NTNU – Trondheim
Norwegian University of
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Estimating runoff from ungauged catchments using regional modelling

Ekaterina Lobintceva

Hydropower Development
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Supervisor: Knut Alfredsen, IVM
Co-supervisor: Ånund Killingtveit, IVM
Kjetil Vaskinn, SWECO AS

Norwegian University of Science and Technology
Department of Hydraulic 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: **Ekaterina Lobintceva**

Topic: **Estimating runoff from ungauged catchments using regional modeling.**

1. Background

Establishing runoff series from ungauged catchment is a central challenge in hydrology and in the application of hydrological data for engineering purposes. In Norway this is particularly evident in the design of small hydropower where the location of the power plant often is in small catchments with no or little data available. The current practice involves scaling of data from neighboring gauged catchments, which often is uncertain due to catchment size and location.

Over the latest years, a number of short term data series have been collected as a part of the planning process of small hydro. SWECO AS has established runoff gauging stations as part of the planning process for small hydropower for a large number of projects, resulting in a large volume of runoff data for many small rivers. These data could be a basis for testing new methods for estimating runoff from ungauged catchments by using them to test computations of runoff in the catchment based on the established NVE gauging stations. This thesis will build on initial work on preparing runoff data collected by SWECO during the summer of 2013.

An approach for finding data from ungauged site is to calibrate a hydrological model for a region, finding a common parameter set for the entire region based on as many observed data as possible. SINTEF Energy Research has developed the ENKI platform for hydrological modeling, which contains the tools needed to establish a hydrological model for a region and do model calibration on multiple runoff series. Further, parameter analysis and model diagnostics can be carried out within this framework.

In this project the objective is to do a calibration for one or two regions in which SWECO has measured short term data series. The regional model should be based on all available long time series in the region and results from the SWECO catchments should be extracted from the regional model and compared to the observed time series for the catchments. Based on this, the application of this methodology should be evaluated.

2. Main questions for the thesis

The project will consist of the following topics (though not necessarily be limited to these):

1. The region(s) that will be used in the modeling should be selected based on data availability and the number of SWECO time series available. For the selected region all possible climate data, runoff data and map-based data should be collected and evaluated for representatively in the region and data quality. Data should then be structured and prepared for use in ENKI.

2. ENKI should be set up for the region and calibrated. Decisions should be made on the modules to include in the model and the strategy used for areal computation of precipitation and temperature. The calibrated parameters should be evaluated and parameter uncertainty estimated for the regional setup. For the latter case, a single catchment calibration for a selected number of gauged catchment could be carried out. It is particularly interesting to evaluate the results from individual catchments in the regional setup and try to identify the variability and reasons for differences.

3. For each of the sites where SWECO has measured discharge, the discharge should be extracted from the regional model and compared to observations. Relevant metrics for comparison should be selected. It will be particularly interesting to look at duration curves and low flow values, which are important in small hydro design. The results from the regional model could also be compared to a traditional scaling approach to further evaluate the applicability of the method, and if the data series allow it a single catchment calibration for one of the SWECO sites could also be included in the evaluation.

4. Evaluate if including the longest of the SWECO series in the calibration process improves the regional calibration and the quality of the results extracted for smaller catchments. If time permits, an evaluation of model sensitivity should be carried out for the regional model.

3. Supervision

Supervisor: Professor Knut Alfredsen, NTNU

Co-supervisor: Professor Ånund Killingtveit, NTNU

Dr. Kjetil Vaskinn, SWECO AS

This specification for the thesis should be reviewed after about 6 weeks, and not later than 1/4. If needed, the text could then be modified, based on proposal from the candidate and discussions with the supervisor.

4. Report format

Professional structuring of the report is important. Assume professional senior engineers as the main target group. The report shall include a summary, offering the reader the background, the objective of the study and the main results. The thesis report shall be using NTNU's standard layout for Thesis work. Figures, tables, etc shall be of good report quality. Table of contents, list of figures, list of tables, list of references and other relevant references shall be included. The complete manuscript should be compiled into a PDF file and submitted electronically to DAIM for registration, printing and archiving. Three hard copies, in addition to the students own copies, should be printed out and submitted. The entire thesis may be published on the Internet as full text publishing. All documents and data shall be written on a CD thereby producing a complete electronic documentation of the results from the project. This must be so complete that all computations can be reconstructed from the CD.

Finally, the candidate is requested to include a signed statement that the work presented is his own and that all significant outside input has been identified.

The thesis shall be submitted no later than **Tuesday 17 June, 2014**

Department of Hydraulic and Environmental Engineering, NTNU

Knut Alfredsen

Professor

FOREWORDS

This Master's thesis titled "Estimating runoff from ungauged catchments using regional modeling" is carried out under the supervision of Professor Knut Alfredsen, Department of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway.

The thesis work started in January 2014 and was completed in June 2014 based on the data collected during the summer internship in Sweco Company in the summer 2013.

I hereby confirm that all the work carried in this thesis is my own and significant outside efforts have been acknowledged.

Ekaterina Lobintceva

June 2014

Trondheim, Norway

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First of all, I would like to acknowledge Prof. Knut Alfredsen, Department of Hydraulic 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. He has been so generous for giving time during discussions and arranged for new programs and software required for thesis work.

I would also like to extend my gratitude to my co-supervisors Prof. Ånund Killingtveit, NTNU and Dr. Kjetil Vaskinn, SWECO AS for their supports during the thesis work.

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Likewise, I would like to thank all of my friends here in Trondheim for their support during the entire Masters degree at NTNU and especially during the thesis period.

At last but not the least, I would like to express my great thanks to my husband Vyacheslav Lobintsev for his love, support and care and inspiration during my studies.

ABSTRACT

Establishing runoff series from ungauged catchment is a central challenge in hydrology. In Norway this is particularly evident in the design of small hydropower. The location of the power plant often is in small catchments with little little or no data available. The application of regional modeling for estimating runoff in ungauged catchments is one of the promising methods. The main goal of this study is to use ENKI hydrological model to calibrate free set of parameters which can be applied everywhere within selected region in order to estimate runoff in basins where Sweco Company was carrying out their own measurements.

The study region located in central Norway and contain Sør-Trøndelag, Nord-Trøndelag and Møre og Romsdal Counties. The ENKI model has been set-up and all necessary hydro-meteorological and geographical input data for the period from 2000 to 2012 have been collected and processed. Three cases of calibration were carried out to obtain the best regional set of parameters for the entire study area.

The first case of calibration was done including all the catchments and calibration period is from 2001 to 2005. The results showed variability of R^2 from -0.24 (Farstadelva v/Farstad catchment) to 0.85 (Eggafoss catchment) for individual calibration. The regional set of parameters for the first case of calibration resulted in Nash efficiency of 0.15 which is comparatively very low.

Second calibration run was done to improve Nash efficiency results. In this case the catchments which were giving poor R^2 values have been excluded and calibration has been carried out over 9 catchments. The variability of R^2 for second case is from 0.375 (Vistdal catchment) to 0.85 (Eggafoss catchment). The regional set of parameters has been improved and resulted in R^2 = 0.55. Validation of the model has been carried out for the period from 2005 to 2011 and resulted with regional value of R^2 = 0.583 indicating that the model is applicable for predicting runoff. Second case of calibration has been used for extraction runoff data series for Sweco catchments.

The third case of calibration differs from the second one by performance of PcorrRain and PcorrSnow parameters as raster maps with best values from first case of individual calibration. The regional set for the third case of calibration resulted in R^2 = 0.452 which is lower than the result from second calibration.

The simulated runoff for Sweco catchments was extracted and compared with observed values. Applicability of ENKI regional modeling has been compared to scaling approach.

The overall results were not satisfactory for small catchments which can be improved in further studies.

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LIST OF ABBREVIATIONS

AET	Actual Evapotranspiration
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
R^2	Nash Sutcliffe Efficiency
T	Temperature
SINTEF	Stiftelsen for industriell og teknisk forskning
Qsim	simulated runoff
UTM	Universal Transverse Mercator

1 INTRODUCTION

1.1 BACKGROUND

In Norway, in our days focus is concentrated on development of small hydropower plants. Planning process requires runoff data series, but most discharge measurement stations locate on primary rivers with large catchments. In order to make necessary hydrological analysis, runoff data usually derived from neighboring gauging station by scaling runoff data series from large catchment to small ones. In most cases such method gives large uncertainty in runoff data series.

Sweco AS Company deals with hydropower planning. As part of planning process for small hydropower, Sweco have established their own runoff gauging stations. Runoff data from Sweco measurements stations have been used in this thesis work in order to check applicability of regional modeling with ENKI and compare predicted runoff data with observed one.

ENKI hydrological modeling framework, developed by SINTEF Energy Research Company has been assigned to use in this thesis in order to estimate runoff in Sweco catchments for letter evaluation of applicability of the method. The ENKI model contains tools for regional model setting and calibration. The aim is to obtain a common set of parameters through calibration for selected study region in central Norway, which will bring as close as possible fit of predicted runoff data series to observed one. Selection of the region was based on availability of input data, such as runoff, precipitation and temperature data series.

1.2 OBJECTIVE OF THE PROJECT

This thesis work is carried out in order to obtain runoff data series in ungauged catchments by using ENKI regional hydrological modeling. The main objective of this study is to generate synthetic runoff data in region where Sweco AS Company has many measured data series. The results from calibration will be compared with observed Sweco runoff data series to evaluate the applicability of this method.

1.3 SCOPE OF THE PROJECT

The scope of the study is as follows:

i. Theory review on the methods of hydrological modeling
ii. Collection of meteorological and hydrological information related to the study area
iii. Collection of meteorological and hydrological data and processing of collected data
iv. Collection of geographical data of the project area, preparation of maps in GIS and conversion of these maps into ENKI readable format (Idrisi)
v. ENKI model set-up, calibration and validation of the model
vi. Extracting discharge from the regional model and comparison with Sweco measured observations
vii. Comparison of the results from the regional model to a traditional scaling approach and evaluating the applicability of the method

1.4 METHODOLOGY OF THE STUDY

The methodology of the study includes following steps:

i. Theory review
ii. Input data collection and data processing
iii. ENKI model set-up
iv. ENKI model calibration and validation
v. Extracting runoff data series for Sweco catchment
vi. Comparison of ENKI model results with scaling approach

1.5 STRUCTURE OF THE THESIS

This thesis covers all necessary requirements which are needed for obtaining runoff data series in ungauged catchments by using ENKI regional hydrological modeling. The chapters are written in order to describe different tasks. Each chapter contains description of working process, methodology of the process and relevant conclusion.

The structure of the thesis is as follows:

- Chapter 1 describes the background information, objectives of the thesis, scope of study and methodology used for carrying out the study.
- Chapter 2 represents study area along with land use characteristics including information related to climate, temperature and precipitation.
- Chapter 3 describes theory review of hydrological modeling, in particular, regional modeling with ENKI.
- Chapter 4 presents data collection and quality control.
- Chapter 5 describes geographical data preparation for ENKI using GIS.
- Chapter 6 describes the ENKI model set-up.
- Chapter 7 describes the ENKI model calibration and validation along with runoff data extraction for Sweco catchments and discussions based of obtained results.
- Chapter 8 presents conclusion and recommendations for further study.

2 IDENTIFICATION OF STUDY AREA

2.1 INTRODUCTION

Norway is ideal country for hydropower generation due to its geographical, climatic and geological conditions. Till now, so many hydropower plants have been built, there is large potential of developing small hydropower plants.

Climate and hydrology of Norway determined by its geographical location and closeness to Atlantic Ocean, which brings favorable environment by presents of Gulf Stream. Norway lies via the paths of Atlantic cyclones which brings large amount of precipitation to the land. (Hveding, 1992)

2.2 STUDY AREA

The region for further investigation has been selected based on availability of Sweco measured data series and its stations location. For the last decades Sweco, as part of planning routine has established number of gouging stations across Norway. For this study the interest for estimating runoff in ungauged river basin focused in central region in Norway. The boundary of selected rectangular region lies between 69° 13' and 70° 83' North latitude and 37° 14' and 67° 04' East longitudes. The total area of the region is approximately 50 000 square kilometers. The study region contains 11 Sweco runoff stations and 17 NVE runoff measurement stations within Sør-Trøndelag, Nord-Trøndelag and Møre og Romsdal County. The Gaulfoss catchment has the largest area of 3083.58 km^2.The Svattjørnbekken darainage basin has the smallest area of 3.413 km^2. The detailed description of catchments presented in Chapter 4-4. The selected region with Sweco stations represented in Figure 2-1.

The stations are well distributed over entire region. Table 2-1 shows the location of Sweco gauging stations.

Table 2-1 Sweco runoff stations locations within selected study region

Numer	Stasjonsnavn	UTM Zone	X_UTM_North	Y_UTM_East	KOMMNAVN	FYLKENAVN
1	Tangvella	32 V	583409	7013268	Selbu	Sør-Trøndelag
2	Usma	32 V	613424	6995895	Selbu	Sør-Trøndelag
3	Eidåa	33 V	246926	6995437	Meldal	Sør-Trøndelag
4	Instefjord	32 V	525093	7029092	Snillfjord	Sør-Trøndelag
5	Tunseslva	32 V	596073	7092948	Verran	Nord-Trøndelag
6	Erga	32 V	507318	6938389	Sunndal	Møre og Romsdal
7	Skorgeelva	32 V	430466	6939992	Rauma	Møre og Romsdal
8	Malmedalselva	33 V	104238	6986364	Frμna	Møre og Romsdal
9	Vassdalselva	32 V	491627	6994813	Surnadal	Møre og Romsdal
10	Trøkna	32 V	511285	6996050	Rindal	Møre og Romsdal
11	Kanndalen	32 V	459245	6950609	Nesset	Møre og Romsdal

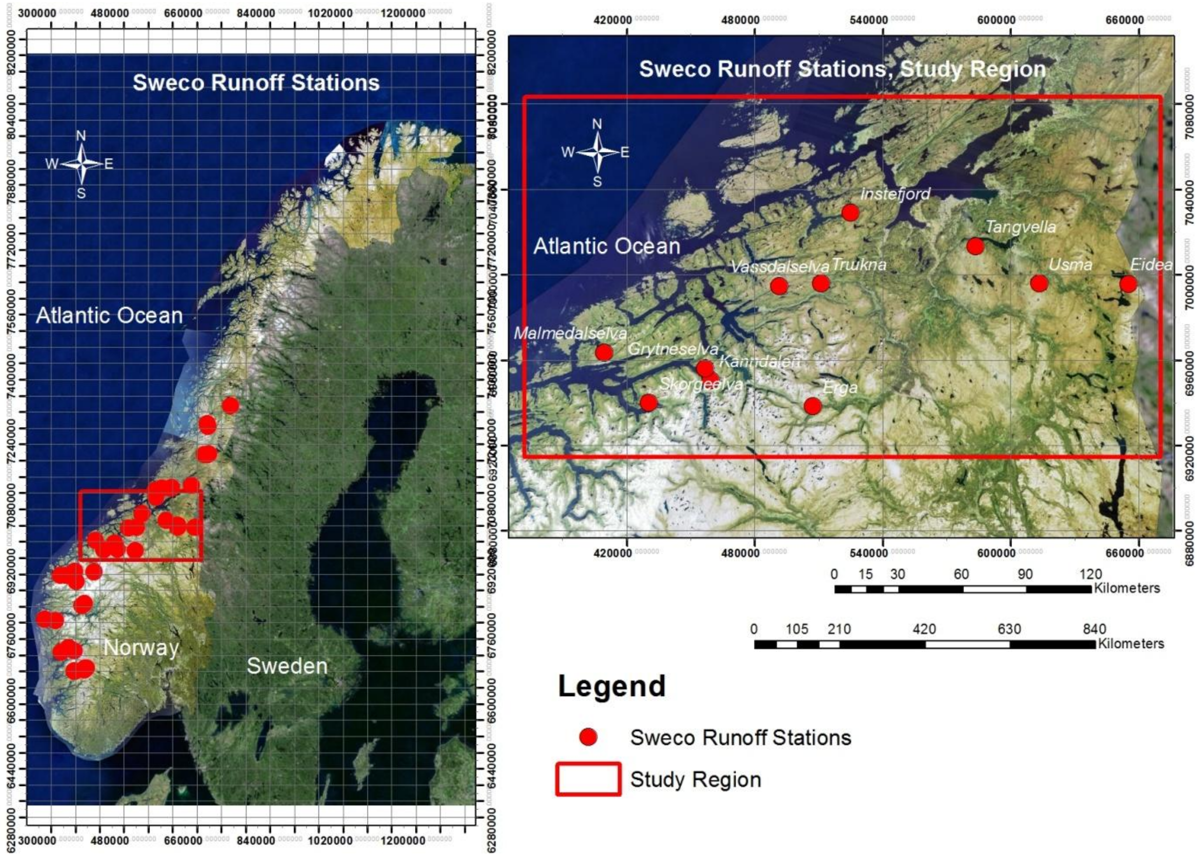


Figure 2-1 Selected region with Sweco stations

2.3 LAND USE

Land is a resource, which influence people's lives and it is very important to use the land resources in right manner form environmental, social and economical point of view. The changes in landscape affects on nature ecology, which in its turn resulting on negative impact on people's health and life quality.

The total surface area in Norway is 385,230 km^2. The sea area covers 1,878,961 km^2; it is including the economic, the fisheries protection zones and zone around Svalbard and Jan Mayen. The population in Norway is just has 4.9 million people, it is nearly 12.5 people per km^2. Due to difficult climatic conditions, rough topography and poor soils the large part of Norway is not appropriate for agriculture use or for living. There is only 1 per cent of total land area occupied by urban settlements, which is about 2 340 square kilometers. Approximately 3 per cent of total land resources in Norway are used for agriculture purpose. But there is about 7.4 per cent of developed land for agriculture is not in use at the present time. The areas which was not in use for agriculture for a long time become as a forest. Forest area covers from 37 to 39 per cent. Conifers and birch trees are predominant in Norway. About half of forested area used in combination with pastureland. (Www.Environment.no) The forest mainly grows near river banks, around lakes and on valleys. The input land use map for ENKI model shown in Figure 5-6.

For the ENKI model setup the input land use map should be prepared within ArcGIS program and convert to the Idrisi format. The land use map has to be reclassified for two classes. The lake surface area should be equal to 1 and the rest of the area should be equal to 2. The model has to understand the land use for calculating runoff in turn that the lakes appear as natural storage for the precipitation.

2.4 CLIMATE OF STUDY AREA

Norway is the country that lies between 58° latitude and 71° toward north, total length is approximately 1700 km. For about half of the Norway locates beyond the Arctic Circle. Due to warm waters of Gulf Stream Norway has mild climate. Precipitations formed by Atlantic cyclones which bring moist air from the ocean to the land. (Hveding, 1992)

The study area locates in central part of Norway within Sør-Trøndelag, Nor-Trøndelag and Møre og Romsdal counties. The western part of the region lies on coastal line with typical Norwegian coastal climate and eastern side of the region is within inland climate.

Coastal climate commonly has evenly spread precipitation along the year. Such climate usually has less variation in temperature than inland climate. Winters are not cold, summers are partly warm.

The annual temperature in coastal part of the study area is between 4 °C to 6 °C. The eastern part of selected study region locates in inland climate. Inland climate differs from coastal one by high variety in temperature between summer and winter. Summers are generally warmer than summers with coastal climate and the winters are colder due to distant location from coastal and presents of mountain range. The annual temperature with inland part of the study area varies between -5 °C to -4 °C (NMI). About half of the study area locates in mounting range with elevation above sea level between 300 and 1200 masl (Hveding, 1992).

2.5 AIR TEMPERATURE

The air temperature differs due to solar activity, spatial location on the Earth, topography and seasonal variations. It is another very important meteorological factor in hydrology which control hydro-meteorological cycle and defines the type of precipitation.

In Norway the air temperature varies significantly. Due to its geographical location, the country is covering four climatic zones which lead to great difference in air temperature. Western and southern part of Norway, which located close to coastal have highest annual temperatures. The inland areas experience colder air temperature and higher variety between the seasons. The western part of selected study region has normal annual temperature in range from 1 °C to 8 °C. The central and south-eastern part of the region has lower normal annual temperature due to its inland location and higher altitude. The annual temperature varies between 2 °C to -3 °C. (NMI) The most severe cold might be experienced in Røros, Sør-Trøndelag. The record was fixated with air temperature of -50 °C. (Wikipedia)

The annual normal temperature is shown in Figure 2-2.

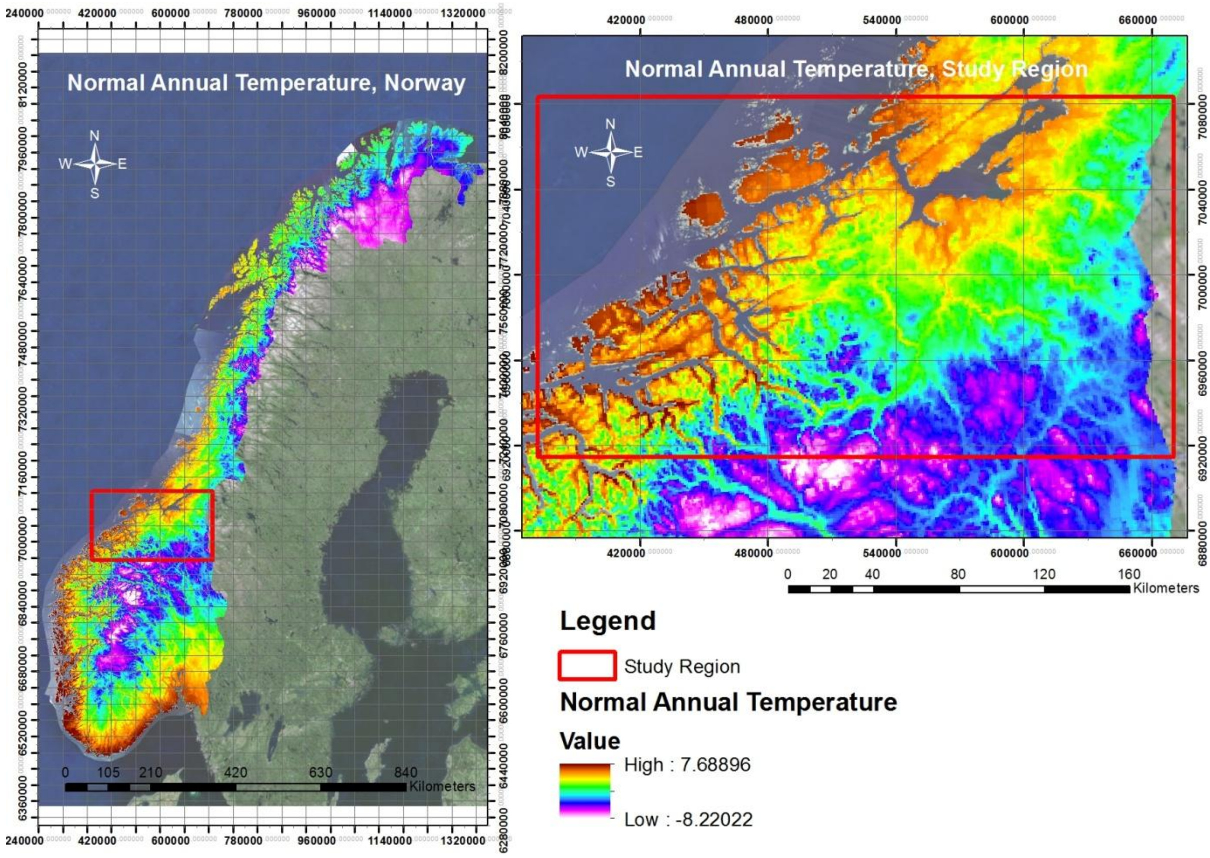


Figure 2-2 Norma annual temperature of selected region for period 1961-1990 (NMI)

2.6 PRECIPITATION

In Norway there are significant differences in annual precipitation. The wettest area locates on south-western part of Norway along coastal line of Atlantic Ocean. In this region mountain range locates near the coastal. Such relief caused the lifting of warm air mass which comes from Atlantic cyclones and adiabatic cooling leads to condensation and precipitation. Such precipitation type calls orographic or relief rainfall. During autumn and winter periods those areas experienced the largest amount of precipitation. Inland areas, which locates on eastern part of the country receives less precipitation.

Normal annual precipitation differs between 700-1000 mm/year in central and south-eastern areas and about 300-500 mm/year in northern part of Norway.

Within selected study area at the western part of Møre og Romsdal and Sør-Trøndelag counties experienced the highest normal annual precipitation due to influencing of coastal climate and closeness location of mountain range to coastal line, which in its tern brings a lot of orographic rainfalls with Atlantis cyclones. The normal annual precipitation at the western part of study area receives about 1500-2500 mm/year. The eastern areas of the region obtain approximately 700-1500 mm/year. (NMI)

The description of normal annual precipitation is presented in the Figure 2-3.

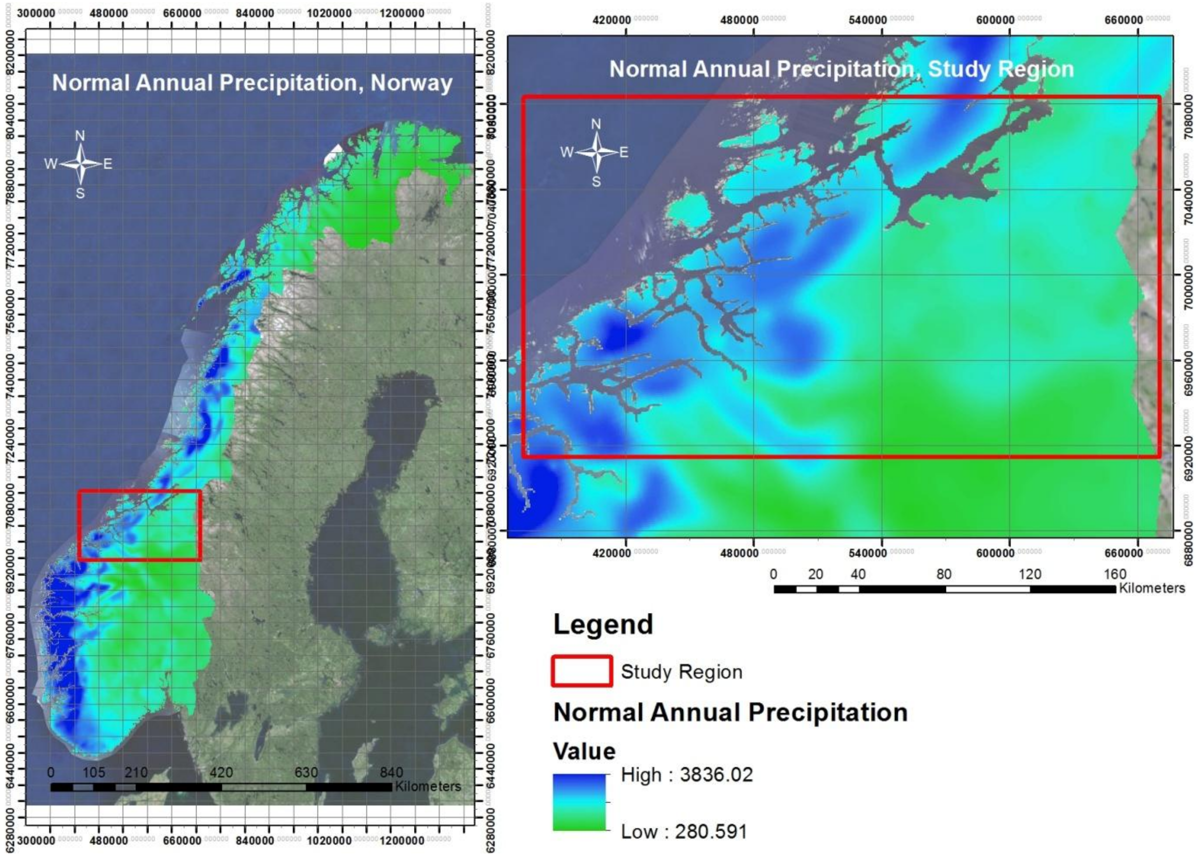


Figure 2-3 Norma annual precipitation of selected region for period 1961-1990 (NMI)

3 THEORY REVIEW

3.1 INTRODUCTION

Predicting of water processes behavior is the main aim of hydrological modeling. Many methods and researches have been made in order to solve that problem. Some of the methods become very popular and broadly used such as:

- Scaling from neighboring catchment;
- Using hydrological modeling for predicting runoff.

Grate challenge in hydrological predictions for ungauged basins comes from insufficient understanding of important physical hydrological processes. The complexity of the physical hydrological properties becomes as so due to their simultaneous representation. The concept of hydrological modeling is that physical properties of the catchment converted to numerical value which calls parameters. During this study project the aim was focused on application of regional modeling for estimating runoff from ungauged catchment. The concept of regional modeling is to use the parameters calculated from the catchments with available data series and to apply the same set of average best calibrated parameters to ungauged catchments within the same region. More detailed description of theory comes in bellow sections.

3.2 THE ROLE OF HYDROLOGICAL MODELLING AND IT'S COMPONENTS

The quantitative description of the characteristics of water is the subject of hydrological modeling. The environment in which hydrological circle takes place is treated as system and the mechanisms that underlie the processes are embedded in models of these systems. The models can then be manipulated and used to simulate system responses. By simulating various alternatives, the consequences of the utilization can be assessed. Using different sets of meteorological input data allow the consequences to be estimated under different climatic conditions. (Singh, 1995)

Modeling requires a systems view of the hydrological cycle (Figure 3-1). The physical hydrological cycle should be divided in three parts in order to be described as various systems which represent whole complexity of natural water movement processes. Such subsystems are:

- The atmospheric water system containing the processes of precipitation, evaporation and transpiration;
- The surface water system is responsible for the processes of snow accumulation and melt, overland flow, surface runoff, subsurface and groundwater outflow and runoff to streams and the ocean;
- The subsurface water system containing the processes of infiltration, ground water recharge, subsurface flow and groundwater flow.

