Eggafoss is 0.74 and as an overall of 0.6. As it is shown in the following table and graphs of some best representative performance values. In the table, the last row is called R^2 Specific which means the best specific performance among all the calibrated ones have been compared and picked out, so literally this is the best in my setup and calibration figures, but the overall does not make sense in this column since all the other best performed ones listed above, that is the one found with the best overall performance, thus corresponding specific performance figures exist at the same time. While for picking out the best performed specific catchments' values, the average cannot be reached in my set model.

After running for more iteration times, I found that it seems the model has reached its "equilibrium" which means it is no longer possible or with extreme low possibilities that the performance can be improved due to the current set-up, parameter range given and data at hand.

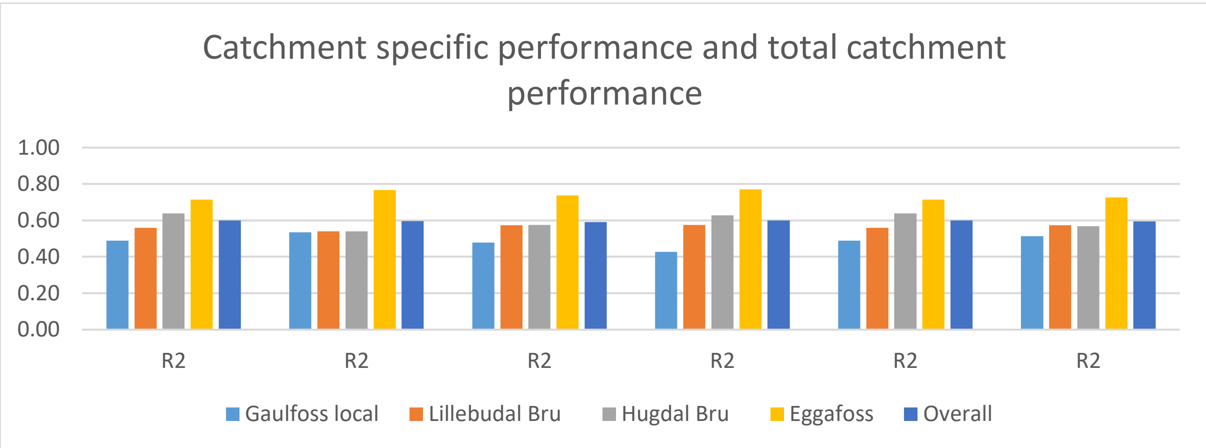


Figure 29 Overview of the catchment specific performance and total catchment performance

One can easily get some hints that the total catchment performance (average of the specific catchment ones) is around 0.6 whereas the highest one is Eggafoss usually reaching 0.72. With the lowest as a whole of Gaulfoss local, is around 0.5 only. Huddal Bru and Lillebudal Bru seems to be stable between 0.55 and 0.60 while Hugdal Bru usually outperforms than LillebudalBru, which makes sense because of the data.

Table 16 Some selected best overall performance and specific catchment performance

	Gaulfoss local	Lillebudal Bru	Hugdal Bru	Eggafoss	Overall
R^2	0.49	0.56	0.64	0.71	0.60
R^2	0.53	0.54	0.54	0.77	0.60
R^2	0.48	0.57	0.58	0.74	0.59
R^2	0.43	0.58	0.63	0.77	0.60
R^2	0.49	0.56	0.64	0.71	0.60
R^2	0.51	0.57	0.57	0.73	0.60
R^2	0.49	0.56	0.64	0.71	0.60
R^2 SPECIFIC	0.61	0.59	0.64	0.77	0.65