The objective of hydrological system analysis is to study the system operation and predict its internal states and output. The inputs and outputs are measurable hydrological variables and the model's structure is a set of equations linking input to output. (Killingtveit and Sælthun, 1995)

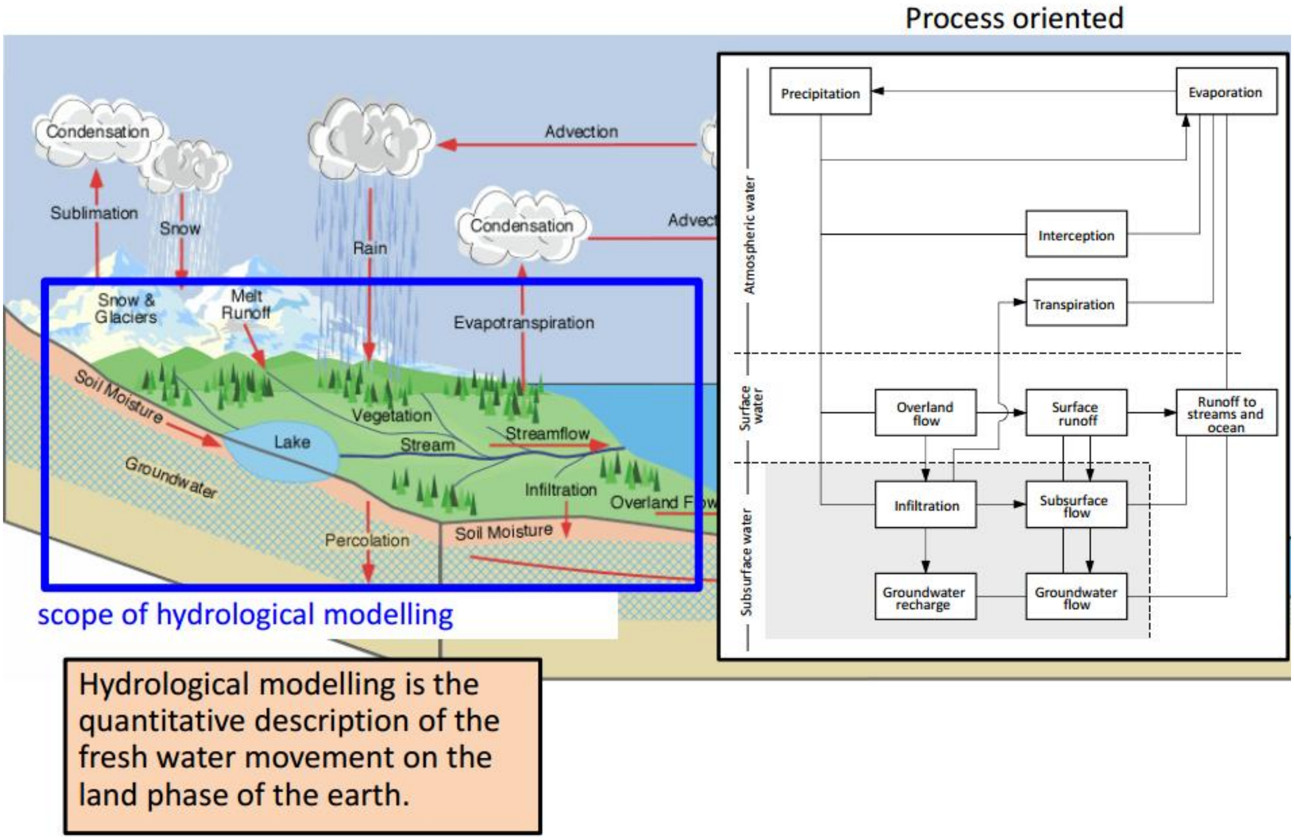


Figure 3-1 The systems view of hydrological cycle (Rinde, 2013a)

The input and the output of the model can be described as a function of time *I(t)* input and *O(t)* output. The system performs a transformation of the input into output by a transformation operator or equation. Due to great complications of natural processes it is not possible to describe all the physical phenomena within the watershed with exact physical laws. Knowing the concept of natural water movement it is possible to construct the model representing the most important processes, and their interaction within the total system. A conceptual knowledge of the physical system will still be valuable to determine the main processes, and to develop a simplified but useful model. (Killingtveit and Sælthun, 1995)

The catchment represents the elementary unit for most hydrological models. The runoff from a catchment is a function of a complex series of processes. Water from precipitation is moving through a series of storages in for example snow, soil and groundwater, through the influence of gravity. Finally, after a short or long delay, the water flows out as river runoff, but some also as evaporation back to the atmosphere and groundwater flow below the soil surface is closely linked to precipitation falling on the contributing catchment. The catchment represents the elementary unit for most hydrological models. (Rinde, 2013c)

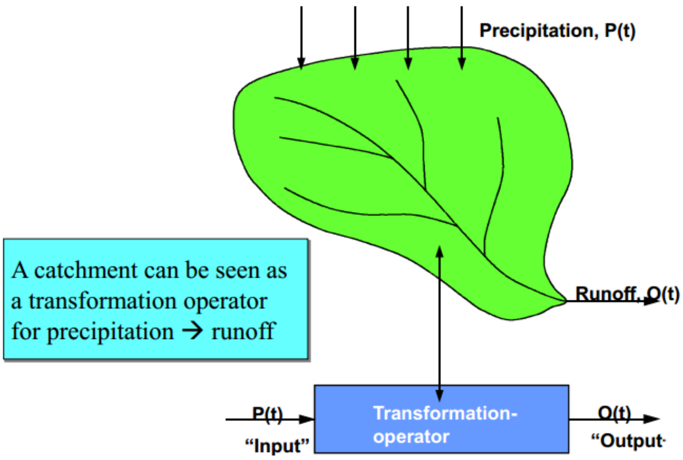


Figure 3-2 A catchment as a hydrological transformation operator (Rinde, 2013c)

Within each catchment there are three main steps should be identified and included:

- The first one is to understand how much areal precipitation is within the catchment. It is important to determine the average value for the rainfall, hens it is not always easy to obtain the average precipitation, based on several available point measurements
- The second important issue is to determine the amount of water which generates the stream from particular catchment
- Movement of water from the source to the outlet point is the next issue which should be considered. In the countries with cold climate the storage of snow and snow melt process should be included to the model. (Rinde, 2013c)

3.3 HYDROLOGICAL MODEL CLASSIFICATION

There are two main categories in hydrological model classification: 1) physical models and 2) abstract models. Physical model is the real scaled down and minimized copy of the object or the process. The abstract model is the model, the process in which can be described by mathematical equations. The equations can be set as description of the system and represent the algorithm, which in its tern can be coded to the computer program. The hydrological model classification can be divided by three main criteria:

- Randomness (deterministic of stochastic)
- Spatial variation (lumped or distributed)
- Time variability (time-depended, time -independent)

The models can be classified by complexity. The simplest type of model is a deterministic lumped time-independent model. The most complex type is the stochastic model with space variation in three dimensions and with time variation. (Killingtveit and Sælthun, 1995)

The scheme of hydrological model classification presented on Figure 3-3.

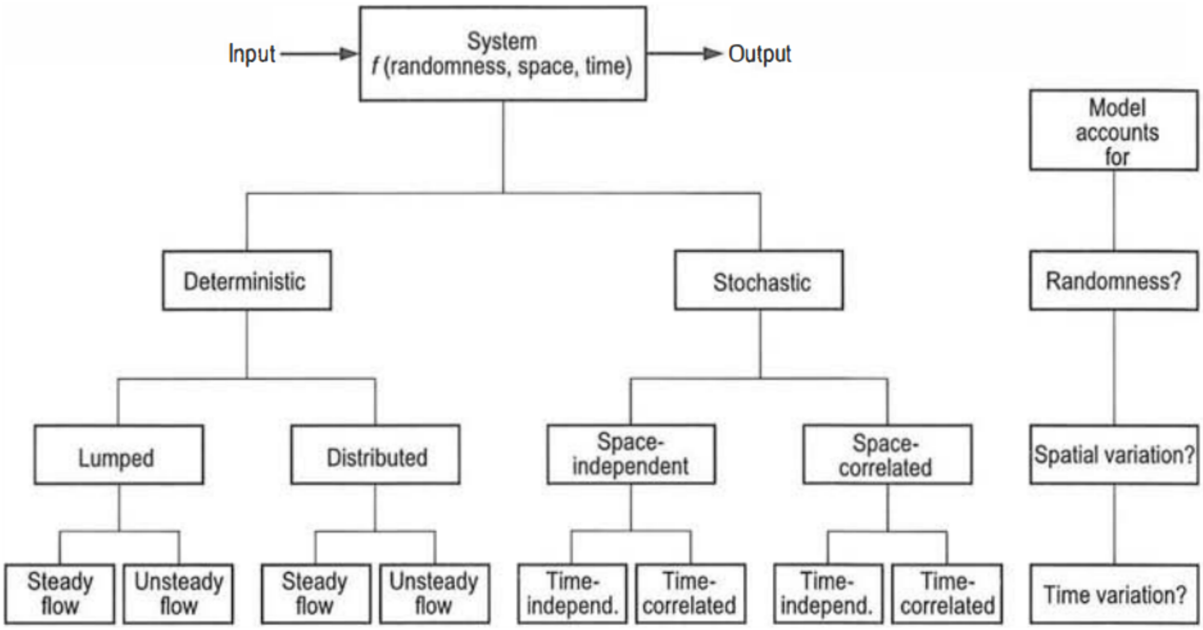


Figure 3-3 Classification of hydrological models adapted from (Chow et al., 1988)

3.3.1 LUMPED AND DISTRIBUTED HYDROLOGICAL MODELS

As was described above the hydrological models differs by complexity which in its turn have to be chosen by the needs of objectives should be achieved. There are lumped and distributed models.

Lumped model is the model in which a catchment is handled as one homogeneous unit and the models parameters applied to the whole catchment area. Distributed hydrological model differs from the lumped one by the grid representation of the catchment. Within distributed model the input parameters should be determined for each grid, e.g. soil type, land use and elevation are different within each sell of the catchment. Schematic representations of the lumped and distributed hydrological models are shown on Figure 3-4.

There are numbers of lumped and distributed models have been developed for hydrological modeling. Conceptual lumped rainfall-runoff models are: Stanford Watershed Model, HBV-model, TOPMODEL. The distributed rainfall-runoff modals are: The systeme Hydrologique Europeen (SHE) model, IHDM, LANDPINE-NTNU, ENKI-SINTEF. (Rinde, 2013c)

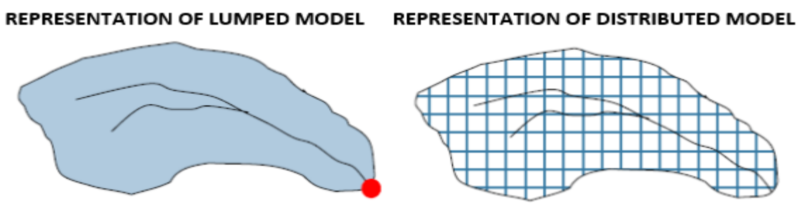


Figure 3-4 Concept of lumped and distributed hydrological models (Rinde, 2013c)

3.4 REGIONAL MODELLING

The objective of regional modeling is to estimate free model parameters set which can be applied everywhere within a region in order to estimate runoff in ungauged basins without any measured runoff time series.

Free model parameters are based on climate and landscape characteristics, and they are used to calculate the water balance in ungauged areas. The regional parameter set should be reliable and not too dependent of the catchment and time period used for calibration. The calibration and validation results are only can be utilized within the region.

In order to solve the ungauged catchment problem many researches and different approaches were developed. Early methods were mostly based on regressions of the model parameters values or runoff coefficients determined for gauged catchments against variables representing the characteristics of those catchments (Beven, 2000). The regression equations can be used in hydrological modeling for estimating the free parameters for ungauged catchments. There are at least two approaches that can apply as appropriate tools - the multi objective method and the Bayesian method. Within multi-objective method the model is performed for several possible parameter sets and catchments. On the basis of one or several error criteria it is possible to make judgments which parameter sets give acceptable simulations and which is not. This method provides a decision rule as how to select the parameter sets that performs satisfactory for all catchments. The several possible parameter sets is a result in the multi-objective method.

The Bayesian method based on estimation of probability distribution of the parameters. Parameter sets are given probability based on a quality measure describing the goodness of fit between observed and simulated values. Both the multi-objective method and the Bayesian methods consider the uncertainty in the choice of parameter sets values. The ENKI system utilized similar procedure as in the multi-objective method so that the ENKI model is performed for several numbers of catchments and iterated for possible range of several free parameters. These calibrated parameters are judged by R^2, which named as Nash efficiency.(Shrestha, 2012)

3.5 REGIONAL MODELLING WITH ENKI

The ENKI framework for hydrological modeling was invented by SINTEF Energy Research and Statkraft Companies. The ENKI modeling system contains tools for regional model setting and calibration. The objective of ENKI regional modeling is to calibrate the set of parameters in different catchments within selected region and to validate the obtained results. The best set of parameters should be used for extracting discharge in ungauged sites. The structure and procedure of ENKI described below, more detailed information can be fined in technical report of SINTEF Energy Research Company.

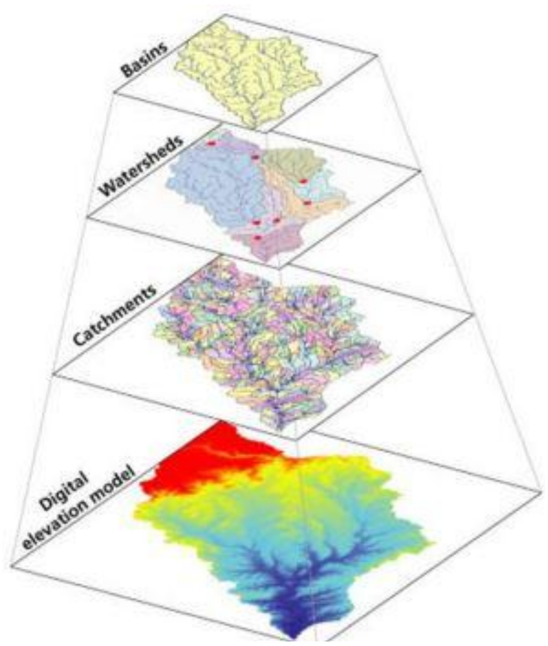
3.6 ENKI MODELLING SYSTEM

3.6.1 INTRODUCTION

The key principle within ENKI framework is that the input catchment is gridded and model applied in each cell.

The basic function of INKI is to build a model from a library of subroutines, and to run this model for a geographical region containing all process data. The INKI framework itself contains only the administrative functions and interfaces. All process data are GIS data; in raster form, as point-vector data, or as discrete variables. For each time step (each day), the framework reads a new time slice from the input database into the region, and writes a time slice from the region to the output database.

As mentioned above, the model is composed from a number of subroutines, which for each time step are organised by user-specified order. A subroutine is an instance of a method, which implements the simulation equations. The methods are separately coded and compiled as dynamic-link libraries. Each dynamic-link libraries implements a class inheriting from a parent class defined in the ENKI core. The operator builds a model by selecting the desired dynamic-link libraries, and linking their variable interfaces to the region's data. Hence, the subroutines in a model do not access each other, only the region's data.



The region contains number of maps collected in GIS format. Data in GIS presented in one of three formats, raster (regular grid), network (point collection) and scalar (single value). Digital vector and raster maps are shown on Figure 3-5. 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)

Figure 3-5 Digital vector and raster maps in GIS format (Rinde, 2013c)

3.6.2 THE ENKI MODEL STRUCTURE

The input data for ENKI model are observations of precipitation, air temperature and runoff. The air temperature data series are used for calculations of snow accumulation and melt.

The ENKI framework divided into two parts: the model and the region. The model part contains the equations and it navigates which one should be used. The equations or subroutines, operates in particular order. The region links the model (set of subroutine) to the region which contains all properties of the region such as catchment size, elevation, all maps, raster and all parameters which are used within equations in model.

The "All Subroutine" window contains from two parts. On the right side locates all the subroutines for particular model, which contains group of equations. All subroutine written in order and calculation within ENKI organized for each cell and each day.

On the left side of the "Add Subroutine" window locates all the routines which are available to be chosen from.

The ENKI hydrological model framework considered as flexible, due to availability of different subroutines. By changing combinations of subroutine, user is able to create a unique model. The HBV model is organised in different way with standard set of equations. The model structure for ENKI is shown in Figure 3-6.

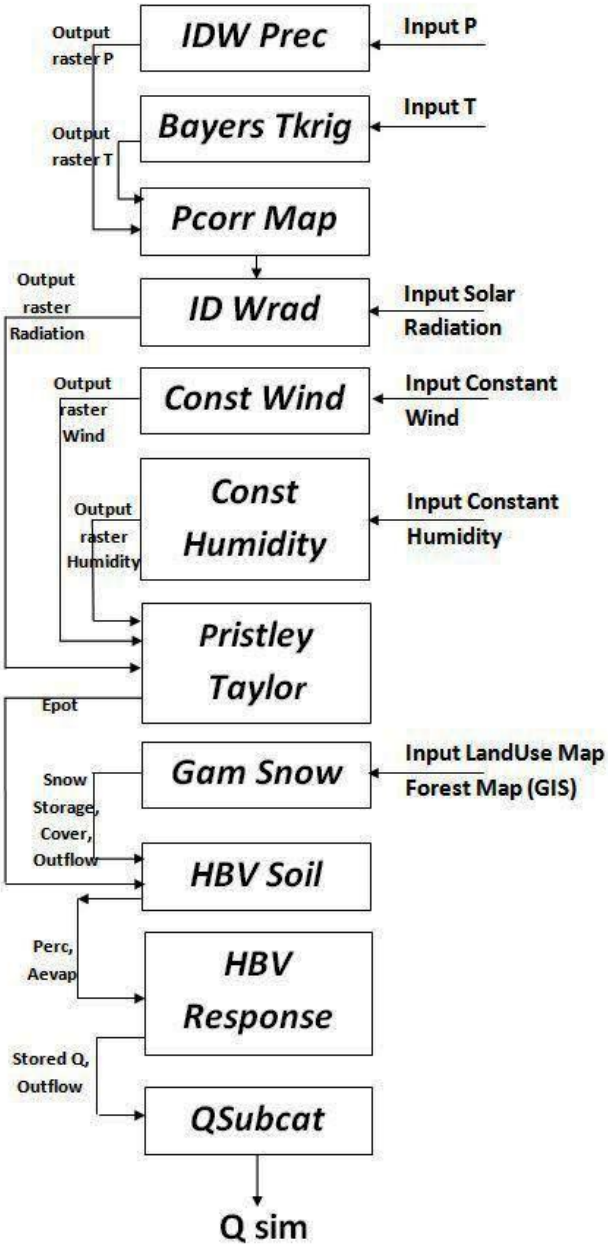


Figure 3-6 The ENKI model structure

3.6.3 THE PRECIPITATION AND TEMPERATURE INTERPOLATION

The first subroutines within ENKI call IDWPrec and Bayes Tkrig. Those subroutines calculate precipitation and air temperature in each cell for each day. It uses Inverse – Distance Weighted method to interpolate the precipitation and Bayes kriging method to interpolate air temperature along the region. First step for ENKI is to calculate input values of precipitation and air temperature from each available station and interpolate it to each cell. After that ENKI creates a rasters with interpolated precipitation and temperature.

3.6.4 GAM SNOW ROUTINE

The Gam Snow routine within ENKI model is represents energy balance. The input parameters are: temperature, radiation, precipitation, wind speed and humidity. The respond from Gam Snow routine is: snow cover/snow area, snow – water equivalent and the outflow of water from every cell from snow melt. The Gam Snow routine contains states and parameters. States is a raster which changes each time step and contains information about the present condition in the catchment. Parameters is spatial dependent values which describes the catchment and not dependent on the time.

3.6.5 PRIESTLEY-TAYLOR EVAPOTRANSPIRATION

The Priestley-Taylor method for calculating evapotranspiration is utilized within ENKI framework for entire model.

The Priestley-Taylor equation, a simplification of the Penman equation, was used to allow calculations of evapotranspiration under conditions where soil water supply limits evapotranspiration. The Priestley-Taylor coefficient, α, was calculated to incorporate an exponential decrease in evapotranspiration as soil water content decreases. The Priestley-Taylor method is appropriate for use when detailed meteorological measurements are not available. The data required to determine the parameter for α coefficient are net radiation, soil heat stream, average air temperature, and soil water content. (A. L. Flint 1991)

3.6.6 SOIL ROUTINE

Soil moisture routine computes storage of water in upper soil, evaporation from soil and vegetation and runoff generating precipitation (Rinde, 2013b).The ENKI uses the same soil moisture accounting as for the HBV model. It based on modification of the bucket theory in that it assumes a statistical distribution of storage capacities in a basin. This is the main part controlling runoff formation. This routine is based on the three parameters, BETA, LP and FC, as shown in the Figure 3-7. The BETA controls the contribution to the response function or the increase in soil moisture storage from each millimeter of rainfall or snow melt. LP is a soil moisture value above which evapotranspiration reaches its potential value, and FC is the maximum soil moisture storage capacity in the model. The parameter LP is given as a fraction of FC. (SMHI)

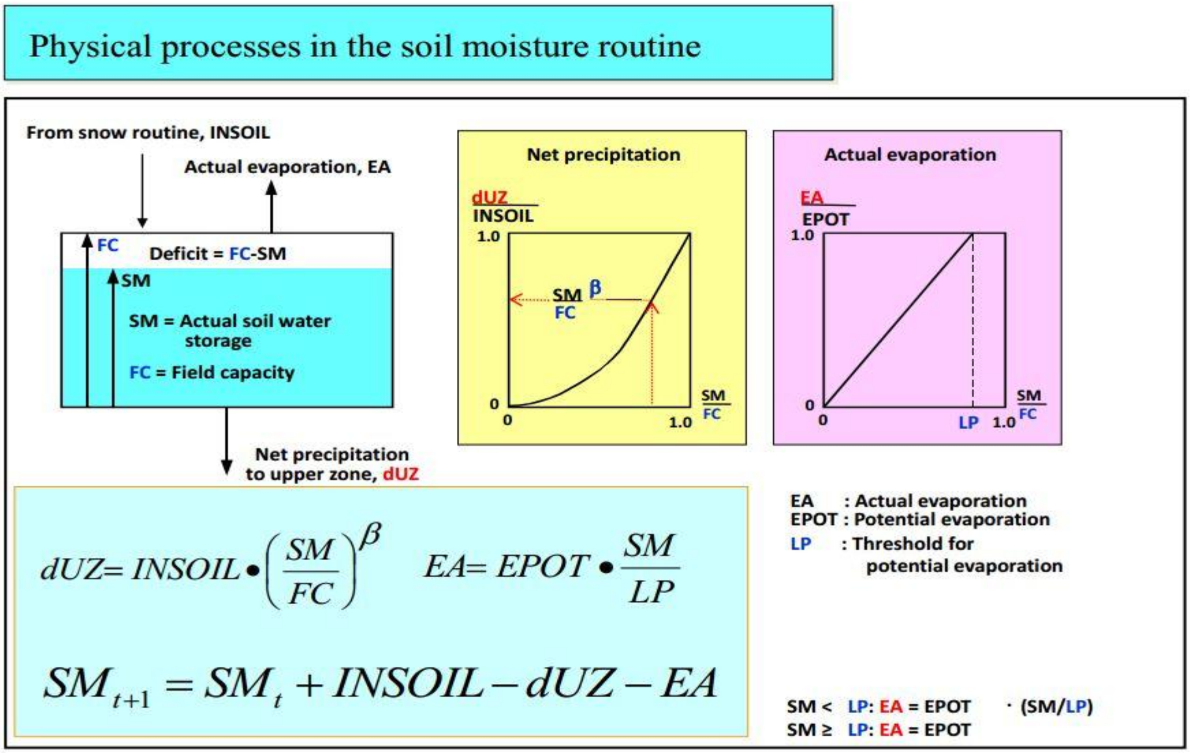


Figure 3-7 Soil moisture routine in the HBV-model (Killingtveit and Sælthun, 1995)

3.6.7 RESORSE FUNCTION AND ROUTING

The runoff generation routine is the response function which transforms excess water from the soil moisture zone to runoff. It also includes the effect of direct precipitation and evaporation on a part which represents lakes, rivers and other wet areas. The function consists of one upper, non-linear, and one lower, linear, reservoir. These are the origin of the quick (superficial channels) and slow (base-flow) runoff components of the hydrograph. Level pool routing is performed in lakes located at the outlet of a subbasin. The separation into submodels, defined by the outlets of major lakes, is thus of great importance for determining the dynamics of the generated runoff. The routing between subbasins can be described by the Muskingum method (Shaw, 1988). Each one of the subbasins has individual response functions (SMHI). Schematic representation of runoff response routine shown on Figure 3-8.

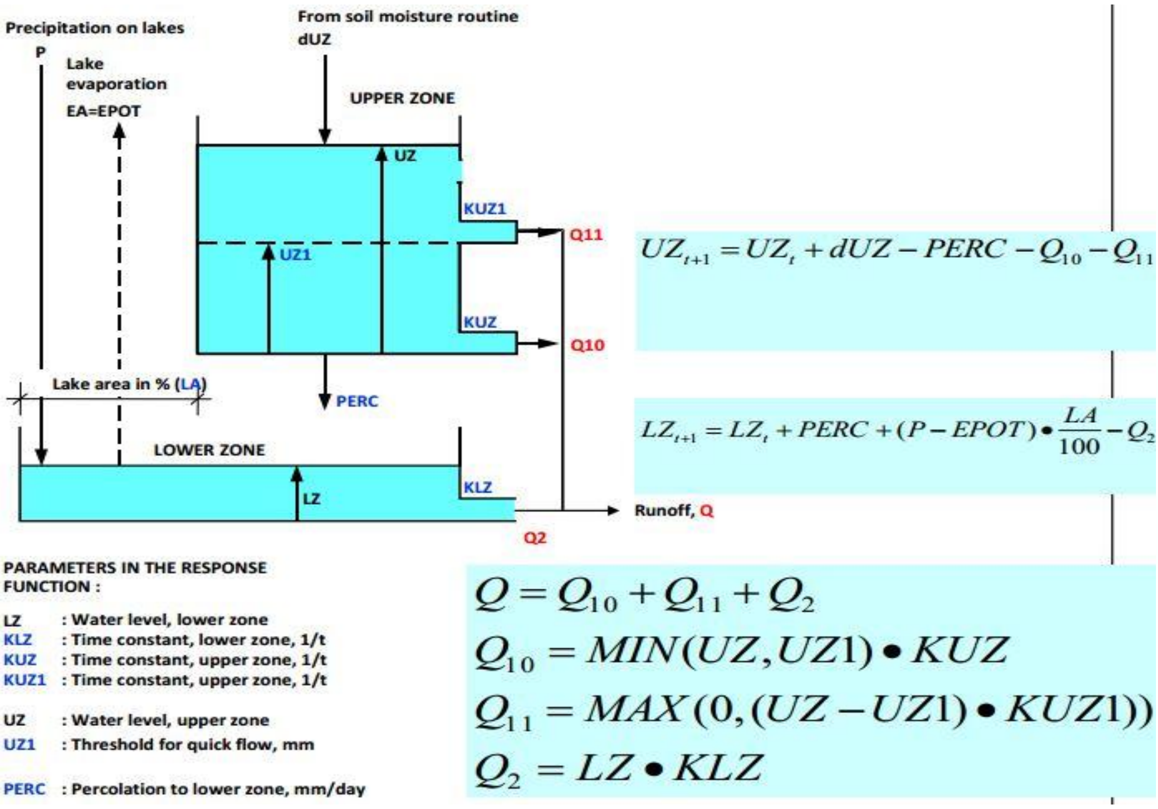


Figure 3-8 Runoff response routine in the HBV-model (Killingtveit and Sælthun, 1995)

3.6.8 LAKES IN ENKI MODEL

Lakes in ENKI are responding the same way as within HBV model.

Precipitation for lakes will be the same as for a non-forested zone at the same altitude and will be added to the lake water regardless of ice conditions in the same way for both rain and snow. Evaporation from lakes will be equal the potential evaporation but can be modified by a parameter and will occur only when there is no ice. Transformation of runoff is taking place after water routing through the lake according to a rating curve. If no specific rating curve for the lake is given as input, the model will assume a general rating curve. (SMHI)

3.7 ENKI MODEL CALIBRATION

The principles and techniques for ENKI model calibration described in following section. During the model calibration it is always necessary to have a clear understanding of the model structure, and to remember how the different parameters affect the model response. It is almost impossible to find the optimal set of parameters just by trial and error, due to the large number of possible combinations for all parameters.

For ENKI hydrological model calibration process it is very important to distinguish between confined and unconfined parameters. Free parameters must be determined by a process of calibration of the model. The range for free parameters are determined before the model is taken in operational use, and later kept constant. The model may be recalibrated as more and better input data are collected for the catchment. The Monte Carlo parameter auto calibration is used within ENKI framework. The most important free parameters for ENKI and HBV model are listed in Table 3-1. The initial set of parameters for further calibration with ENKI is created after calibration from 2000 to 2001 year.

Table 3-1 Important parameters in the HBV and ENKI model (Killingtveit and Sælthun, 1995)

Name	Meaning	Value range	Default value	Units
Tx	Threshold temperature Rain/Snow	-1.0 -2.0	1.0	°C
Ts	Threshold temperature for snowmelt	-1.0 -2.0	0.0	°C
Cx	Degree-day factor	3.0 -6.0	4.0	mm/°C*Day
CFR	Re-freezing efficiency	0.0 -0.01	0.005	n/a
PKORR	Precipitation correction: Rainfall	1.05 -1.2	1.05	n/a
SKORR	Precipitation correction: Snowfall	1.15 -1.5	1.2	n/a
TTGRAD	Temperature lapse rate for clear days	-0.6 - -1.0	-1.0	°C/100m
TVGRAD	Temperature lapse rate during precip.	-0.4 - -0.6	-0.4	°C/100m
PGRAD	Precipitation lapse rate	1.0 – 1.10	1.05	n/a
FC	Field capacity in soil moisture zone	75 - 300	150	mm
LP	Threshold value for potential evapotronspiration in soil moisture	1.0 – 4.0	2.0	n/a
BETA	Parameter in soil moisture routine	1.0 – 4.0	2.0	n/a
UZL	Threshold level for quick runoff in Upper zone	10 - 40	20	mm
KUZ1	Recession constant in Upper zone	0.1 – 0.5	0.3	1/day
KUZ	Recession constant in Upper zone	0.05 – 0.15	0.1	1/day
PERC	Percolation from Upper to Lowe zone	0.5 – 1.0	0.6	mm/day
KLZ	Recession constant for Lower zone	0.005 – 0.002	0.001	1/day

3.7.1 CALIBRATION PROCESS

Model calibration in this context means to determine the set of free parameters in the model that gives the best possible correspondence between observed and simulated runoff or a catchment. A general method for model calibration process is performed in Figure 3-9.