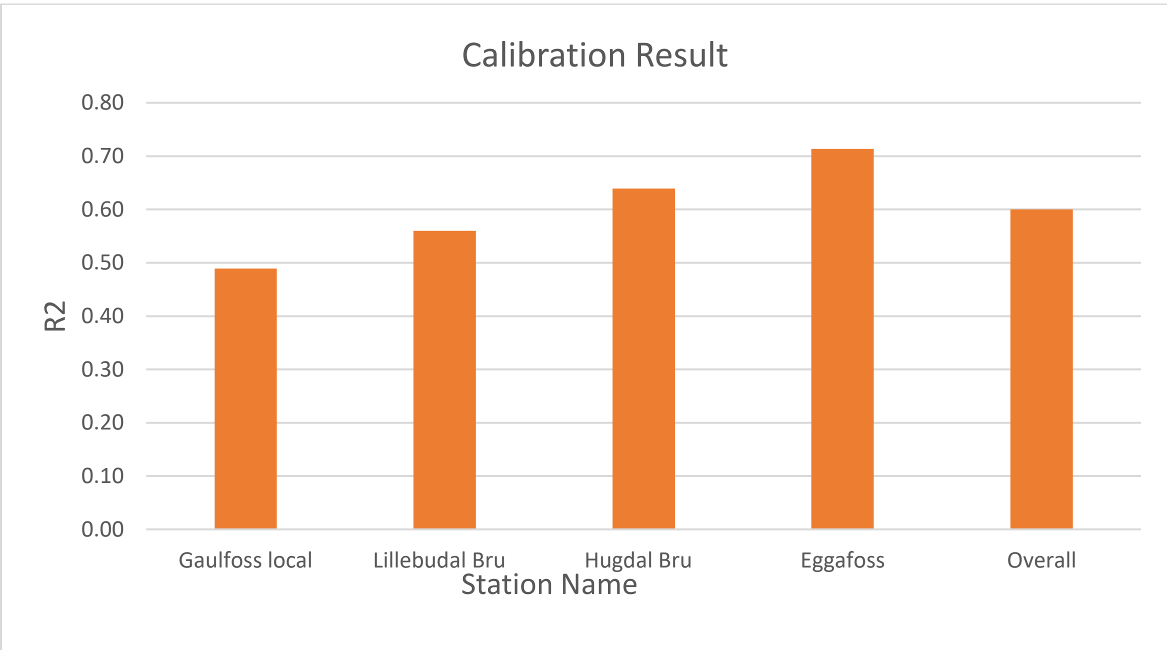


Figure 30 Best overall performance 1

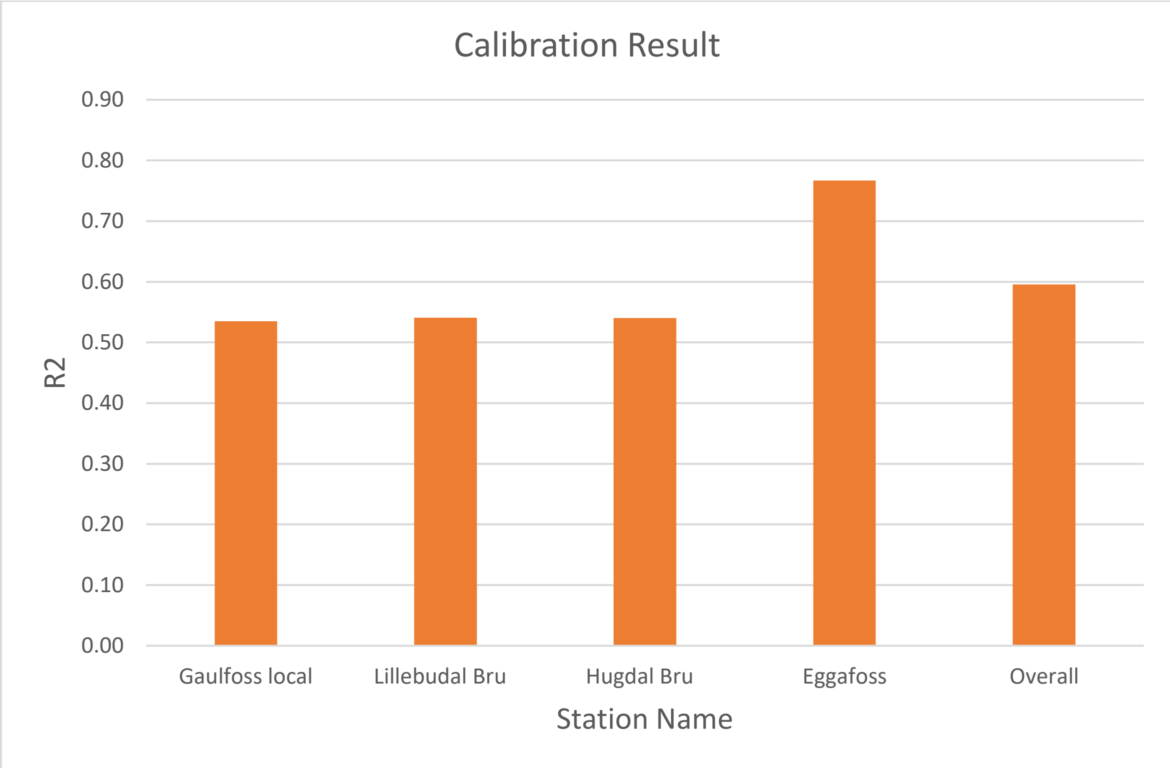


Figure 31 Best overall performance 2

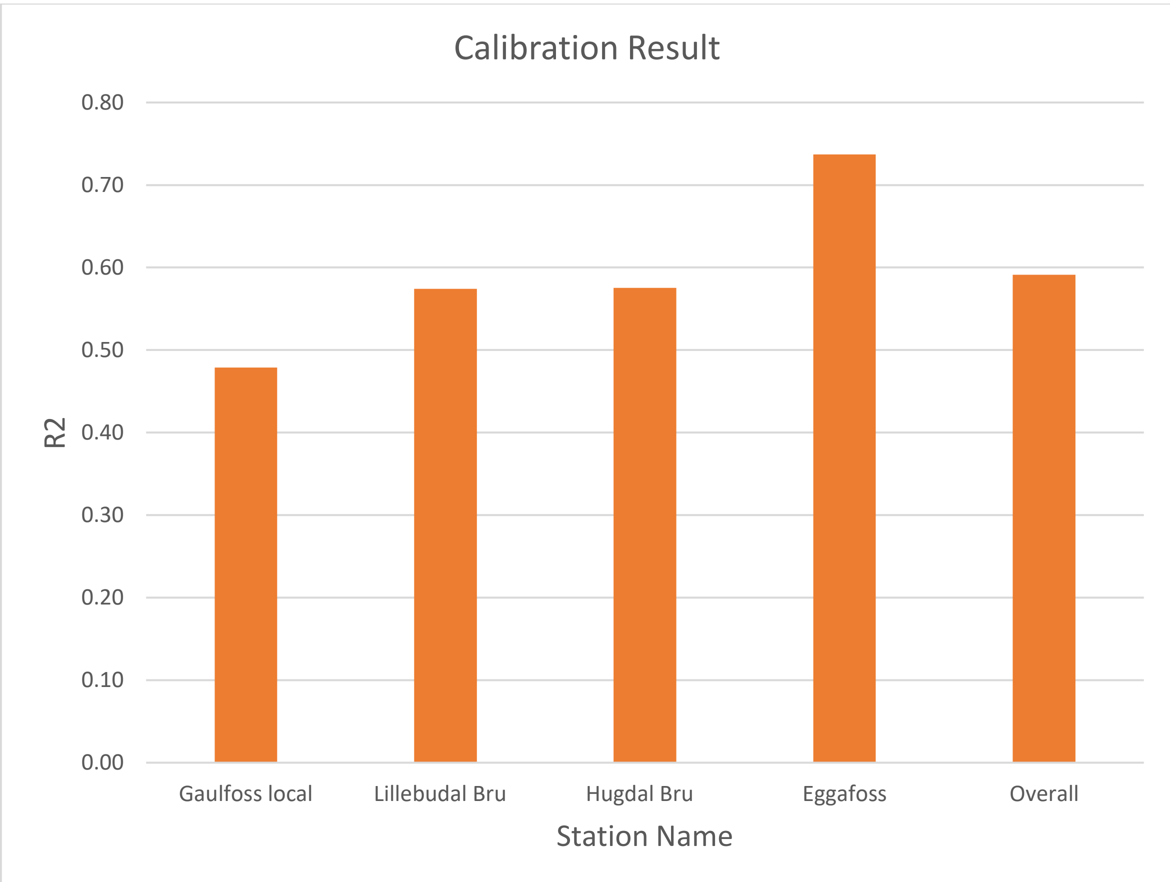


Figure 32 Best overall performance 3

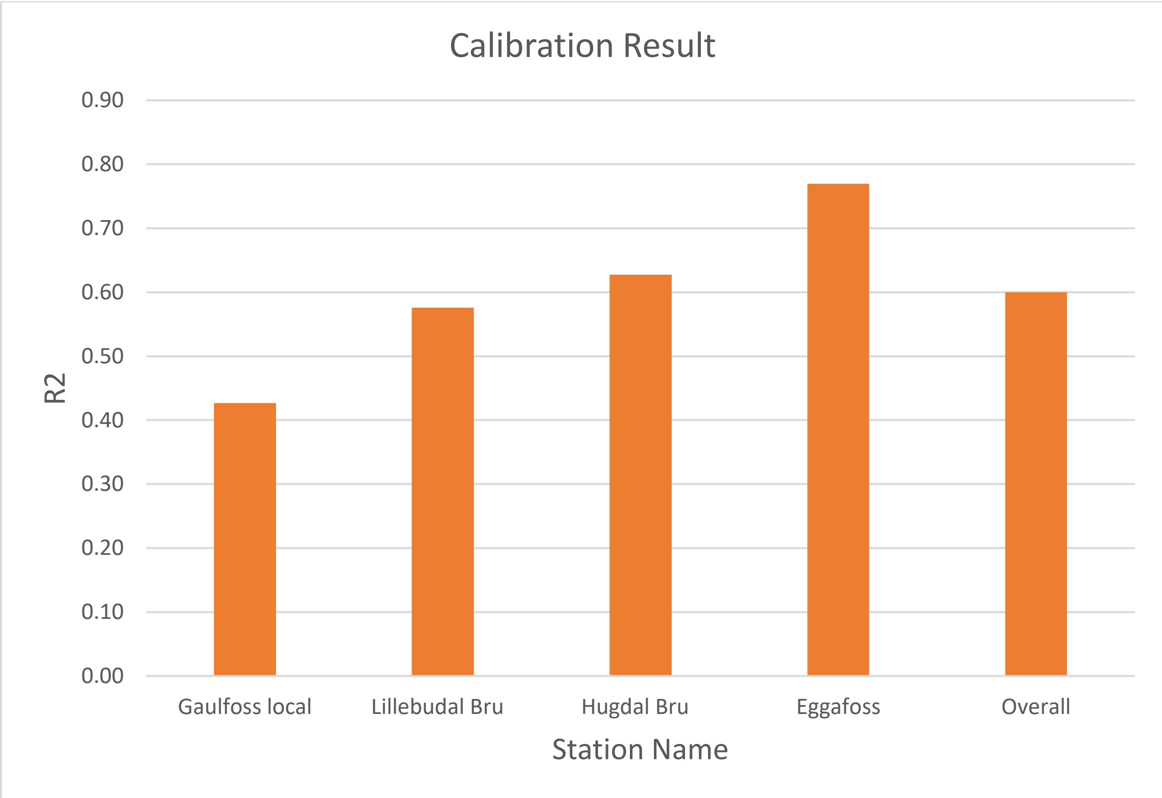


Figure 33 Best overall performance 4

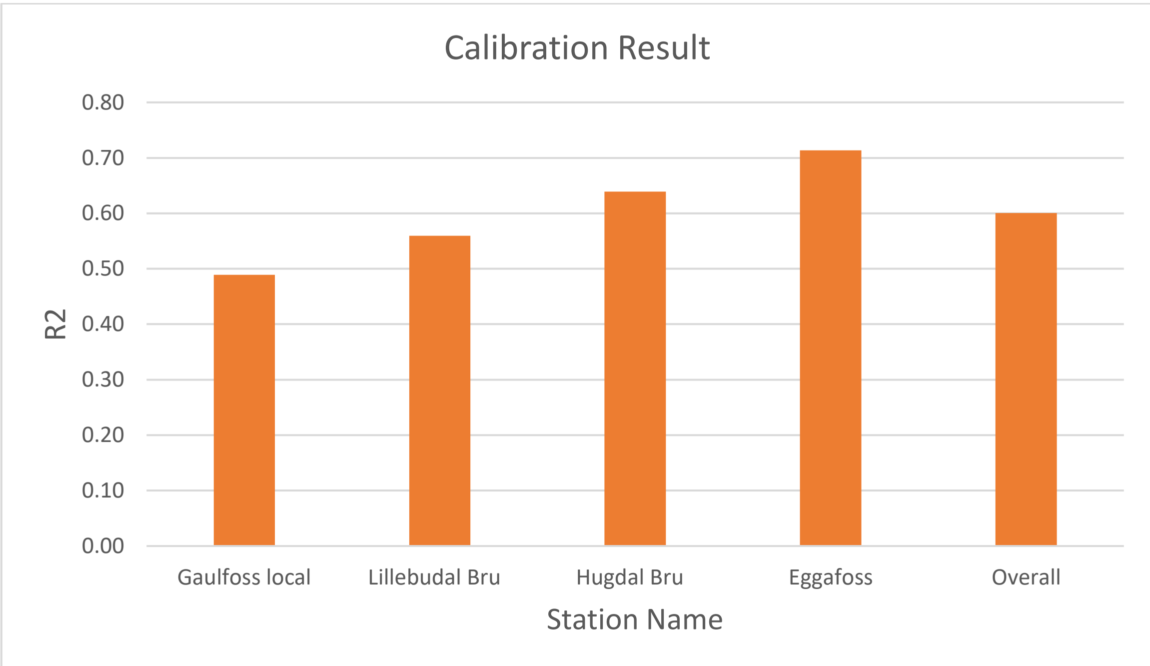


Figure 34 Best overall performance 5

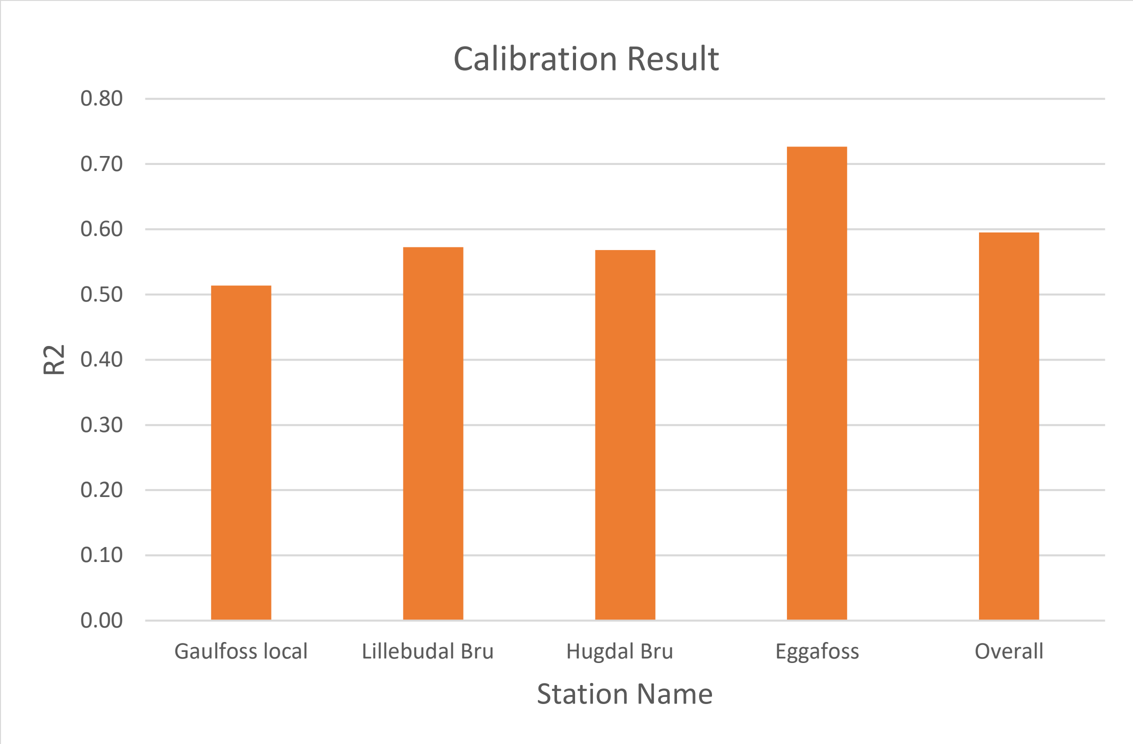


Figure 35 Best overall performance 6

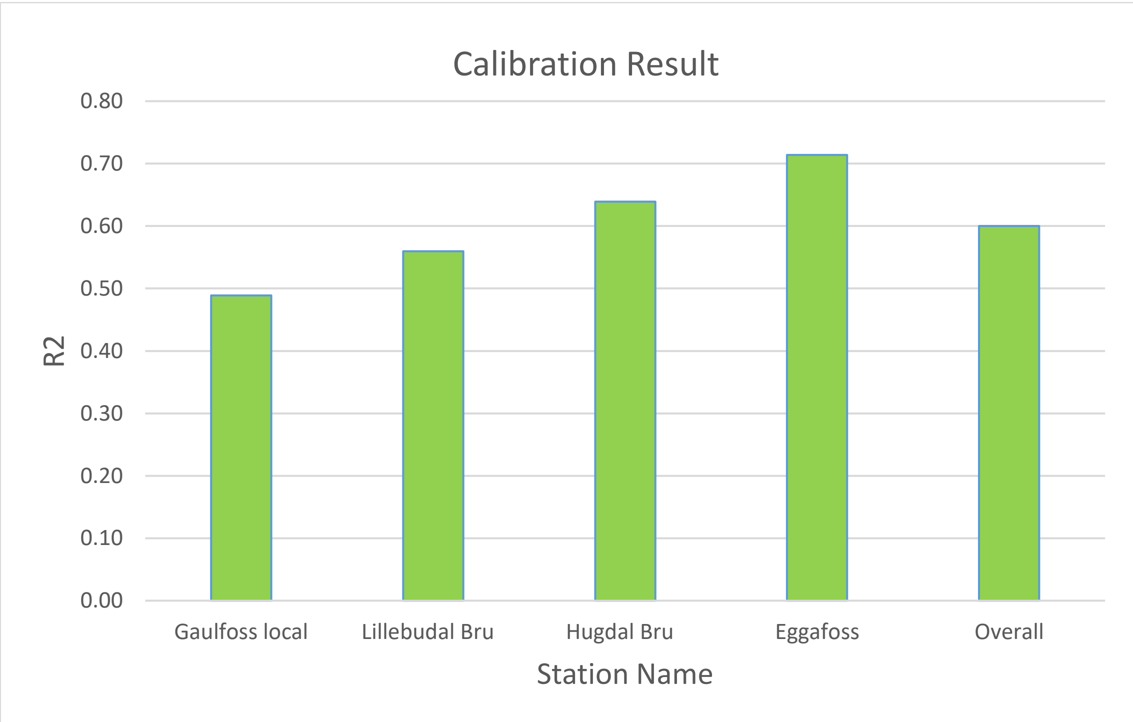


Figure 36 The Best overall performance

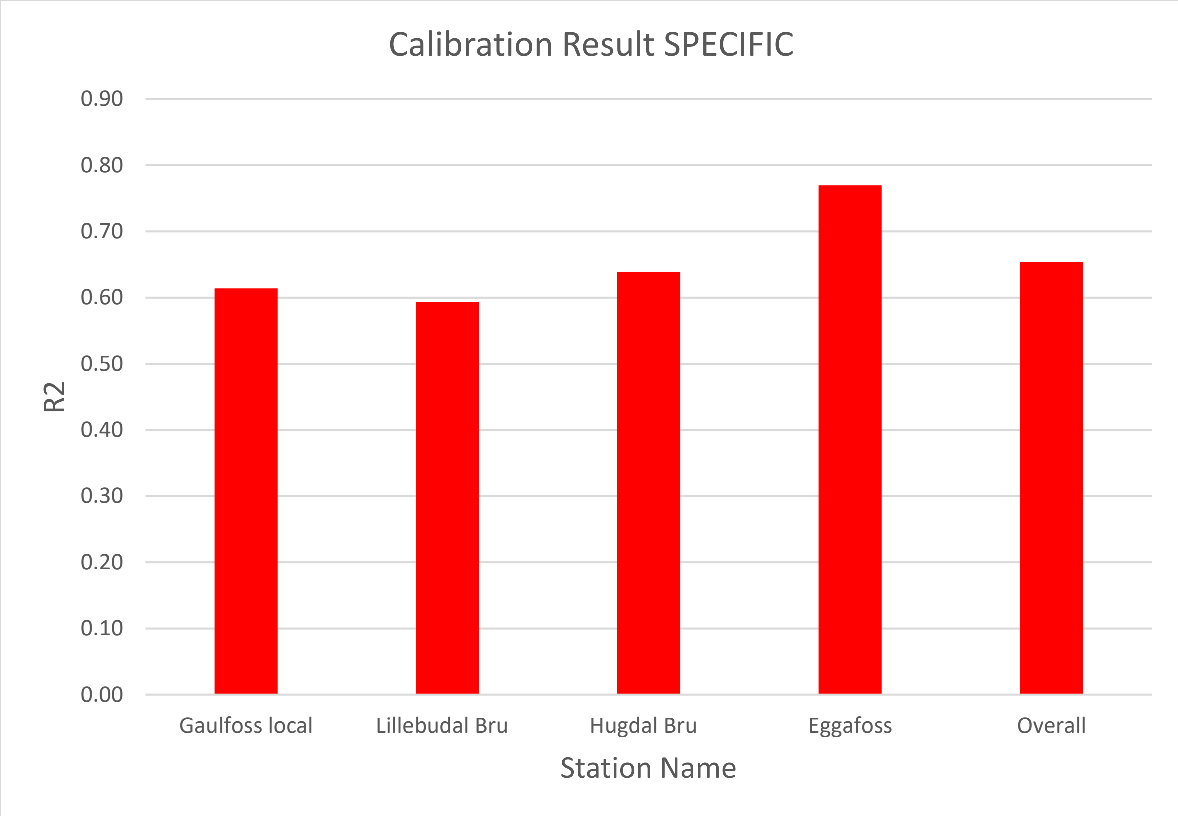


Figure 37 Best catchment specific performance

The best parameter set obtained in shown below:

Table 17 Best parameter set obtained

Parameters	Calibration figure
TX	-0.966583
PcorrRain	1.01711
PcorrSnow	1.04171
Windscale	4.61534
Windconst	1.3285
MaxLWC	0.154919
FastDecayRate	8.59831
SlowDecayRate	27.0679
ResetSnowDepth	37.4464
landalbedo	0.344192
PT_alpha	1.14947
fieldcap	292.924
LP	0.711944
BETA	2.18939

k2	3.54853
k1	0.631231
k0	0.17118
perc	9.76903
Rtreshold	43.3487

The following hydrographs are plotted by ENKI after the best calibration has achieved, by the right side of the operation interface one can find the button. The following one is the four simulated runoff series in one plot.

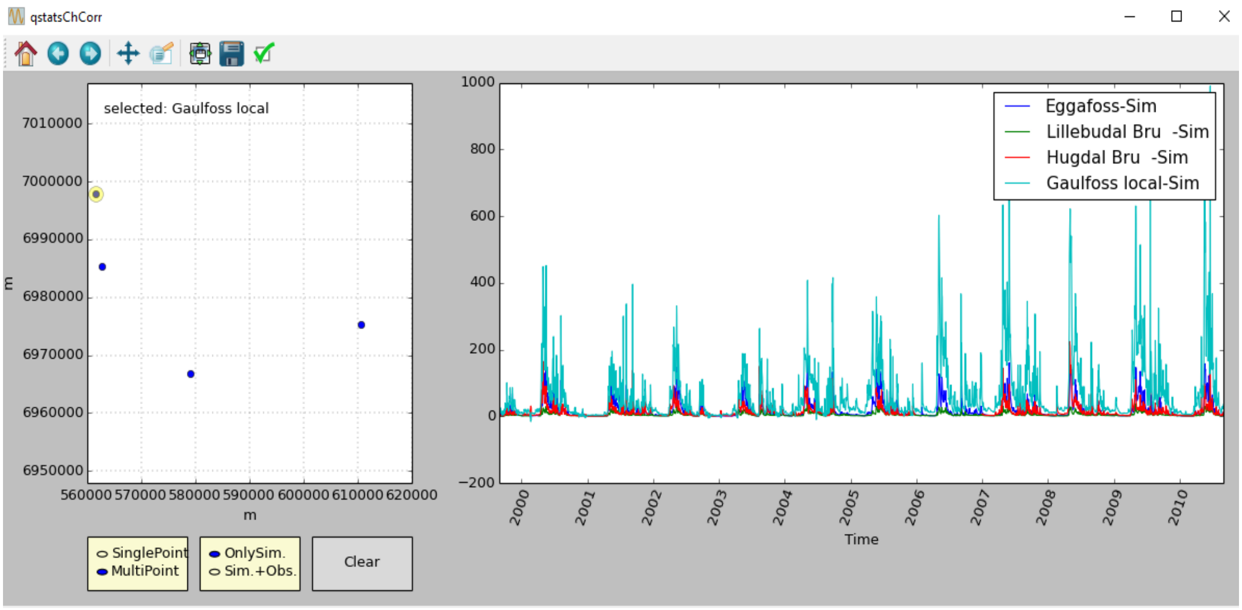


Figure 38 The four simulated runoff data series plotted by ENKI

The following ones are the separated ones plotted in separated axis which contains observed data and simulated data at the same time from each station. One has to note that these plots can be easily compared since there are four plots corresponding to each best specific catchment performance.

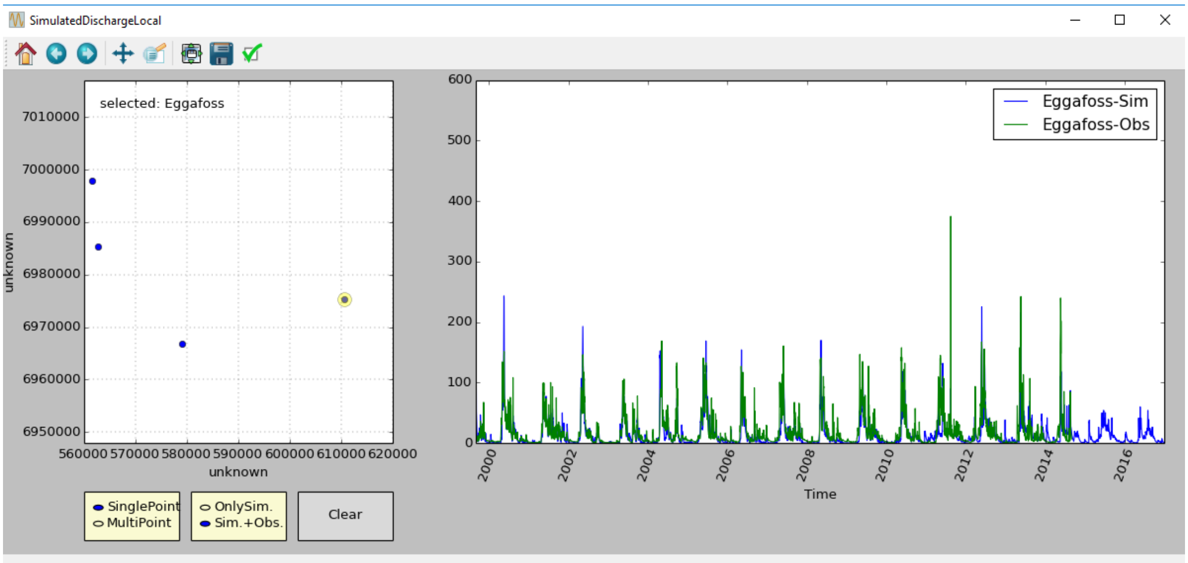


Figure 39 Eggafoss – observed v.s. simulated under Eggafoss specific best performance

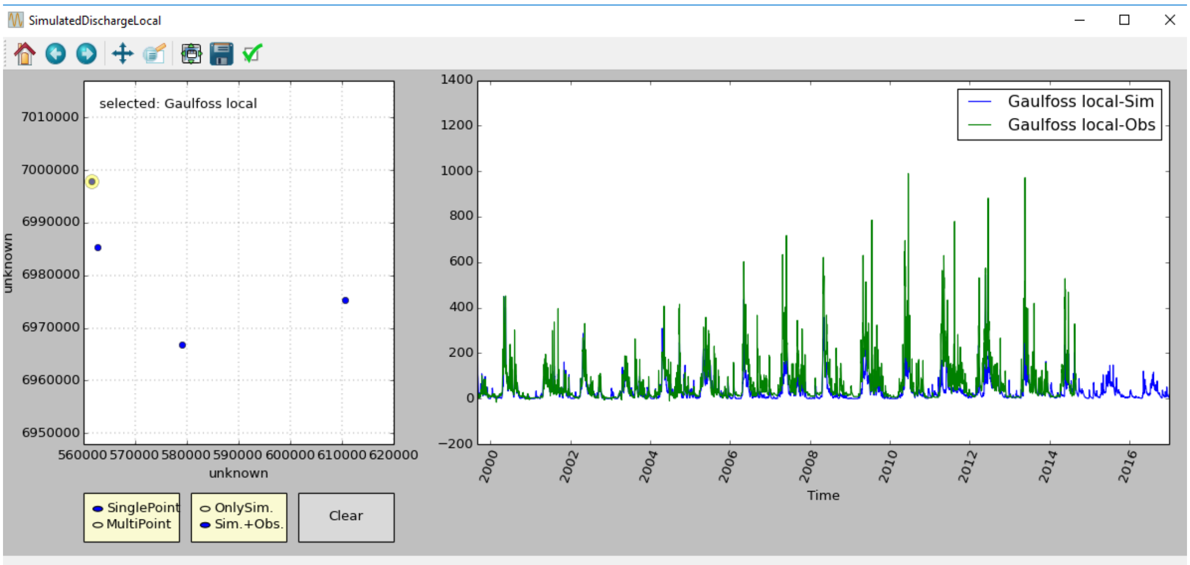


Figure 40 Gaulfoss – observed v.s. simulated under Eggafoss specific best performance

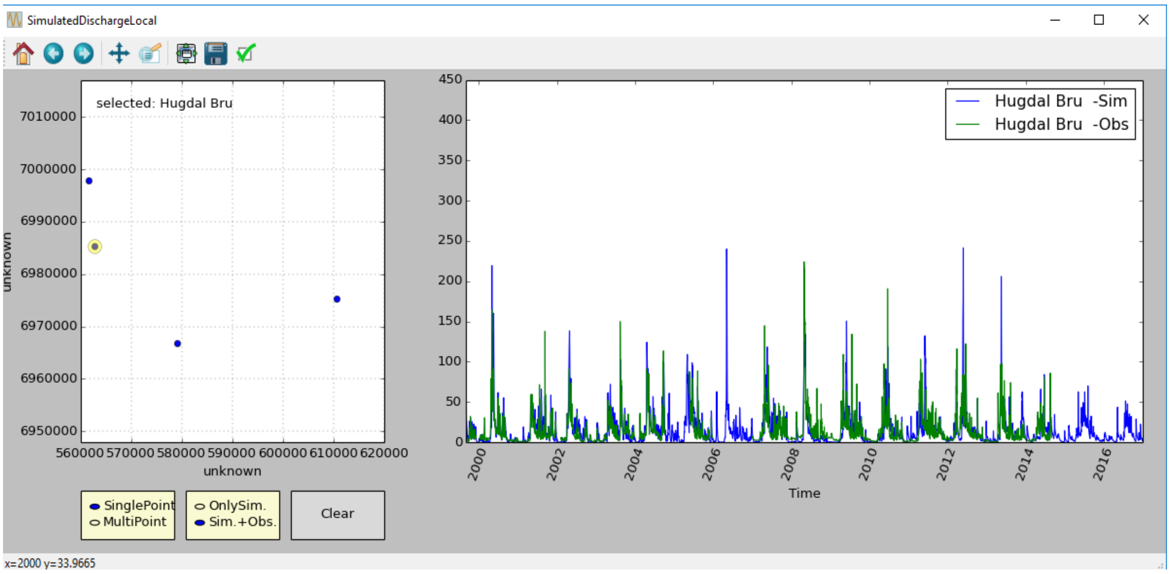


Figure 41 Hugdal Bru – observed v.s. simulated under Eggafoss specific best performance

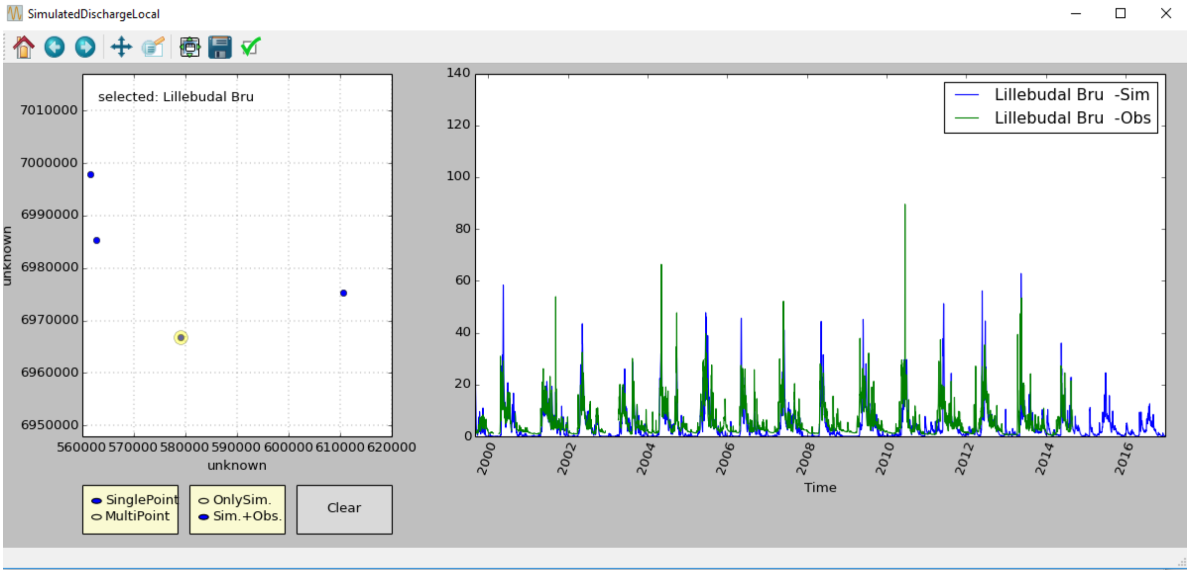


Figure 42 Lillebudal Bru – observed v.s. simulated under Eggafoss specific best performance

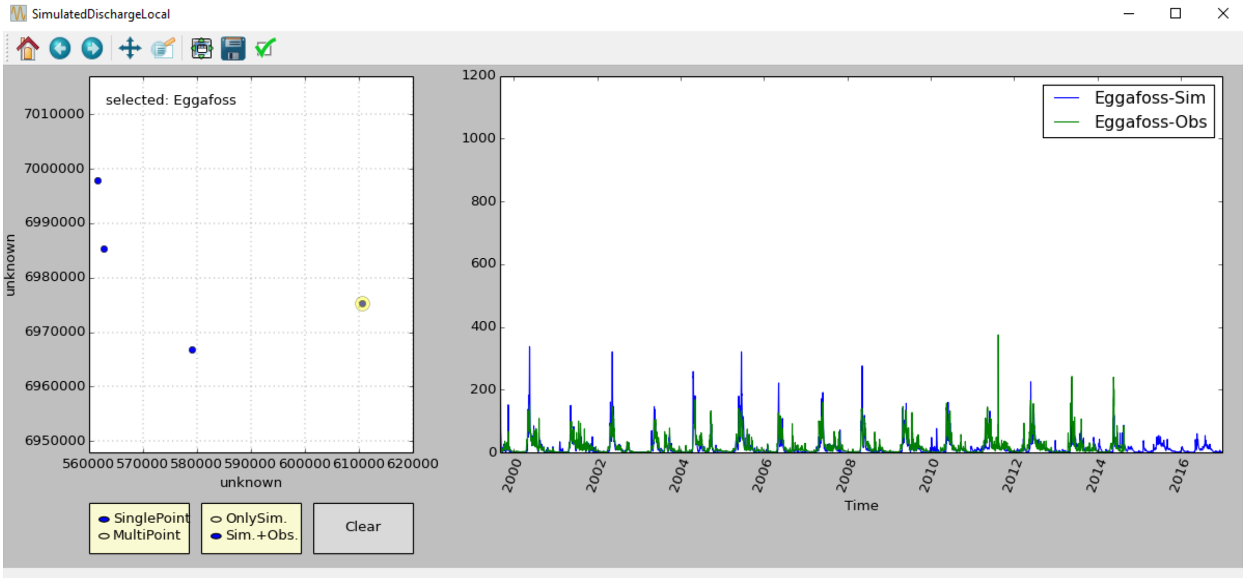


Figure 43 Eggafoss – observed v.s. simulated under Gaulfoss specific best performance

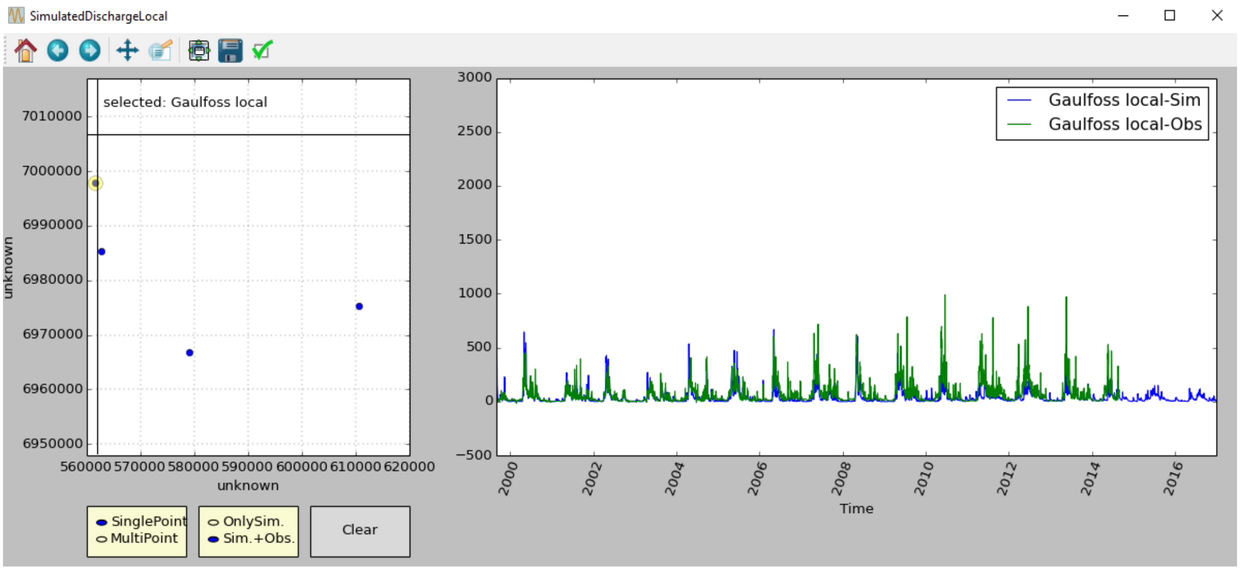


Figure 44 Gaulfoss – observed v.s. simulated under Gaulfoss specific best performance