Hydrological model calibration is a trial and error procedure, where free parameters are chosen, model simulation performed and the computed and observed runoff compared. The most difficult part of the procedure is the evaluation of the difference between observed and simulated runoff, and to decide which parameters should be changed and for how much. To decide if another set of parameters really give better fit for the model, a method or criterion to determine the goodness of fit is also needed. Two main types of methods are used: subjective and objective methods.

The subjective methods are usually based on study of plots of input data and observe and computed hydrographs. Flow duration curves and cumulative deviation curves may be used.

By using an objective method an error function has to be defined, to uniquely (objectively) define the goodness of fit. Several types of error functions are used in model calibration all based on a function of type $f(Q_{obs} - Q_{sim})$.

$$R^2 = \frac{\sum (Q_0 - \overline{Q}_0)^2 - \sum (Q_s - Q_0)^2}{\sum (Q_0 - \overline{Q}_0)^2}$$

Where:

Q_o = Observed runoff

Q_o= Average runoff

Q_s = Simulated runoff

The R2 error function can vary from - ∞ to + 1 .0, the higher the value the better the model fit. In addition to the R^2 criterion three other types of error functions are commonly used:

- Cumulative difference (water balance) $\sum(Q_0 - Q_s)$
- Cumulative squared difference $\sum(Q_0 - Q_s)^2$
- Cumulative absolute difference $\sum|Q_0 - Q_s|$

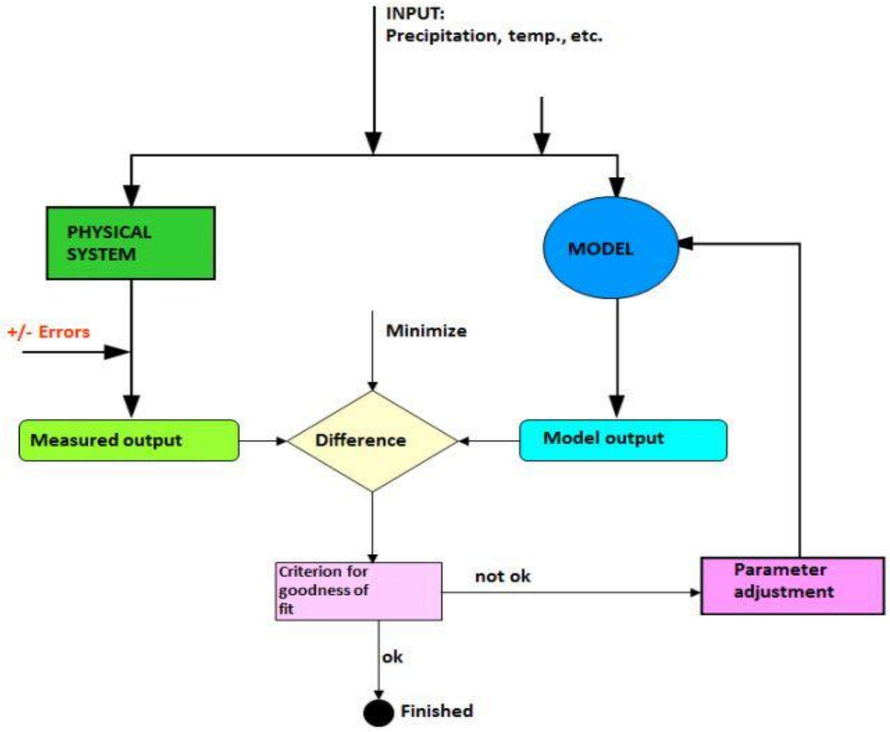


Figure 3-9 Model calibration process (Killingtveit and Sælthun, 1995)

4 DATA ACQUISITION AND CONTROL

4.1 INTRODUCTION

Collecting, storing and proceeding of meteorological and hydrological data are national responsibility in Norway. The Norwegian Water Resources and Energy Directorate (NVE) is the main national organization which responsible for hydrological data. Norwegian consulting companies, like Sweco Company, also has their own hydrological data, collected as a part of planning routine. For this study project, part of hydrological data series was borrowed from Sweco Company by a mutual agreement with owners of the data. The other part of hydrological data was collected from “HYDRA II” database, which available as open sours from NVE.

The meteorological data was collected from the Norwegian Meteorological Institute through eKlima web portal. EKlima is a web portal for all users which gives free access to the climate database of the Norwegian Meteorological Institute. The meteorological database provides data from all present and past weather stations of the Norwegian Meteorological institute, also data from other institutions by a reciprocal agreement that are allowed for distribution. (Norwegian Meteorological Institute)

The hydro-meteorological data can hold numbers of errors. Most errors occur at the gauge. Quality assurance control measures should be an integrated part of the processing line.

Quality assurance has three main purposes:

- To prevent errors from occurring by sound design and administration of the data collection system and processing line
- To detect and rectify error sources at sensor and in the processing line
- To detect and correct or reject erroneous data

The control system should be an integral part of the data collection and processing system, both technically and administratively.

Data errors can be:

- Jumps
- Single errors
- Long term trends
- Variations

The jumps and single errors types are easiest to detect, and should normally not pass the primary control. Trends are far more difficult to detect.

A quality control system should have three main stages - a primary stage, run as the data is received – a secondary stage, run yearly, checking consistency – and a tertiary stage, checking homogeneity and trends. (Killingtveit and Sælthun, 1995)

4.2 ACQUISITION OF METEOROLOGICAL DATA

4.2.1 PRECIPITATION DATA COLLECTION

The precipitation data series for selected study region was obtained from the eKilma web portal, which is available for all users after simple registration. The rainfall data is input parameter for ENKI model. In order to retrieve rainfall data from eKlima following steps should be maid:

- At first should be selected the variable of interest and period of observation. In that thesis project daily precipitation data series are used for the period from 01/01/2000 to 01/01/2012.
- At the next phase the stations should be selected from the region of interest. The selected study region for this thesis work includes Nord-Trøndelag, Sør-Trøndelag, Hedmark, Oppland and Møre og Romsdal Conties (Figure 4-1). Table 4-1 represents all selected rainfall stations with description of location.
- The report format for delivery the data series from eKlima web portal have to be chosen after selecting preferable precipitation stations. Eklima generates automatic report with rainfall data series and can be delivered on personal e-mail.

Table 4-1 Selected precipitation stations with detailed description of location

№	Stnr	Name	UTM	X Easting	Y Northing	Altitude	County
1	69100	VÆRNES	32V	596468.92	7038211.26	12	Nord-Trøndelag
2	69150	KVITHAMAR	32V	593598.07	7041358.82	40	Nord-Trøndelag
3	69420	KLUKSDAL	32V	645644.55	7020697.97	521	Nord-Trøndelag
4	69550	ØSTÅS I HEGRA	32V	617205.72	7042005.76	175	Nord-Trøndelag
5	69960	BURAN	32V	625631.8	7068303.46	182	Nord-Trøndelag
6	70150	VERDAL - REPPE	32V	631839.11	7075484.09	81	Nord-Trøndelag
7	71000	STEINKJER - SØNDRE EGGE	32W	619755.04	7101824.35	6	Nord-Trøndelag
8	71200	MOSVIK - TRØAHAUGEN	32V	598367.62	7077693.52	39	Nord-Trøndelag
9	71280	LEKSVIK - MYRAN	32V	579502.23	7062980.26	138	Nord-Trøndelag
10	70850	SNÅSA - KJEVLIA	33W	376940.45	7117145.34	195	Nord-Trøndelag
11	70930	SNÅSA - NAGELHUS	33W	375892.1	7127259.91	107	Nord-Trøndelag
12	10300	HÅSJØEN - SOLGLØTT	32V	643082.22	6929591.8	650	Sør-Trøndelag
13	10380	RØROS LUFTHAVN	32V	620824.27	6940696.16	625	Sør-Trøndelag
14	10600	AURSUND	32V	625633.78	6951624.84	685	Sør-Trøndelag
15	63580	ÅNGÅRDSVATNET	32V	510075.37	6948926.94	596	Sør-Trøndelag
16	63705	OPPDAL - SÆTER	32V	534225.89	6941679.53	604	Sør-Trøndelag
17	65230	HEMNE - LENES	32V	500577.29	7014703.09	45	Sør-Trøndelag
18	66070	SKJENALDFOSSEN I ORKDAL	32V	536558.17	7018565.46	84	Sør-Trøndelag
19	66620	RENNEBU - RAMSTAD	32V	542511	6970712.45	223	Sør-Trøndelag
20	67150	LEINSTRAND	32V	563788.1	7022768.47	13	Sør-Trøndelag
21	68270	LØKSMYR	32V	572201.21	7012191.08	173	Sør-Trøndelag

22	68420	AUNET	32V	629747.12	6994375.53	302	Sør-Trøndelag
23	68840	STUGUDAL - KÅSEN	32V	645482.15	6977148.89	730	Sør-Trøndelag
24	71810	ÅFJORD - MOMYR	32W	574527.66	7109085.74	280	Sør-Trøndelag
25	61820	ERESFJORD	32V	454212.62	6948415.5	14	Møre Og Romsdal
26	62700	HUSTADVATN	32V	410764.3	6976634.73	80	Møre Og Romsdal
27	62900	EIDE PÅ NORDMØRE	32V	418178.58	6974523.63	49	Møre Og Romsdal
28	63100	ØKSENDAL	32V	470403.48	6950682	47	Møre Og Romsdal
29	63530	HAFSÅS	32V	498830.94	6930941.26	698	Møre Og Romsdal
30	64900	RINDAL	32V	511154.35	6989842.21	228	Møre Og Romsdal
31	14050	SJOA	32V	529441.17	6838179.46	330	Oppland
32	15430	BØVERDAL	32V	460057.26	6843298.46	701	Oppland
33	15480	SKJÅK II	32V	471981.81	6860670.82	374	Oppland
34	15660	SKJÅK	32V	456418.66	6863463.22	432	Oppland
35	16270	HØVRINGEN	32V	524795.08	6862038.44	935	Oppland
36	16610	FOKSTUGU	32V	514934.65	6886834.95	973	Oppland
37	16790	LESJA - SVANBORG	32V	495782.59	6885957.95	551	Oppland
38	420	HEGGERISET - NORDSTRAND	32V	658528.32	6842706.86	481	Hedmark
39	730	VALDALEN	33V	352289.29	6885846.02	794	Hedmark
40	770	ELLEFSPLASS	32V	627573.56	6899322.12	713	Hedmark
41	810	TUFSINGDAL - MIDTDAL	32V	641760.6	6908098.29	687	Hedmark
42	8450	ATNDALEN - RØNNINGEN	32V	579140.78	6851811.17	535	Hedmark
43	8720	ATNSJØEN	32V	559912.17	6862474.08	749	Hedmark
44	8970	EINUNNA KRAFTVERK	32V	569742.16	6900703.7	746	Hedmark
45	9870	BLANKTJERNMOEN I KVIKNE	32V	573174.87	6923198.37	690	Hedmark
46	66850	KVIKNE I ØSTERDAL	32V	565263.93	6941242.99	549	Hedmark

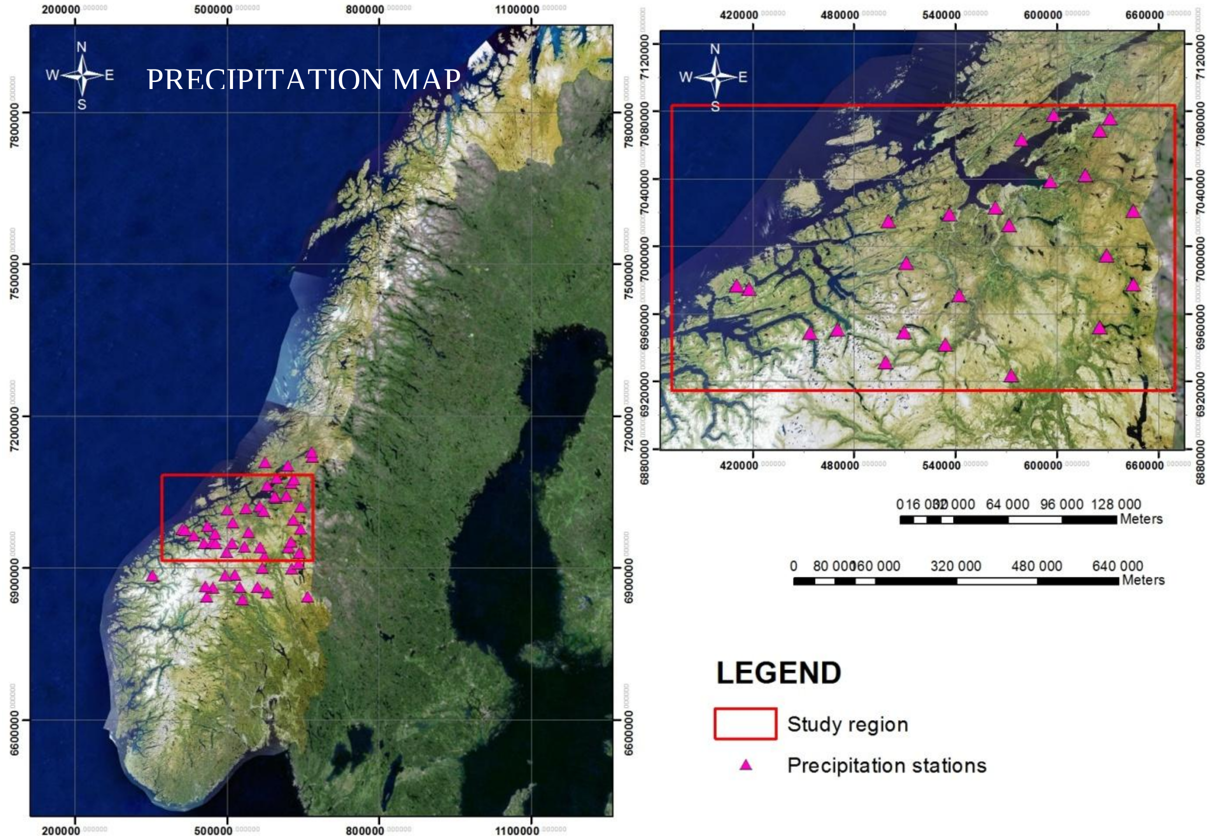


Figure 4-1 Projected map of study region with precipitation stations (ESRI)

4.2.1.1 PRICIPITATION DATA QUALITY CHECK

There are 46 precipitation stations were collected during data acquisition survey. Some of them are locate outside of the boundaries of selected study region. The 32 precipitation stations locate within the selected region were further processed and checked for errors and homogeneity. Stations located within selected region with determined number of missing values are tabulated in Table 4-2.

In order to determine possible error in precipitation data series following steps were made:

1) Visual inspection of the data
2) Accumulation plot for check long series time development
3) Double mass analysis for consistency of recorded time series

Table 4-2 Precipitation data availability

№	Station Name	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Missing Data
1	VÆRNES	×	×	×	×	×	×	×	×	×	×	×	×	×	2
2	KVITHAMAR			×	×	×	×	×	×	×	×	×	×	×	930
3	KLUKSDAL		×	×	×	×	×	×	×	×	×	×	×	×	244
4	ØSTÅS I HEGRA	×	×	×	×	×	×	×	×	×	×	×	×	×	0
5	BURAN	×	×	×	×	×	×	×	×	×	×	×	×	×	7
6	VERDAL - REPPE	×	×	×	×	×	×	×	×	×	×	×	×	×	0
7	MOSVIK - TRØAHAUGEN	×	×	×	×	×	×	×	×	×	×	×	×	×	4
8	LEKSVIK - MYRAN	×	×	×	×	×	×	×	×	×	×	×	×	×	6
9	HÅSJØEN - SOLGLØTT	×	×	×	×	×	×	×	×	×	×	×	×	×	159
10	RØROS LUFTHAVN				×	×	×	×	×	×	×	×	×	×	1301
11	AURSUND	×	×	×	×	×	×	×	×	×	×	×	×	×	25
12	ÅNGÅRDSVATNET	×	×	×	×	×	×	×	×	×	×	×	×	×	0
13	OPPDAL - SÆTER	×	×	×	×	×	×	×	×	×	×	×	×	×	0
14	HEMNE - LENES	×	×	×	×	×	×	×	×	×	×	×	×	×	7
15	SKJENALDFOSSEN I ORKDA	×	×	×	×	×	×	×	×	×	×	×	×	×	6
17	RENNEBU - RAMSTAD	×	×	×	×	×	×	×	×	×	×	×	×	×	1
18	LEINSTRAND	×	×	×	×	×	×	×	×	×	×	×	×	×	5
19	LØKSMYR	×	×	×	×	×	×	×	×	×	×	×	×	×	6
20	AUNET	×	×	×	×	×	×	×	×	×	×	×	×	×	3
21	STUGUDAL - KÅSEN	×	×	×	×	×	×	×	×	×	×	×	×	×	20
22	ERESFJORD	×	×	×	×	×	×	×	×	×	×	×	×	×	13
23	ISTAD KRAFTSTASJON	×	×	×	×	×	×	×	×	×	×	×	×	×	1131
24	HUSTADVATN	×	×	×	×	×	×	×	×	×	×	×	×	×	5
25	EIDE PÅ NORDMØRE	×	×	×	×	×	×	×	×	×	×	×	×	×	1
26	ØKSENDAL	×	×	×	×	×	×	×	×	×	×	×	×	×	0
27	SUNNDALSØRA III	×	×	×	×	×	×	×	×	×	×	×	×	×	254
28	HAFSÅS	×	×	×	×	×	×	×	×	×	×	×	×	×	10
29	HALSAFJORD II	×	×	×	×	×	×	×	×	×	×	×	×	×	387
30	ÅLVUNDFJORD	×	×	×	×	×	×	×	×	×	×	×	×	×	192
31	RINDAL	×	×	×	×	×	×	×	×	×	×	×	×	×	97
32	BLANKTJERNMOEN I KVIKN	×	×	×	×	×	×	×	×	×	×	×	×	×	6

Within visual inspection of the data it was defined that several stations has large amount of missing values. The decision was made to drop the stations with long term of missing data and proceed the work with remaining stations which tabulated in Table 4-3. Accumulated plot and double mass analysis was carried out.

Accumulated values at some station were plotted against the values at other nearest station. Correct data represent good linear development over the time period.

Table 4-3 Selected precipitation stations for modeling process

№	Station Name	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Missing Data
1	VÆRNES	×	×	×	×	×	×	×	×	×	×	×	×	×	2
2	KLUKSDAL		×	×	×	×	×	×	×	×	×	×	×	×	244
3	ØSTÅS I HEGRA	×	×	×	×	×	×	×	×	×	×	×	×	×	0
4	BURAN	×	×	×	×	×	×	×	×	×	×	×	×	×	7
5	VERDAL - REPPE	×	×	×	×	×	×	×	×	×	×	×	×	×	0
6	MOSVIK - TRØAHAUGEN	×	×	×	×	×	×	×	×	×	×	×	×	×	4
7	LEKSVIK - MYRAN	×	×	×	×	×	×	×	×	×	×	×	×	×	6
8	AURSUND	×	×	×	×	×	×	×	×	×	×	×	×	×	25
9	ÅNGÅRDSVATNET	×	×	×	×	×	×	×	×	×	×	×	×	×	0
10	OPPDAL - SÆTER	×	×	×	×	×	×	×	×	×	×	×	×	×	0
11	HEMNE - LENES	×	×	×	×	×	×	×	×	×	×	×	×	×	7
12	SKJENALDFOSSEN I ORKDAL	×	×	×	×	×	×	×	×	×	×	×	×	×	6
13	RENNEBU - RAMSTAD	×	×	×	×	×	×	×	×	×	×	×	×	×	1
14	LEINSTRAND	×	×	×	×	×	×	×	×	×	×	×	×	×	5
15	LØKSMYR	×	×	×	×	×	×	×	×	×	×	×	×	×	6
16	AUNET	×	×	×	×	×	×	×	×	×	×	×	×	×	3
17	STUGUDAL - KÅSEN	×	×	×	×	×	×	×	×	×	×	×	×	×	20
18	ERESFJORD	×	×	×	×	×	×	×	×	×	×	×	×	×	13
19	HUSTADVATN	×	×	×	×	×	×	×	×	×	×	×	×	×	5
20	EIDE PÅ NORDMØRE	×	×	×	×	×	×	×	×	×	×	×	×	×	1
21	ØKSENDAL	×	×	×	×	×	×	×	×	×	×	×	×	×	0
22	HAFSÅS	×	×	×	×	×	×	×	×	×	×	×	×	×	10
23	RINDAL	×	×	×	×	×	×	×	×	×	×	×	×	×	97
24	BLANKTJERNMOEN I KVIKNE	×	×	×	×	×	×	×	×	×	×	×	×	×	6

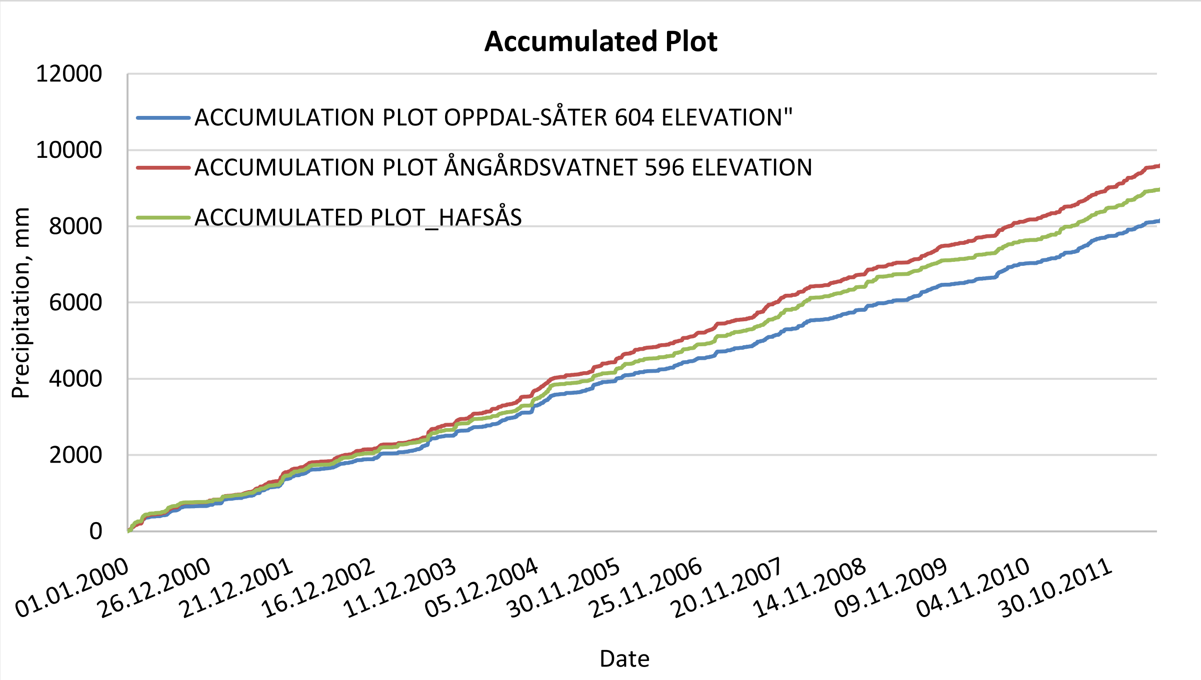


Figure 4-2 Accumulated plot of three neighboring precipitation stations

The plots of three neighboring rainfall stations (Figure 4-2), the Oppdal, Åndprdsvatnet and Hafsås stations are show good linear development over the time period. It is indicates that the data is correct.

Double mass analysis was also carried out in order to check the consistency of a hydrological data series (Figure 4-3). Double mass analysis is considered as an essential tool before utilizing data for modeling purpose. (http://www.wikipedia.org/). The double mass plot shows consistent linier development, which can refer to good quality of the rainfall data.

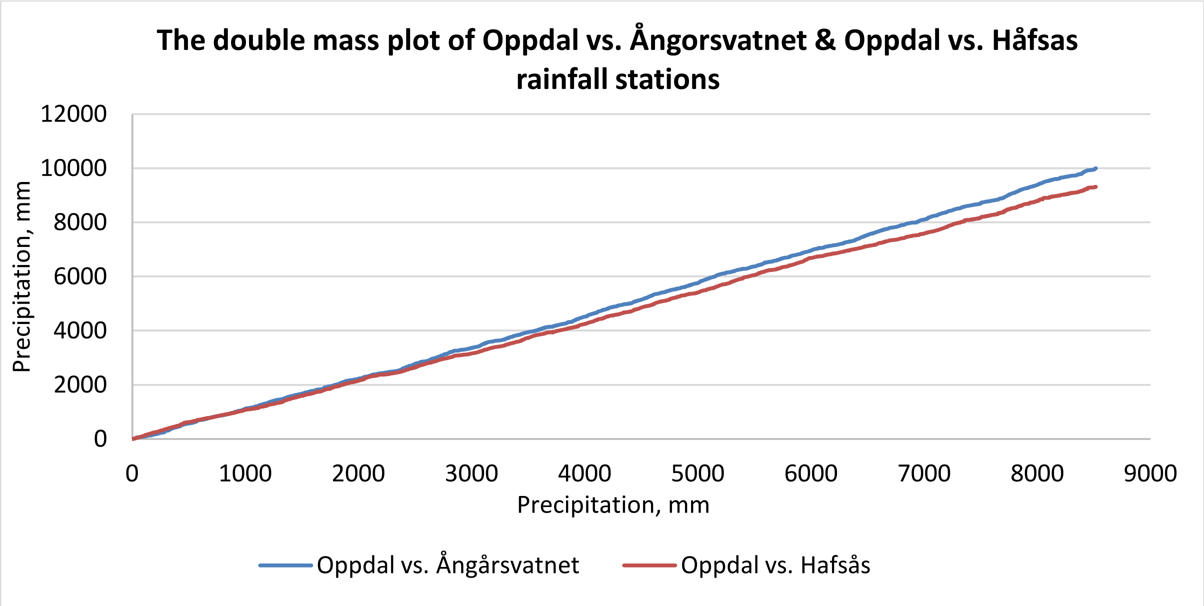


Figure 4-3 The precipitation double mass plot

The pattern of local precipitation during study period from 2000 to 2012 year has been undertaken based on daily recorded rainfall data. This is displayed in Figure 4-4. The values of average mean precipitation for study period are shown in Table 4-4.

It can be seen that the precipitation throughout the period consists of spikes of high and low rainfall events. It is noted that the period of lower rainfall events are within late spring and summer months and higher events are during autumn and winter time period. The Oksendal, Eide på Nordmore, Hustadvatn, Hemne – Lenes and Eresfjord stations witch locates close to the coastal line shows much higher spikes.