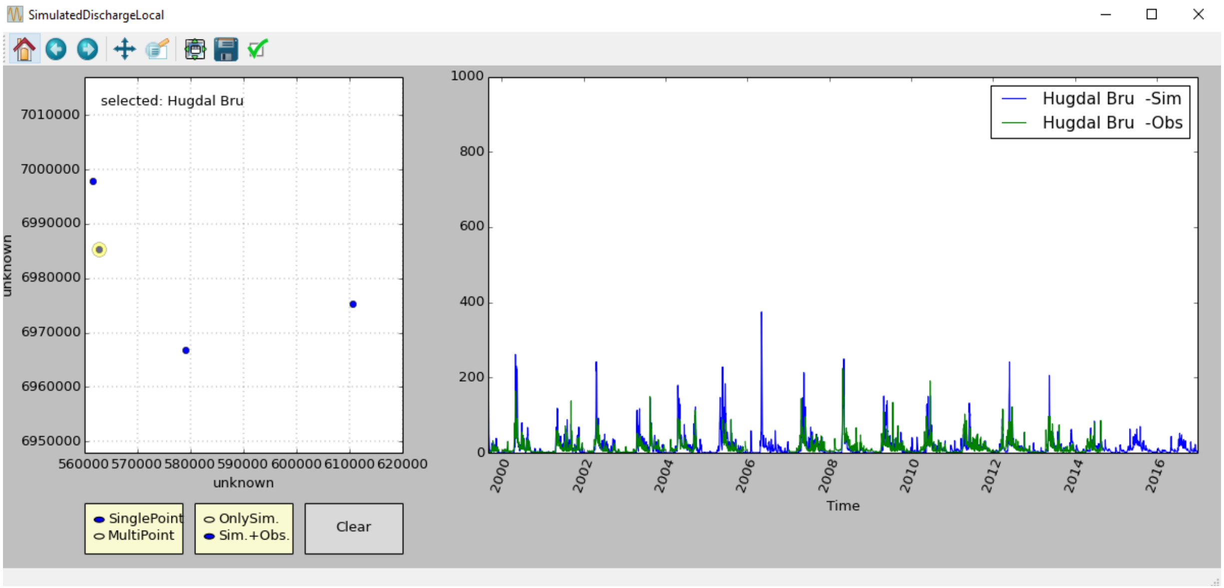


Figure 45 Hugdal Bru – observed v.s. simulated under Gaulfoss specific best performance

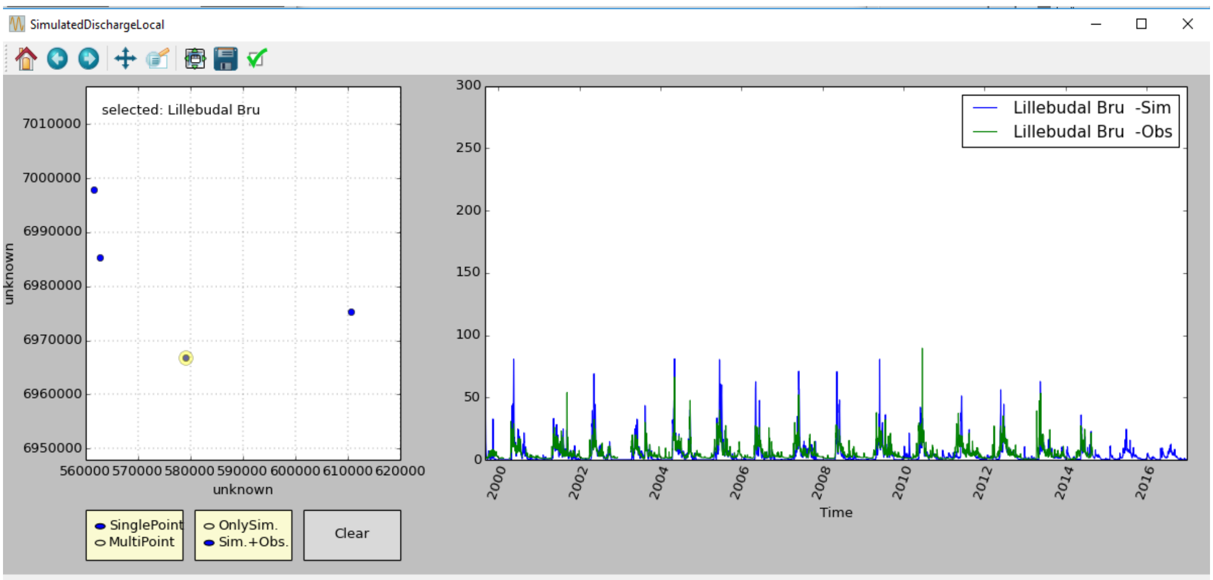


Figure 46 Lillebudal Bru – observed v.s. simulated under Gaulfoss specific best performance

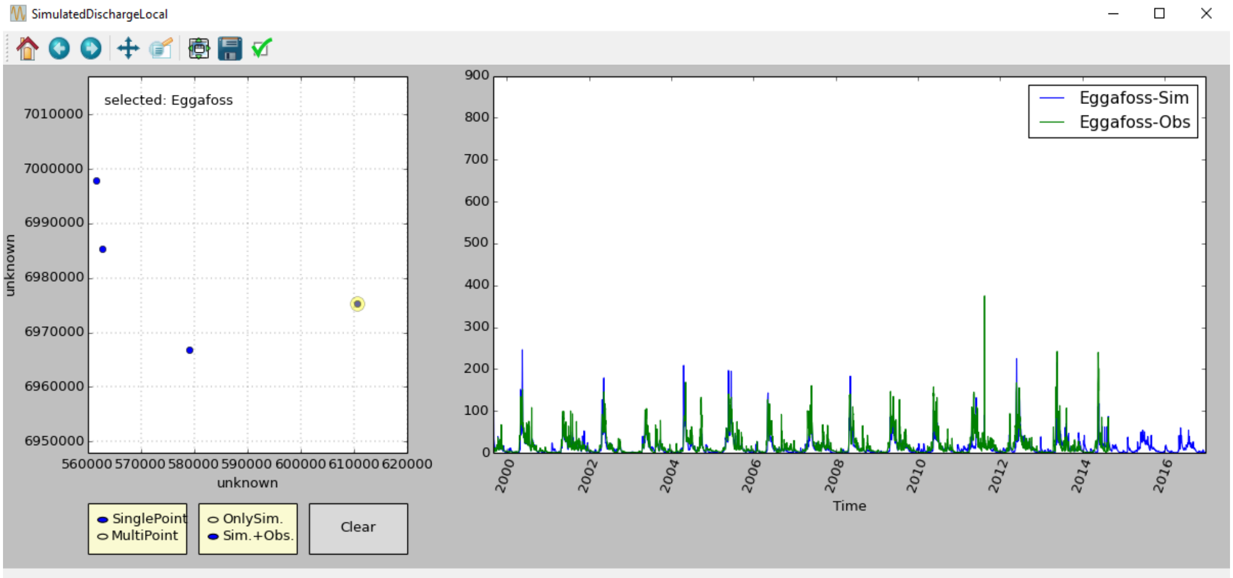


Figure 47 Eggafoss – observed v.s. simulated under Hugdal Bru specific best performance

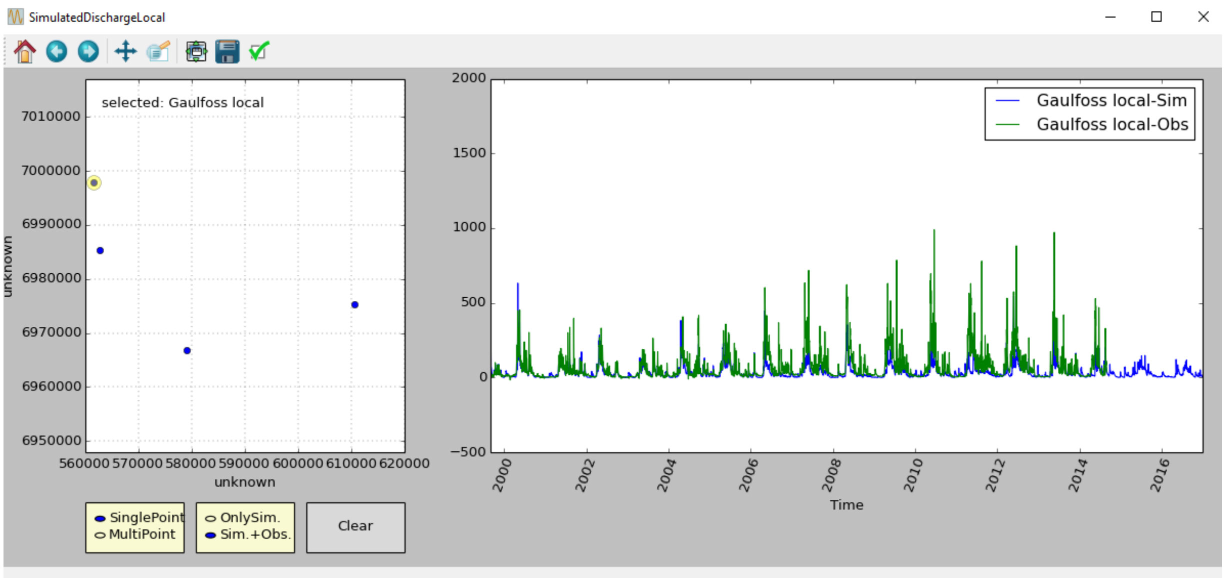


Figure 48 Gaulfoss – observed v.s. simulated under Hugdal Bru specific best performance

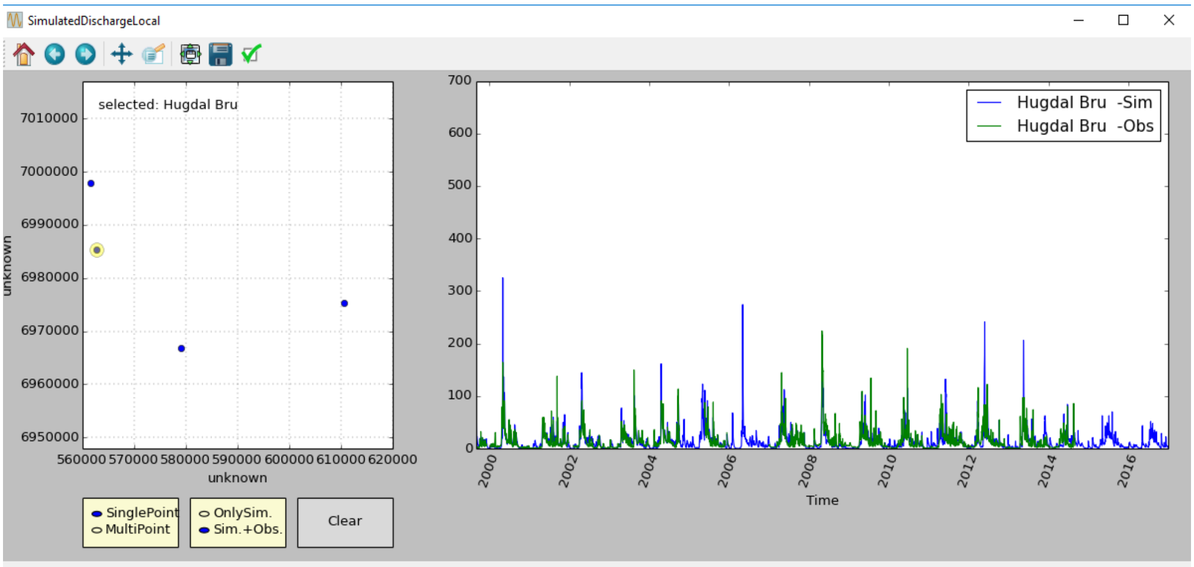


Figure 49 Hugdal Bru – observed v.s. simulated under Hugdal Bru specific best performance

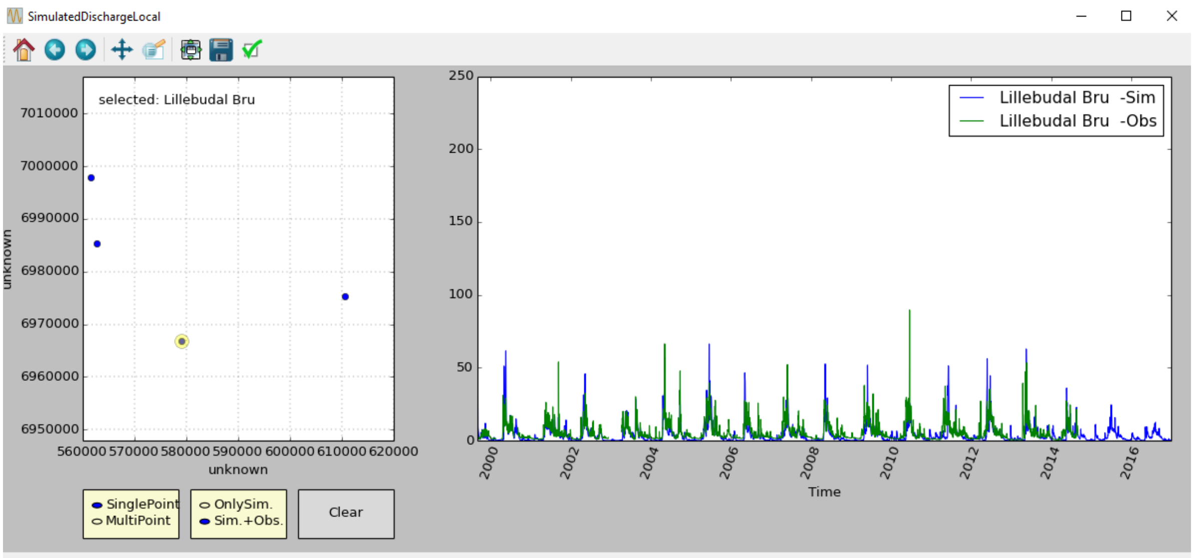


Figure 50 Lillebudal Bru – observed v.s. simulated under Hugdal Bru specific best performance

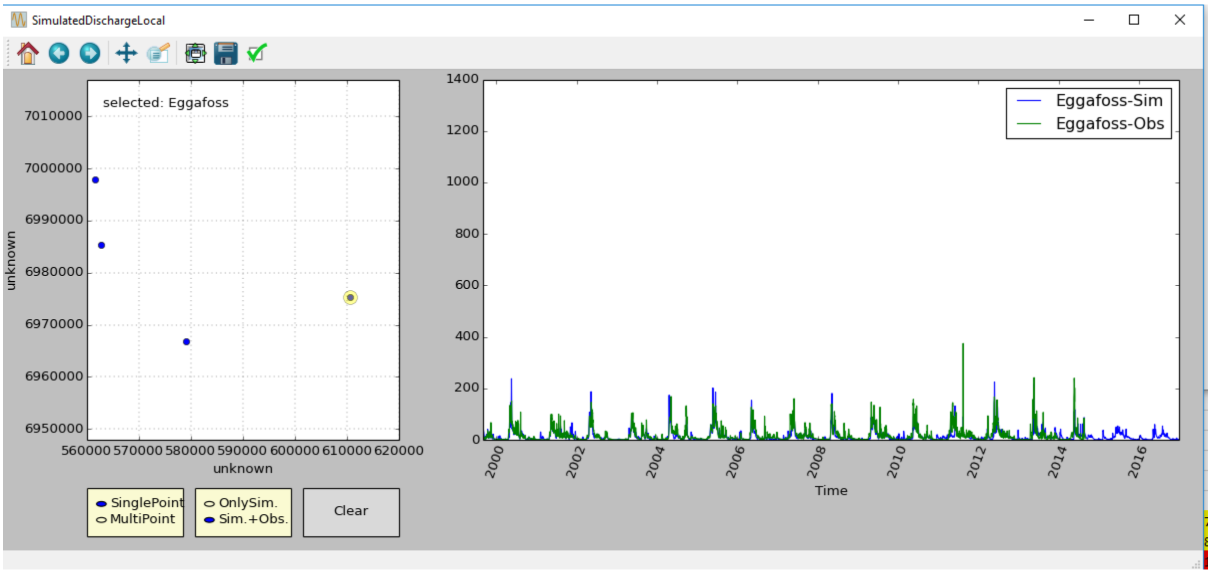


Figure 51 Eggafoss – observed v.s. simulated under Lillebudal Bru specific best performance

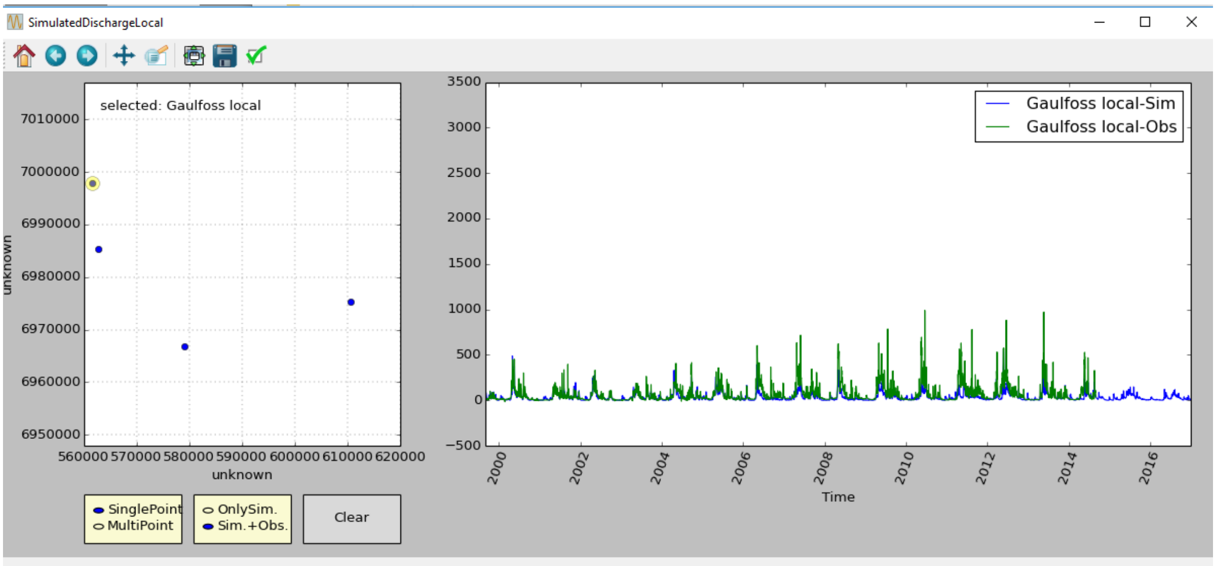


Figure 52 Gaulfoss – observed v.s. simulated under Lillebudal Bru specific best performance

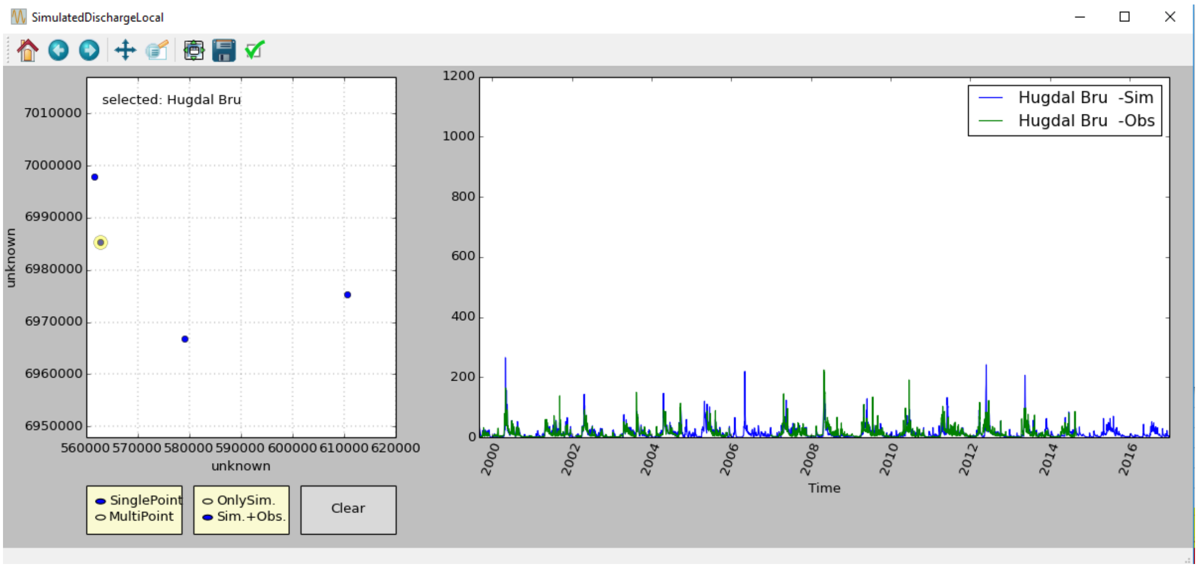


Figure 53 Hugdal bru – observed v.s. simulated under Lillebudal Bru specific best performance

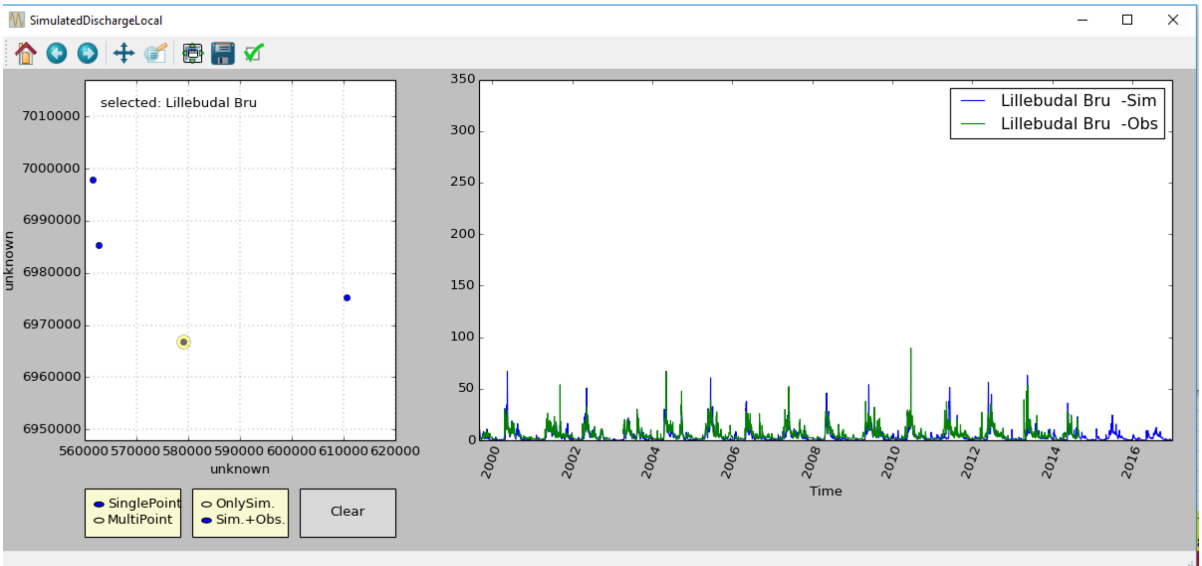


Figure 54 Lillebudal – observed v.s. simulated under Lillebudal Bru specific best performance

It is easy to find that by the beginning of the plot, even if the best performance corresponding to the best scenario, it is a bit too big, since the first year is used here for warm up, so when plot the hydrograph to compare the simulation and observation, it is suggested to omit the warmup period which may give a wrong understanding of the performance of the model.

Once the calibration process is finished, it is found that even though the general performance is not so satisfactory, still the simulation behaves well in catching the peaks which means it is profitable to carry on the flood analysis with the model generated runoff series, still the observation data series can be applied to compared the result obtained from both data.

But here I chose to carry out manual calibration as well since there still should be room to improve a bit in fitting the patterns of observed data for simulation. More manual calibration was finished until the peak are more precisely caught while the overall performance does not change much. PcorrRain, PcorrSnow, CX and the different k, k_1 and k_2 all have effect of the model's peak performance. For each of the parameters, in principle, it is operatable to find the most suitable one but the combination for all the parameter can be infinitive, for example, I found for PcorrRain when it is set for 1.2 all the other conditions stay the same as indicate for the best scenario, this gives the best performance, but if there is a slight change in PcorrSnow for example, if it is testified that PcorrSnow is also at its best performance point, the overlapping "best" does not give you an overall best output.

After calibration, the model needs to be validated for the rest data in the coming years. Validation does not give a good result like calibration did, but in my case, the drop from calibration to calibration is bit higher than I expected. The final overall performance gives a validation R^2 of 0.42, and the corresponding result of Gaulfoss, lillebudal Bru, Hugdal Bru and Eggafoss are respectively 0.5, 0.3, 0.2 and 0.65. I consulted several references and re-ran the calibration for many more times, but it still did not give a better result. So I decided to carry on to the flood frequency analysis part since I do not have enough time. This problem would be discussed in the conclusion and recommendation part.

5.3 RESULT OF FLOOD FREQUENCY ANALYSIS AND COMPARISON OF TATAL AREA AND SUB-CATCHMENTS UPSTREAM

Based on the observed and simulated data, Gumbel Distribution is used to analyze flood in this region both the overall region and the other two upstream catchment are also analyzed. As mentioned before, flood frequency analysis can either calculate the magnitude of the flood event when a return period is given, or to calculate the return period with a certain magnitude of a flood event. Annual peak flow is picked for the analysis. In the analysis, both the observed discharge and simulated discharge are analyzed compared. A data series from 2000 to 2010 is used while analyzing since the calibration performance is much better than the validation data for the total area and the two separated sub-catchments. While the overall analysis is also carried out with the full length of data shown later.

Gumbel distribution can be fit by the equations below:

$$Q_T= Q_{av} + K\sigma \qquad (24)$$

Where Q_T denotes the magnitude of a T-year flood event
K denotes frequency factor
Q_{av} denotes mean flow
σ denotes the standard deviation of maximum instantaneous flows

The frequency factor can be expressed as

$$K=-\sqrt{6}/\pi(\lambda-\ln(\ln(T-\ln(T-1))) \qquad (25)$$

Where π =3.14
λ denotes Euler Constant which equals 0.5772
T denotes return period

The result is shown below:
The blue dots is based on existing data (either observation or simulation in this case), the orange line is based on theoretical calculation with Gumbel Method.

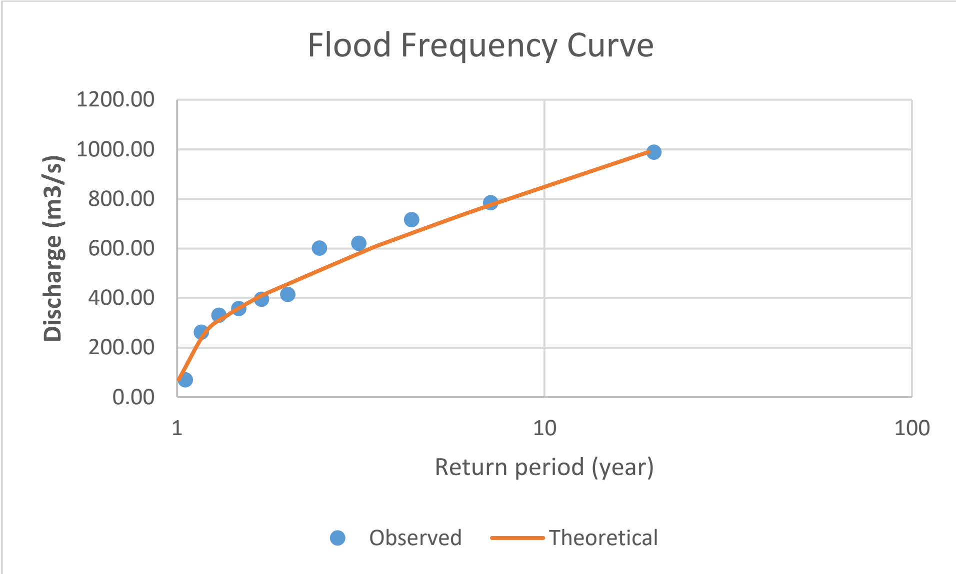


Figure 55 Gaulfoss flood frequency analysis based on observation

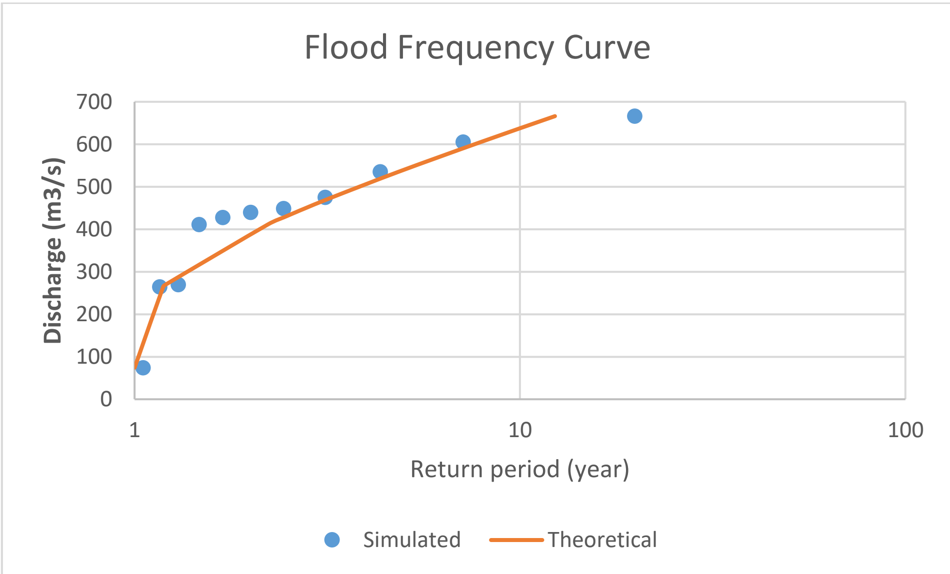


Figure 56 Gaulfoss flood frequency analysis based on simulation

The result of the analysis indicates that the match degree between the flood frequency analysis of Gaulfoss is 80%.

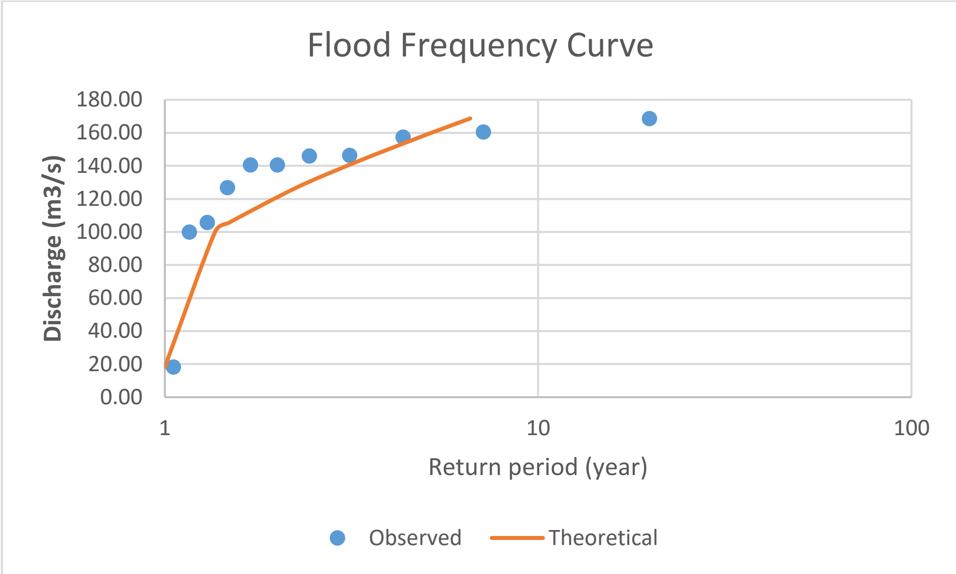


Figure 57 Eggafoss flood frequency analysis based on observation

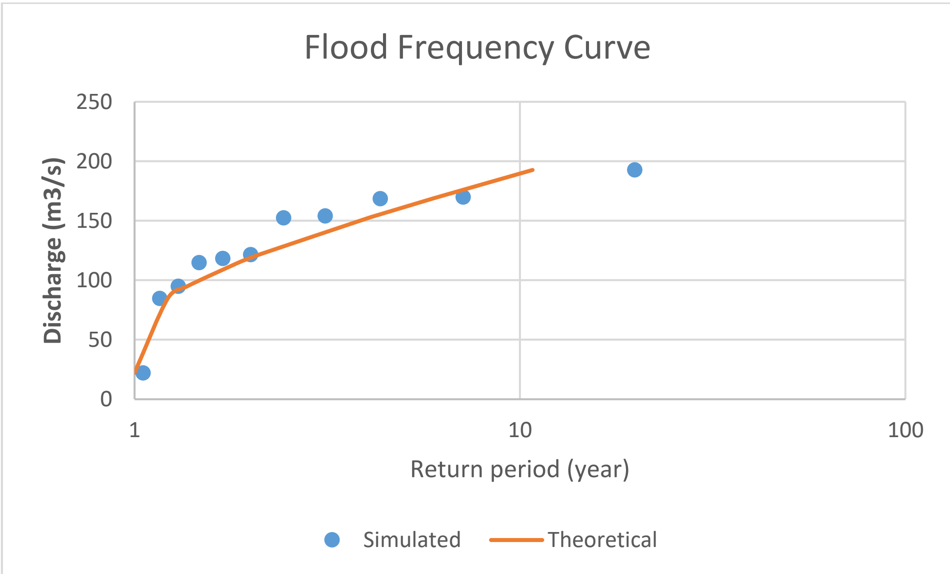


Figure 58 Eggafoss flood frequency analysis based on simulation

The result of the analysis indicates that the match degree between the flood frequency analysis of Eggafoss is quite good which is more than 95%.

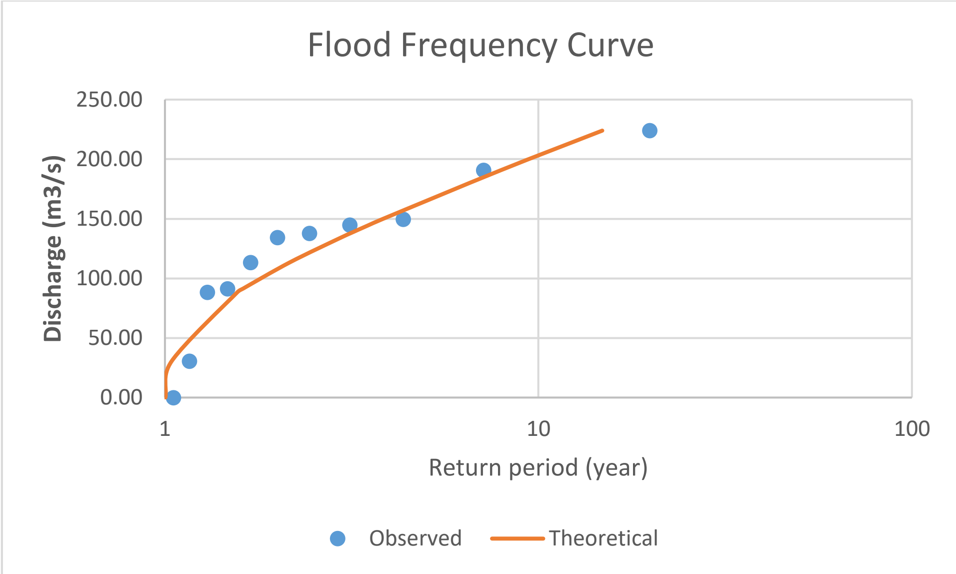


Figure 59 Hugdal Bru flood frequency analysis based on observation

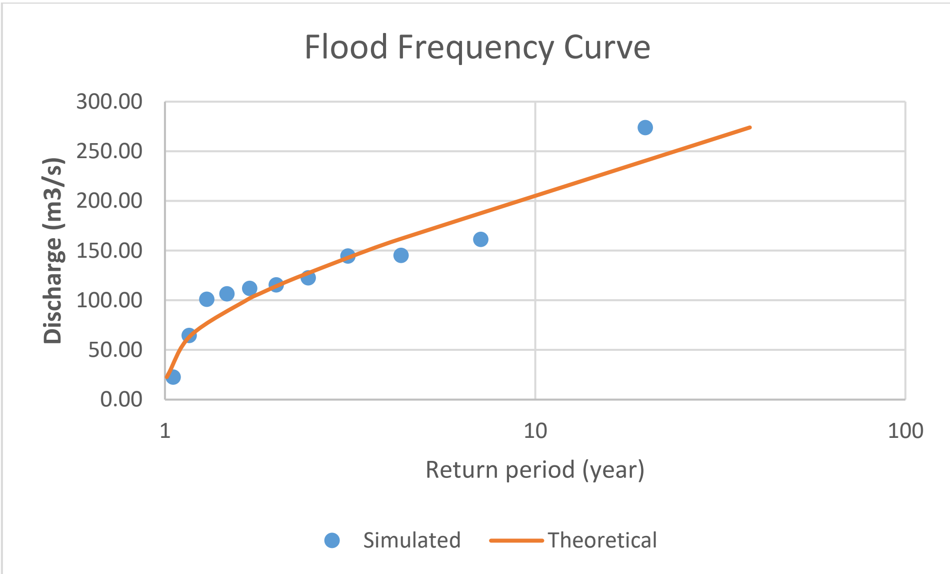
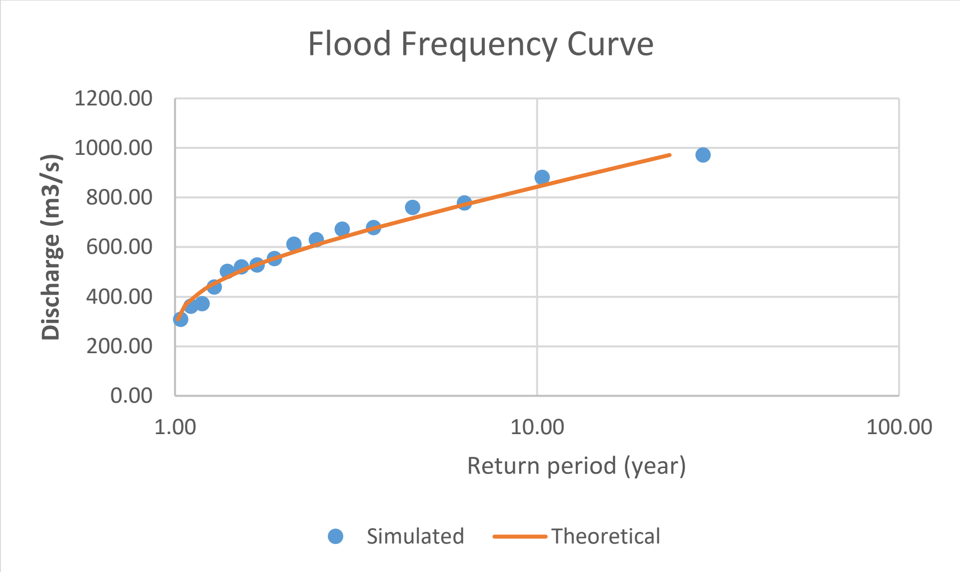


Figure 60 Hugdal Bru flood frequency analysis based on simulation

The result of the analysis indicates that the match degree between the flood frequency analysis of Hugdal Bru is also quite good which is more than 95%.

So it can be concluded that the performance of this extreme value distribution method (Gumbel Method) is quit applicable when analyzing the small catchment with a small peak and shorter return period. This makes sense as it is revealed in the literature review that the short return period, the more accurate the result would be.

Though the validation did not give very impressive results as one can imagine, still I have the data series, so the flood frequency analysis is carried out to extend the data series. The result is shown below:



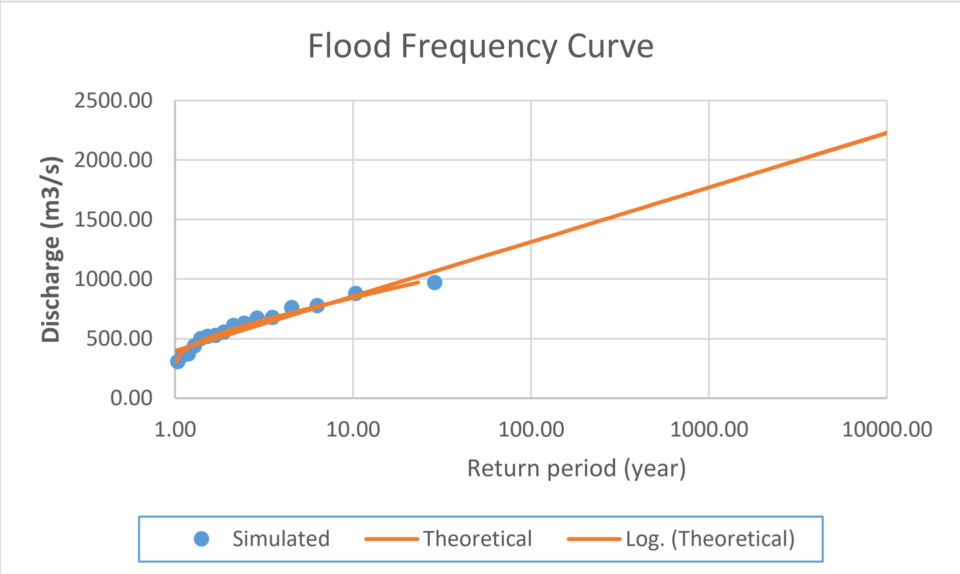


Figure 61 Flood frequency analysis for the whole catchment after data extension

From the curve above, one can find that the blue dots give a good "simulation" according to the orange line. This is also one of the advantages of Gumbel Method that is seldom overestimates the trend in a long run rather than the normal statistical probability analysis which I also carried out. Due to limited time, I do not have the chance to present it here, but when I submit the work, this would be included in the supplementary documents. One can compare if interested.

6 CONCLUSIONS AND RECOMMENDATIONS

Floods frequency analysis is carried out with the Gumbel Method as the main one in the work. But several methods have been discussed and compared in the previous chapters and the natural hazard of floods in both China and Norway has been presented in a great detailed way to show the importance in carrying out such analysis.

In the Gaula Catchment, data related to ENKI model has been collected and related subroutines have been implemented in the framework. Certain setup, calibration and validation have been operated though the results are not so satisfactory. One of the possibilities is the data quality, in Norway I suppose it is already one of the best countries in keeping and retrieving data regarding these issues. Still uncertainties exist in restoring, transferring etc.. Though massive data was collected for such a small catchment, but quality is more important the quantity. Since there are lots of data missing for example from the precipitation gauging stations. Then a better and suitable resolution should be applied as well, since my task is to deal with daily data, while I think it may give better result if the monthly data was used but with a longer period, in order to maintain the feature of flood. Scaling data have been done both by myself and by the model itself, but it is in different ways. I would like to have a look and compare the difference between the data fixed by the model itself and the data feed by my fixing. Since I do not have time to do that, I think this can be a further study part.

As for the model, as I discussed with my supervisor, I found the setup can be improved. As discussed in the model part, the model can only understand the sub-catchment scale and calculate if you have sub-catchment inside a big one and both of the two scales existing at the same time in the model. So the Gaulfoss local was extracted where I guess a lot of extra problems are raised. I would like to suggest improving the model setup, so that the Gaulfoss as a whole can be studied and analyzed directly which can bring less problems.

For the map that ENKI can read, is the raster map. While I found that there might be deviation when one transfer shape file to a raster file since shape file is more common and easily to obtain. There exists software in converting the shape file to a raster map, as I can see there are possibilities that the deviation may occur.

As mentioned, Gaula is one of the sorrow rives in Norway even though the salmon production is among the highest, but historically speaking, this river has a long history problem with floods, especially recent years, the frequency increases, so I would like to suggest some further studies should be carried out in such regions which is small in scale but can be affected easily in many ways like the climate change and human activities. More stations should be set also so that the monitoring can be improved which in a way provides solid foundation for model work.

7 REFERENCE

Killingveit, Å., and N. R. Sælthun. "Hydrological models." Hydropower Development 7 (1995): 99-128.

Midttømme, G., Pettersson, L.E., Holmqvist, E., Nøtsund, Ø., Hisdal, H. and Sivertsgård, R. (2011) Retningslinjer for flomberegninger (Guidelines for flood calculations). Retningslinjer no. 04/2011. 59 pp. Available at www.nve.no

Hosking, J.R.M., Wallis, J.R. (1997) Regional frequency analysis: an approach based on L-moments, Cambridge University Press.

Andersen, J.H., Sælthun, N.R., Hjukse, T. and Roald, L. (1983) Hydrologisk modell for flomberegninger, NVE Rapport nr. 2/83.