Table 4-4 Monthly average precipitation for 2000-2012 period

№	Station Name	Jan	Feb	March	April	May	Juny	July	Aug	Sep	Oct	Nov	Dec	Yearly Mean
1	VÆRNES	2.42	2.40	2.32	1.23	1.93	2.38	2.68	2.59	3.49	2.23	2.56	2.68	2.41
2	KLUKSDAL	2.71	2.35	2.08	1.46	2.20	2.84	3.60	3.16	3.82	2.35	2.69	2.55	2.65
3	ØSTÅS I HEGRA	3.22	3.22	3.18	1.70	2.55	3.35	3.55	3.70	4.69	2.93	3.20	3.27	3.21
4	BURAN	2.09	1.82	1.76	1.27	2.02	2.62	3.32	2.68	3.52	2.23	2.22	2.25	2.32
5	VERDAL - REPPE	2.67	2.21	2.13	1.31	2.12	2.66	3.17	2.85	3.72	2.34	2.45	2.54	2.51
6	MOSVIK - TRØAHAUGEN	3.90	3.45	3.42	1.73	1.75	2.10	2.20	2.40	3.80	3.02	3.46	3.86	2.92
7	LEKSVIK - MYRAN	5.53	4.75	4.85	2.68	2.35	2.72	2.30	2.85	4.81	4.10	4.90	5.24	3.92
8	AURSUND	2.09	1.79	1.42	0.96	1.44	2.27	2.84	2.93	2.65	1.58	1.88	1.57	1.95
9	ÅNGÅRDSVATNET	2.40	2.25	2.16	1.07	1.06	2.04	2.51	2.90	2.73	1.66	2.54	2.12	2.12
10	OPPDAL - SÆTER	2.27	1.95	1.63	0.90	0.94	1.92	2.67	2.69	1.96	1.15	2.12	1.53	1.81
11	HEMNE - LENES	5.77	5.39	4.91	2.52	2.31	3.15	2.30	3.57	5.42	3.97	5.54	5.44	4.19
12	SKJENALDFOSSEN I ORKDAL	4.46	3.95	3.62	1.89	2.07	2.69	2.53	3.17	3.97	3.20	4.16	3.88	3.30
13	RENNEBU - RAMSTAD	2.48	2.20	2.05	1.17	1.34	2.60	2.59	2.70	2.57	1.69	2.45	2.09	2.16
14	LEINSTRAND	2.47	2.48	2.15	1.23	1.82	2.34	2.43	2.91	3.65	2.29	2.52	2.31	2.38
15	LØKSMYR	4.06	3.76	3.37	1.79	2.36	2.94	2.98	3.24	4.15	2.92	3.87	3.33	3.23
16	AUNET	2.88	2.65	2.39	1.22	1.84	2.97	3.20	3.48	3.89	2.21	2.52	2.46	2.64
17	STUGUDAL - KÅSEN	3.19	2.72	2.38	1.46	1.82	2.76	3.48	3.11	3.12	1.99	2.46	2.06	2.55
18	ERESFJORD	4.89	5.03	4.43	2.41	2.80	4.07	3.23	4.66	4.70	3.82	5.19	4.74	4.17
19	HUSTADVATN	6.90	6.60	5.57	3.61	3.93	4.67	3.30	6.03	9.22	6.77	6.94	6.72	5.85
20	EIDE PÅ NORDMØRE	7.32	7.59	6.24	3.46	3.54	4.65	2.93	5.58	9.22	6.85	7.62	7.29	6.03
21	ØKSENDAL	3.79	3.89	3.22	1.69	2.07	3.05	2.44	3.78	4.67	2.71	4.24	3.73	3.27
22	HAFSÅS	2.84	2.18	2.20	0.91	0.97	1.93	2.21	2.52	1.42	1.47	2.50	1.85	1.92
23	RINDAL	4.04	3.62	3.54	1.71	1.73	3.24	2.44	3.84	4.54	2.84	4.06	3.84	3.28
24	BLANKTJERNMOEN I KVIKNE	1.12	0.87	0.84	0.67	1.16	2.17	2.71	2.81	1.75	1.10	1.07	0.75	1.42

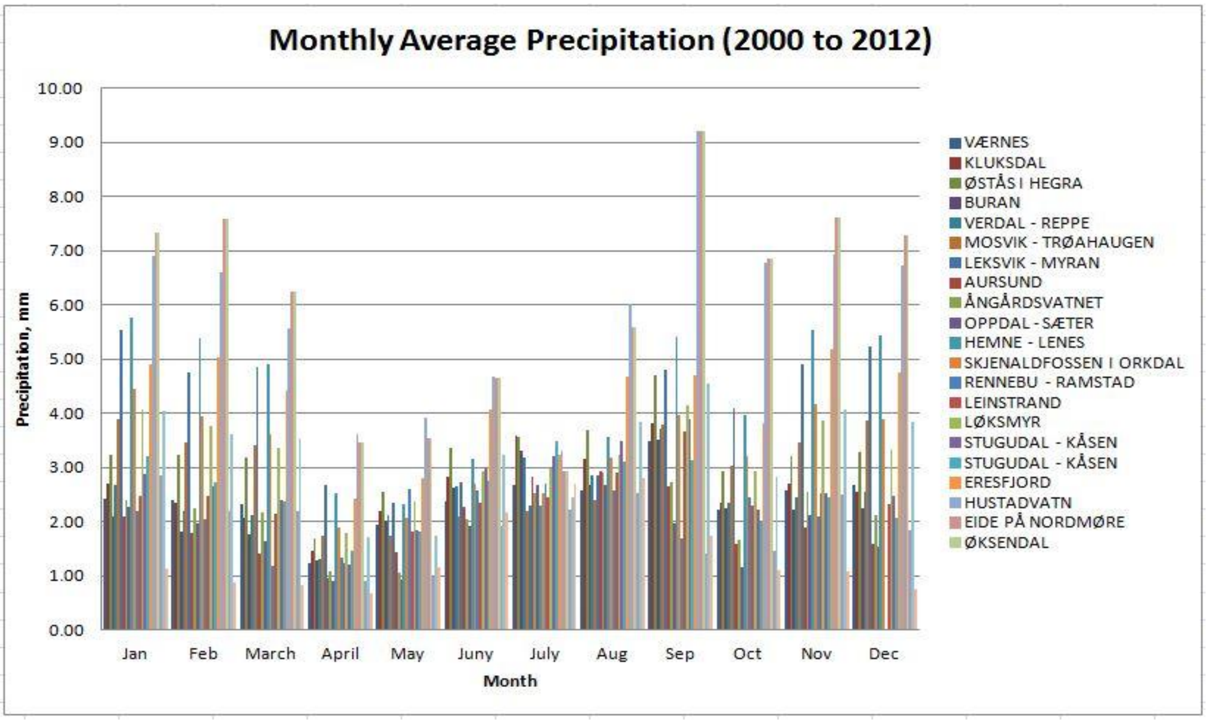


Figure 4-4 Monthly average precipitation pattern of the region

4.2.1.2 PRECIPITATION MISSING DATA INTERPOLATION

Rainfall data quality check and missing data identification is important before handling the hydrological modeling. There are several potential reasons for error sources in precipitation data:

- Errors due to wind (considered the most important)
- Personal error
- Error due to operational difficulties
- Mechanical error

The missing data can be filled up by interpolating from neighboring precipitation station. The following equation can be used for that procedure:

$$p_0 = \frac{1}{G}\sum_{1}^{G} p_g$$

Where,

p_0 - The missing value

p_g - Observed value for corresponding day at g = 1, 2, 3…G

The ENKI program equipped with tool which responsible for filling the missing values. It uses the Inverse - Distance Weighting method. This approach weights the p_g values only by their distances, d_g, from the gage with the missing data and so does not require information about average annual precipitation at the gages. First, it should be decided whether the weights should be inversely proportional to distance (b = 1) or to distance squared (b = 2) and compute (Dingman, 2008):

$$D = \sum_{g=1}^{G} d_g^{-b}$$

Then, the missing value should be estimated as:

$$p_0 = \frac{1}{D} * \sum_{g=1}^{G} d_g^{-b} * p_g$$

Where,

d_g - distance from the gauge with missing data

p_0 - The missing value

p_g - Observed value for corresponding day at g = 1, 2, 3…G

4.2.2 TEMPERATURE DATA COLLECTION

The temperature data was also obtained from eKlima web data base. The procedure for receiving the data was the same as for retrieving the precipitation data. It was found 10 temperature stations within and close to the study region, which are shown in Figure 4-5. The daily temperature data series is collected for period from 2000 to 2012 year. The temperature data is also input parameter for ENKI model and it is used in order to understand the type of precipitation, snow melting and potential evaporation in each cell for each day. The location of the temperature stations is performed in Table 4-5.

Table 4-5 Description of location of the temperature stations

№	Name	UTM	X Easting	Y Northing	Longitude	County
1	VÆRNES	32V	596468.92	7038211.26	10.9352	Nord-Trøndelag
2	KVITHAMAR	32V	593598.07	7041358.82	10.8795	Nord-Trøndelag
3	VERDAL - REPPE	32V	631839.11	7075484.09	11.6752	Nord-Trøndelag
4	SNÅSA - KJEVLIA	33W	376940.45	7117145.34	12.4692	Nord-Trøndelag
5	STEINKJER - SØNDRE EGGE	32W	619755.04	7101824.35	11.4508	Nord-Trøndelag
6	RØROS LUFTHAVN	32V	620824.27	6940696.16	11.3518	Sør-Trøndelag
7	TRONDHEIM - VOLL	32V	572602.83	7032162.2	10.4539	Sør-Trøndelag
8	ØRLAND III	32V	530175.48	7064230.59	9.6105	Sør-Trøndelag
9	OPPDAL - SÆTER	32V	534225.89	6941679.53	9.6667	Sør-Trøndelag
10	FOKSTUGU	32V	514934.65	6886834.95	9.2862	Oppland

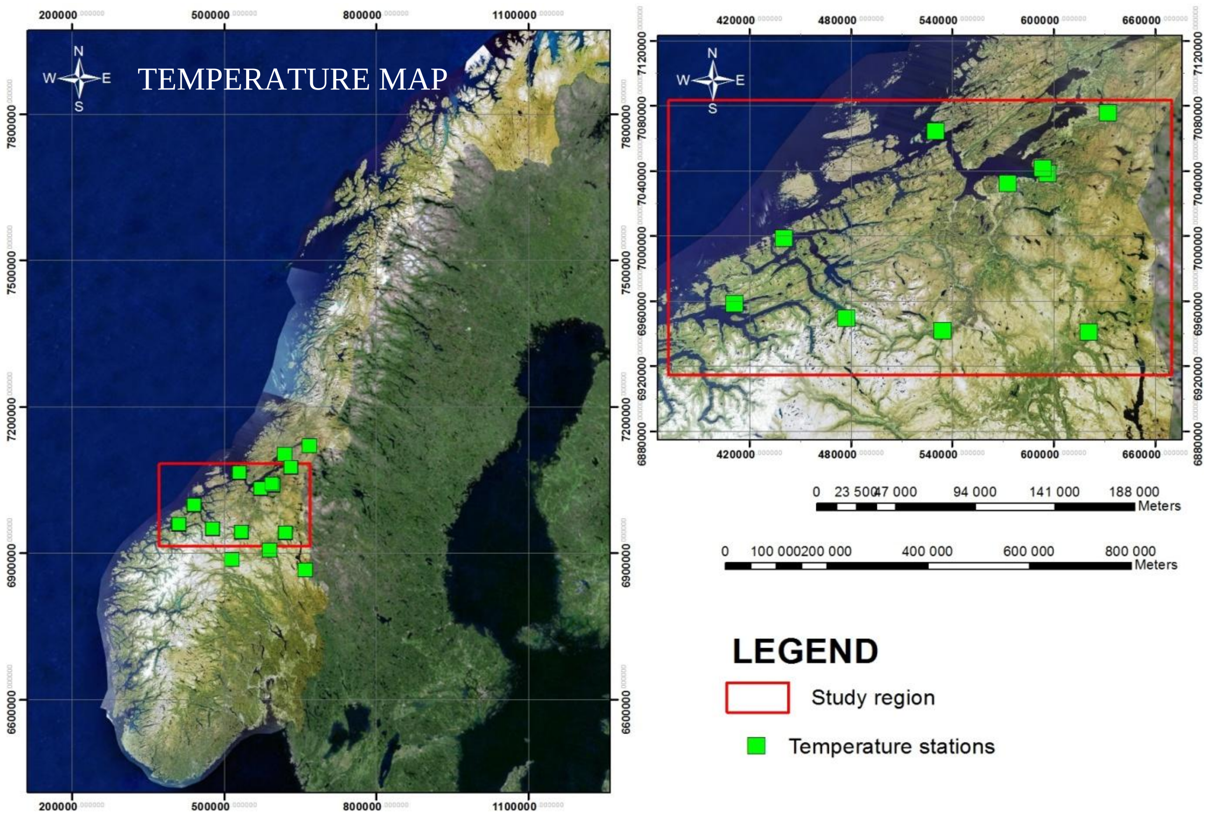


Figure 4-5 Projected map of study region with temperature stations (ESRI)

The altitude of temperature stations is also considered. It is important due to the temperature lapse rate. The temperature lapse rate is the rate of decreasing the atmospheric temperature with increasing of altitude. There are three main conditions, which influencing the air temperature: the clouds on the skies, the clear skies and average conditions as shown on Figure 4-6. For computation, the average value of temperature lapse rate -0.6 C/100 m elevations is utilized. (Killingtveit and Sælthun, 1995)

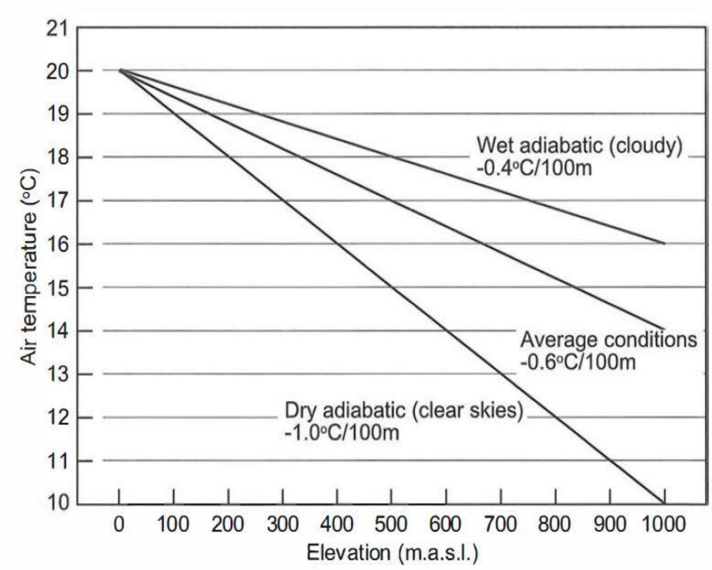


Figure 4-6 The air temperature lapse rate (Killingtveit and Sælthun, 1995)

4.2.2.1 TEMPERATURE DATA QUALITY CHECK

The 10 temperature stations locate within selected region were processed and checked for errors and consistency of the recorded time series. Stations located within selected region with determined number of missing values are tabulated in Table 4-6.

Table 4-6 Temperature data availability

Station Name	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Missing Data
VÆRNES	×	×	×	×	×	×	×	×	×	×	×	×	×	0
KVITHAMAR	×	×	×	×	×	×	×	×	×	×	×	×	×	70
VERDAL - REPPE	×	×	×	×	×	×	×	×	×	×	×	×	×	0
RØROS LUFTHAVN			×	×	×	×	×	×	×	×	×	×	×	868
TRONDHEIM - VOLL	×	×	×	×	×	×	×	×	×	×	×	×	×	64
ØRLAND III	×	×	×	×	×	×	×	×	×	×	×	×	×	21
OPPDAL - SÆTER	×	×	×	×	×	×	×	×	×	×	×	×	×	0
HUSTADVATN			×	×	×	×	×	×	×	×	×	×	×	769
SUNNDALSØRA II	×	×	×	×	×	×	×	×	×	×	×	×	×	4
SUNNDALSØRA III	×	×	×	×	×	×	×	×	×	×	×	×		769

To identify the errors and consistency of the temperature data series the same steps as for precipitation inspection have been processed:

1) Visual inspection of temperature data
2) Accumulation plot for check long series time development
3) Double mass analysis for consistency of recorded time series

Visual inspection showed that SUNNDALSØRA III, HUSTADVATN and RØROS LUFTHAVN stations has several years of missing values. It was decided to drop those stations from following analysis; the remaining stations are selected for further inspection (Table 4-7).

Table 4-7 Temperature stations for modeling process

Station Name	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Missing Data
VÆRNES	×	×	×	×	×	×	×	×	×	×	×	×	×	0
KVITHAMAR	×	×	×	×	×	×	×	×	×	×	×	×	×	70
VERDAL - REPPE	×	×	×	×	×	×	×	×	×	×	×	×	×	0
TRONDHEIM - VOLL	×	×	×	×	×	×	×	×	×	×	×	×	×	64
ØRLAND III	×	×	×	×	×	×	×	×	×	×	×	×	×	21
OPPDAL - SÆTER	×	×	×	×	×	×	×	×	×	×	×	×	×	0
SUNNDALSØRA II	×	×	×	×	×	×	×	×	×	×	×	×	×	4

Accumulation plot (Figure 4-7) and double mass analysis (Figure 4-8) is processed for selected temperature stations.

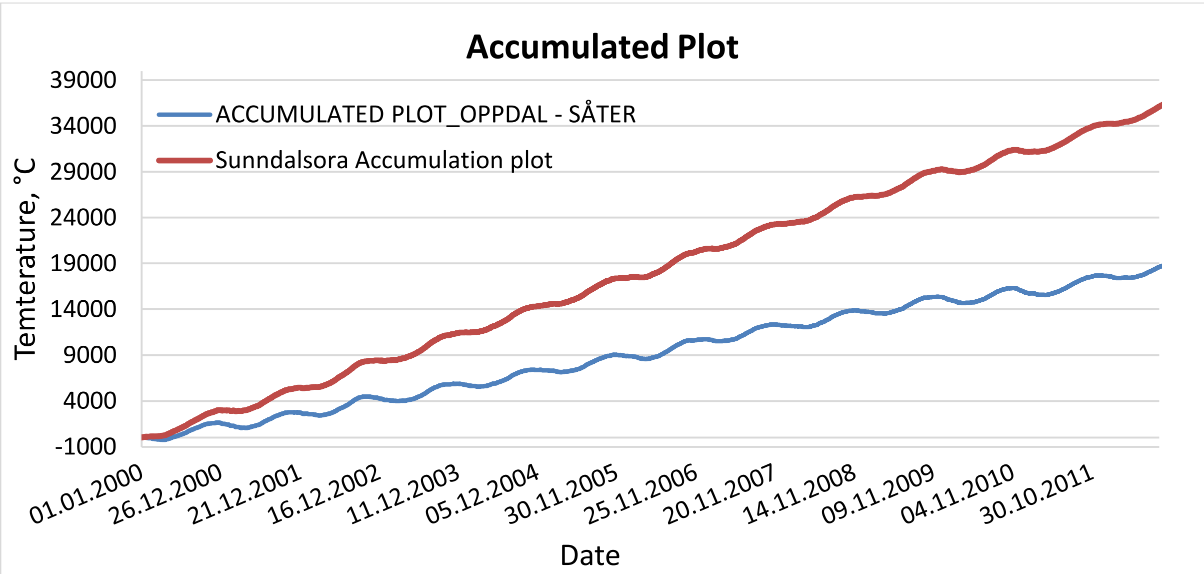


Figure 4-7 Accumulated plot of three neighboring temperature stations

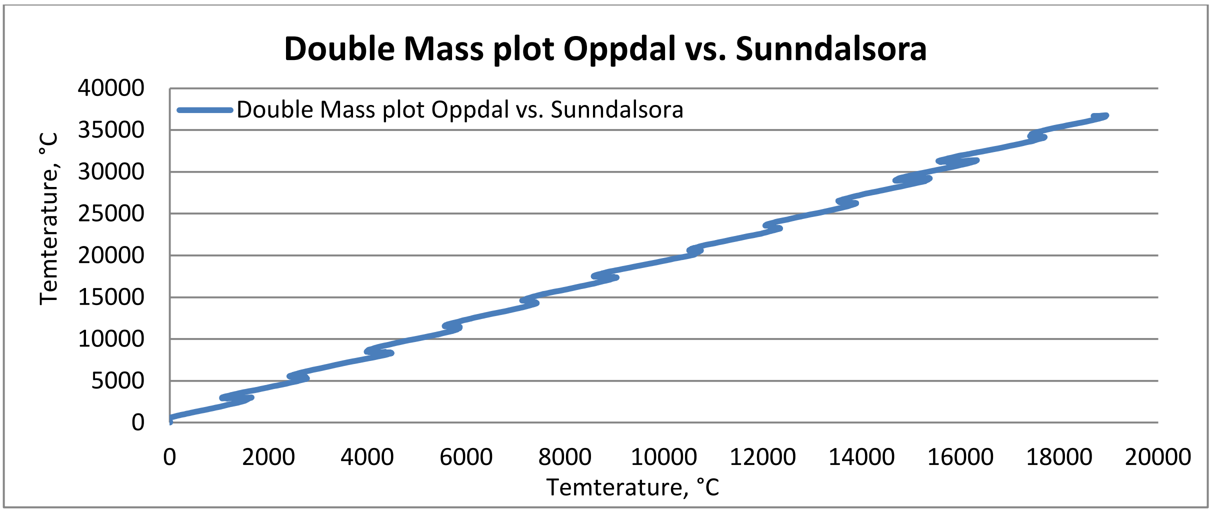


Figure 4-8 The temperature double mass plot

The accumulation plots of tow neighboring temperature stations, the Oppdal–Soter and Sunndalsora II are shows good linear development over the time period. It is indicates that the data is correct. The double mass plot shows consistent linier development, which can refer to good quality of the temperature data.

The temperature pattern analysis has been undertaken for the study period from 2000 to 2012 years based on daily temperature data. The results are shown in Table 4-8. The graphical representation of the temperature pattern of the region is displayed in Figure 4-9.

It can be seen from the graph that the temperature within winter period oscillating not far below 0°C. The temperature at Oppdal–Sæter shows the lowest temperature during winter period and within summer months as well. It is due to the fact that the station locates at the high elevation in the mountain range within inland climatic condition. The Orland III temperature station shows the highest temperature for late autumn, winter and early spring period. That is due to the fact that station locates at coastal climatic zone and affected by warm Atlantis cyclones and closeness of Gulf Stream. The temperature stations are not equally distributed across the region. Most of the stations locate on North-East side of the region and tow temperature stations locates on South-West part of the study region.

Table 4-8 Monthly average temperature for 2000-2012 period

Station Name	Jan	Feb	March	April	May	Juny	July	Aug	Sep	Oct	Nov	Dec	Yearly Mean
VÆRNES	-1.29	-1.67	0.77	5.71	9.44	12.53	15.40	14.75	10.84	6.10	1.98	-1.60	6.08
KVITHAMAR	-1.47	-1.80	0.66	5.38	9.42	12.52	15.27	14.60	10.81	5.96	1.95	-1.35	6.00
VERDAL - REPPE	-2.13	-2.65	0.06	5.15	9.11	12.45	15.50	14.77	10.51	5.69	1.46	-1.81	5.68
SUNNDALSØRA II	-2.39	-2.91	-0.15	4.96	8.90	11.98	15.28	14.48	9.45	4.96	0.86	-2.08	5.28
TRONDHEIM - VOLL	-1.12	-1.63	0.79	5.37	8.92	12.13	15.00	14.33	9.70	5.93	1.88	-1.24	5.84
ØRLAND III	0.93	0.10	1.98	5.89	9.04	11.69	14.21	14.27	11.00	7.09	3.84	1.21	6.77
OPPDAL - SÆTER	-3.18	-3.87	-1.37	3.20	6.86	10.21	13.23	12.43	8.69	3.95	0.18	-3.54	3.90

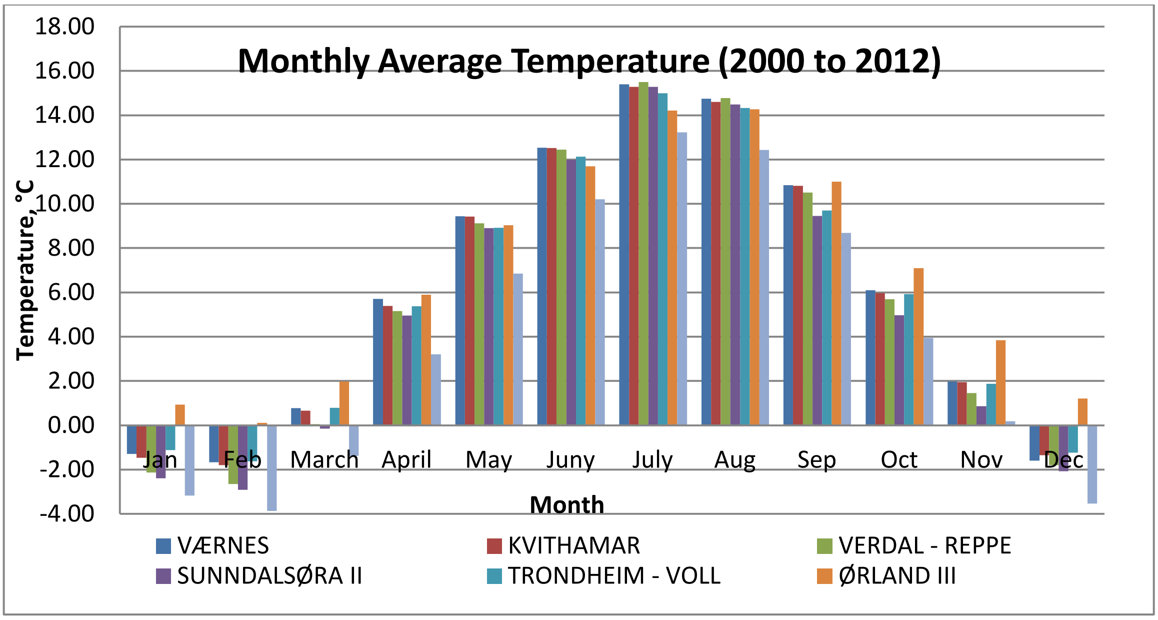


Figure 4-9 Monthly average temperature pattern for the region

4.2.2.2 TEMPERATURE MISSING DATA INTERPOLATION

The temperature missing data processing follows the same routine as for precipitation. Which have been described in above chapter.

The ENKI program can interpolate missing temperature values by utilizing Inverse - Distance Weighting method equations.

$$D = \sum_{1}^{G} d_g^{-b}$$

$$T_0 = \frac{1}{D} \sum_{1}^{G} d_g^{-b} * T_g$$

Where,

d_g - Distance from the gauge with missing data to the gauge with available data

b - Weights to the distance

T_0 – Interpolated daily mean air temperature at the gauge with available data

T_g - Daily mean air temperature at the known gauge stations g=1, 2, 3…G (Dingman, 2008)

4.2.3 RADIATION DATA

The radiation data is input network data which is required for IDWrad subroutine within ENKI model. The real measured radiation data is not used during this project work. The radiation has been calculated based on day of the year, position of the Earth with relation to the Sun and latitude in selected study region. Data for radiation has been obtained from

Niccolo Bonfadini, employee of Statkraft Company. Currently working with ENKI model at the catchment, within the same region as in that study project.

4.3 ACQUISITION OF HYDROLOGICAL DATA

4.3.1 RUNOFF DATA COLLECTION

As was described above, the hydrological data for this study project was collected from two sources: from NVE open database and from Sweco Consulting Company. Data from NVE HYDRA-II open source is used for simulation. The hydro-data from Sweco Company is utilized in order to compare the simulated runoff with observed one.

Relevant runoff stations and catchment areas are obtained from NVE Lavvan Atlas. The runoff data from NVE's HYDRA-II contains the historical observations for all public stream flow and water stage gauging stations in Norway. HYDRA-II also contains catchment data for all catchments upstream the gauging stations. HYDRA-II offers a number of programs for data analysis, flood-frequency calculation, calculation of energy production potential, and more. (Rinde, 2013a)

There are 32 runoffs stations were fined within and close to selected study region. Daily runoff data series for period from 2000 to 2012 is collected from NVE HYDRA-II database. The main criterion of selection the runoff stations is their outside location from regulated catchments. The daily runoff data from 2001 to 2005 are utilized for model calibration and the period from 2005 to 2000 is used for model validation. The location of NVE gauging stations are tabulated in Table 4-9 and visual performance of the stations are shown in Figure 4-10.

The description and visual location of Sweco runoff stations are performed in Table 2-1 and in Figure 2-2.

Table 4-9 Location of selected NVE gauging stations for runoff data series

№	Stnr	Name	UTM	X Easting	Y Northing
1	124.2.0.1001.1	Høgges bru	33	318729.63	7045669.16
2	127.13.0.1001.1	Dillfoss	33	340492.48	7074776.77
3	122.14.0.1001.1	Lillebudal bru	33	273298.59	6973745.09
4	122.16.0.1001.1	Gaua	33	258034.09	7006020.6
5	111.9.0.1001.1	Søya v/Melhus	33	175366.184	6990640.35
6	109.21.0.1001.1	Driva v/Svoni	33	216874.1	6914670.38
7	109.9.0.1001.1	Driva v/Risefoss	33	221768.9	6942811.52
8	123.31.0.1001.1	Kjeldstad i Garbergelva	33	305904.41	7021100.49
9	104.23.0.1001.1	Vistdal	33	140290.78	6971580.32
10	2.457.0.1001.1	Fossum bru	33	271384.15	6858104.93
11	100.1.0.1001.1	Valldøla	33	111189.68	6933501.83
12	122.17.0.1001.1	Hugdal bru	33	259314.31	6994207.95
13	122.11.0.1001.1	Eggafoss	33	306304.41	6979306.59
14	128.5.0.1001.1	Støafoss	33	339631.39	7103107.36
15	128.8.0.1001.1	Hekkadalbrua	33	329193.56	7103957.34
16	139.26.0.1001.1	Embrethølen	33	376569.94	7142687.12
17	139.35.0.1001.0	Trangen	33	378755.41	7147386.13

18	50.4.0.1001.1	Viveli	33	67449.21	6715766.08
19	71.1.0.1001.0	Skjerping	33	54949.77	6774977.45
20	72.71.0.1001.1	Frønningen dam	33	73903.39	6799282.37
21	138.1.0.1001.1	Øyungen	33	310123.87	7130033.37
22	139.17.0.1001.0	Bertnem	33	358955.47	7152374.83
23	122.9.0.1001.1	Gaulfoss	33	259399.34	7006617.24
24	121.29.0.1001.1	Gisnes	33	240033.12	6962945.03
25	126.2.0.1001.0	Engstad	33	311895.56	7065660.58
26	123.95.0.1001.1	Kobberdammen	33	264820.15	7041299.605
27	119.4.0.1001.0	Rovatn	33	200500.16	7028353.39
28	114.1.0.1001.1	Myra	33	155225.85	7029076.48
29	133.7.0.1001.0	Krinsvatn	33	265308.97	7083926.29
30	123.29.0.1001.0	Svarttjørnbekken	33	282182.47	7028667.96
31	103.20.0.1001.1	Isa v/Morstøl bru	33	138553.64	6958948.38
32	107.3.0.1001.1	Farstadelva v/Farstad	33	103328.99	7006875.85

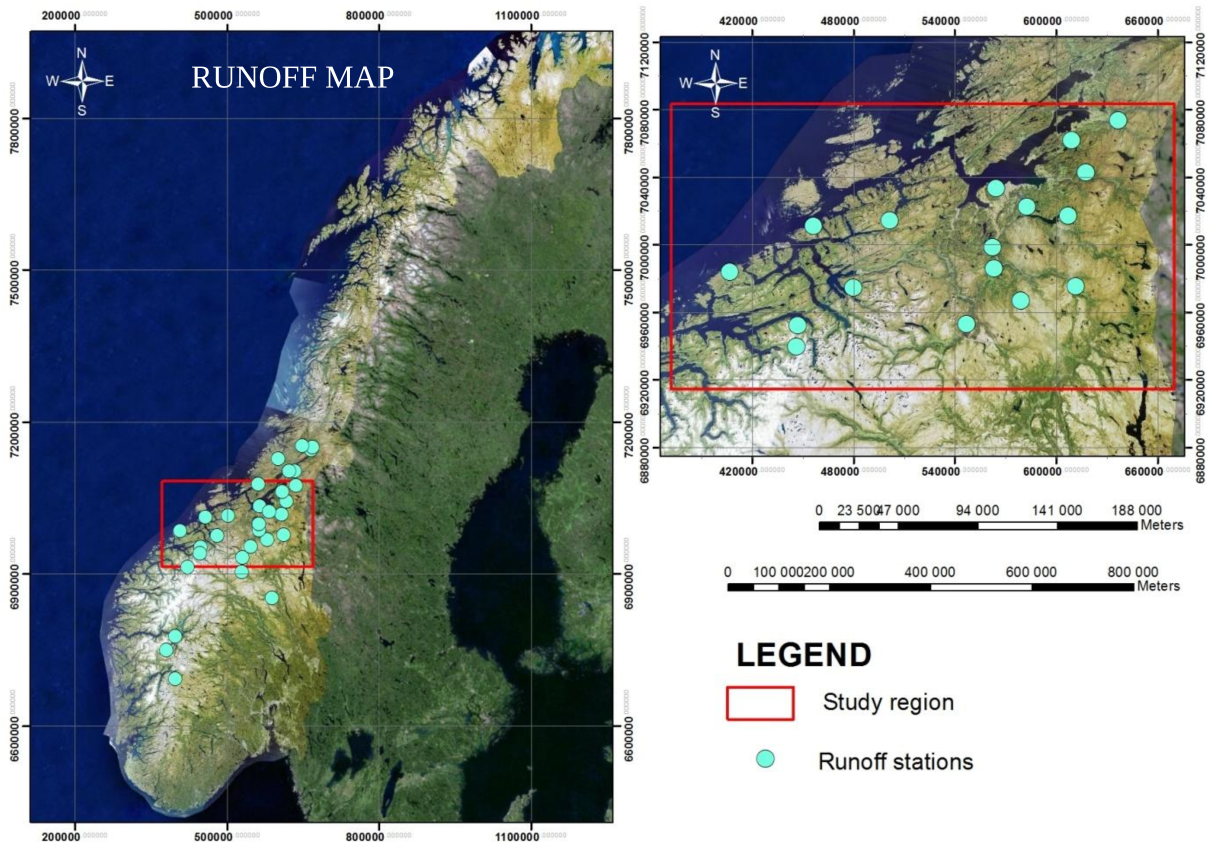


Figure 4-10 Projected map of study region with runoff stations (ESRI)

4.3.1.1 RUNOFF DATA QUALITY CHECK

Gaps in runoff data series may be filled in the same way as described for precipitation data, by first establishing correlations and then scaling values from other runoff series according to the ratio between their mean values over the correlation period. However, runoff series in Norway are strongly influenced by snowmelt. The catchments hypsography is therefore of crucial importance when selecting correlation series, sometimes more important than proximity.