Sælthun, Nils Roar, et al. "Climate change impact on Norwegian water resources." *NVE publication V42 Norwegian Water Resources and Energy Administration Oslo* (1990).

Madsen, Henrik, Peter F. Rasmussen, and Dan Rosbjerg. "Comparison of annual maximum series and partial duration series methods for modeling extreme hydrologic events: 1. At-site modeling." *Water resources research* 33.4 (1997): 747-757.

Cunnane, C. "Statistical distributions for flood frequency analysis." *Operational Hydrology Report (WMO)* (1989).

Wilson, Donna, et al. "A review of NVE's flood frequency estimation procedures." *NVE Report* (2011): 9-2011.

Hosking, J. R. M. "JR wallis, 1997. Regional frequency analysis: an approach based on L-moments."

Ulén, Barbro. "Concentrations and transport of different forms of phosphorus during snowmelt runoff from an illite clay soil." *Hydrological Processes* 17.4 (2003): 747-758.

Saelthun, N. R., and J. H. Andersen. "New procedures for flood estimation in Norway." *Hydrology Research* 17.4-5 (1986): 217-228.

Cunnane, C. "Factors affecting choice of distribution for flood series." *Hydrological Sciences Journal* 30.1 (1985): 25-36.

Changnon Jr, Stanley A. "Climate fluctuations and impacts: The Illinois case." *Bulletin of the American Meteorological Society* 66.2 (1985): 142-151.

Killingtveit, A. "Flood regimes and flood prevention in Norway: Lessons learnt from the 1995 flood." *Recent trends offloads and their preventive measures* (1996): 57-61.

Kolberg, Sjur, and Oddbjørn Bruland. "An Open Source modular platform for hydrological model implementation." *EGU General Assembly Conference Abstracts*. Vol. 12. 2010.

陈永, and 柏方. "洪水影响的综述." 水科学进展 5.1 (1994): 78-84.

Yongbai, Chen, and Fang Zhiyun. "A Survey of Flood Impact." ADVANCES IN WATER SCIENCE (1994): 01.

于瑞宏, et al. "无测站流域径流预测区域化方法研究进展." 水利学报 47.12 (2016): 1528-1539.

Xiong, L-H., S-L. Guo, and C-J. Wang. "Advance in regional flood frequency analysis from abroad." Advances in Water Science 15.2 (2004): 260-267.

熊立华, 郭生练, and 王才君. "国外区域洪水频率分析方法研究进展." 水科学进展 15.2 (2004): 261-267.

张建云. "中国水文预报技术发展的回顾与思考." 水科学进展 21.4 (2010): 435-443.

Zhang, Jianyun, and Zhiyu Liu. "Hydrological monitoring and flood management in China." IAHS Publications-Series of Proceedings and Reports 305 (2006): 93-102.

Lindström, Göran, et al. "Development and test of the distributed HBV-96 hydrological model." Journal of hydrology 201.1-4 (1997): 272-288.

Lei, Aquije, and Ku Pak Peng. Analysis and modelling of recent large floods on the river Gaula. MS thesis. NTNU, 2015.

Mujere, Never. "Flood frequency analysis using the Gumbel distribution." International Journal on Computer Science and Engineering 3.7 (2011): 2774-2778.

Lobintceva, Ekaterina. Estimating runoff from ungauged catchments using regional modelling. MS thesis. Institutt for vann-og miljøteknikk, 2014.

http://streamflow.engr.oregonstate.edu/analysis/floodfreq/

https://www.slideshare.net/vivek6002/flood-frequency-analyses

https://serc.carleton.edu/hydromodules/steps/168500.html

http://eschooltoday.com/natural-disasters/floods/effects-of-flooding.html

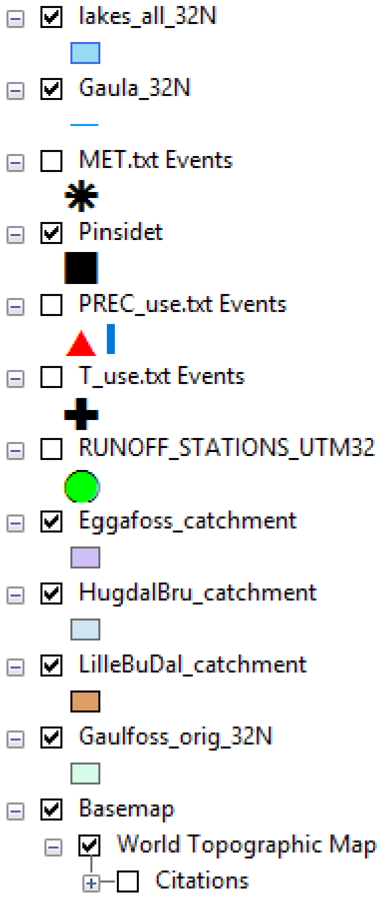
https://en.wikipedia.org/wiki/Norway

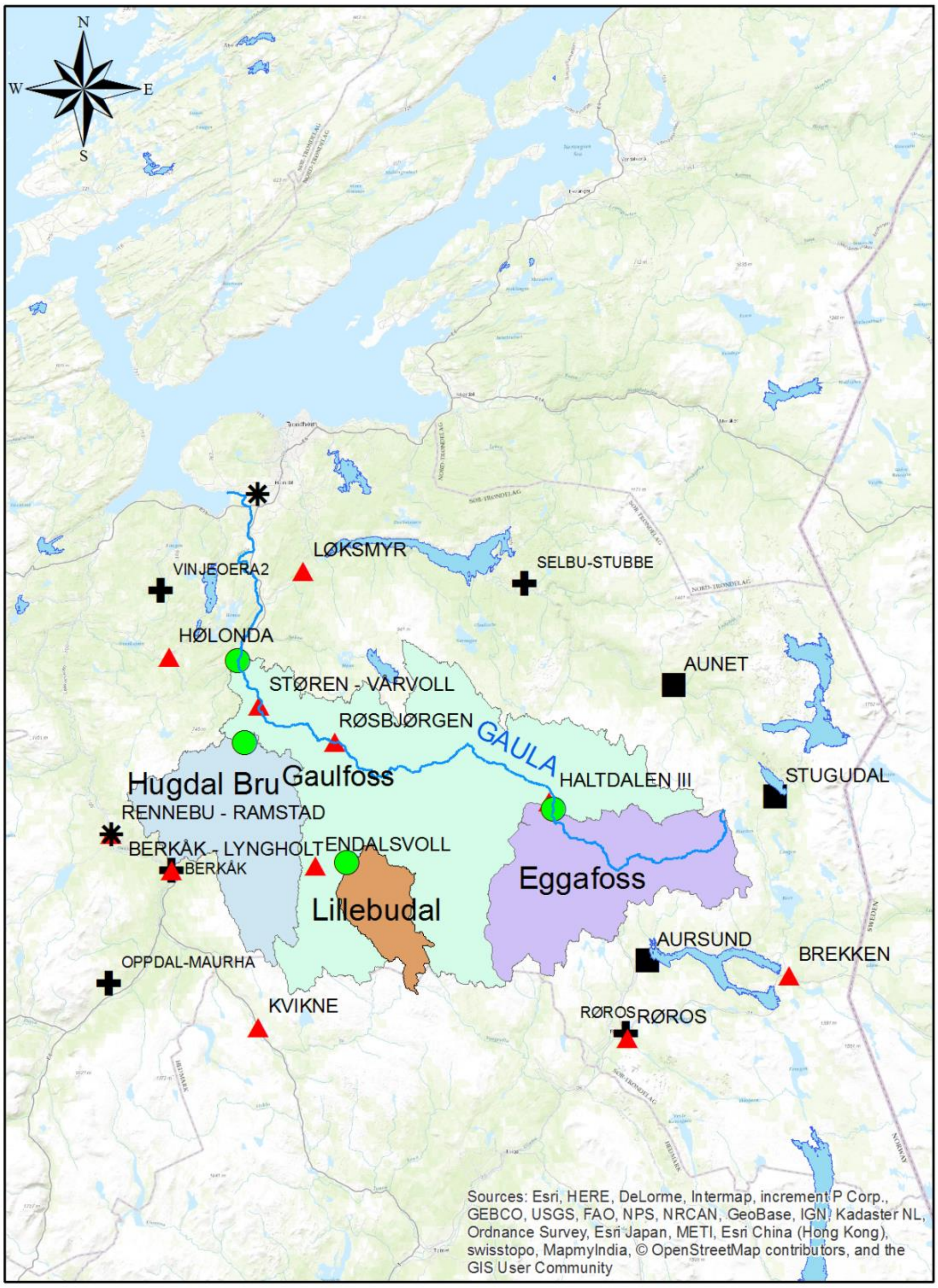
http://presentations.copernicus.org/EGU2012-13630_presentation.pdf

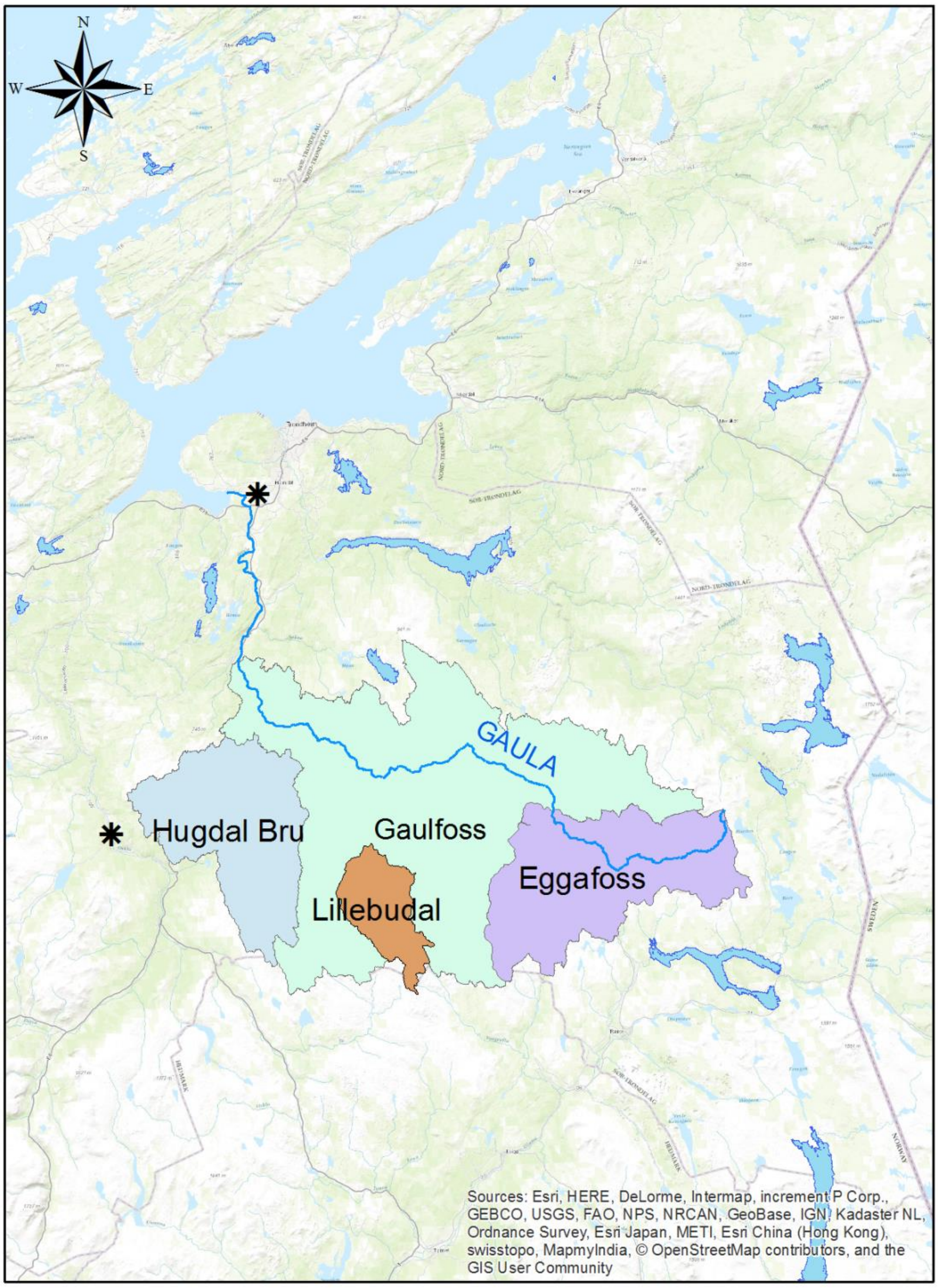
http://cesmma.unical.it/wrf-hydro2014/pdf/Burkhart_ENKI-WRF.pdf

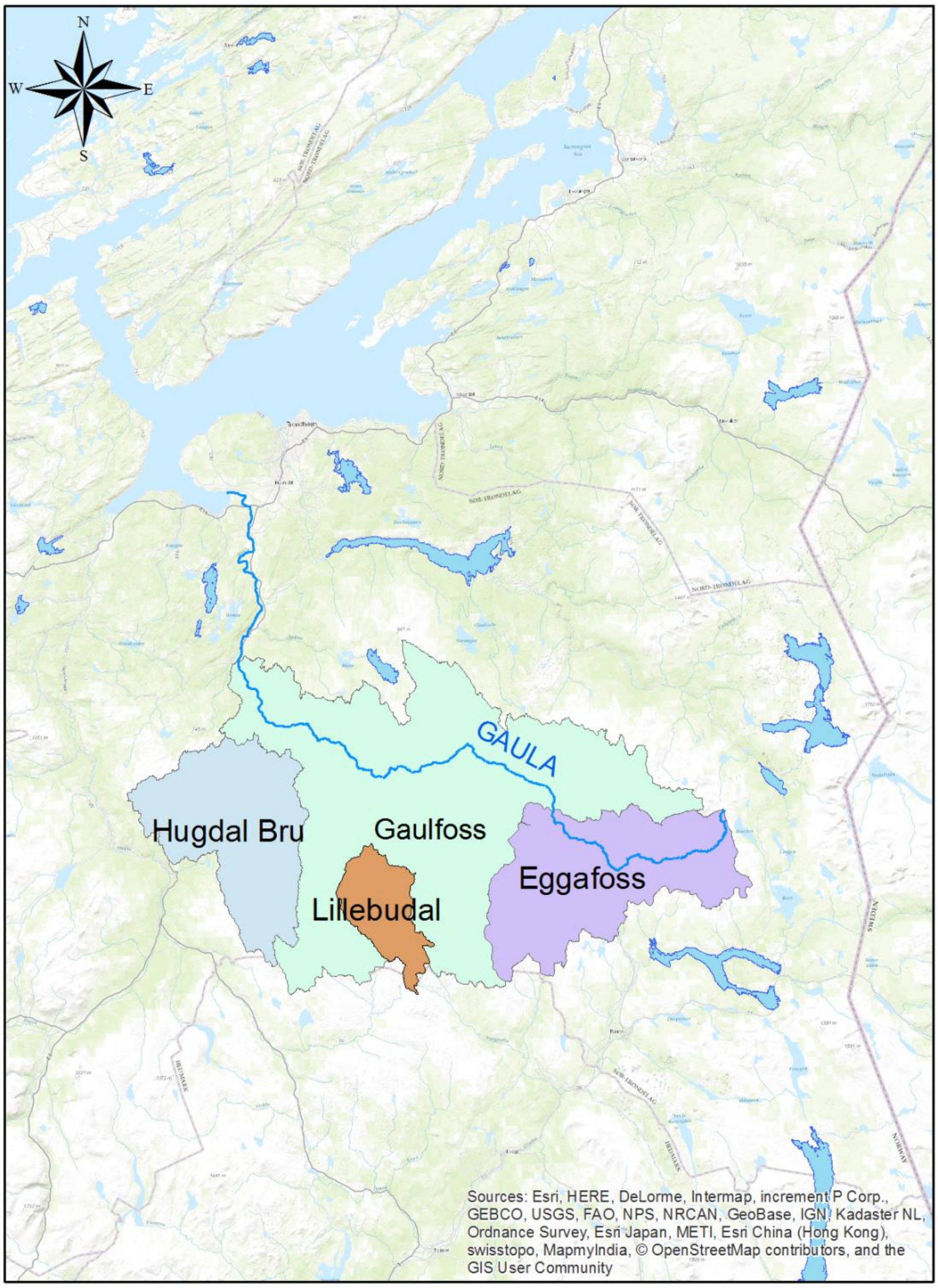
8 APPENDIXES

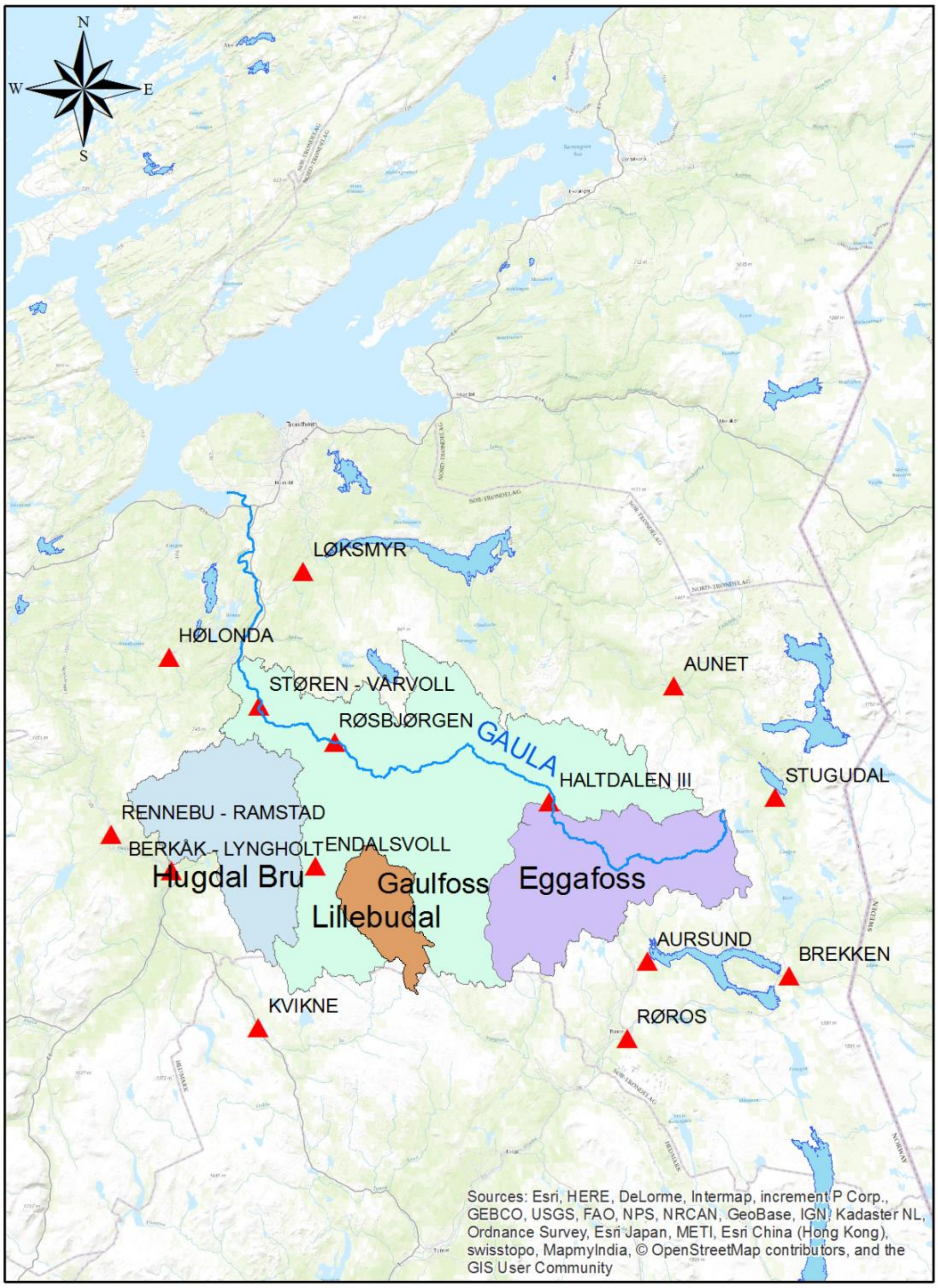
8.1 APPENDIXES A

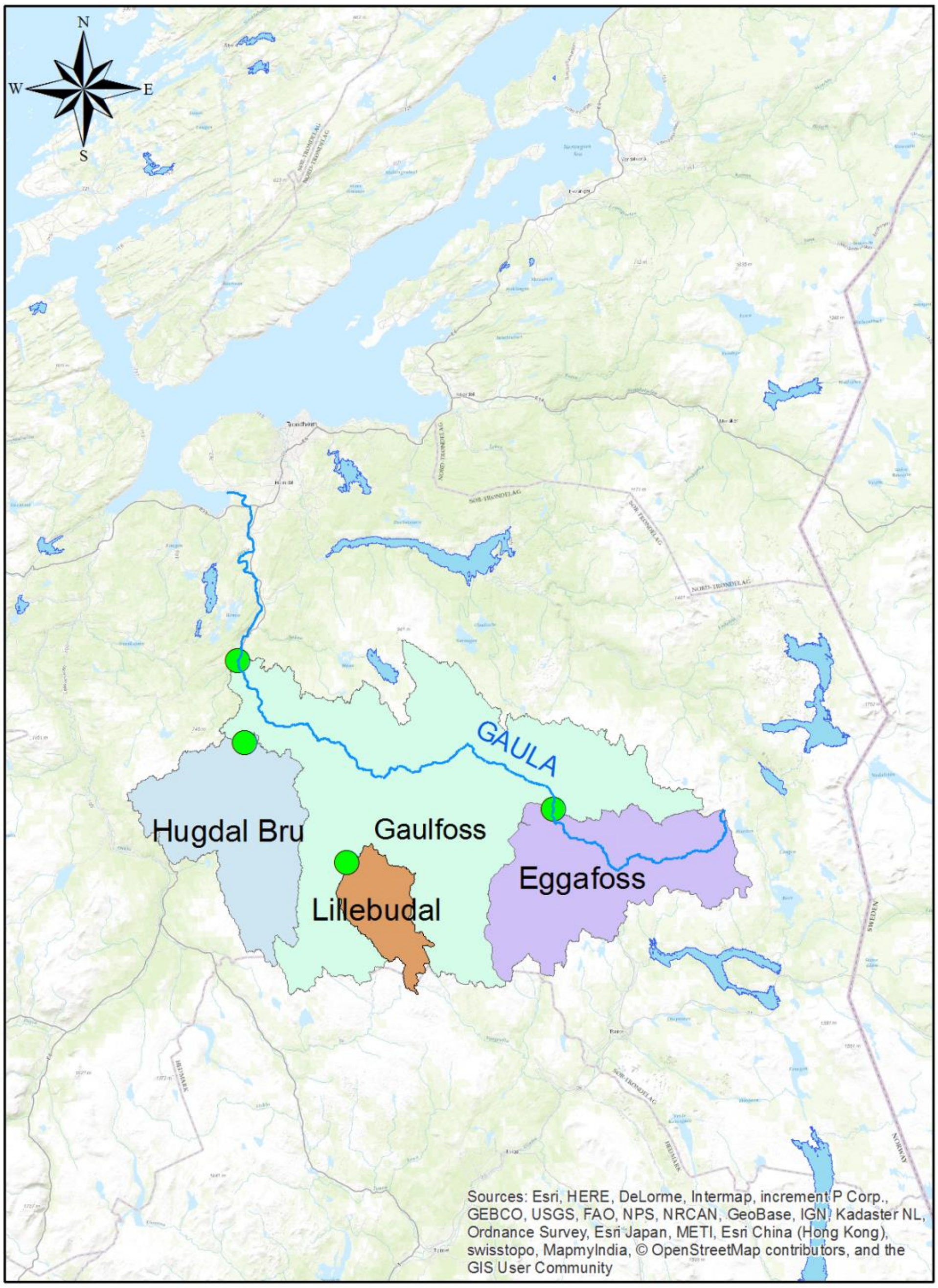

lakes_all_32N
Gaula_32N
MET.txt Events
Pinsidet
PREC_use.txt Events
T_use.txt Events
RUNOFF_STATIONS_UTM32
Eggafoss_catchment
HugdalBru_catchment
LilleBuDal_catchment
Gaulfoss_orig_32N
Basemap
World Topographic Map
Citations

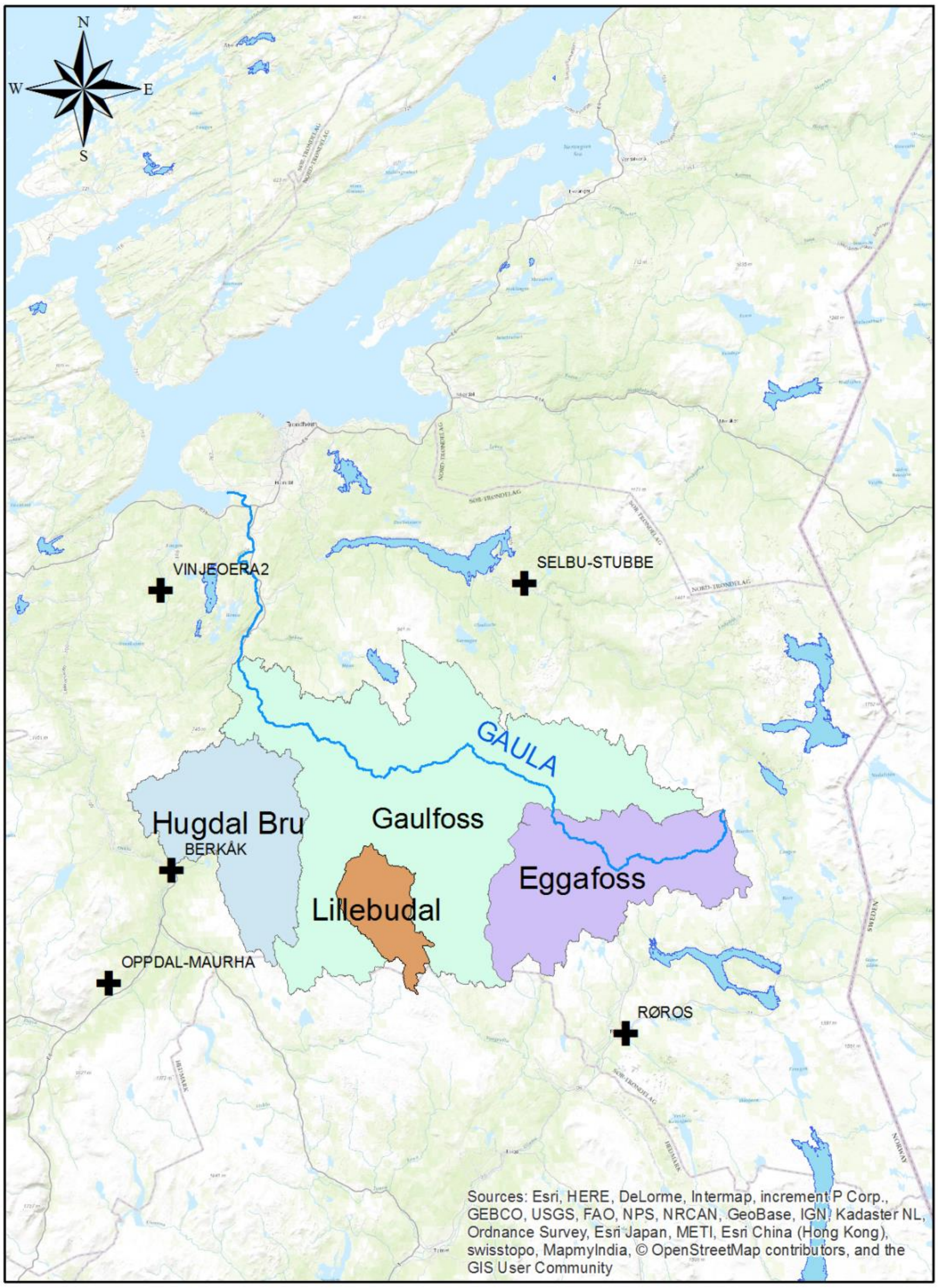

N
W
E
S
LØKSMYR
VINJEOERA2
SELBU-STUBBE
HØLONDA
AUNET
STØREN - VARVOLL
RØSBJØRGEN
GAULA
Hugdal Bru
Gaulfoss
HALTDALEN III
STUGUDAL
RENNEBU - RAMSTAD
BERKÅK - LYNGHOLT
ENDALSVOLL
BERKÅK
Eggafoss
Lillebudal
AURSUND
BREKKEN
OPPDAL-MAURHA
KVIKNE
RØROS
RØROS
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community


N
S
W
E
GAULA
Hugdal Bru
Gaulfoss
Lillebudal
Eggafoss
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community


N
W
E
S
GAULA
Hugdal Bru
Gaulfoss
Lillebudal
Eggafoss
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

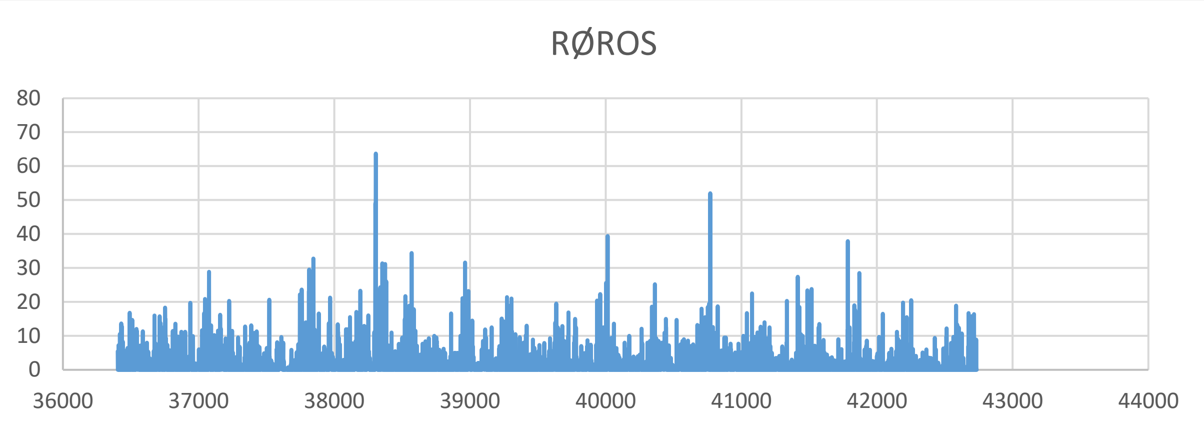

N
W
E
S
LØKSMYR
HØLONDA
STØREN - VARVOLL
RØSBJØRGEN
GAULA
AUNET
HALTDALEN III
STUGUDAL
RENNEBU - RAMSTAD
BERKÅK - LYNGHOLT
ENDALSVOLL
Hugdal Bru
Gaulfoss
Eggafoss
Lillebudal
AURSUND
BREKKEN
KVIKNE
RØROS
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

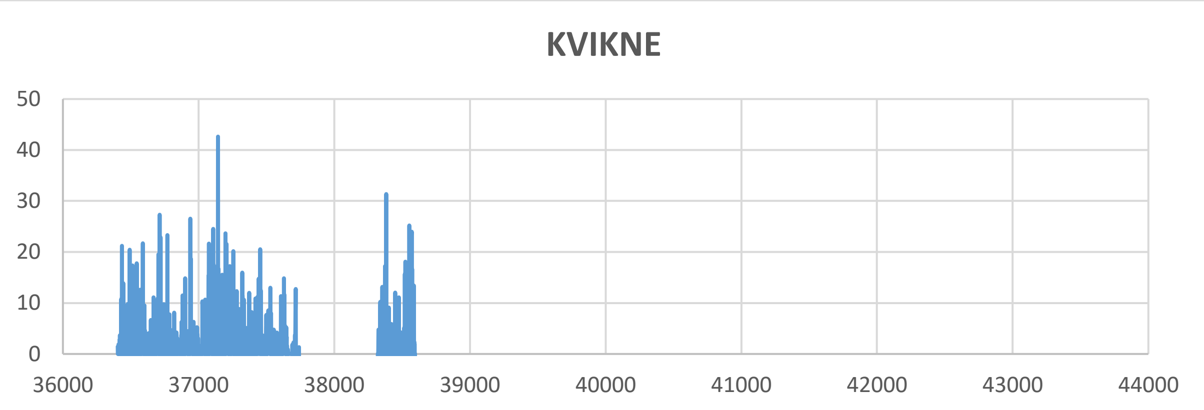

N
W
E
S
GAULA
Hugdal Bru
Gaulfoss
Eggafoss
Lillebudal
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

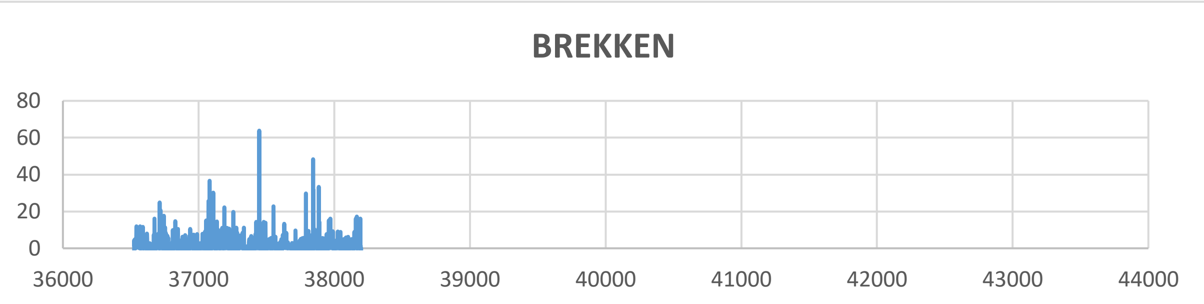

N
W
E
S
VINJEOERA2
SELBU-STUBBE
GAULA
Hugdal Bru
Gaulfoss
BERKÅK
Eggafoss
Lillebudal
OPPDAL-MAURHA
RØROS
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