Filling in missing values in a runoff series from a reliable series requires that the reliable catchment has several characteristics:

- It is reasonably close to the reliable catchment (for similarity in precipitation and temperature forcing)
- Has similar hypsographic distribution as the reliable catchment (for similarity in snow melt variation)
- Has similar size and lake percentage as the reliable catchment (for similarity in runoff dampening)

In practice it is very difficult to fulfill all these requirements. By reasonably close catchment will often just mean within the same weather region, and relatively large differences in size and lake portion must often be accepted. Often the best approach is to use a calibrated HBV-model to simulate the period with missing run-off data. (Rinde, 2013a)

In this study project runoff data have been collected from NVE database, which is considered as reliable source.

32 runoff stations have been collected during data acquisition survey. 18 discharge stations locate within borders of selected study region. Visual inspection of the data series showed that most of the stations have no missing values, except for missing observations in 2012 year for Engstad, Rovatn and Isa v/Morstø I bru. The 2012 year is used for further validation in this study project (Table 4-10). The decision was made to exclude the Gaua runoff station from the ENKI modeling process due to long period of missing values.

Table 4-10 Availability of NVE runoff data

№	Name	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Missing Value
1	Høgges bru	×	×	×	×	×	×	×	×	×	×	×	×	×	0
2	Dillfoss	×	×	×	×	×	×	×	×	×	×	×	×	×	0
3	Lillebudal bru	×	×	×	×	×	×	×	×	×	×	×	×	×	0
4	Gaua	×	×	×	×	×	×		×	×		×	×	×	730
5	Driva v/Risefoss	×	×	×	×	×	×	×	×	×	×	×	×	×	0
6	Kjeldstad i Garbergelva	×	×	×	×	×	×	×	×	×	×	×	×	×	0
7	Vistdal	×	×	×	×	×	×	×	×	×	×	×	×	×	0
8	Hugdal bru	×	×	×	×			×	×	×	×	×	×	×	230
9	Eggafoss	×	×	×	×	×	×	×	×	×	×	×	×	×	0
10	Gaulfoss	×	×	×	×	×	×	×	×	×	×	×	×	×	0
11	Gisnes	×	×	×	×	×	×	×	×	×	×	×	×	×	0
12	Isa v/Morstøl bru	×	×	×	×	×	×	×	×	×	×	×	×		365
13	Farstadelva v/Farstad	×	×	×	×	×	×	×	×	×	×	×	×	×	0
15	Myra	×	×	×	×	×	×	×	×	×	×	×	×	×	9
16	Rovatn	×	×	×	×	×	×	×	×	×	×	×	×		386
17	Svarttjørnbekken	×	×	×	×	×	×	×	×	×	×	×	×	×	0
18	Engstad	×	×	×	×	×	×	×	×	×	×	×	×		219

Further runoff data quality check is made with respect to unreliable data (picks). The hydrographs of the discharge data series have been plotted against nearest precipitation station data series (Figure 4-11).

The NVE runoff stations characteristics tabulated in Table 4-11. The runoff plot for largest catchment Gaulfoss against data series from nearest rainfall stations is shown on Figure 4-12.

It can be noted that the pattern of the hydrographs is typical for the areas with cold winters when the precipitation are stored as snow and hydrographs shows low discharge within that period , and warm summers with periods when hydrographs repeats the rainfall events with certain delay in time.

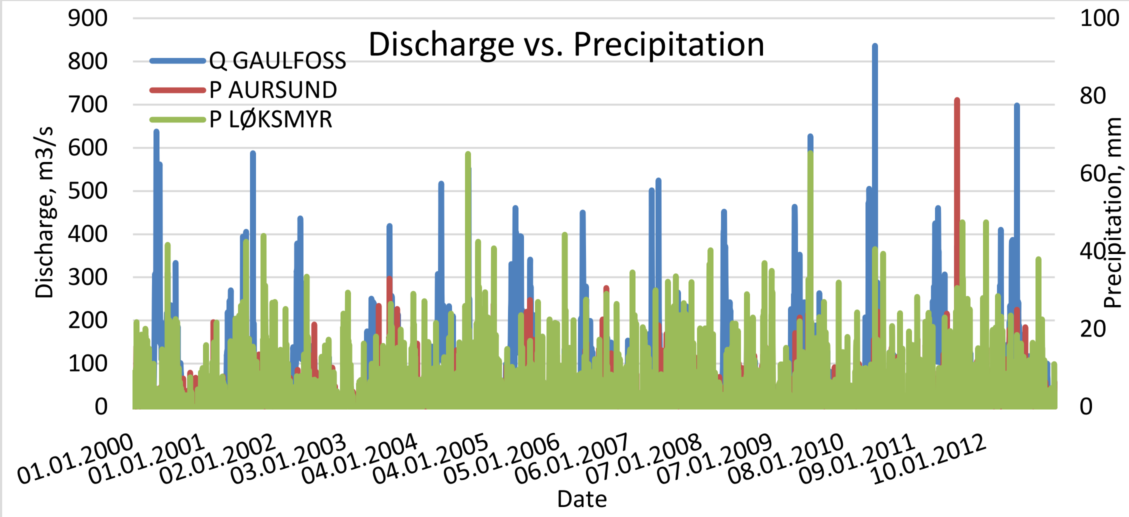


Figure 4-11 Daily runoff against daily precipitation

4.3.1.2 RUNOFF MISSING DATA INTERPOLATION

Records of hydrological observation in Norway have long history. The old stations have long term data series, but the quality is unknown. The new automatic gauging stations are recently used for data recording. Such stations considered as more reliable compare to human data recording. But inconsistency of the data might happen due to several reasons such as: breakage of measuring equipment, low battery charge, disturbance by external force, interruption due to landslides/ hurricanes or accidental loss of measured data in the computer system. There are different methods of filling missing data such as: scaling from neighboring catchment, interpolation approach, and regression analysis. In this study no any specific method is used for filling missing data. The ENKI program equipped with tools for filling missing data by interpolation method.

4.3.2 SWECO RUNOFF DATA

As was described in above there are 11 runoff stations collected from Sweco Company. The runoff data is available only for 7 stations. Sweco runoff data stations availability tabulated in Table 4-12. Data quality control for these stations has been carried out during summer internship with Sweco AS Company in Trondheim, 2013 year.

4.4 CATCHMENTS CHARACTERISTICS

Data series for selected NVE runoff stations are available for the period from 2000 to 2012 year; except for the Engstad, Rovatn, Isa v/Morstøl bru and Hugdal bru stations with has data from 2000 to 2011 year (Table 4-11). The selected time period for calibration is from 2001 to 2005 year, the 2012 year with missing data for those stations is not affecting the calibration result.

Data series for selected Sweco runoff stations are available for different time period within selected one (Table 4-12).

The coordinates for all runoff stations have been converted to WGS 84 / UTM zone 32N by “Calculate Geometry” tool within ArcGIS framework:

Select **Attribute Table** => Select column with **X/Y coordinates** => **right click** => **Calculate Geometry** => **X/Y Coordinate of Centroid**

Table 4-11 NVE runoff data series availability, location and catchment area

Stations Name	Years of operation		UTM Zone	Coordinates		Catchment area, km2
	From	To		X_UTM_North	Y_UTM_East	
Vistdal	2000	2012	32	446819.9	6952338.8	66.32
Gisnes	2000	2012	32	546815.4	6953016.2	94.32
Lillebudal bru	2000	2012	32	578910.4	6966854.1	167.97
Søya v/Melhus	2000	2012	32	479921.4	6974550.2	137.29
Eggafoss	2000	2012	32	611241.3	6975459.9	653.89
Gaulfoss	2000	2012	32	562019.1	6998269.2	3083.58
Kjeldstad i Garbergelva	2000	2012	32	606946.9	7017021.3	144.92
Høgges bru	2000	2012	32	617415.8	7042674.4	494.6
Dillfoss	2000	2012	32	636352.4	7073688.3	480.55
Svarttjørnbekken	2000	2012	32	582631.6	7022337	3.41
Farstadelva v/Farstad	2000	2012	32	406797.9	6983983.7	24.14
Myra	2000	2012	32	456314.3	7010889.8	16.37
Engstad	2000	2011	32	608741.5	7061932.8	20.14
Rovatn	2000	2011	32	501401.1	7014396.5	236.37
Isa v/Morstøl bru	2000	2011	32	446265.7	6939619.9	44.26
Hugdal bru	2000	2011	32	563090.8	6985914.2	545.4

Table 4-12 Sweco runoff data series availability, location and catchment area

Stations Name	Years of operation		UTM Zone	Coordinates		Catchment area, km2
	From	To		X_UTM_North	Y_UTM_East	
Tangvella	30.06.2005	20.09.2012	32	583409	7013268	33.90
Usma	01.01.2000	31.12.2009	32	613424	6995895	69.70
Malmedalselva	22.03.2007	28.09.2011	32	409610	6963682	29.70
Skorgeelva	20.09.2007	19.05.2011	32	430466	6939992	42.30
Erga	05.04.2005	15.08.2010	32	507318	6938389	26.70
Eidaa	01.01.2000	05.01.2011	32	550650	6985983	17.30
Vassdalselva	01.05.2003	02.08.2005	32	491627	6994813	16.90

The characteristics of the catchment which are most influencing into runoff are: the slope of the catchment, the elevation- distribution, forest/lake percentage. This has been checked by drawing the elevation – distribution curve for each of the catchment and taking into consideration while analyzing the data (Figures 4-14; 4-15). Data of elevation – distribution characteristics of the catchments are taken from open source NVE Lavvann http://gis.nve.no/ge/Viewer.aspx?Site=Lavvann. Hypsographic curves of all stations are performed in Appendix A.

Slope of the catchment affecting on runoff. If the slope is steep it will bring quicker and more runoff. If area of the catchment is relatively flat, the precipitation will have time to percolate into the ground, which in its turn will create less runoff.

The high vegetation influencing on runoff by catching the precipitation by leafs. The grass restricting the velocity of runoff. So it will have more time for percolation and less water will come to the runoff.

The lakes within a catchment act as storage for precipitation. At first the water has to fill up the lake, and only after that it can overflow into runoff. The main characteristics of the catchment tabulated in Table 4-13. Visual relation between catchment, forest and lake areas are shown in Figures 4-12; 4-13. Figure 4-12 represents main characteristics of all catchments. It is obvious that Gaulfoss catchment has the dominating area. For better visual presentation, the Gaulfoss catchment has been removed from the plot (Figure 4-13).

Table 4-13 Main characteristics of the catchment

Stations Name	Area, km2	Specific Runoff, l/s/km2	River Gradient, m/km	Forest		Lake	
				%	km2	%	km2
Tangvella_S	33.90	31,4	31,0	0.259	118.104	0.025	11.4
Usma_S	69.70	38,6	37,2	0.275	170.5	0.019	11.78
Malmedalselva_S	29.70	64,9	44,8	0.44	104.28	0.022	5.214
Skorgeelva_S	42.30	49,8	58,7	0.317	140.748	0.026	11.544
Erga_S	26.70	30,6	194.10	0.979	449.361	0	0
Eidaa_S	17.30	35,1	44,5	0.192	136.128	0.034	24.106
Vassdalselva_S	16.90	57,5	83,3	0.075	34.2	0.041	18.696
Vistdal	66.32	58,6	14,5	0.319	145.145	0.023	10.465
Gisnes	94.32	25,7	26,1	0.295	213.285	0.006	4.338
Lillebudal bru	167.97	29,0	20,0	0.217	166.873	0.011	8.459
Søya v/Melhus	137.29	61,2	40,5	0.358	104.178	0.009	2.619
Eggafoss	653.89	25,6	15,1	0.246	176.136	0.028	20.048
Gaulfoss	3083.58	27,1	7,9	0.367	195.978	0.021	11.214
Kjeldstad i Garbergelva	144.92	38,9	20,6	0.433	192.685	0.022	9.79
Høgges bru	494.6	41,7	7,5	0.287	115.374	0.074	29.748
Dillfoss	480.55	34,5	10,2	0.41	145.96	0.027	9.612
Svarttjørnbekken	3.41	27,9	44,7	0.812	257.404	0.027	8.559
Farstadelva v/Farstad	24.14	45,2	5,5	0.198	5.94	0.044	1.32
Myra	16.37	47,1	38,2	0.386	23.546	0.004	0.244
Engstad	20.14	21,2	8.1	0.339	29.493	0.012	1.044
Rovatn	236.37	47,6	20,1	0.386	108.08	0.071	19.88
Isa v/Morstøl bru	44.26	68,9	100,3	0.18	103.68	0.02	11.52
Hugdal bru	545.4	23,0	22,1	0.536	269.072	0.01	5.02

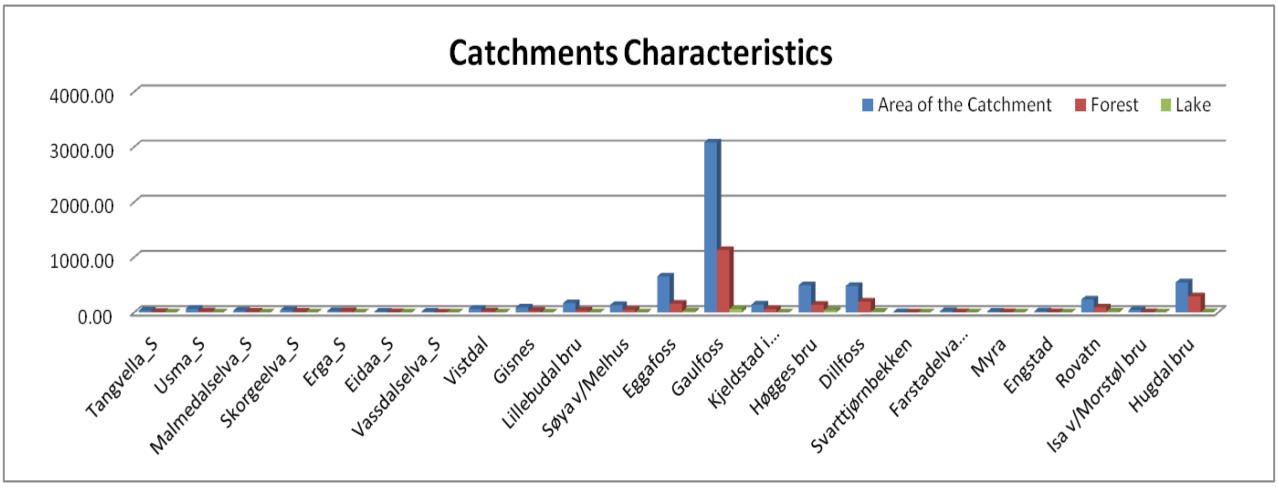


Figure 4-12 Catchment characteristics (all catchments)

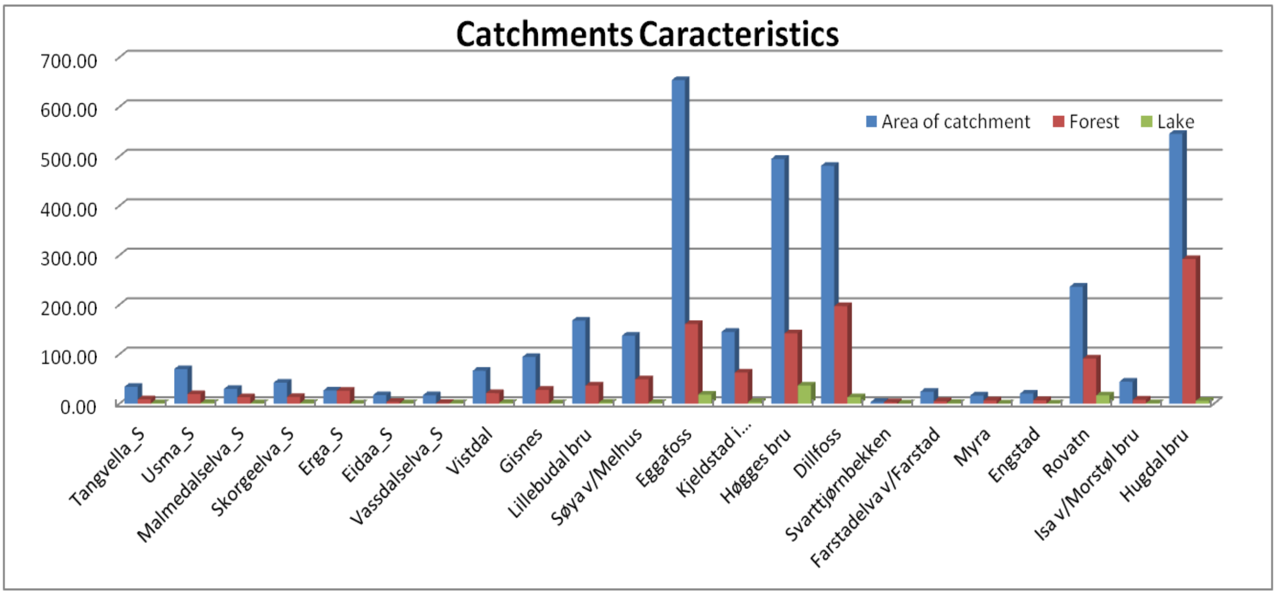


Figure 4-13 Catchment characteristics (except Gaulfoss catchment)

Table 4-14 Elevation – distribution characteristics of the catchments

Stations Name	Area Elevation Distribution										
	Hmin	H10	H20	H30	H40	H50	H60	H70	H80	H90	Hmax
Tangvella_S	356	413	456	493	527	566	588	631	683	748	929
Usma_S	447	585	620	656	697	736	768	803	846	905	1061
Malmedalselva_S	115	185	237	262	294	352	411	480	559	662	968
Skorgeelva_S	174	370	444	533	610	681	723	785	863	957	1202
Erga_S	330	407	459	512	556	601	643	705	782	847	924
Eidaa_S	537	657	709	741	765	791	824	867	919	984	1140
Vassdalselva_S	203	421	456	502	531	557	587	640	698	757	912
Vistdal	46	254	455	575	655	737	792	860	946	1072	1525
Gisnes	580	638	723	804	858	910	957	1017	1093	1184	1563
Lillebudal bru	516	675	769	847	907	948	983	1016	1046	1089	1295
Søya v/Melhus	28	148	291	412	510	578	633	703	788	911	1420
Eggafoss	283	622	716	774	811	843	878	917	964	1021	1284
Gaulfoss	52	436	534	597	662	735	812	878	945	1019	1325
Kjeldstad i Garbergelva	179	375	445	498	534	573	614	675	738	833	1166
Høgges bru	98	378	402	434	469	505	547	596	647	749	1246
Dillfoss	38	271	356	421	470	507	538	565	599	645	1031
Svarttjørnbekken	280	304	317	328	334	342	353	368	386	414	509
Farstadelva v/Farstad	11	28	30	37	43	55	106	300	414	476	770
Myra	28	46	61	84	163	217	290	378	466	592	891
Engstad	60	78	87	98	103	111	122	140	155	166	227
Rovatn	13	156	280	318	368	412	460	519	579	650	1027
Isa v/Morstøl bru	110	332	576	743	852	912	1002	1114	1229	1347	1723
Hugdal bru	128	443	502	542	583	623	663	717	816	933	1254

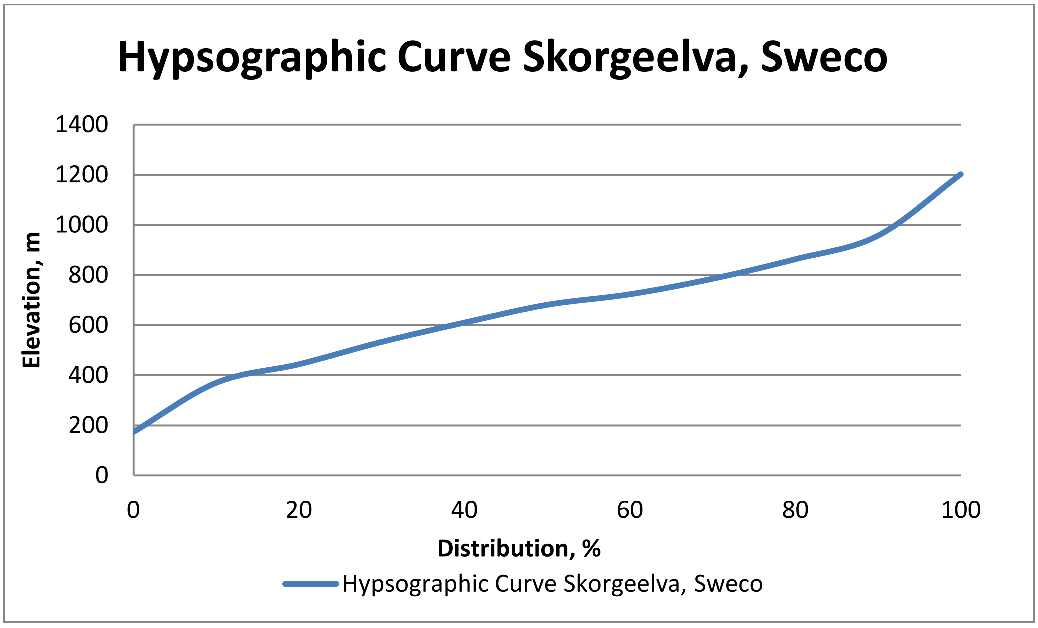


Figure 4-14 Elevation-distribution curve of Skorgeelva catchment

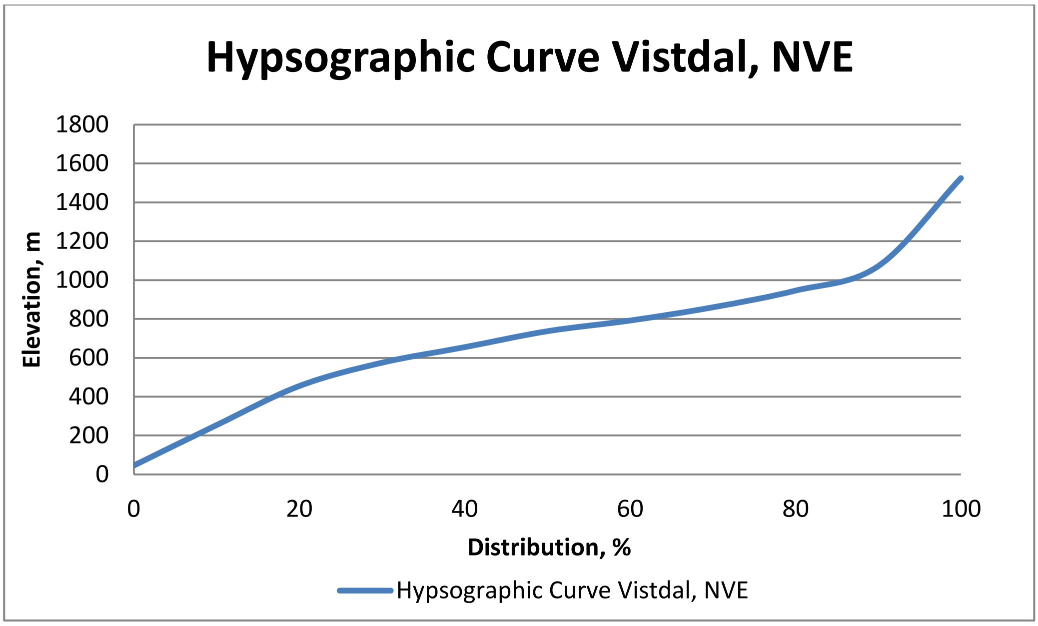


Figure 4-15 Elevation-distribution curve of Vistdal catchment

4.5 DATA ACQUISITION SUMMARY

Daily values of meteorological data, as precipitation and temperature and hydrological data, as runoff have been collected within data acquisition survey and inspected for further hydrological modeling. The results are presented in tabulated form in Table 4-15.

Table 4-15 Data acquisition summary

Type of data	Units	Number of stations	Time period
Precipitation	P, mm	24	2000 - 2012
Temperature	T, °C	7	2000 - 2012
Runoff (NVE)	Q, m^3/s	16	2000 – 2012
Runoff (Sweco)	Q, m^3/s	7	Different time periods from 2000 to 2012

4.6 DISCUSSION AND CONCLUSION

The quality control for 24 precipitation stations, 7 temperature stations and 16 runoff stations gained form eKlilma and NVE data base have been processed. Accumulation plots and double mass curve analysis has given practical information about the consistency of recorded time series. The analysis showed that time series has good quality. 7 runoff stations have been collected from Sweco Company. The data availability and consistency have been checked. The precipitation and discharge stations are well distributed all over the study region. The temperature stations are distributed not equally. Most of the stations locate on North – East part of the region, and 2 stations are at South – West part. Description and analysis of all the catchments has been taken into consideration. Selected hydro – meteorological data and catchments are shown in Figure 4-16.

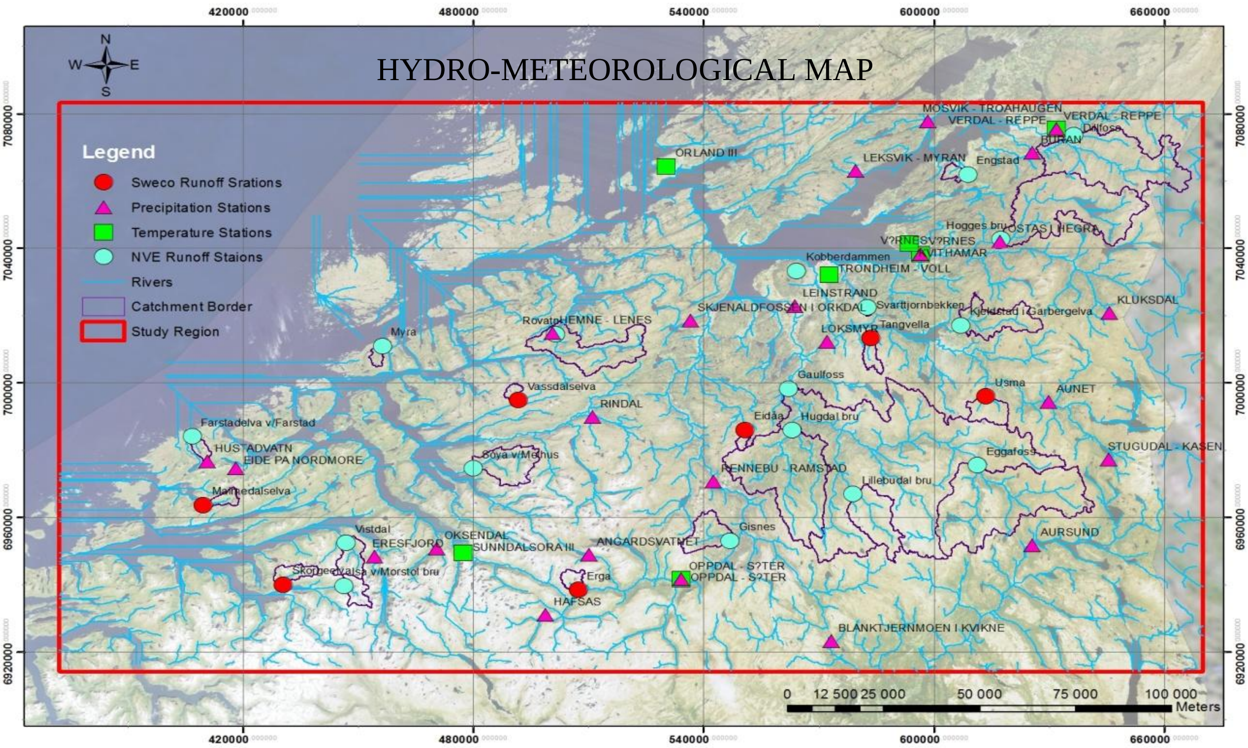


Figure 4-16 Hydro-meteorological and catchment map

5 GEOGRAPHICAL DATA PREPARATION

5.1 INTRODUCTION

The rainfall runoff modeling is a type of hydrologic modeling, which determines how much water will become runoff on given landscape. It finds the discharge at a location for a given precipitation (Figure 5-1). GIS then scan the terrain and summaries the hydrologic characteristics of the watershed for input to a model. It maps natural processes onto software and aggregate landscape characteristics to calculate the runoff.

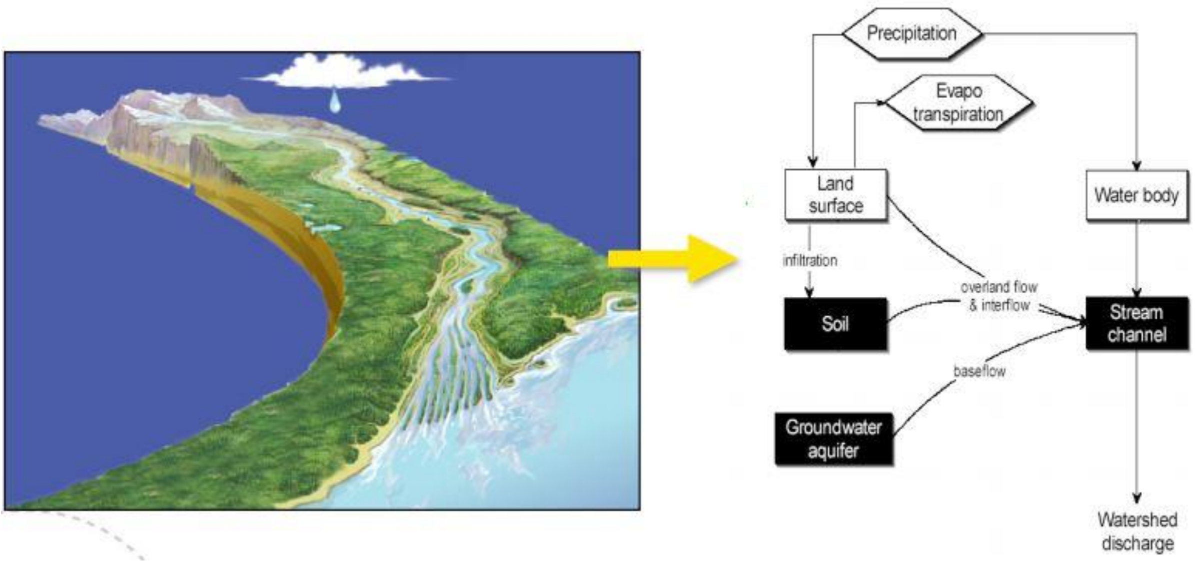


Figure 5-1 GIS in hydrological modeling (Alfredsen, 2013)

The GIS data can be represented in vector and raster data.
Vector data can be in the form of:

- Points
- Polylines
- Polygons

It stores the spatial data and attributes and topology information, as well as the catchment boundaries and river network.

Raster data is the representation of data in an array of points. The grid spacing determines the resolution of the raster. (Alfredsen, 2013)

For this study project GIS data used in shape files and raster maps. The shape files are for determining the precipitation, temperature and runoff stations location (point network) and for determining catchment area (polygons). The maps with raster data calls DEM (Digital Elevation Model). It represents the digital terrain of the study region and its land use. The shape files and raster maps have been collected from \\Progdist.ntnu.no.

5.2 INPUT POINT MAP PREPARATION

The geographical location of hydro-meteorological stations is the input data which gives the information of X, Y and Z coordinates. The coordinates of the stations have been collected from eKlima and NVE data base. The tables with coordinates have been prepared in .excel format and imported to ArcGIS system.

The important issue is to have all maps in the same coordinate system. Norway lies in the projected coordinate system in WGS 84 / UTM zone 32N, UTM zone 33N and UTM zone 35N (Figure 5-2).

The study region locates in WGS 84 / UTM zone 32N. All input maps for modeling with ENKI have been projected in this coordinate system. The map of study region with projected point network of hydro-meteorological data is shown on Figure 4-17.

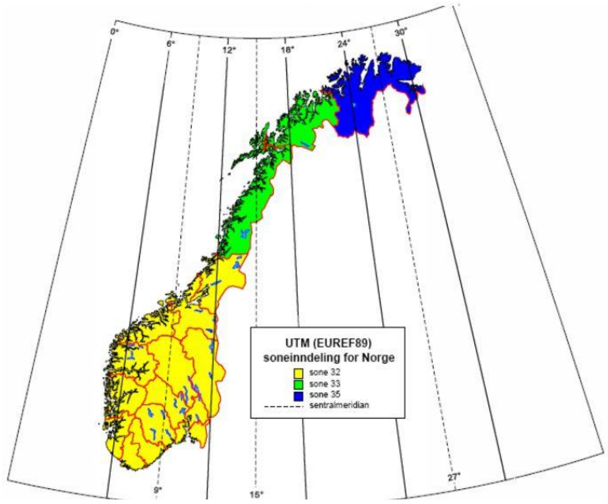


Figure 5-2 Norway's UTM zone (Alfredsen, 2013)

5.3 WATERSHED DELINEATION

5.3.1 INTRODUCTION

The watershed or catchment is the area upstream of the given outlet point, from which all the water draining to that particular point. The catchments boundaries determined by the ridge line. Traditional method to define the watershed boundary is to manually draw the catchment on the topographic map through the top points of a ridge. The GIS system is equipped with Arc-hydro tools. Utilizing the Digital Elevation Model (DEM) GIS creates the catchment area automatically.

As was described in above chapters, in this study project the runoff stations have been collected from NVE database and Sweco Company. The shape file with catchment area for the NVE stations has been downloaded from www.NVE.no open source. The catchment for particular stations have been selected and stored in GIS as separate shape file. The watersheds for Sweco stations have been defined by Arc-hydro tools with Digital Elevation Model application.

5.3.2 DIGITAL ELEVATION MODEL (DEM)

A Digital Elevation Model is a digital model or 3D representation of a terrain's surface. It represents the bare ground surface without any objects like plants and buildings (http://www.wikipedia.org/). In this study DEM represented as a raster map. The raster map of Norway with 25 x 25 m grid resolution downloaded as separated file from \\Progdist.ntnu.no. Within this study DEM represented as a raster map with 1000 x 1000 m

Analyst tool have been applied. Within Aggregate tool each output cell contains the Sum, Minimum, Maximum, Mean, or Median of the input cells that are encompassed by the extent of that cell. The Mean extent is used for entire resolution reduction. The DEM of the study region is shown on Figure 5-3.

grid size. In order to reduce the initial grid size the Data Management => Aggregate Spatial

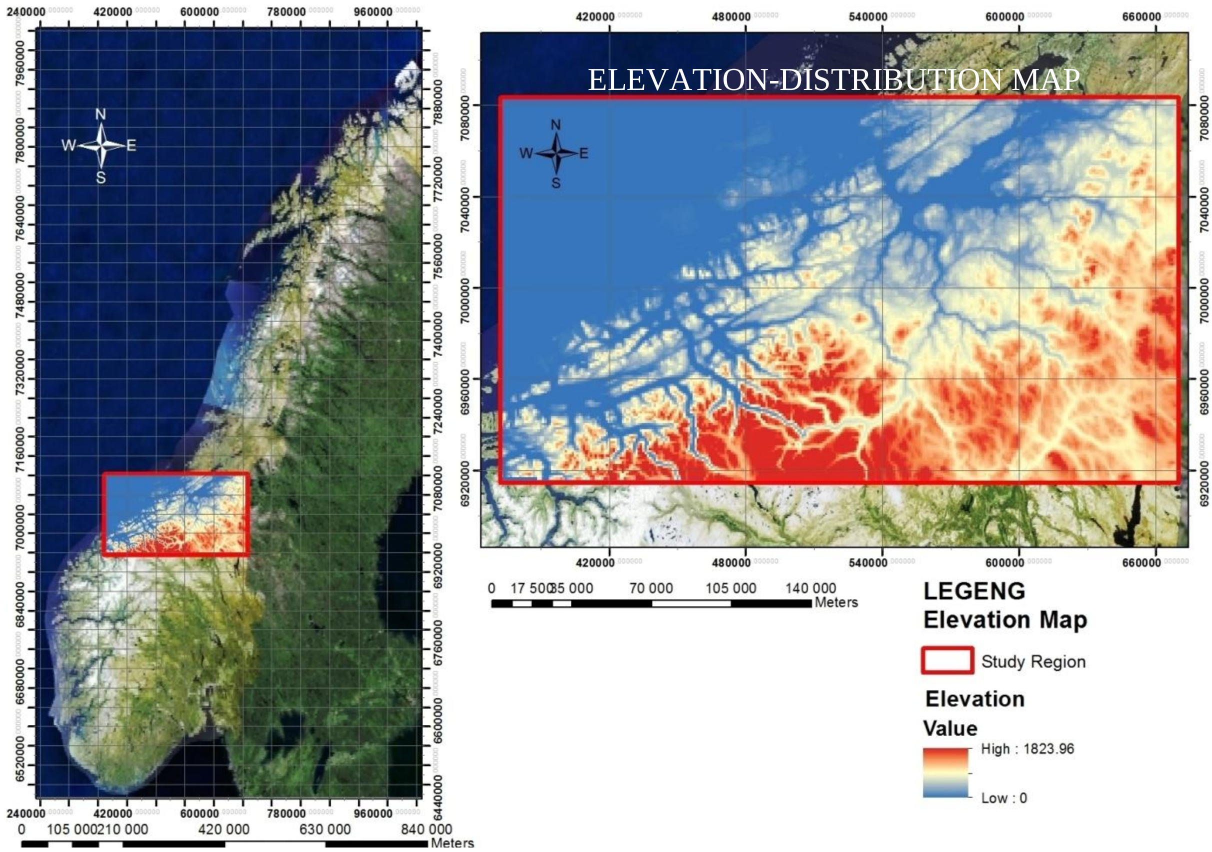


Figure 5-3 Digital Elevation Model of study region

5.3.3 WATERSHEDS DELINIATION PROCEDURE

Watersheds delineation procedure within Arc GIS by Arc-hydro tools can be described by following diagram.

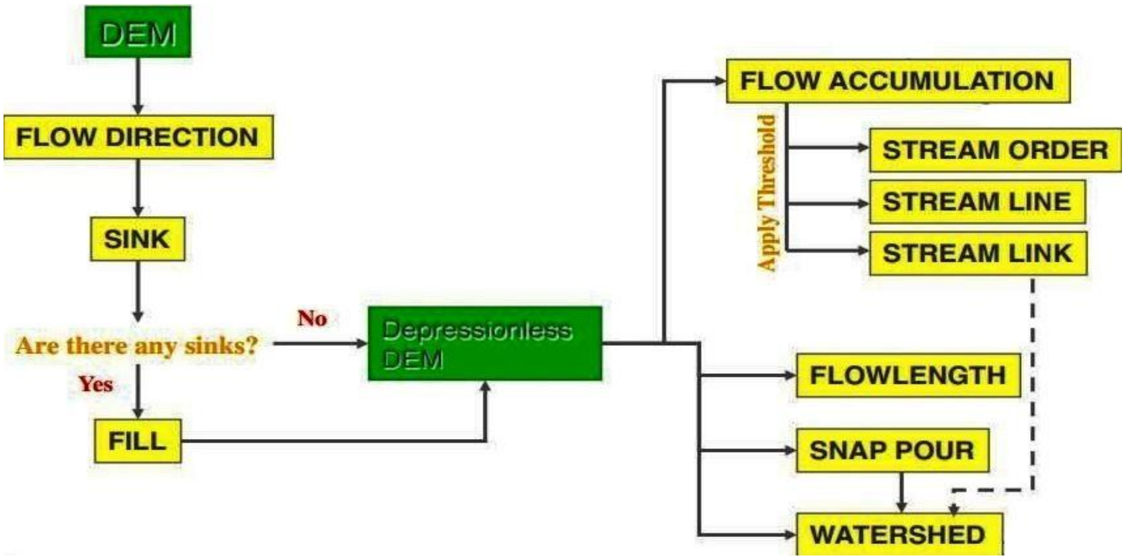


Figure 5-4 Watersheds delineation procedure in Arc GIS (Alfredsen, 2013)

As seen on the diagram the watersheds delineation should be created on the basis of DEM of the study region. The following steps are required:

1. Adjust Flow Direction and Sinks

Amount of water which flowing from upper part of the catchment should be equal the amount of water downstream. But if a sell on DEM surrounded by higher elevation sells, the water is trapped in that sell and cannot flow. The Fill Sinks function modifies the elevation value to eliminate these problem (Shrestha, 2012).

Select **Arc Hydro Tool** => **Terrain Processing** => **Adjust Flow Direction and Sinks**

2. Flow Direction

The values in flow direction cells points the direction of sinking from steepest to lowest cells for computing the flow direction in particular grid.

Select **Arc Hydro Tool** => **Terrain Processing** => **Flow Direction**

3. Flow Accumulation

That function computes the flow accumulation grid which contains the accumulated number of cell, for each cell in the input grid (Shrestha, 2012).

Select **Arc Hydro Tool** => **Terrain Processing** => **Flow Accumulation**

4. Snapping Pour Points

This tool snaps pour points cell of highest accumulation flow to a cell with certain distance.

Select **Arc Hydro Tool** => **Snap Pour Point**

5. Watershed

That tool determined the boundary of area above a set of cells in a raster grid.

Select **Arc Hydro Tool** => **Watershed**

The watersheds have been delineated for seven Sweco stations. In order for create the catchment input map NVE and Sweco station catchments in shape files have been combined together with Merge tool and converted to raster format by Feature to Raster tool. The catchment map is shown in Figure 5-5.

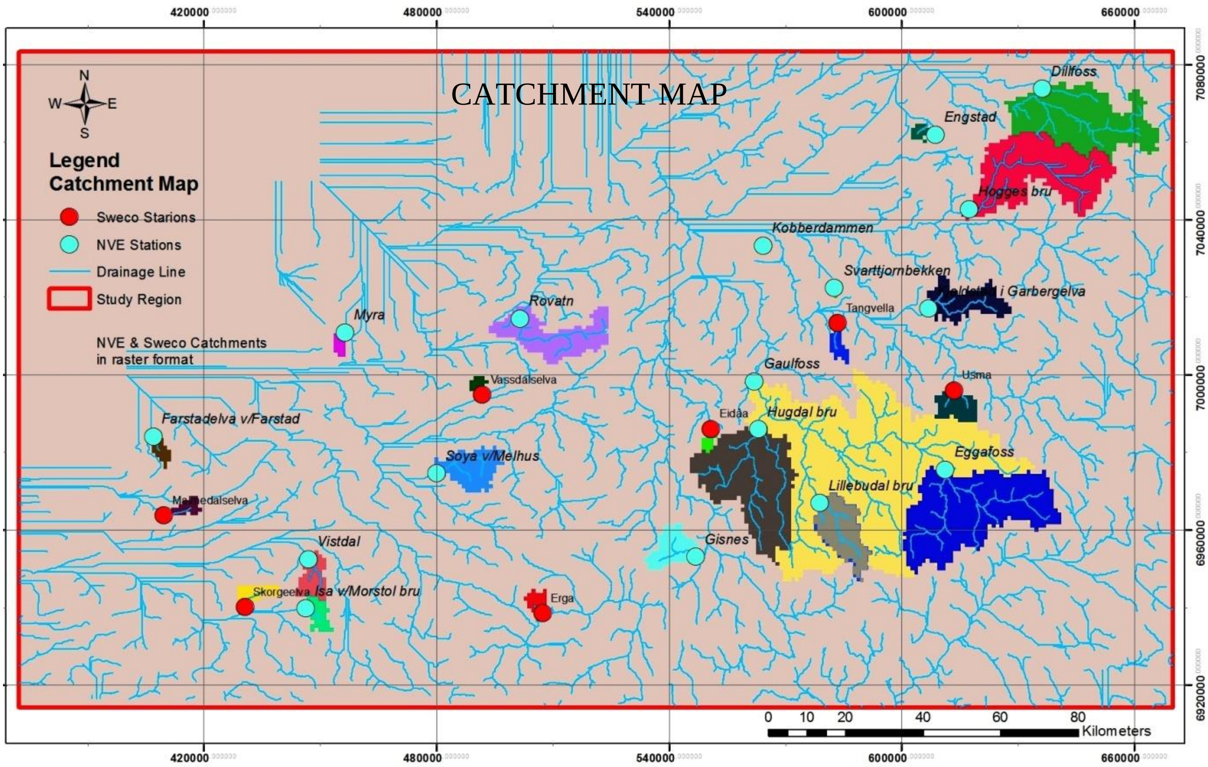


Figure 5-5   Catchments map

5.4 THE LAND USE MAP

The land use map is a simplified representation of lakes distribution over the area. The map for ENKI model system prepared in the way of two objects, the area covered by lakes = 1 and all other area = 2 (Figure 5-6). It can be achieved by reclassifying the DEM of the region. The reclassify tool changes the values in the raster map.

Select **Arc Toolbox** => **Spatial Analyst Tools** => **Reclass** => **Reclassify**

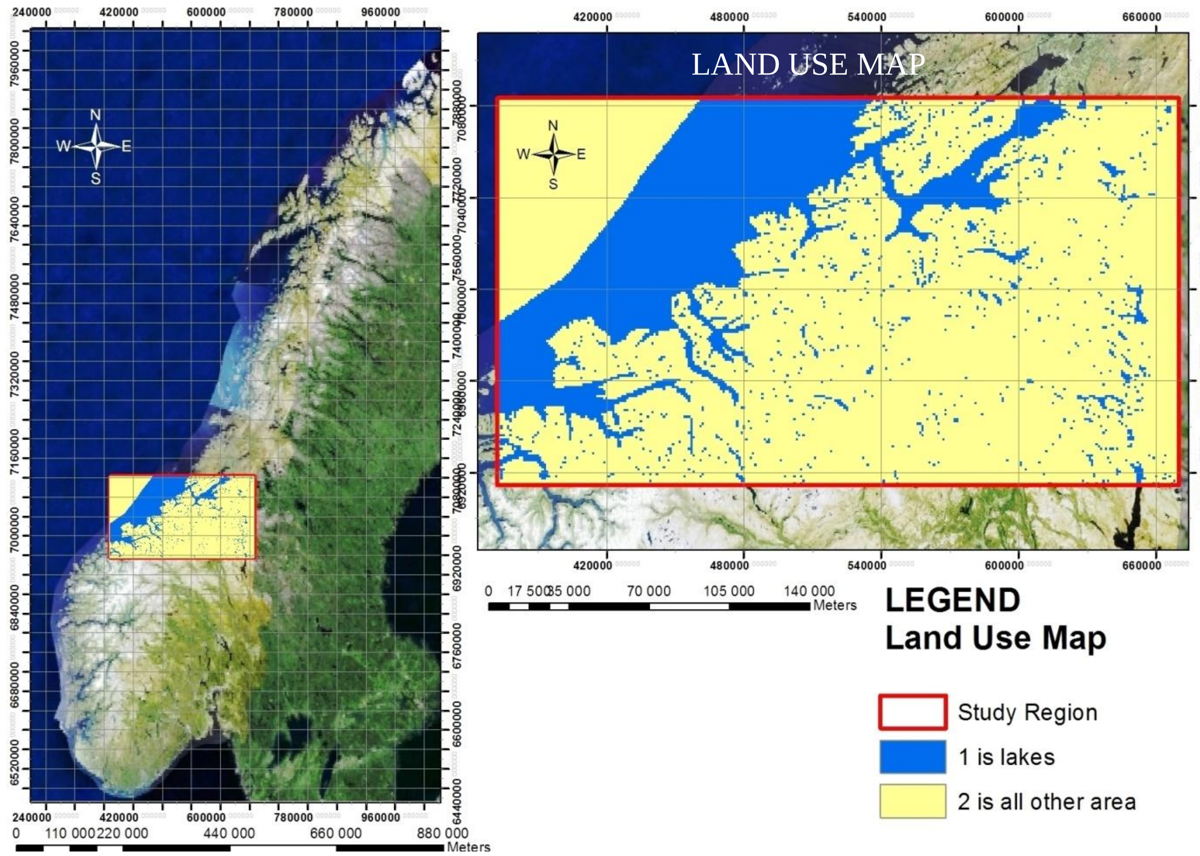


Figure 5-6 Land use map

5.5 SDC_CV, GLACIERS AND INITY MAPS

SDC_CV map is the map which required for Gam Snow routine. It gives to ENKI information of distribution of snow with respect to forest cover. In some cells of the raster map the layer of snow is thicker, in the otters is thinner. When snow is melting it melts faster where the layer is thinner. SDC_CV raster map is prepared in such way as: a forest area has values of 0.1 and all other cells are equal to 0.5 (Figure 5-7). Shape files with digital forest maps collected from \\Progdist.ntnu.no.

The Inity raster map is required for each ENKI model setup. Inity map is a map in which all grids equal to 0.04.

There are no glaciers in the region. Hence the glacier raster map is prepared with no value in each cell.

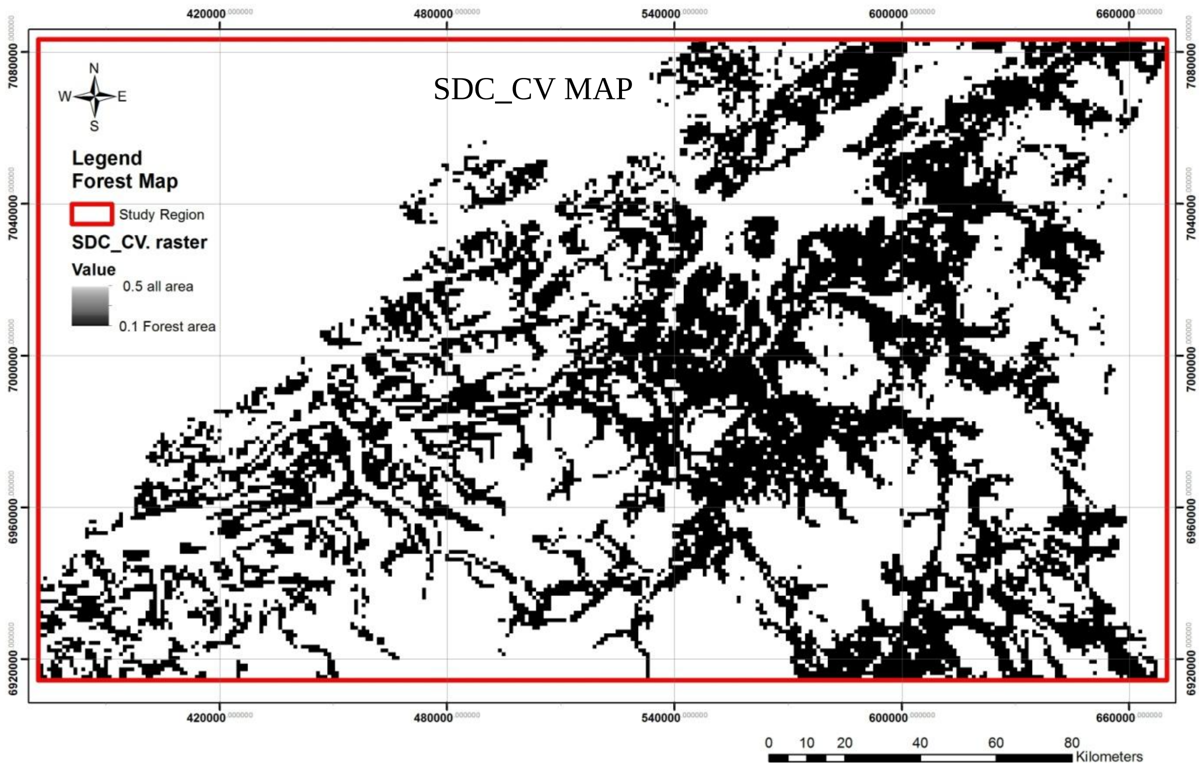


Figure 5-7 SDC_CV map (forest map)

5.6 ENKI MODEL INPUT FORMAT

The ENKI model has its own format for input data. The hydro-meteorological data and all maps should be prepared and converted to the format the ENKI acceptable to read.

5.6.1 THE HYDRO-METEOROLOGICAL INPUT FORMAT

The data for precipitation, temperature and runoff were arranged in special order in Microsoft Office – Excel 2007. All input parameters are prepared in separated .excel files and saved as Tab-Delimited text files. The arranged chronological order of input parameters is a strong requirement for ENKI input files. The chronological order for precipitation input file is shown on Figure 5-8.

	A	B	C	D	E	F
1	Xcoord	573175	498831	534225	454213	510075
2	Ycoord	6923198	6930941	6941679	6948416	6948926
3	network	pstats	pstats	pstats	pstats	pstats
4	name	BLANKTJERNMOEN I KVIKNE	HAFSÅS	OPPDAL - SÆTER	ERESFJORD	ÅNGÅRDSVATNET
5	STNR	9870	63530	63705	61820	63580
6	HOH	690	698	604	14	596
7	RefSystem	utm-32n	utm-32n	utm-32n	utm-32n	utm-32n
8	Point ID	1	2	3	4	5
9	Missing point	-9999	-9999	-9999	-9999	-9999
10	Count	4749	4749	4749	4749	4749
11	01.01.2000	0	0.5	0.3	1.5	3
12	02.01.2000	1.3	0.1	0.6	0.5	0
13	03.01.2000	0	8.6	12	12.9	9.4
14	04.01.2000	0	6.8	1	22	7.7
15	05.01.2000	0.6	5.6	6	8.6	0.5

Figure 5-8 The hydro-meteorological file chronological order

5.6.2 GIS INPUT MAPS FORMAT

All GIS maps for input into ENKI model system should be converted into Idrisi files. First all maps is saved in .tiff format as follows:

Table of Content => **select the raster map** => **right click** => **select Data** => **Export Data** => select TIFF format and save

There are several programs which are able to convert to Idrisi format. The Saga GIS program was used for converting all maps into Idrisi format in this study project.

5.6.2.1 SAGA GIS

SAGA GIS (System for Automated Geoscientific Analyses) is a free and open source geographic information system used for editing spatial data (http://www.wikipedia.org/). SAGA GIS equip by tool for converting raster maps into Idrisi files. The procedure as follows:

Modules => **Import/Export – GDAL/ORG** => **GDAL: Import Raster**

After importing the raster file into the system the message of success or failed procedure operas in the bottom dialog box.

The imported files should be extracted as follows (Figure 6-7):

Modules => **Import/Export – GDAL/ORG** => **GDAL: Export Raster**

The .tiff raster files are converted to Idrisi format for ENKI input.

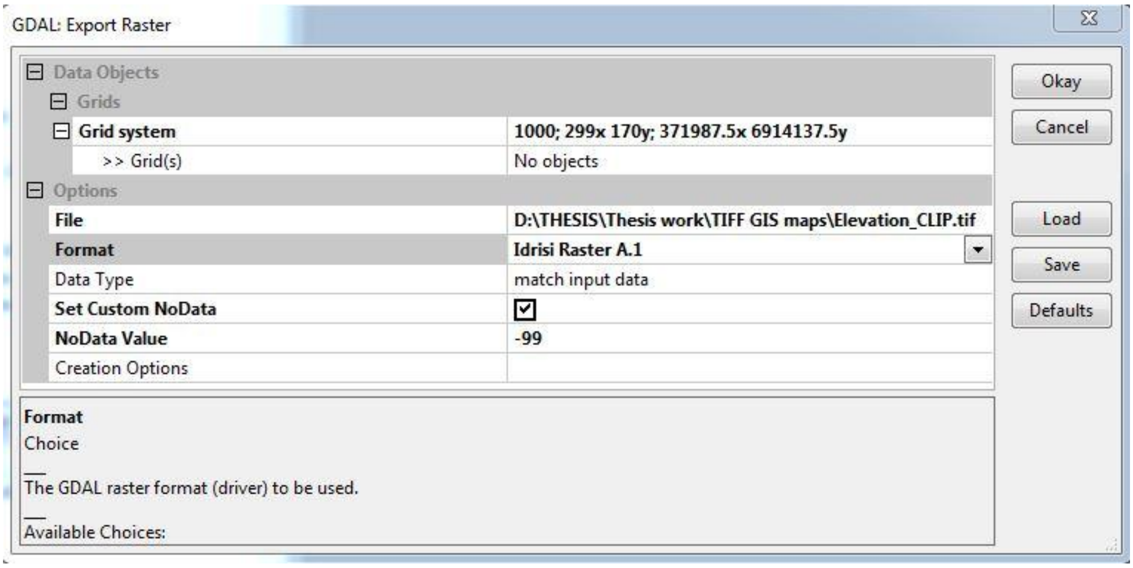


Figure 5-9 Extraction of raster files in Idrisi format using SAGA GIS

Remember! Within SAGA GIS, while using “Export Raster” it is important to have all lines selected and after that one should pres “Enter” and then “Okay” button. Without pressing “Enter” the program is not converting anything.

Table 5-1 Summary of input files for ENKI model

Type of Data	Program Used and Type of File	ENKI Input Format
Hydro-meteorological data	Microsoft Office Excel (.exe)	Text, Tab-delimited (.txt)
Digital Elevation Distribution	ArcGIS 10 raster map (.tif)	Idrisi (.rst)
Catchment area	ArcGIS 10 raster map (.tif)	Idrisi (.rst)
Land use	ArcGIS 10 raster map (.tif)	Idrisi (.rst)
SDC_CV (Forest area)	ArcGIS 10 raster map (.tif)	Idrisi (.rst)
Inity	ArcGIS 10 raster map (.tif)	Idrisi (.rst)
Glaciers	ArcGIS 10 raster map (.tif)	Idrisi (.rst)

6 ENKI MODEL SETUP

6.1 INTRODUCTION

ENKI is a framework which was found at www.opensource-enki.org. In order to download the program, one should create a Google account and make simple registration. The ENKI .zip file locates under "How to get Enki" tab. Two .zip archives the EnkiBin.zip and the Gaula.zip should be downloaded.

The existing Gaula.zip archive contains a complete ENKI example setup. The Gaula setup was modified and changed in order to create my own unique ENKI model. As was mentioned in above chapters, ENKI framework consists from model and region parts. The model part contains subroutines which are written in the order of hydrological cycle. The region part connects the model to the region which contains all properties such as: catchment size, elevation, raster and all parameters which are used within equations in model part. The results from simulation and calibration are stored as separate .txt and .nc files respectively inside ENKI model.

6.2 CREATING A NEW REGION

The Gaula model should be ready for running and all input files are prepared in affordable ENKI format. A new region is ready for set up.

Select **Menu** => **Region** => **New Region**

The "Create new region" box appears on the screen (Figure 6-1). The region name is "Katya region- General Setup". The new region is stored in the folder where all input files located. To set coordinate system the elevation.rst was chosen. The "Default raster geometry" is copied from DEM.rst file, the "Default network geometry" copied as Qstats.vct (precipitation network).