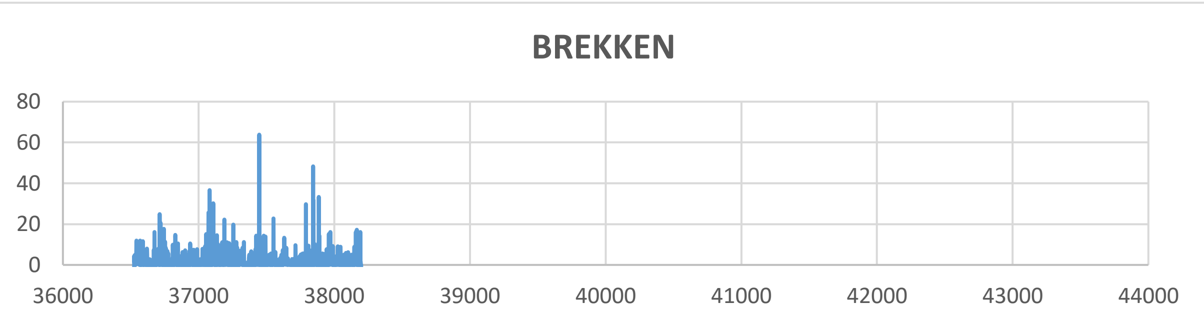
8.2 APPENDIXES B

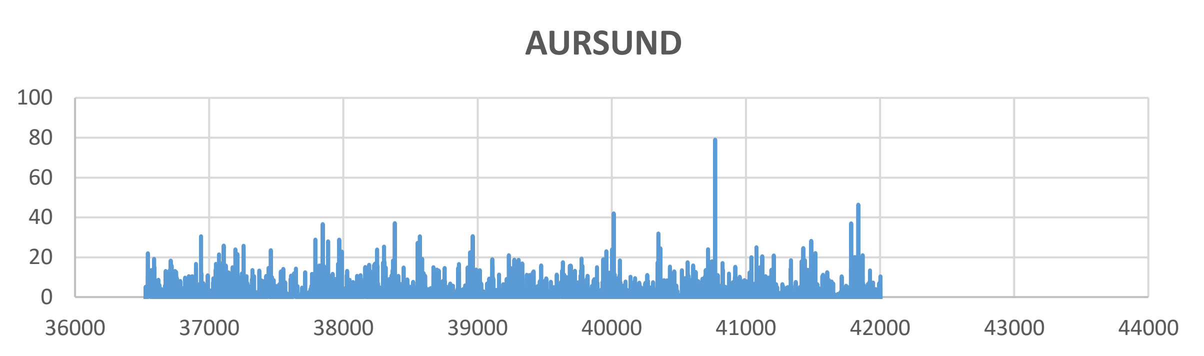
PRECIPITATION

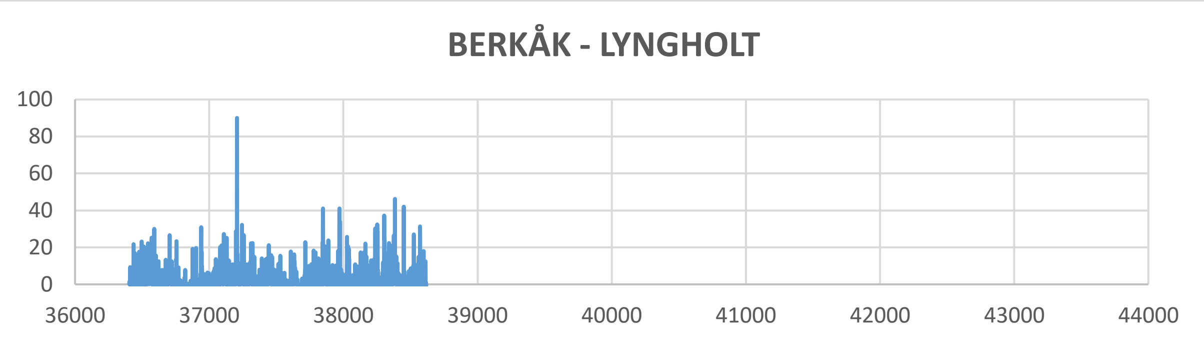


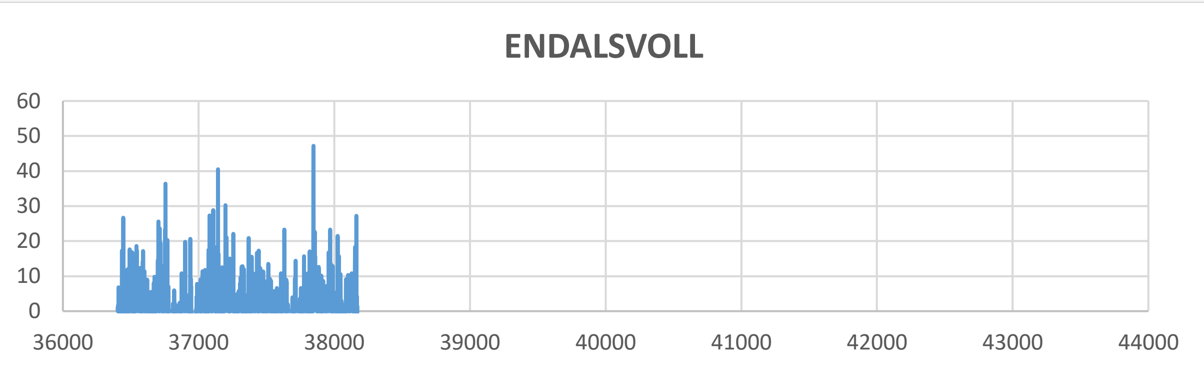


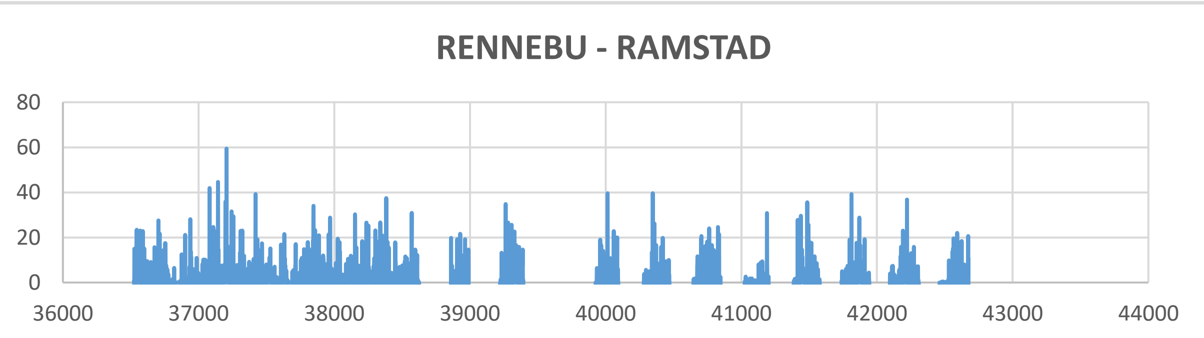


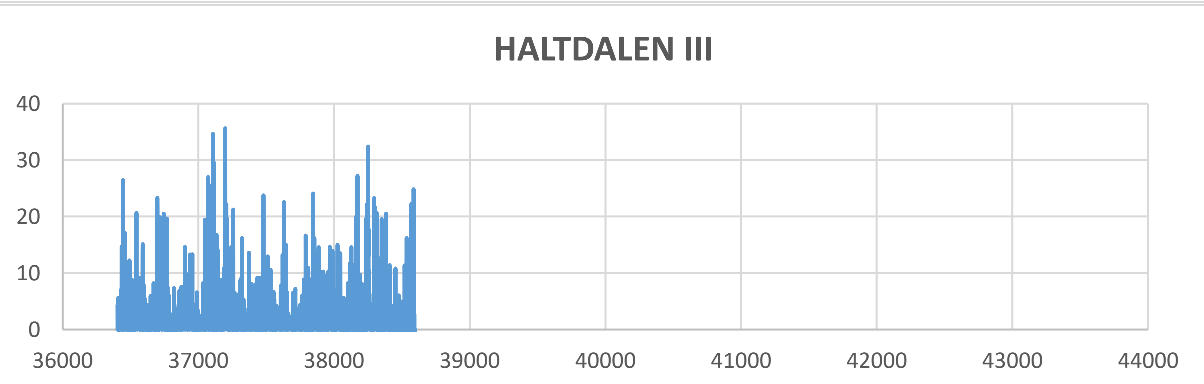



AURSUND
100
80
60
40
20
0
36000
37000
38000
39000
40000
41000
42000
43000
44000

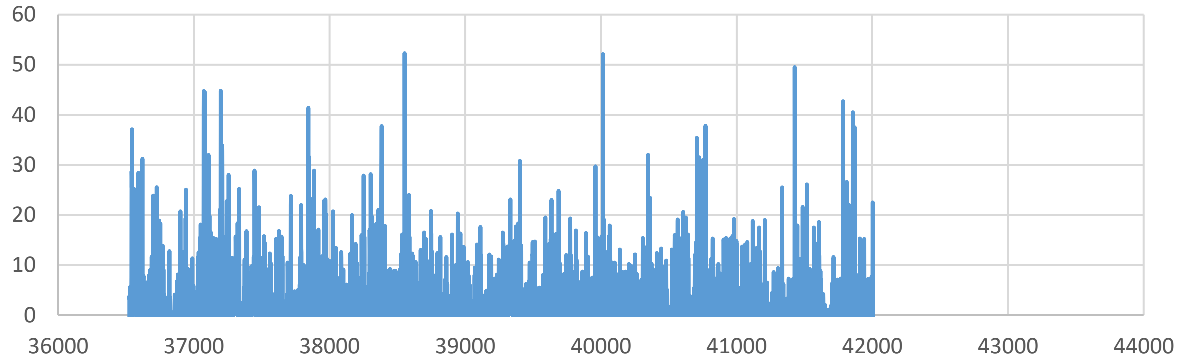

BERKÅK - LYNGHOLT
100
80
60
40
20
0
36000
37000
38000
39000
40000
41000
42000
43000
44000


ENDALSVOLL
60
50
40
30
20
10
0
36000
37000
38000
39000
40000
41000
42000
43000
44000

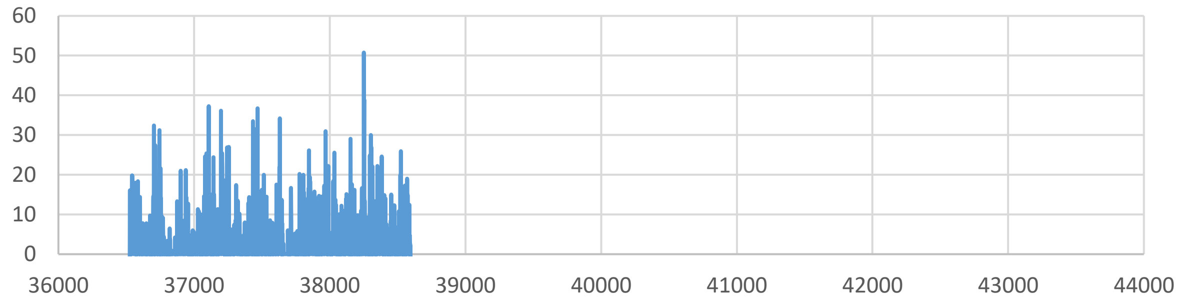

RENNEBU - RAMSTAD
80
60
40
20
0
36000
37000
38000
39000
40000
41000
42000
43000
44000


HALTDALEN III
40
30
20
10
0
36000
37000
38000
39000
40000
41000
42000
43000
44000

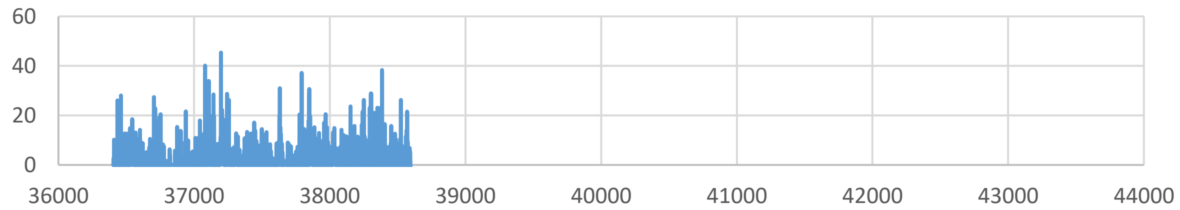
STUGUDAL - ÅSEN



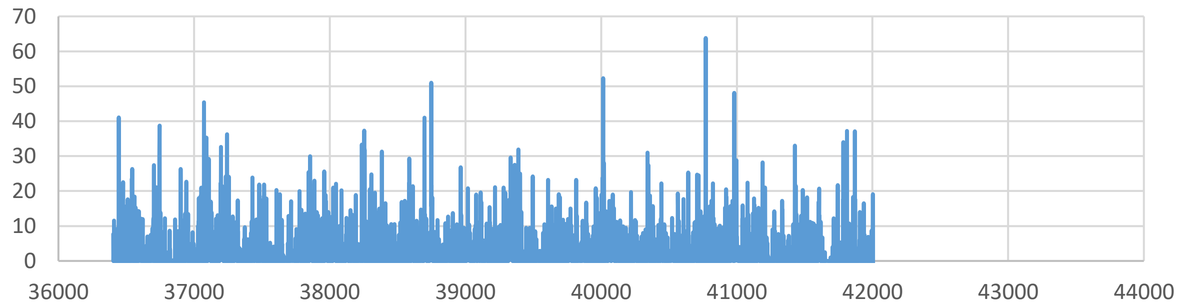
RØSBJØRGEN

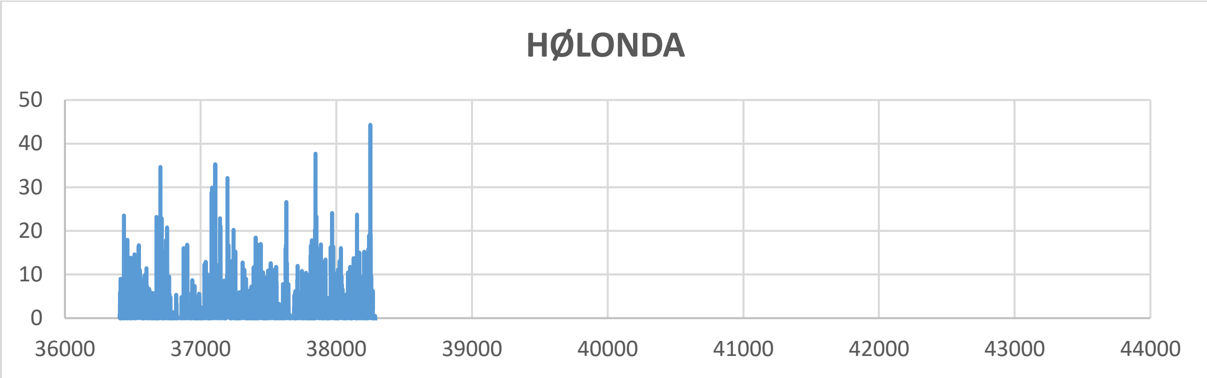


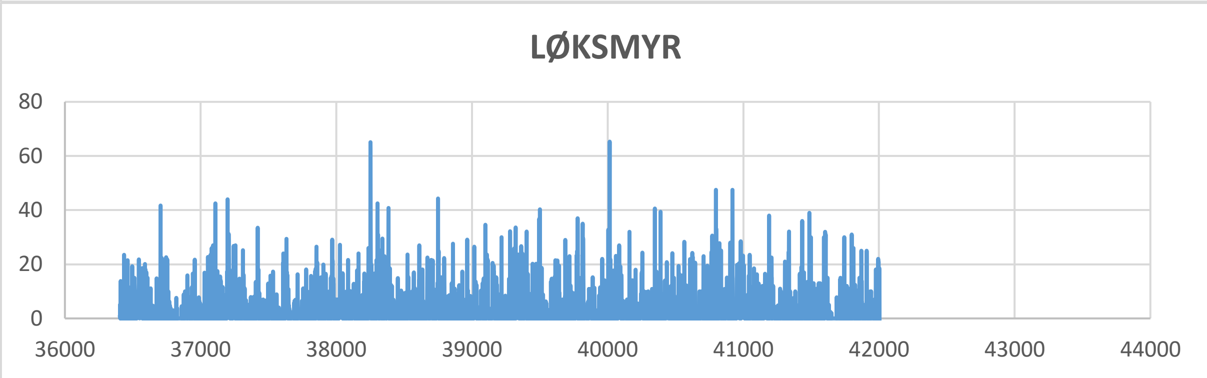
STØREN - VÅRVOLL

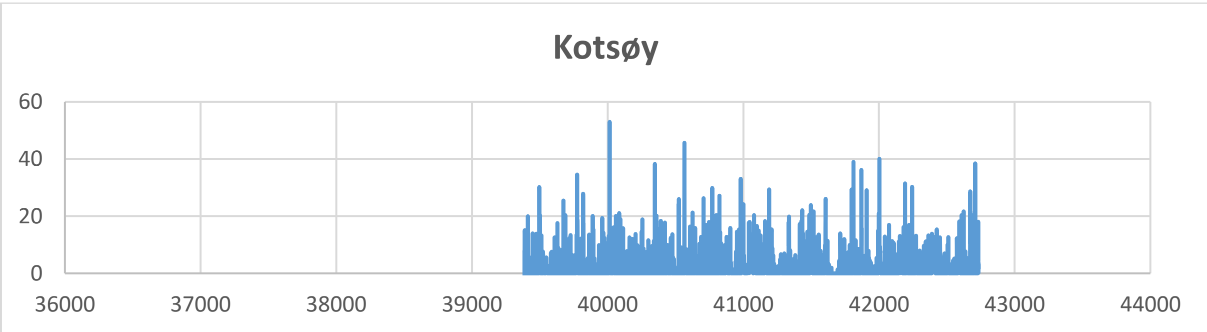


AUNET



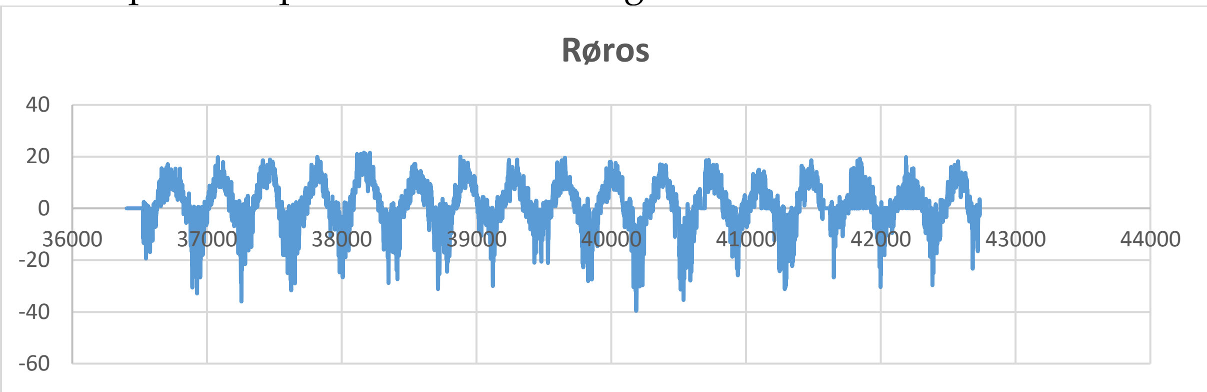

HØLONDA
50
40
30
20
10
0
36000 37000 38000 39000 40000 41000 42000 43000 44000

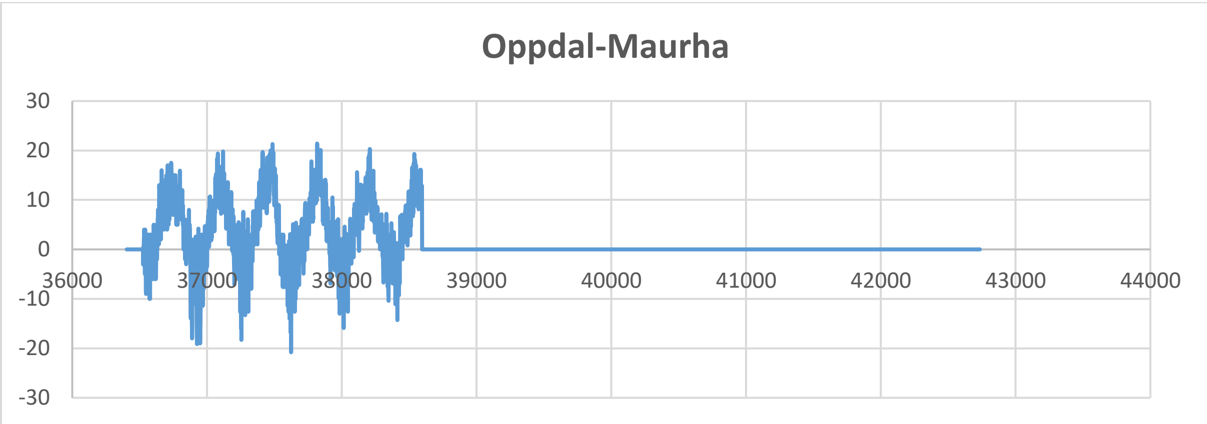

LØKSMYR
80
60
40
20
0
36000 37000 38000 39000 40000 41000 42000 43000 44000

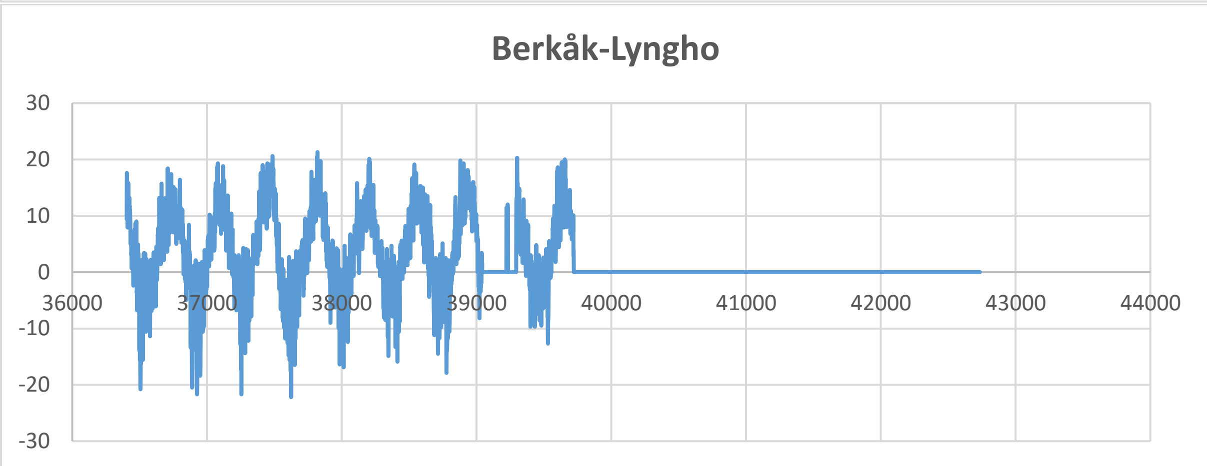

Kotsøy
60
40
20
0
36000 37000 38000 39000 40000 41000 42000 43000 44000

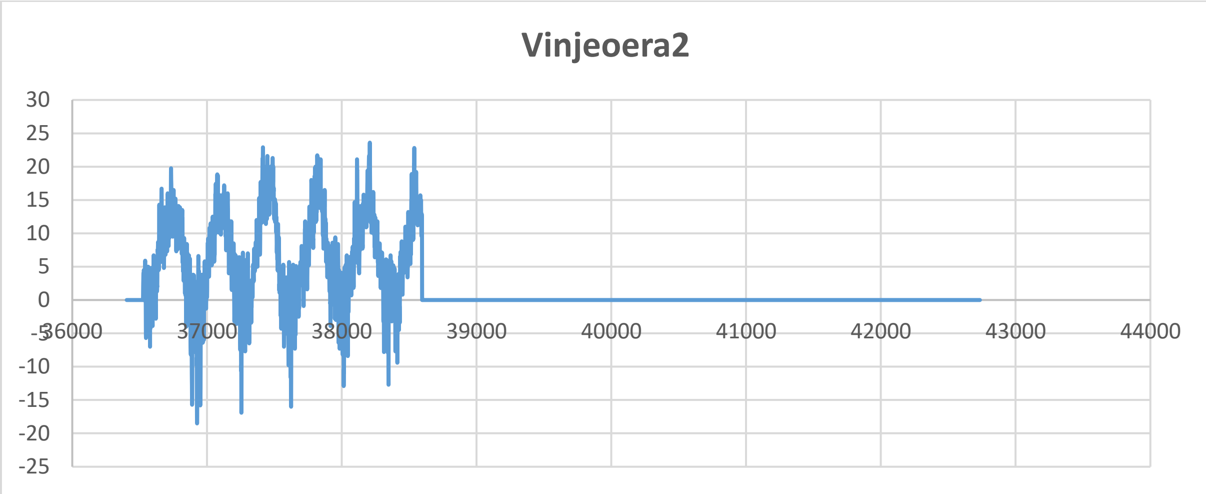
8.3 APPENDIXES C

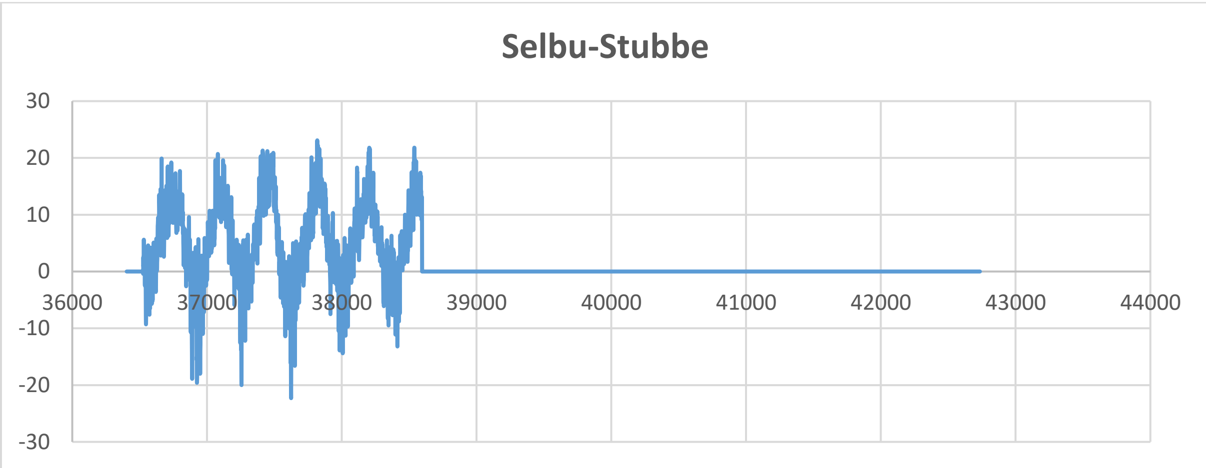
Air temperature plot before data fixing

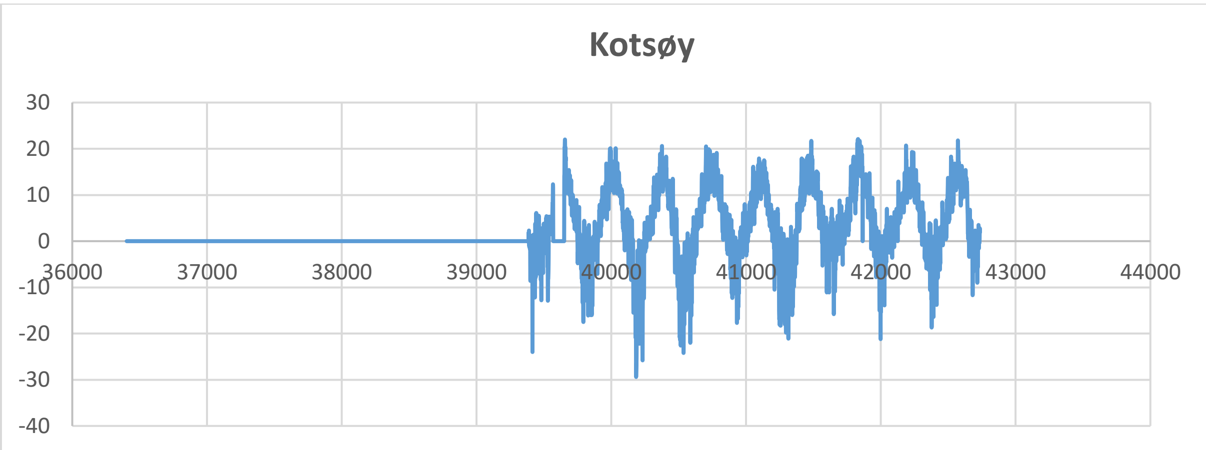


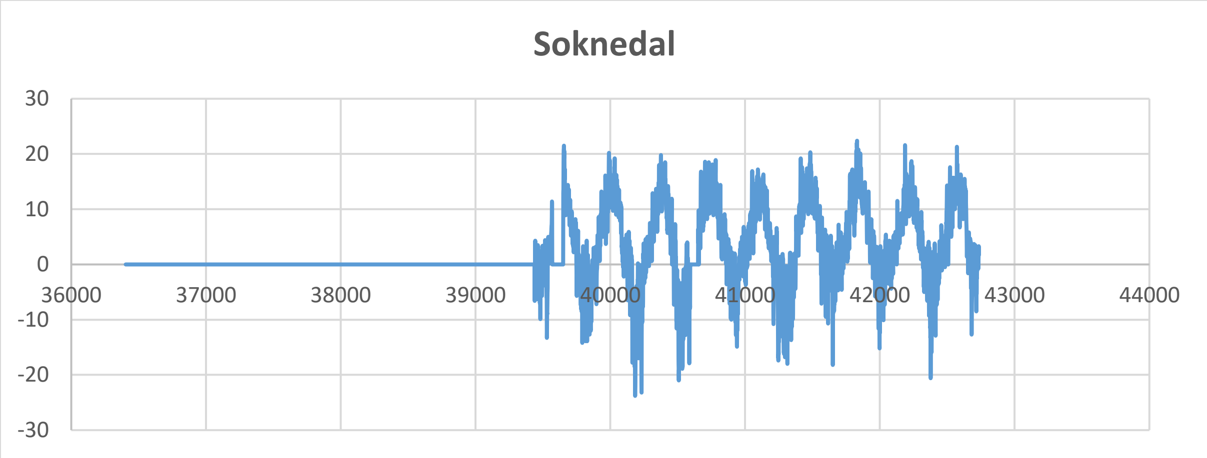




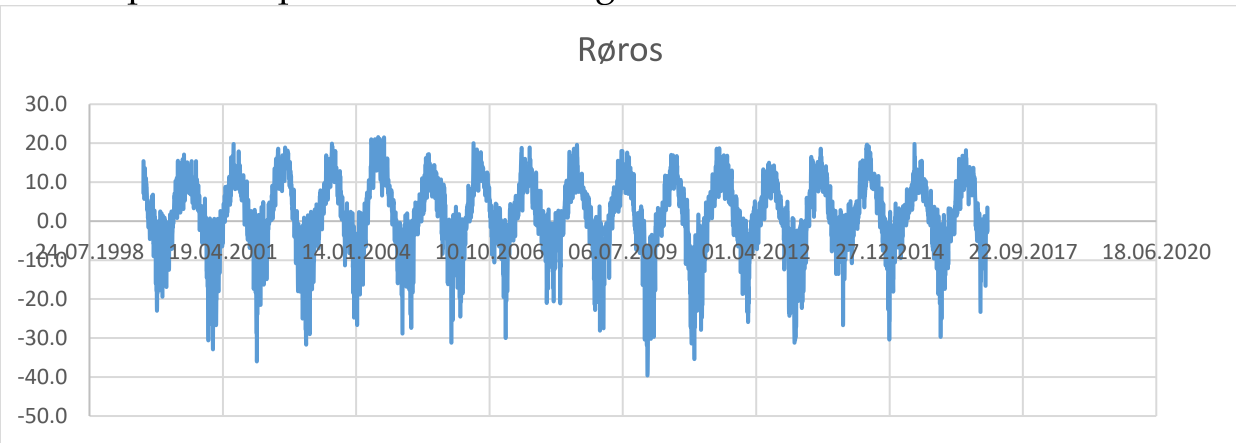

Vinjeoera2
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
36000
37000
38000
39000
40000
41000
42000
43000
44000