Select **Initial boundary coordinate** => **From existing layer** => select **Elevation.rst**

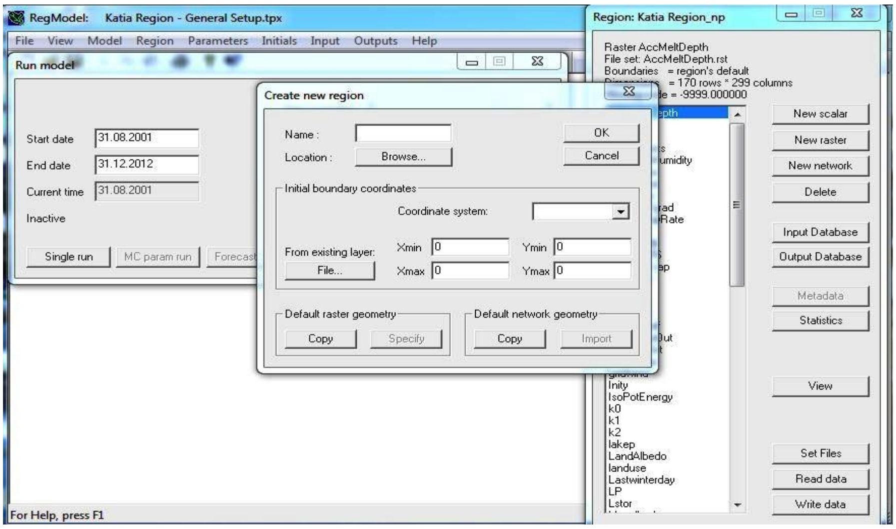


Figure 6-1 Create new region

6.2.1 SELECTING MODEL SUBROUTINES

The subroutines in Gaula setup was modified and changed in order to create new ENKI model.

To see available subroutines and make modifications in model setup:

Select **Model** => **Change**

The list of available and selected subroutines is shown in Figure 6-2.

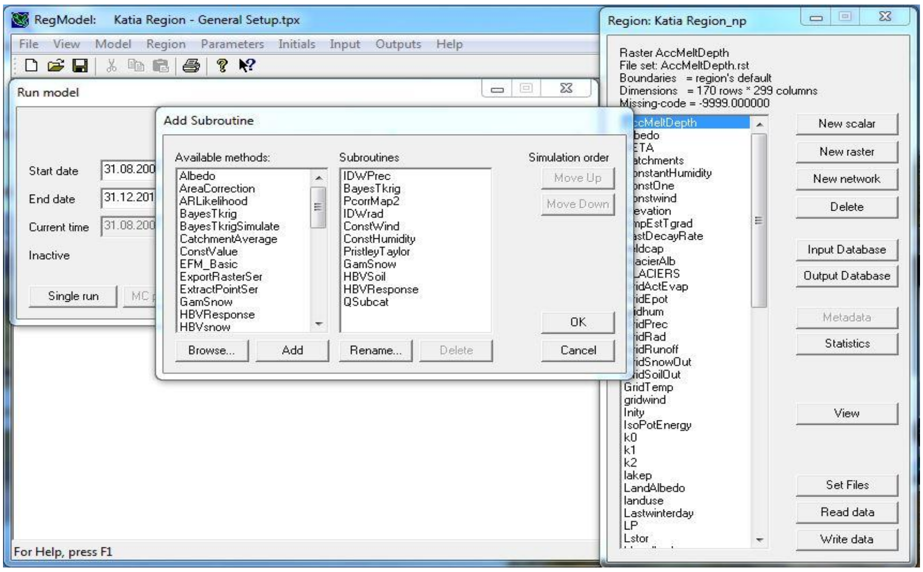


Figure 6-2 Model subroutines

All subroutine written in order and ENKI applies the model for each cell and each day. In this model the first subroutine is IDWPrec. This subroutine calculates precipitation. It uses Inverse – Distance Weight method to interpolate the precipitation. Within PcorrMap2 subroutine ENKI creates a raster with interpolated precipitations. For each day the program runs through all subroutines to calculate the flow in the end.

Remember! The subroutines have to be in right logical order; otherwise the program is not working.

6.2.2 THE INPUT DATABASE

The time series of hydro-meteorological variables is input database for new model. This time series are interpolated to all grids of the region.

It is possible to create a new input database or change the existing one by selecting “Input Database” in the region window.

Select **Input** => **New Database**

New database is created and variables should be imported by"Import ASCII table" command. After importing all variables into database, new variables generates in the region window: tstats _elev, pstats_elev and Rstats_elev (Figure 6-3).

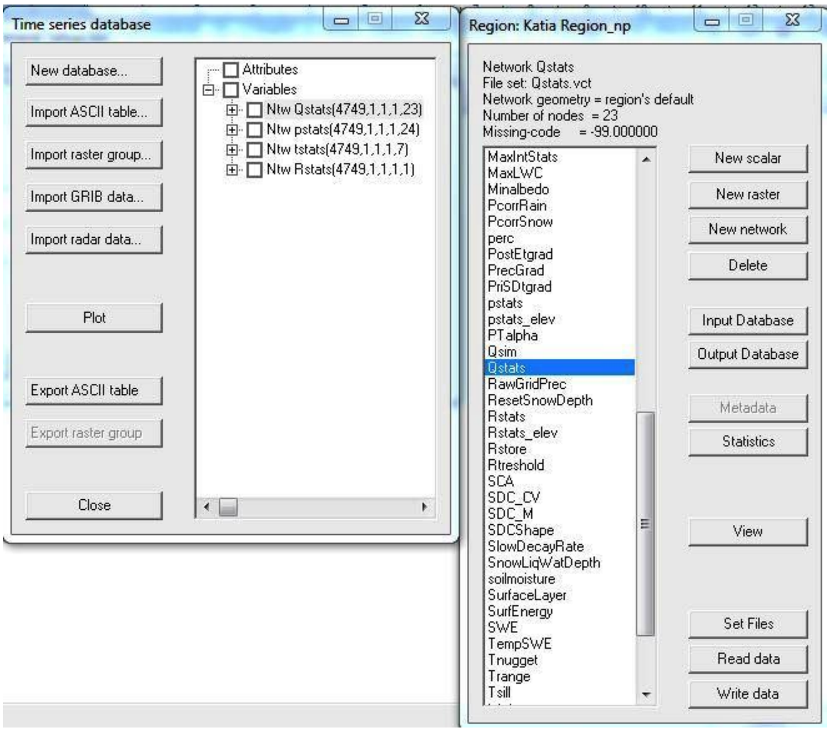


Figure 6-3 Imported variables into time series database

6.2.3 ESTABLISHING INTERNAL LINKS IN THE MODEL

Then the subroutines are chosen and the model is saved the routines are valid but not linked with variables. The following should be done to establish the links in the model:

Select **Menu** => **Model** => **Build Model**

The "Establish internal links in the model" dialog box appeared. Each tab represents subroutines for created model (Figure 6-4).

Within each subroutine tab the variables name, usage, data type, connection and description are listed. The data types are scalar, raster or network. All the variables in each subroutine are connected with variables for the next subroutine, which are input variables for the next one.

After connecting all subroutines the variables in the model should be associated with variables in the region. This process calls "Link Model-Region". It can be checked as follows:

Select **Model** => **Link Model-Region**

If all variables were linked in right order the "Run Model" window will occur (Figure 6-5).

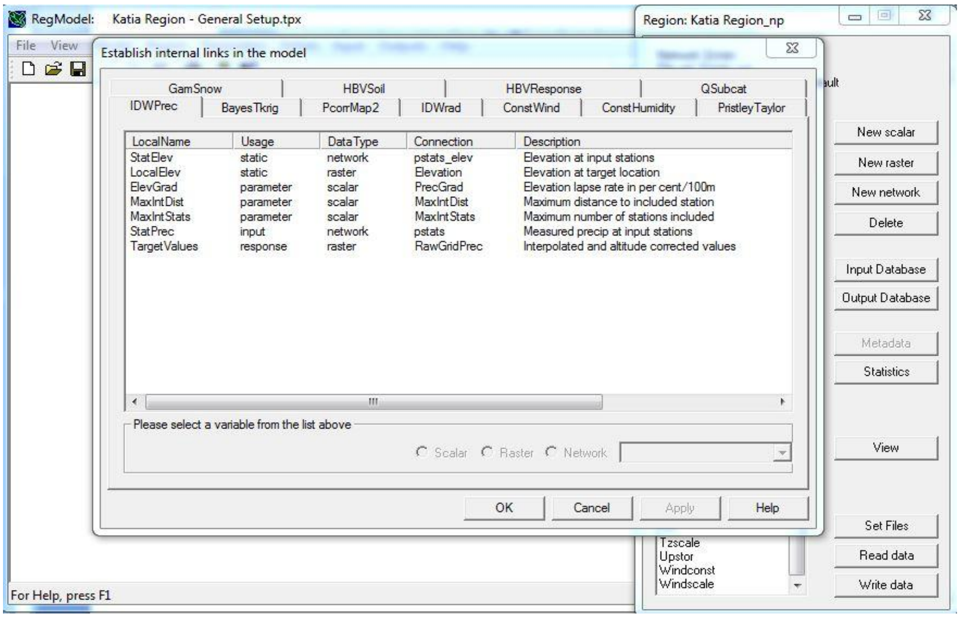


Figure 6-4 Establishing new links in the model

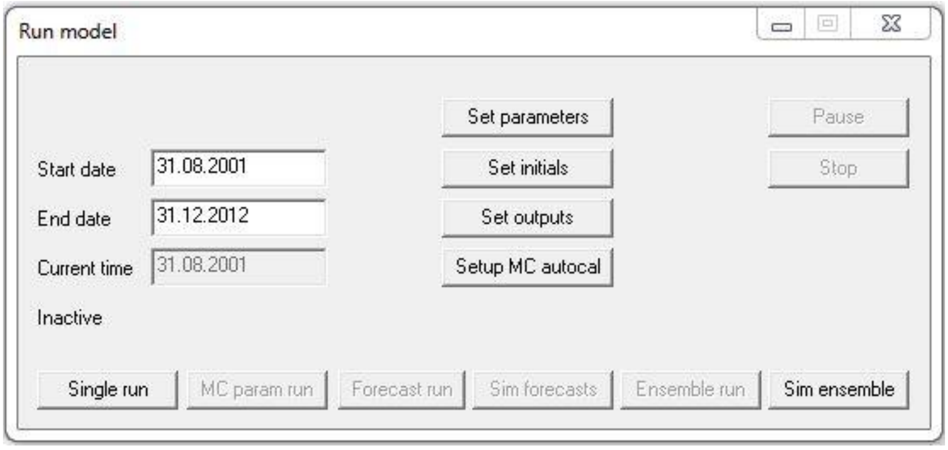


Figure 6-5 The model run window

6.3 RUN MODEL

The run model window is operational window for running the created model. It contains the boxes for initiate simulation or calibration period with available current time observation box. From that window user operates set of parameters, set of initial conditions, set outputs and MC setup can be selected, and model can be started and stopped.

6.3.1 SET PARAMETERS

The “Set parameters” window represents two types of parameters: distributed and scalar (Figure 6-6). All distributed parameters are input raster maps and interpolated pstats_elev and tstats_elev network.

The scalar parameters are physical parameters and free parameters are set as required within selected region. Table with all parameters are listed in Table 7-6.

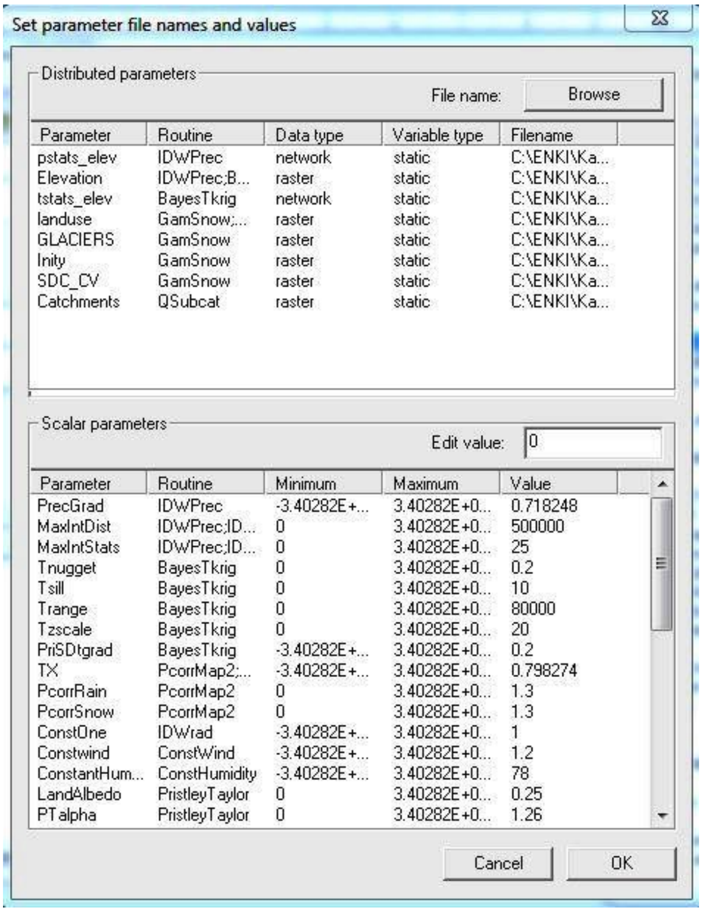


Figure 6-6 Set parameters

6.3.2 SET INITIAL STATES

Before starting the simulations it is important to set the starting point and define conditions of parameters at that time. Scalar parameters are the values; the distributed parameters are given as the file name. The file is created after one year of simulation; the name is Initial_State _2001_New.stx which is used for initialization of starting conditions (Figure 6-7). It is practical to let the program simulate for some short period of time in order to adjust the initial conditions.

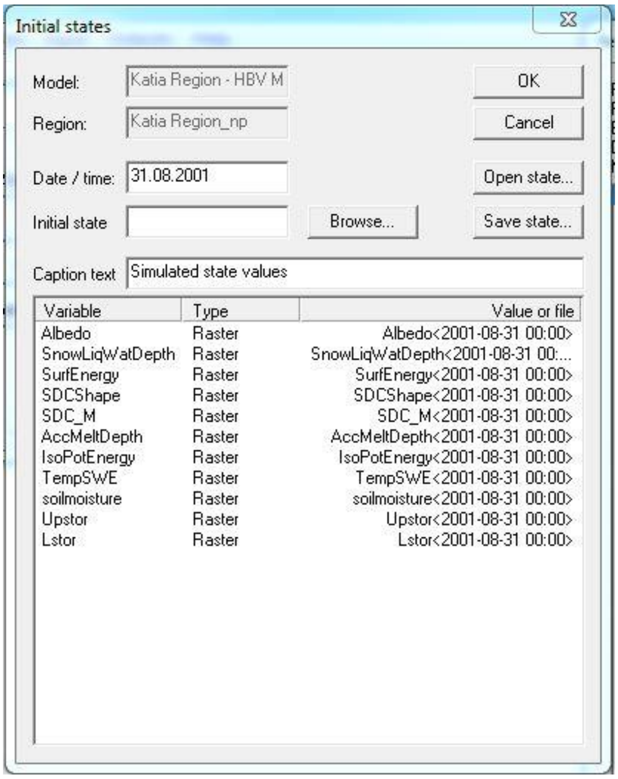


Figure 6-7 Initial states

6.3.3 SET OUTPUTS

The Set Outputs button in the model dialog opens the dialog shown in Figure 6-8. Outputs are associated with performance measures, with "Simulated values only" used for the case when evaluation against measurements is not requested. All model variables are available for export, but distributed models are generating massive amounts of data, ENKI by default exports nothing. The user should specify the variables to be stored in the output database.

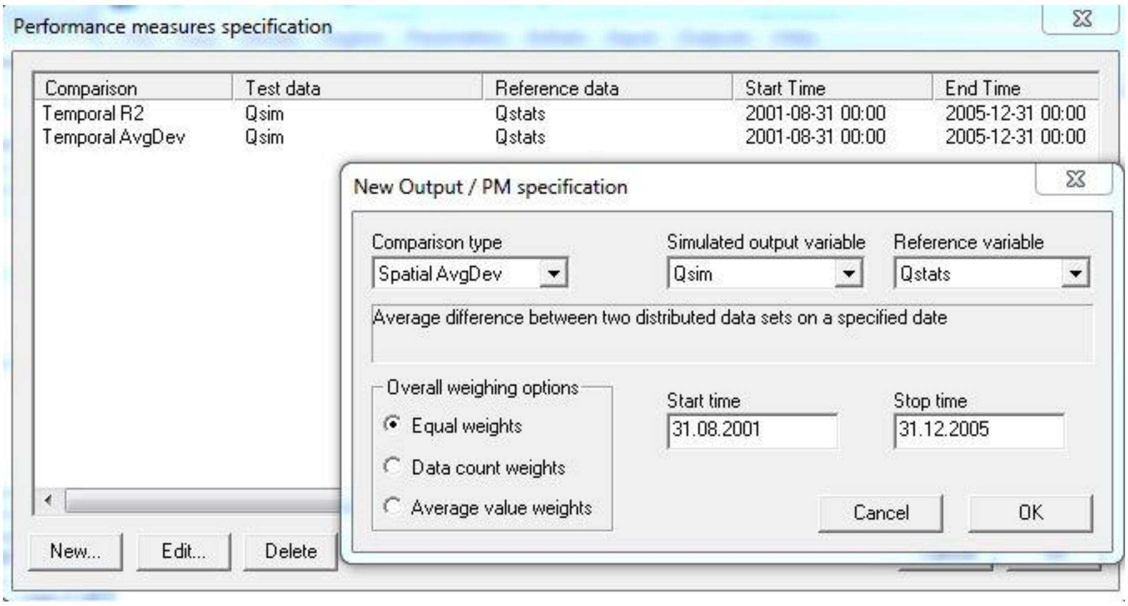


Figure 6-8 Performance measure specification

ENKI has a number of objective functions to choose from, each available in both temporal and spatial versions. A temporal objective functions compares time series, providing a spatial vector of performance measured values. A spatial objective function compares maps, and provides a temporal vector of performance measured values corresponding to the order of observed maps. (SINTEF, 2003)

6.3.4 STARTING A MODEL RUN

When the initialization is done, the Run button is enabled, and will start the simulation after creating a new output database or accepting continued use of the current. ENKI will report the simulation time as it progresses, and also display other progress information. It is always possible to halt the run, perform some operation, and resume the simulation from the next time step. (SINTEF, 2003)

6.3.4.1 STORING OF RESULTS

All output time series are stored in the output database (Figure 6-9). Can be found as follows:

Select **Menu** => **Region** => **Output database** =>**Variables** => Select **SimRunoff** => **Export ASCIITable** => **Excel** document

The vector time series can be exported into MS Excel, or to a TAB-delimited text files. When exporting to Excel directly, ENKI creates separate sheets for each network station with simulated and observed time series.

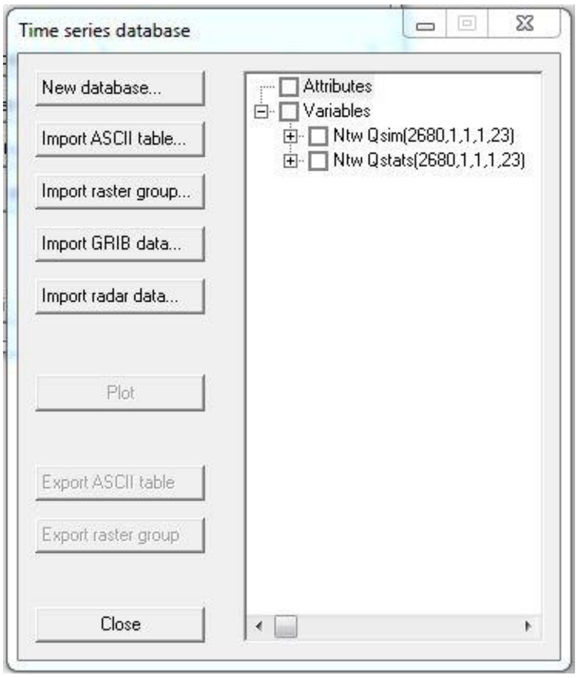


Figure 6-9 Time series database for exporting results

7 CALIBRATION AND VALIDATION WITH ENKI

7.1 INTRODUCTION

ENKI offers two ways of calibration. One is manual calibration which is setting values for all parameters in the "Set Parameters" dialog box. The other way is automatic calibration the selection of parameters algorithms. There are six different algorithms implemented within ENKI which are available in right side of window "MC method":

- Marqardt-Levenberg
  Multi-surface gradient search using the Jacobian matrix (PEST algorithm)
- SCE-UA
  Global shuffled complex evolution. Slow and robust for difficult cases.
- Random MC (GLUE)
  Random drawing from specified distributions.
- DREAM MCMC
  Adaptive Metropolis sampler, best used with likelihood-based PMs.
- Conditional Univariate
  Univariate sampling around an existing optimum, n trials per parameter dimension.
- External list
  Parameter sets read from file.

The automatic calibration setup window is shown in Figure 7-1.

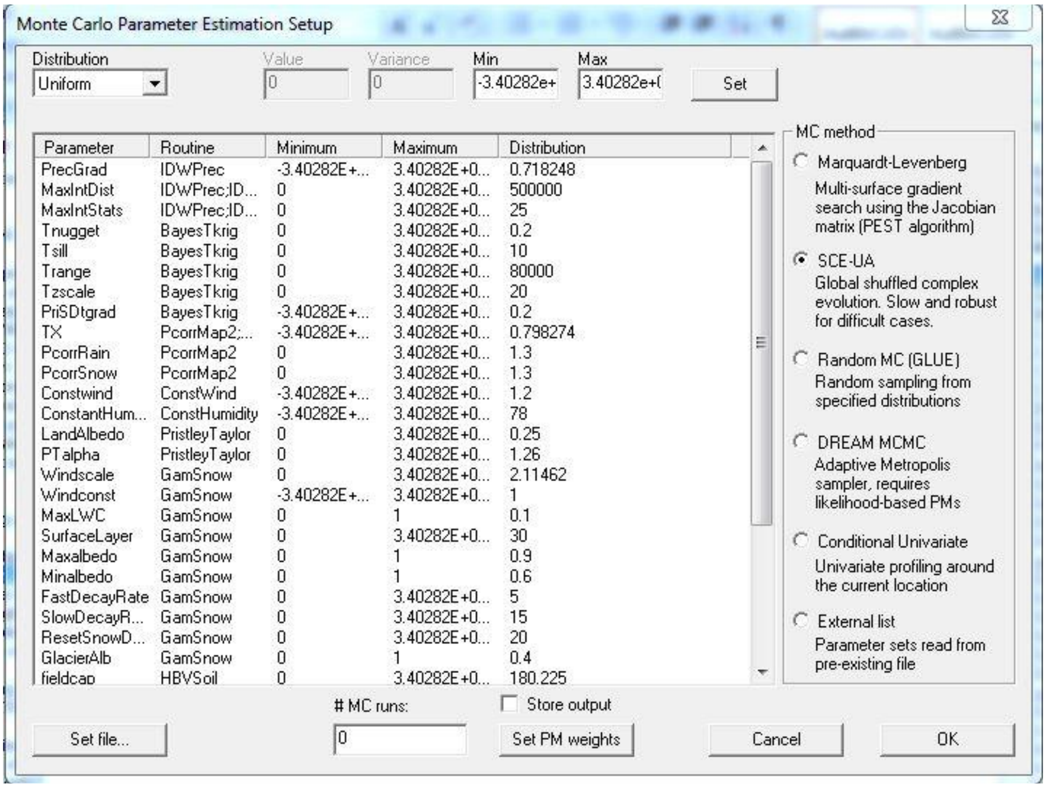


Figure 7-1 Calibration with Monte Carlo parameter Estimation Setup

SCE-UA method for automatic calibration is selected for this study project.

7.2 SCE-UA CALIBRATION

The global search algorithm method SCE-UA is the Shuffled Complex Evolution - University of Arizona. This method come out being able to solve the conceptual rainfall-runoff model optimization problem efficiently and effectively (Q. Duan, 1992). This method is a robust optimization routine designed to find the global optimum also in highly irregular response surfaces. The routine may require thousands of model evaluations to converge, in particular if many parameters are optimized (SINTEF, 2003).

7.3 FIRST CASE CALIBRATION

In the first case, the model calibrated over all the catchments within selected study region. The NVE runoff stations have real measured runoff values as input for calculating R^2 and Sweco runoff data series was converted to missing values (-99) for final extraction of simulated runoff with best average set of regional parameters. The calibration period is from 2001 to 2005 year. For first case the model run 1800 iterations. The range of Monte Carlo parameters values are taken with respect to geographical location of the region, previous experience and proper literature. Less sensitive parameters for calibration are constant values. The range and best set of parameters for all cases is tabulated in Table 7-6.

7.3.1 FIRST CASE CALIBRATION RESULTS

The results from first case calibration performed graphically as hydrographs of observed and simulated runoff. The values of individual Nash-Sutcliffe efficiency (R^2), area of the catchments and number of iterations are tabulated in Table 7-1.

Table 7-1 Calibration results from the first case

Name of the Station	*R2 (second)*	*Area,km2*	*Number of Run*
Farstadelva v/Farstad	-0.242	24.14	1
Myra	0.277	16.37	350
Rovatn	0.302	236.37	179
Isa v/Morstøl bru	0.634	44.26	190
Kjeldstad i Garbergelv	0.595	144.92	649
Svarttjørnbekken	0.223	3.41	141
Høgges bru	0.653	494.6	81
Hugdal bru	0.280	545.4	788
Lillebudal bru	0.564	167.97	551
Gaulfoss	0.732	3083.58	81
Eggafoss	0.848	653.89	625
Gisnes	0.686	94.32	81
Søya v/Melhus	0.268	137.29	930
Vistdal	0.372	66.32	172
Engstad	0.251	20.14	460
Dillfoss	0.456	480.55	57
Average	***0.150***		

The variability of R^2 is from -0.24 to 0.85. The reasons of such high variability can be the size of the catchments, the location, errors in input parameters, low number and not equally distribution of meteorological data.

Runoff pattern highly dependent from size of the catchment. Small catchments have fast response and large catchments utilized longer time for response after rainfall event. The variability of catchment area is from 3.4 km^2 (Svarttjørnbekken) to 3083.6 km^2 (Gaulfoss). The catchments with area more than 50 km^2 have higher R^2 from 0.37 to 0.85, except Hugdal bru with R^2=0.28 and area 545.4 km^2; Søya v/Melhus with R^2=0.268 and area 137.3 km^2; Rovatn with R^2=0.30 and area 236.4 km^2. The Gaulfoss and Eggafoss catchments have largest R^2 and area: R^2 = 0.73 and R^2 = 0.85 and area equal 3083.6 km^2 and 653.9 km^2 respectively. The catchments with area less than 50 km^2 showed worse results, R^2 from – 0.24 to 0.30. It can be concluded that catchments with area less than 25 km^2 did not performed well in calibration process. The relation between R^2 and area of the catchment is shown in Figure 7-2.

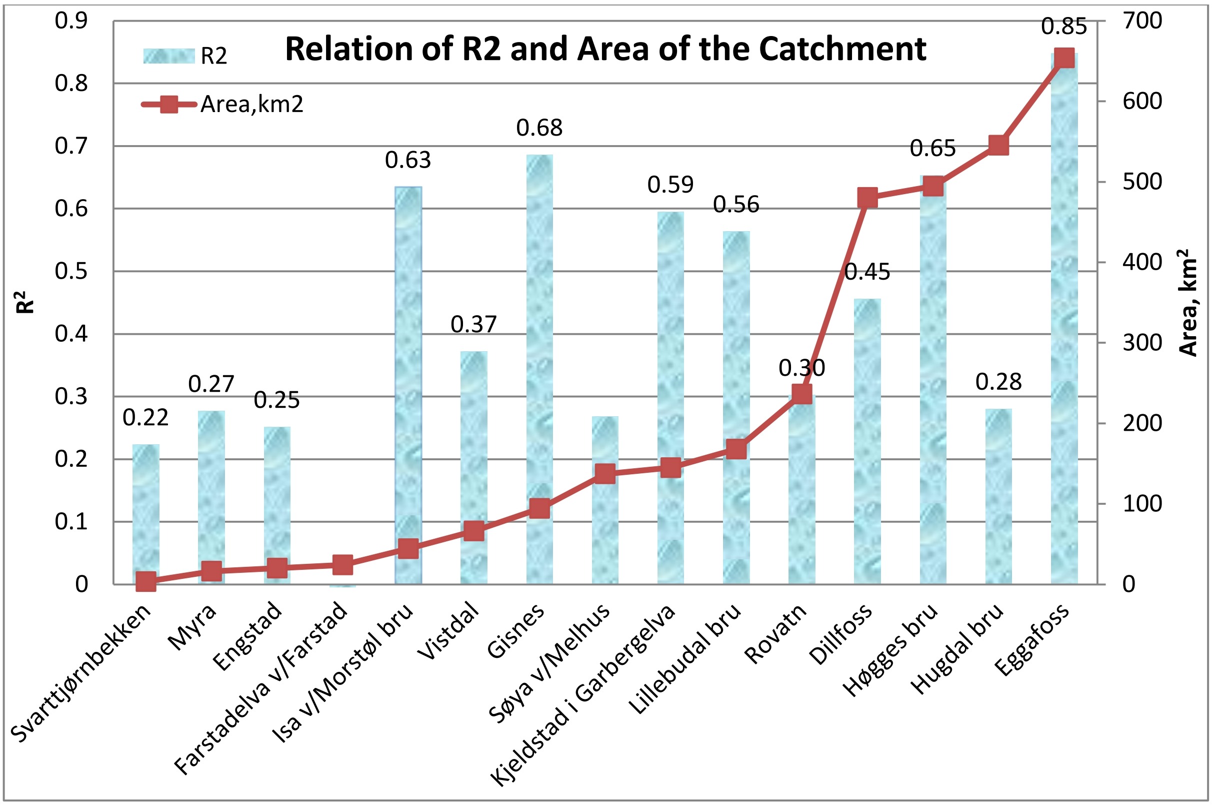


Figure 7-2 Relation between R^2 and area of the catchment

It should be noted that for the first case of calibration the model run 1860 iterations in order to achieve as good as possible R^2 over 16 catchments. The best R^2 have been obtained for first 900 iterations (Figure 7-12).