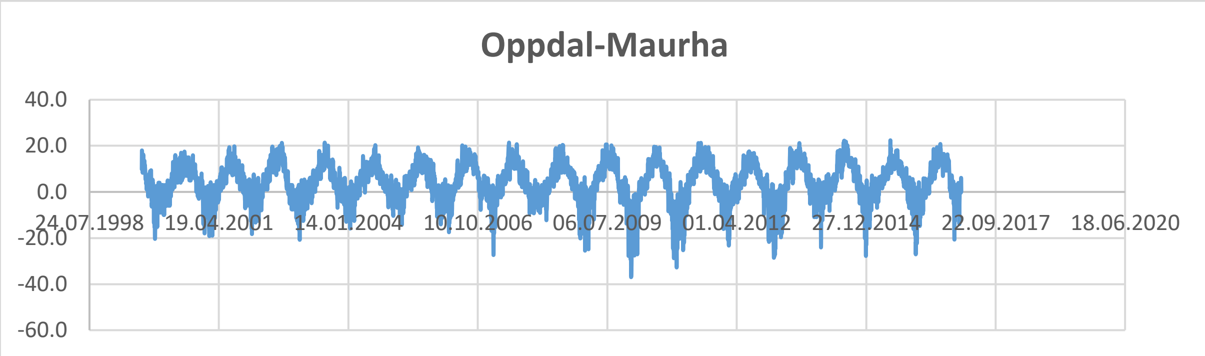

Selbu-Stubbe
30
20
10
0
-10
-20
-30
36000
37000
38000
39000
40000
41000
42000
43000
44000

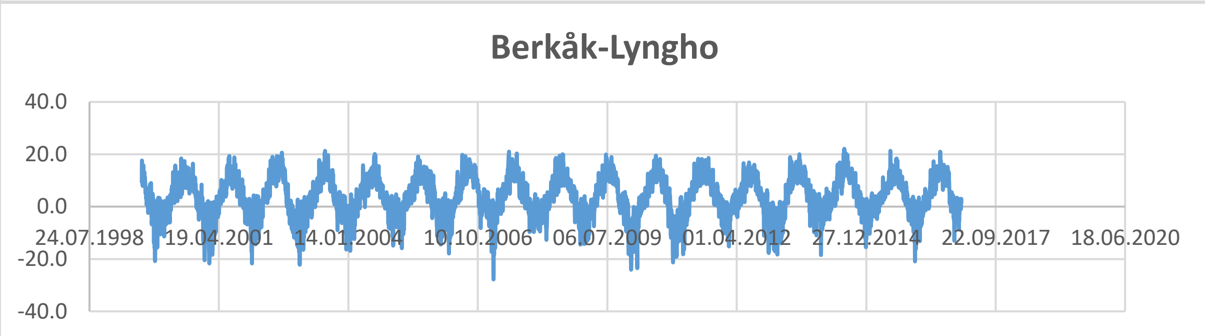

Kotsøy
30
20
10
0
-10
-20
-30
-40
36000
37000
38000
39000
40000
41000
42000
43000
44000

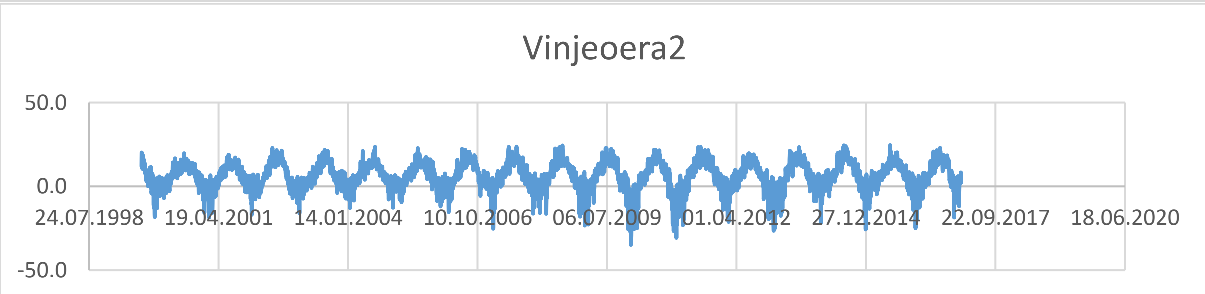

Soknedal
30
20
10
0
-10
-20
-30
36000
37000
38000
39000
40000
41000
42000
43000
44000

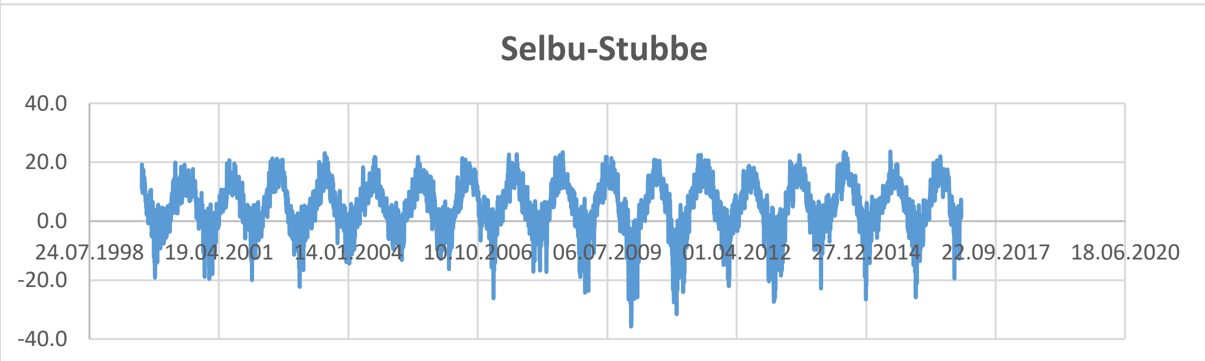
Air temperature plot after data fixing

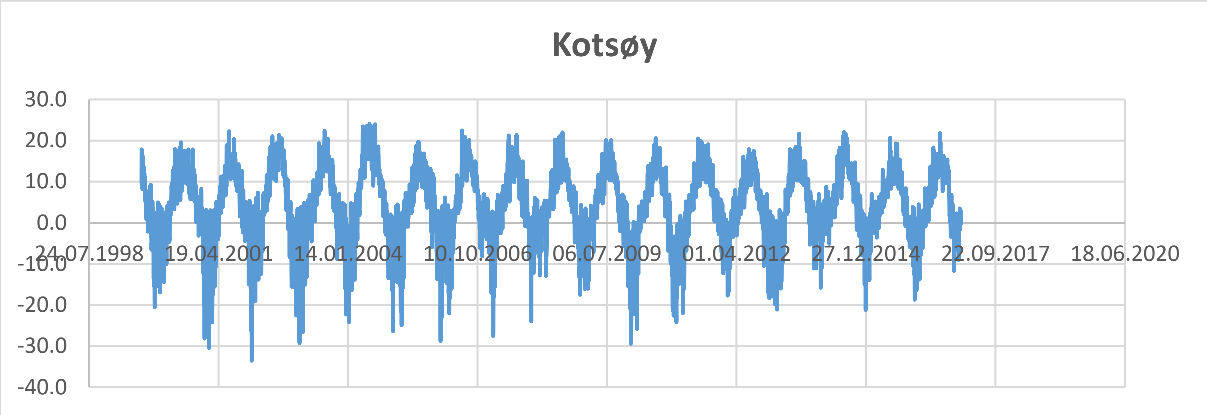


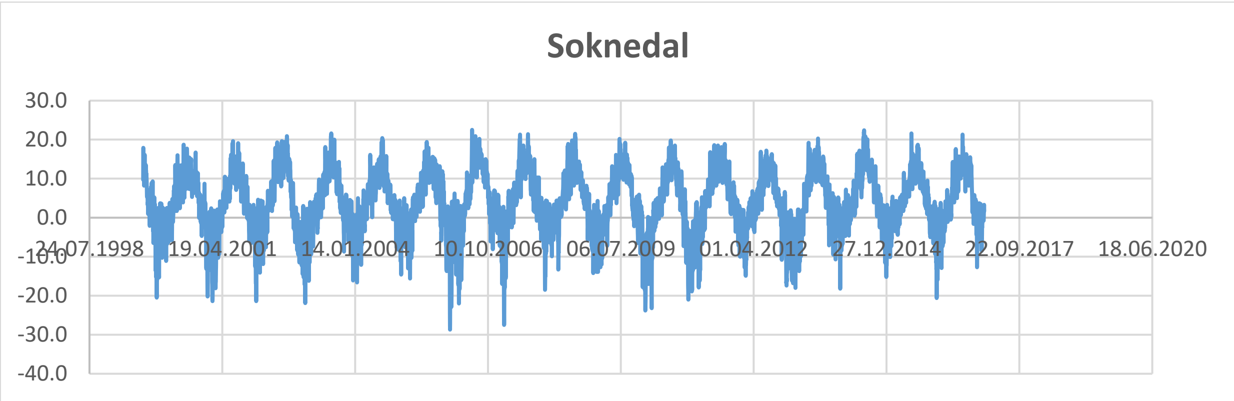




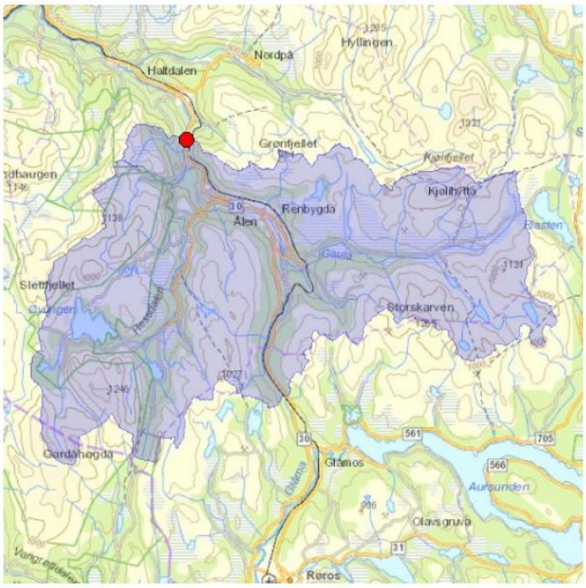





Kotsøy
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
24.07.1998
19.04.2001
14.01.2004
10.10.2006
06.07.2009
01.04.2012
27.12.2014
22.09.2017
18.06.2020


Soknedal
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
24.07.1998
19.04.2001
14.01.2004
10.10.2006
06.07.2009
01.04.2012
27.12.2014
22.09.2017
18.06.2020

8.4 APPENDIXES D



Lavvannskart

Vassdragsnr.:	122.F0
Kommune:	Holtålen
Fylke:	Sør-Trøndelag
Vassdrag:	GAULA

Vannføringsindeks, se merknader	
Middelvannføring (61-90)	25.6 l/(s*km²)
Alminnelig lavvannføring	l/(s*km²)
5-persentil (hele året)	l/(s*km²)
5-persentil (1/5-30/9)	l/(s*km²)
5-persentil (1/10-30/4)	l/(s*km²)
Base flow	-999.0 l/(s*km²)
BFI	

Klima		
Klimaregion	Midt	
Årsnedbør	963	mm
Sommernedbør	434	mm
Vinternedbør	529	mm
Årstemperatur	-0.2	°C
Sommertemperatur	6.4	°C
Vintertemperatur	-4.8	°C
Temperatur Juli	8.4	°C
Temperatur August	9.1	°C

Feltparametere	
Areal (A)	655.4 km²
Effektiv sjø (S_{eff})	0.2 %
Elvelengde (E_L)	45.2 km
Elvegradient (E_G)	14.4 m/km
Elvegradient$_{1085}$ (G_{1085})	14.6 m/km
Feltlengde(F_L)	33.0 km
H_{min}	285 moh.
H_{10}	623 moh.
H_{20}	717 moh.
H_{30}	775 moh.
H_{40}	811 moh.
H_{50}	844 moh.
H_{60}	878 moh.
H_{70}	918 moh.
H_{80}	964 moh.
H_{90}	1021 moh.
H_{max}	1284 moh.
Bre	0.0 %
Dyrket mark	2.1 %
Myr	12.7 %
Sjø	2.9 %
Skog	25.5 %
Snaufjell	43.4 %
Urban	0.1 %

1) Verdien er editert

Norges vassdrags- og energidirektorat

NVE

Kartbakgrunn: Statens Kartverk

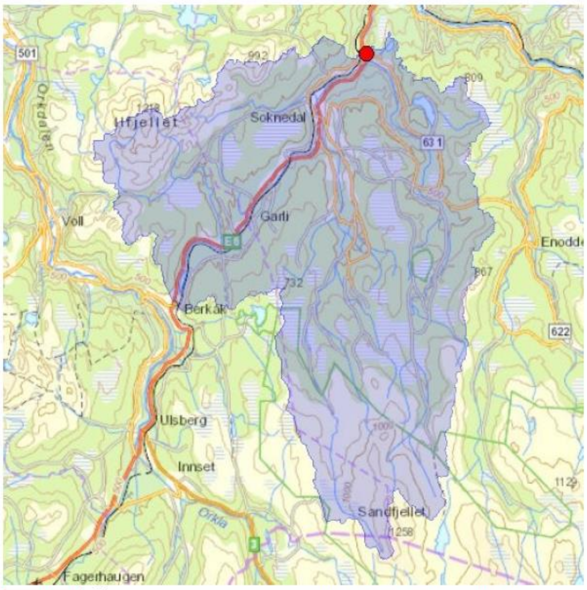
Kartdatum: EUREF89 WGS84

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.



Norges vassdrags- og energidirektorat

NVE

Kartbakgrunn: Statens Kartverk

Kartdatum: EUREF89 WGS84

Projeksjon: UTM 33N

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

Lavvannskart

Vassdragsnr.:	122.BA0
Kommune:	Midtre Gauldal
Fylke:	Sør-Trøndelag
Vassdrag:	SOKNA

Vannføringsindeks, se merknader		
Middelvannføring (61-90)	23.0	l/(s*km²)
Alminnelig lavvannføring		l/(s*km²)
5-persentil (hele året)		l/(s*km²)
5-persentil (1/5-30/9)		l/(s*km²)
5-persentil (1/10-30/4)		l/(s*km²)
Base flow	-999.0	l/(s*km²)
BFI		

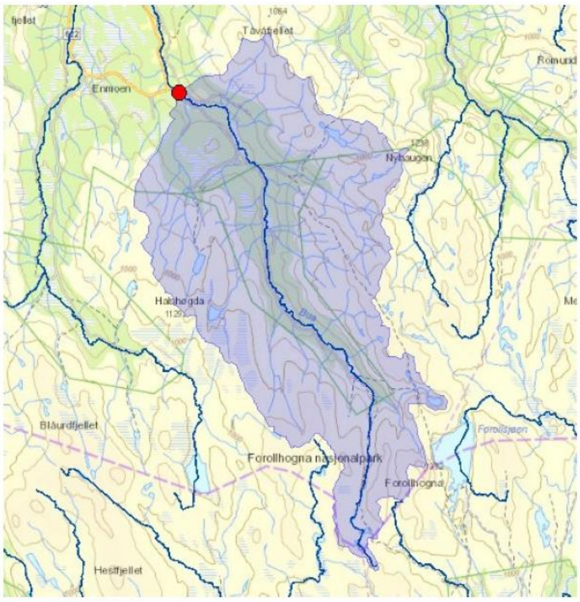
Klima		
Klimaregion	Midt	
Årsnedbør	817	mm
Sommernedbør	379	mm
Vinternedbør	437	mm
Årstemperatur	1.3	°C
Sommertemperatur	7.4	°C
Vintertemperatur	-3.0	°C
Temperatur Juli	9.3	°C
Temperatur August	9.8	°C

Feltparametere	
Areal (A)	545.5 km²
Effektiv sjø (S_{eff})	0.0 %
Elvelengde (E_L)	45.5 km
Elvegradient (E_G)	22.0 m/km
Elvegradient$_{1085}$ (G_{1085})	21.1 m/km
Feltlengde(F_L)	35.0 km
H_{min}	132 moh.
H_{10}	443 moh.
H_{20}	503 moh.
H_{30}	543 moh.
H_{40}	583 moh.
H_{50}	623 moh.
H_{60}	663 moh.
H_{70}	717 moh.
H_{80}	816 moh.
H_{90}	933 moh.
H_{max}	1254 moh.
Bre	0.0 %
Dyrket mark	6.3 %
Myr	16.3 %
Sjø	1.0 %
Skog	53.3 %
Snaufjell	20.9 %
Urban	0.1 %

1) Verdien er editert

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.



Norges vassdrags- og energidirektorat

NVE

Kartbakgrunn: Statens Kartverk

Kartdatum: EUREF89 WGS84

Projeksjon: UTM 33N

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

Lavvannskart

Vassdragsnr.:	122.CB
Kommune:	Midtre Gauldal
Fylke:	Sør-Trøndelag
Vassdrag:	BUA

Vannføringsindeks, se merknader		
Middelvannføring (61-90)	29.0	l/(s*km²)
Alminnelig lavvannføring		l/(s*km²)
5-persentil (hele året)		l/(s*km²)
5-persentil (1/5-30/9)		l/(s*km²)
5-persentil (1/10-30/4)		l/(s*km²)
Base flow	-999.0	l/(s*km²)
BFI		

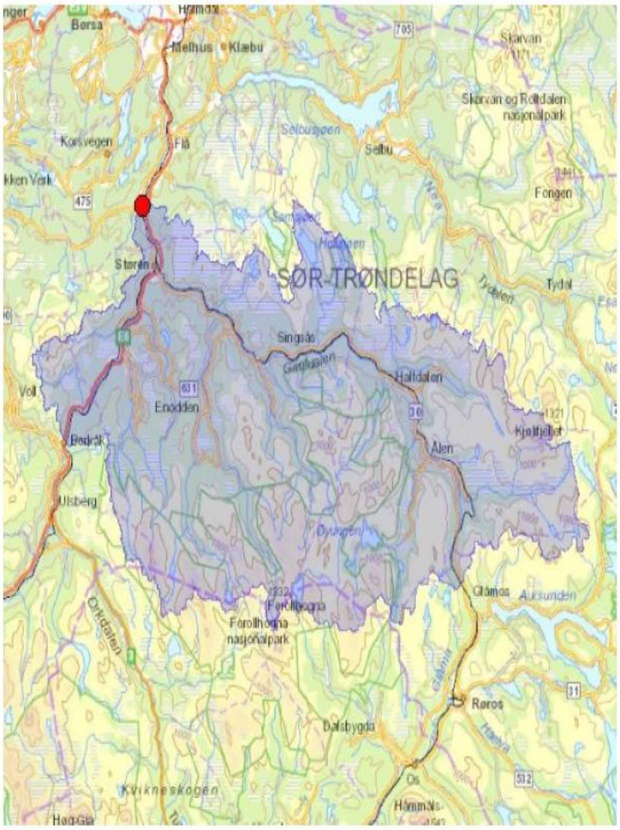
Klima		
Klimaregion	Midt	
Årsnedbør	984	mm
Sommernedbør	435	mm
Vinternedbør	549	mm
Årstemperatur	-0.8	°C
Sommertemperatur	5.7	°C
Vintertemperatur	-5.4	°C
Temperatur Juli	7.7	°C
Temperatur August	8.4	°C

Feltparametere	
Areal (A)	168.3 km²
Effektiv sjø (S_{eff})	0.0 %
Elvelengde (E_L)	29.7 km
Elvegradient (E_G)	20.2 m/km
Elvegradient$_{1085}$ (G_{1085})	20.0 m/km
Feltlengde(F_L)	23.2 km
H_{min}	516 moh.
H_{10}	675 moh.
H_{20}	769 moh.
H_{30}	847 moh.
H_{40}	907 moh.
H_{50}	948 moh.
H_{60}	983 moh.
H_{70}	1016 moh.
H_{80}	1046 moh.
H_{90}	1088 moh.
H_{max}	1303 moh.
Bre	0.0 %
Dyrket mark	0.7 %
Myr	8.7 %
Sjø	1.2 %
Skog	22.0 %
Snaufjell	65.3 %
Urban	0.0 %

1) Verdien er editert

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.



Lavvannskart

Vassdragsnr.:	122.B3
Kommune:	Melhus
Fylke:	Sør-Trøndelag
Vassdrag:	GAULA

Vannføringsindeks, se merknader	
Middelvannføring (61-90)	27.0 l/(s*km²)
Alminnelig lavvannføring	l/(s*km²)
5-persentil (hele året)	l/(s*km²)
5-persentil (1/5-30/9)	l/(s*km²)
5-persentil (1/10-30/4)	l/(s*km²)
Base flow	-999.0 l/(s*km²)
BFI	

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)	3086.0 km²
Effektiv sjø (S_{eff})	0.0 %
Elvelengde (E_L)	117.4 km
Elvegradient (E_G)	7.6 m/km
$Elvegradient_{1085}$ (G_{1085})	6.9 m/km
Feltlengde(F_L)	87.1 km
H_{min}	51 moh.
H_{10}	436 moh.
H_{20}	534 moh.
H_{30}	597 moh.
H_{40}	662 moh.
H_{50}	735 moh.
H_{60}	813 moh.
H_{70}	878 moh.
H_{80}	945 moh.
H_{90}	1019 moh.
H_{max}	1325 moh.
Bre	0.0 %
Dyrket mark	2.8 %
Myr	14.6 %
Sjø	2.1 %
Skog	36.9 %
Snaufjell	35.6 %
Urban	0.1 %

1) Verdien er editert

Norges vassdrags- og energidirektorat

NVE

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.