The other reason of high variability of R^2 might by the location of the catchments. The selected study region is approximately 500 000 km^2 and covering inland and coastal climatic zone. The Farstadelva v/Farstad, Myra, Rovatn, Søya v/Melhus and Engstad catchments located close to the coastal line. Precipitation and temperature pattern for these catchments is affected by coastal climate, which is totally different as the inland climate. It can be concluded that large catchments located in inland climate have much higher R^2 compared to catchments within coastal climatic zone. The distribution of temperature stations is also can be the reason of low R^2 values. The location of the catchments and location of meteorological stations are showed in (Figure7-9).

The hydrographs of observed and simulated runoff data series from first calibration are showed below.

The simulated hydrograph of Farstadelva v/Farstad catchment follows the peaks and low periods of observed hydrograph, but with shift in time and in starting conditions (Figure 7-3). That is why the R^2 value is negative. The reason model showed that shifting might be due to difficulties in interpolating of precipitations in coastal line zone.

Myra catchment locates in coastal zone as well as Farstadelva v/Farstad catchment. The simulated hydrograph follows the pattern of observed one, but the peaks is not repeated (Figure 7-4).

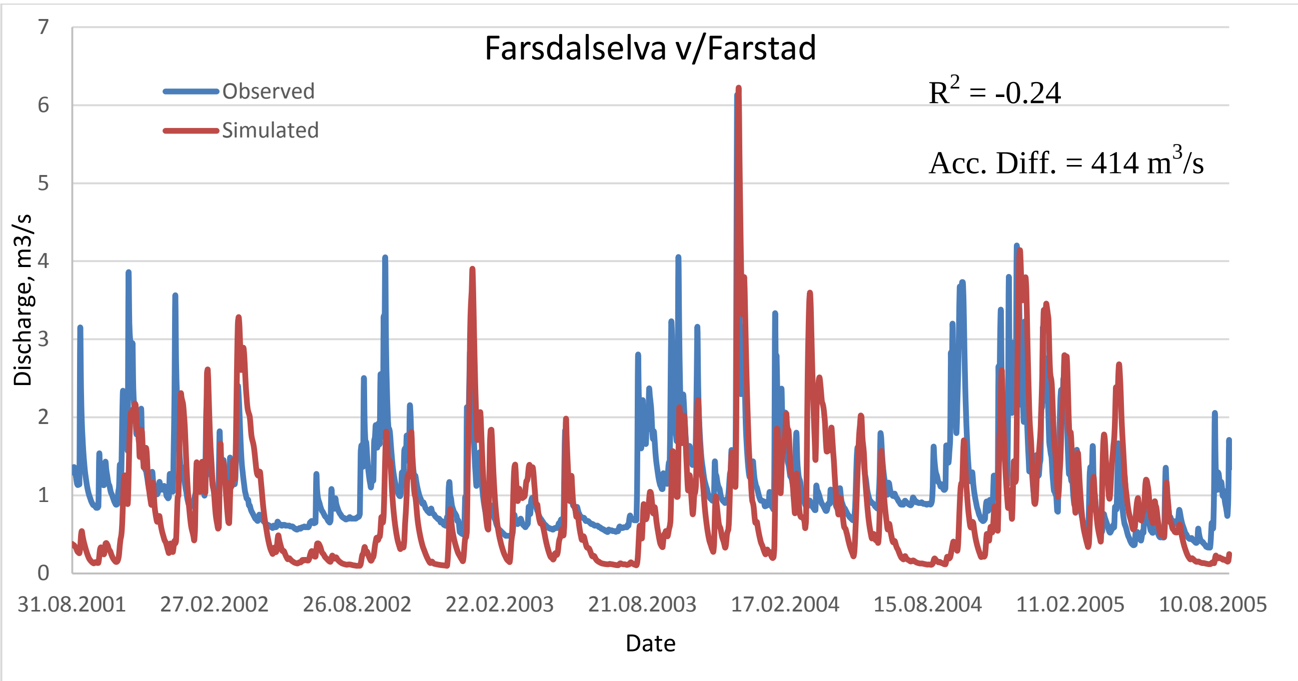


Figure 7-3 First case calibration for Farstadelva v/Farstad catchment

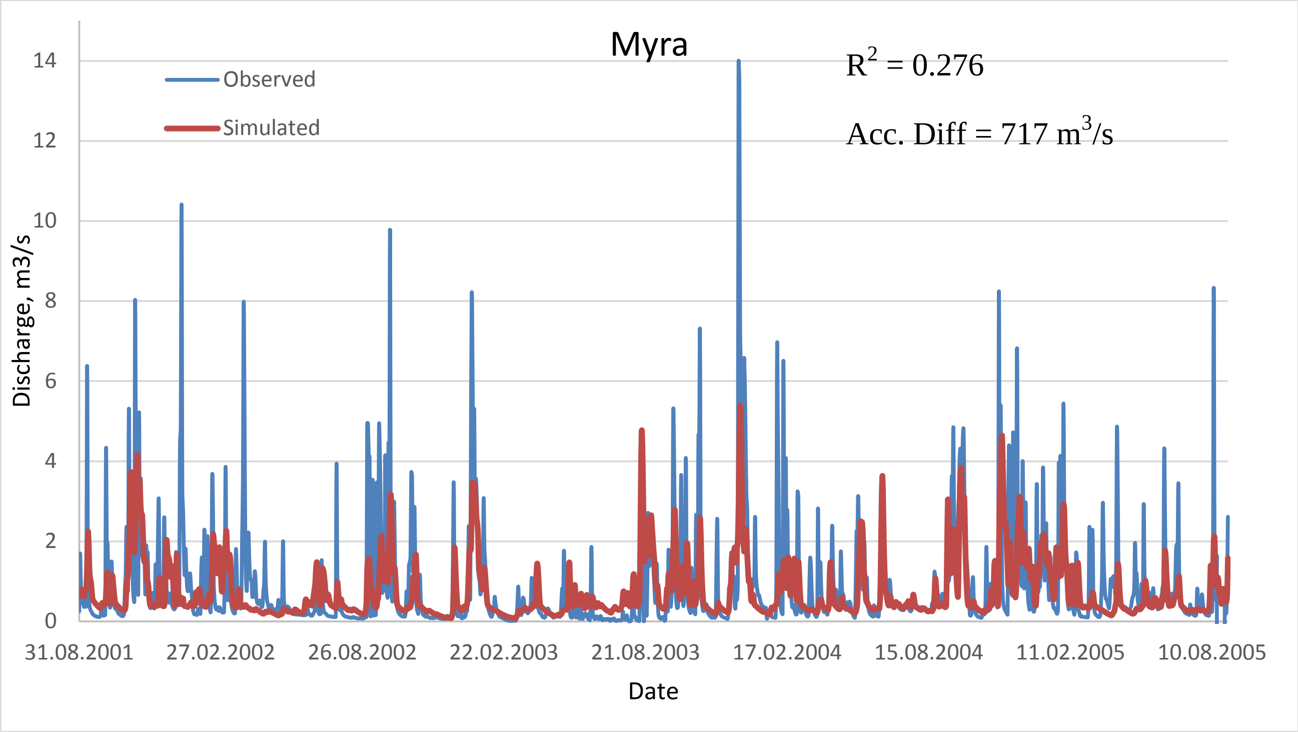


Figure 7-4 First case calibration for Myra catchment

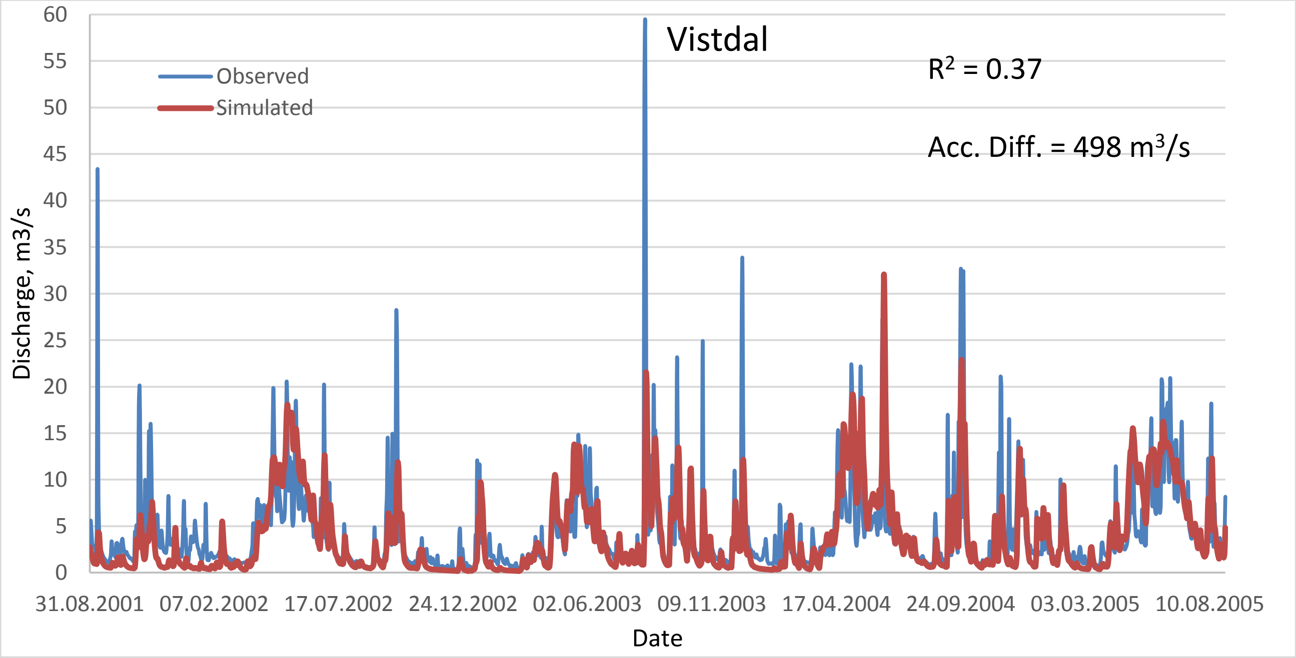


Figure 7-5 First case calibration for Vistdal catchment

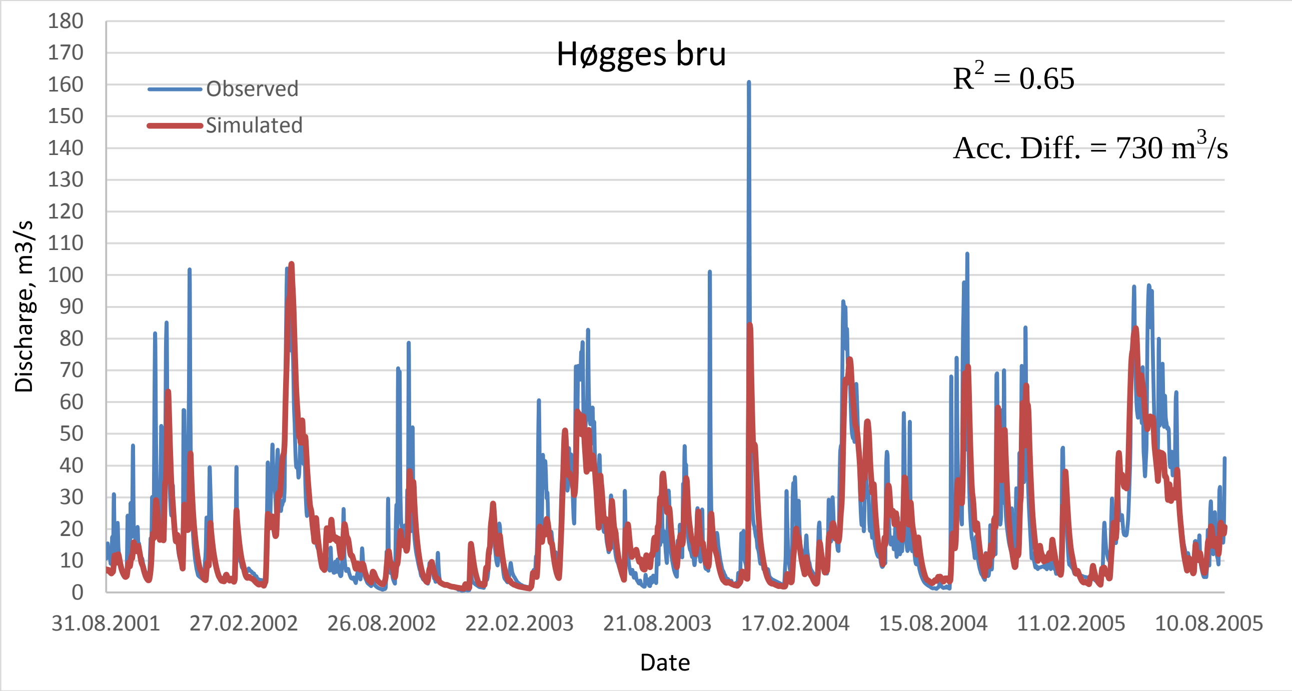


Figure 7-6 First case calibration for Høgges bru catchment

The simulated hydrographs of Vistdal and Høgges bru catchments showed quite reasonable fit in compare to observed one (Figures 7-5; 7-6). The high peaks in autumn periods are not repeated by simulated hydrographs.

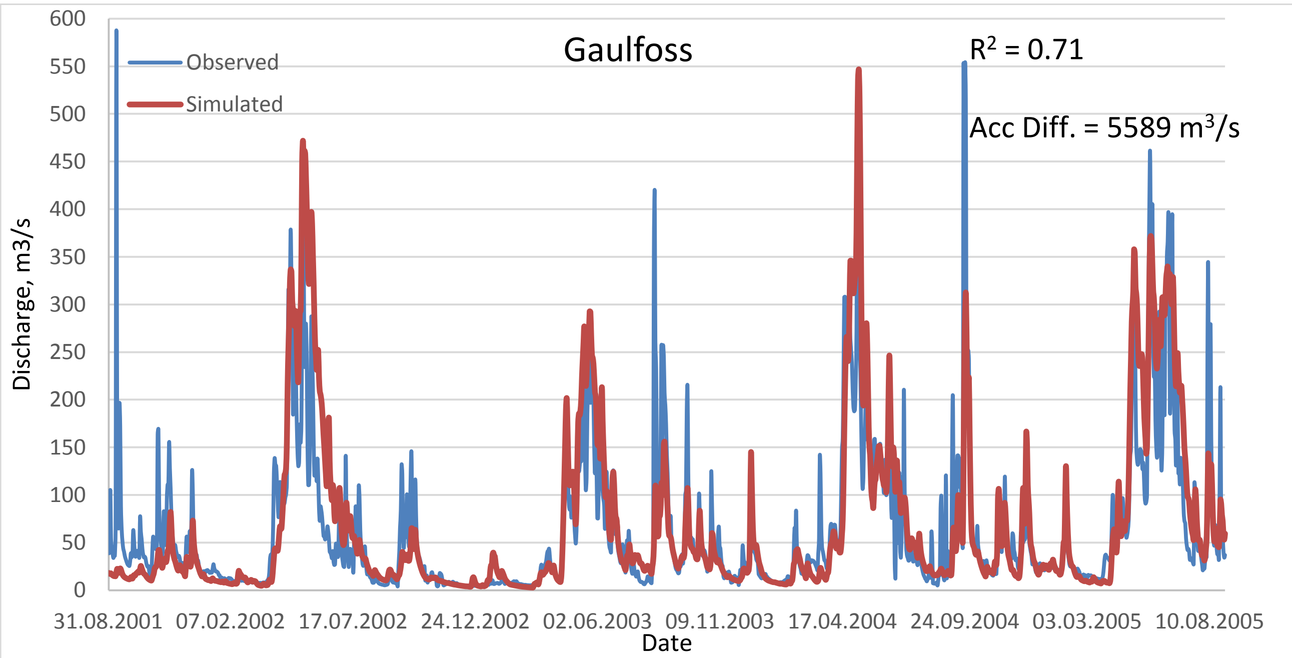


Figure 7-7 First case calibration for Gaulfoss catchment

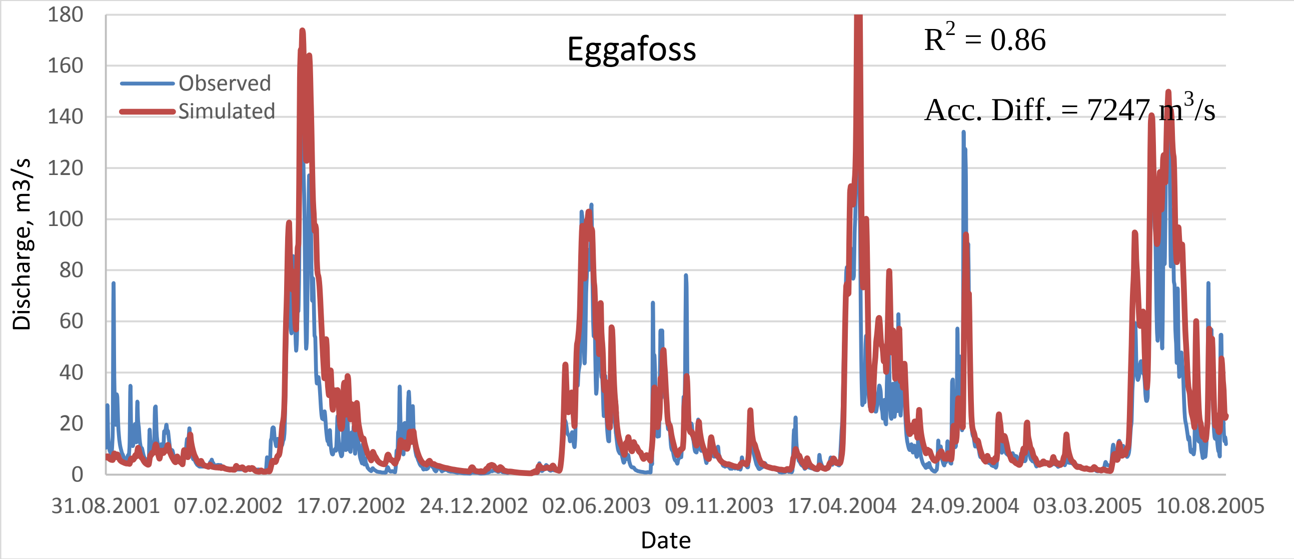


Figure 7-8 First case calibration for Eggafoss catchment

The Gaulfoss and Eggafoss are the largest catchments in the study region. Those two catchments showed the best R^2 value after first calibration. The simulated hydrographs showed good fit during high and low flow (Figure 7-7; 7-8). Some of the peaks in summer and early autumn periods are not reaching the peaks of observed hydrograph. The starting peaks are also missing. It might due to pure estimated starting conditions.

7.4 SECOND AND THIRD CASES OF CALIBRATION

In order to achieve better average R^2 the decision was made to exclude from calibration catchments which did not perform well after first calibration (Table 7-3). The map of excluded and remained catchments is shown in Figure 7-9.

Table 7-2 Excluded catchments from second calibration

Name of Excluded Catchments	***First Case R2***
Farstadelva v/Farstad	-0.242
Myra	0.277
Rovatn	0.302
Svarttjørnbekken	0.223
Hugdal bru	0.280
Såya v/Melhus	0.268
Engstad	0.251

The range of parameters for second and third calibration was expanded for some of the parameters (Table7-4).

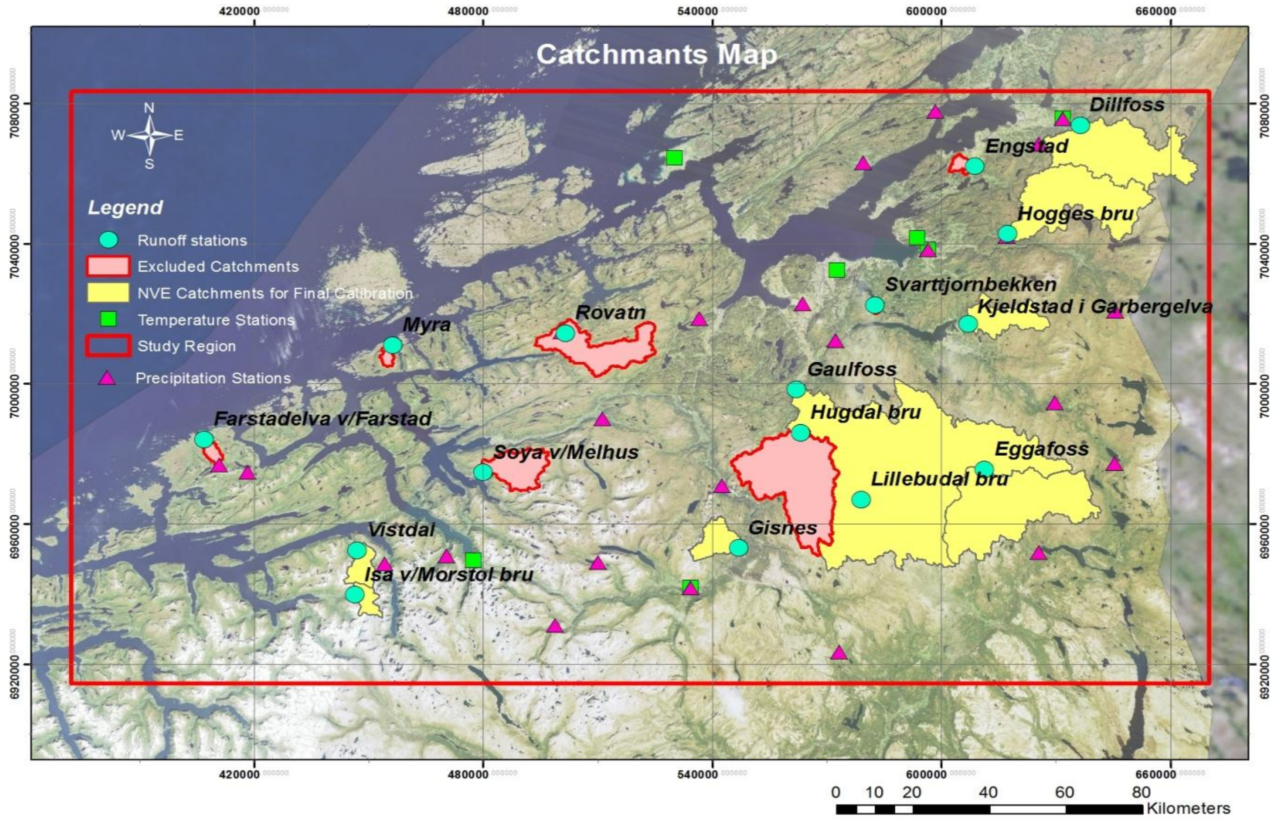


Figure 7-9 Map of excluded and remained catchments for second and third calibrations

For third case of calibration PcorrRain and PcorrSnow parameters were performed as raster maps with best values from first case of individual calibration. Those two parameters are ones of the most influencing in spatial interpolation of precipitation. Two raster maps have been prepared in GIS and converted to Idrisi format. The results of all cases of calibration are shown in Table 7-4.

Table 7-3 Results of first, second and third calibration

	R2		
Name of the Station	***First Case***	***Second Case (excluded catchments)***	***Third Case (excluded catchments + raster Pcorr)***
Farstadelva v/Farstad	-0.242	n/a	n/a
Myra	0.277	n/a	n/a
Rovatn	0.302	n/a	n/a
Isa v/Morstøl bru	0.634	0.621	0.627
Kjeldstad i Garbergelva	0.595	0.606	0.556
Svarttjørnbekken	0.223	n/a	n/a
Høggås bru	0.653	0.683	0.571
Hugdal bru	0.280	n/a	n/a
Lillebudal bru	0.564	0.611	0.352
Gaulfoss	0.732	0.717	0.644
Eggafoss	0.848	0.852	0.839
Gisnås	0.686	0.674	0.471
Såya v/Melhus	0.268	n/a	n/a
Vistdal	0.372	0.375	0.313
Engstad	0.251	n/a	n/a
Dillfoss	0.456	0.469	0.282
Average	***0.15***	***0.551***	***0.452***

For the second case of calibration the model run over 7000 iterations in order to achieve as good as possible R^2 over 9 catchments. The average value of Nash-Sutcliffe efficiency is 0.55.

The R^2 value has been significantly improved after first calibration.

For the third case of calibration the model run over 5200 iterations. The average value of R^2 is 0.45, which is slightly lower in compare with second calibration. It can be concluded that applying constant value for PcorrRain and PcorrSnow did not improve the calibration results in comparison with second case.

The result from second calibration is used for further validation of the model and extraction of simulated runoff data series for Sweco catchments.

7.4.1 SECOND CASE CALIBRATION RESULTS

The best set of parameters for second case of calibration has been achieved for first 2000 iterations from 7000 runs in total. The values of best individual and average R^2 is represented in Table 7-5.

Table 7-4 Results from second calibration

	R2	
Name of the Station	**Best individual calibration**	**Average individual calibration**
Isa v/Morst?l bru	0.621	0.539
Kjeldstad i Garbergelva	0.606	0.422
Høgges bru	0.683	0.611
Lillebudal bru	0.611	0.592
Gaulfoss	0.717	0.629
Eggafoss	0.852	0.801
Gisnøs	0.674	0.658
Vistdal	0.375	0.313
Dillfoss	0.469	0.393
Average		0.550950667

Relation between individual and average Nash efficiency is shown in Figure 7-10. It should be concluded that accuracy of estimation runoff data from average set of parameters is always lower than applying the individual set of parameters. It could be clearly seen by relation between individual and average R^2 value.

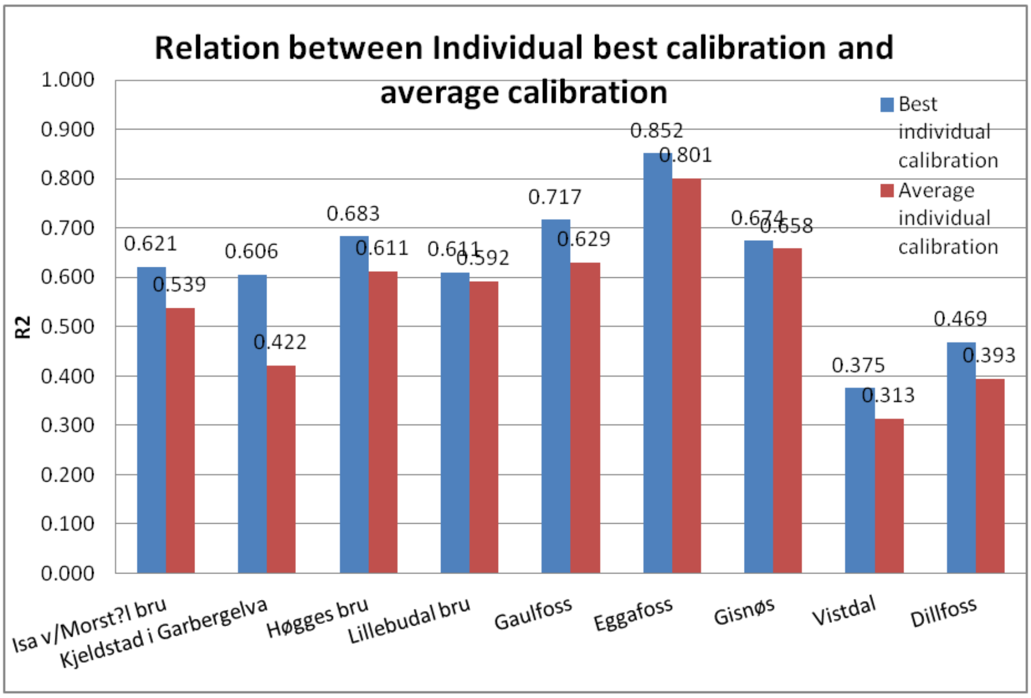


Figure 7-10 Relation of individual best calibration and average calibration

The relation between average and individual R_2 can be calculated by applying the equation, placed in Figure 7-11.

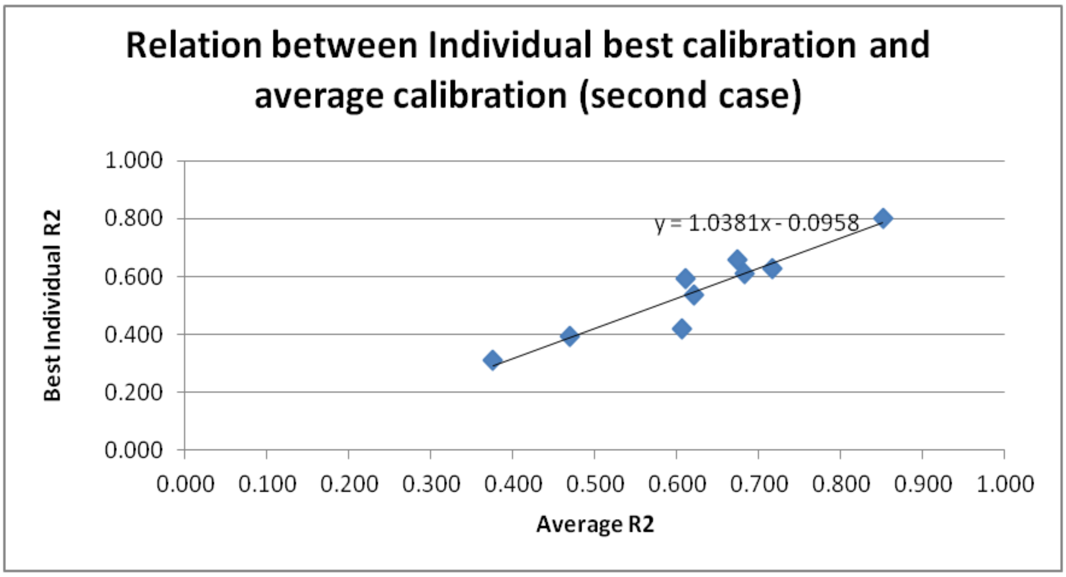


Figure 7-11 Scatter plot of individual and average calibration

Figure 7-12 graphically shows necessary number of model calibration runs for all cases in order to achieve best individual R^2.

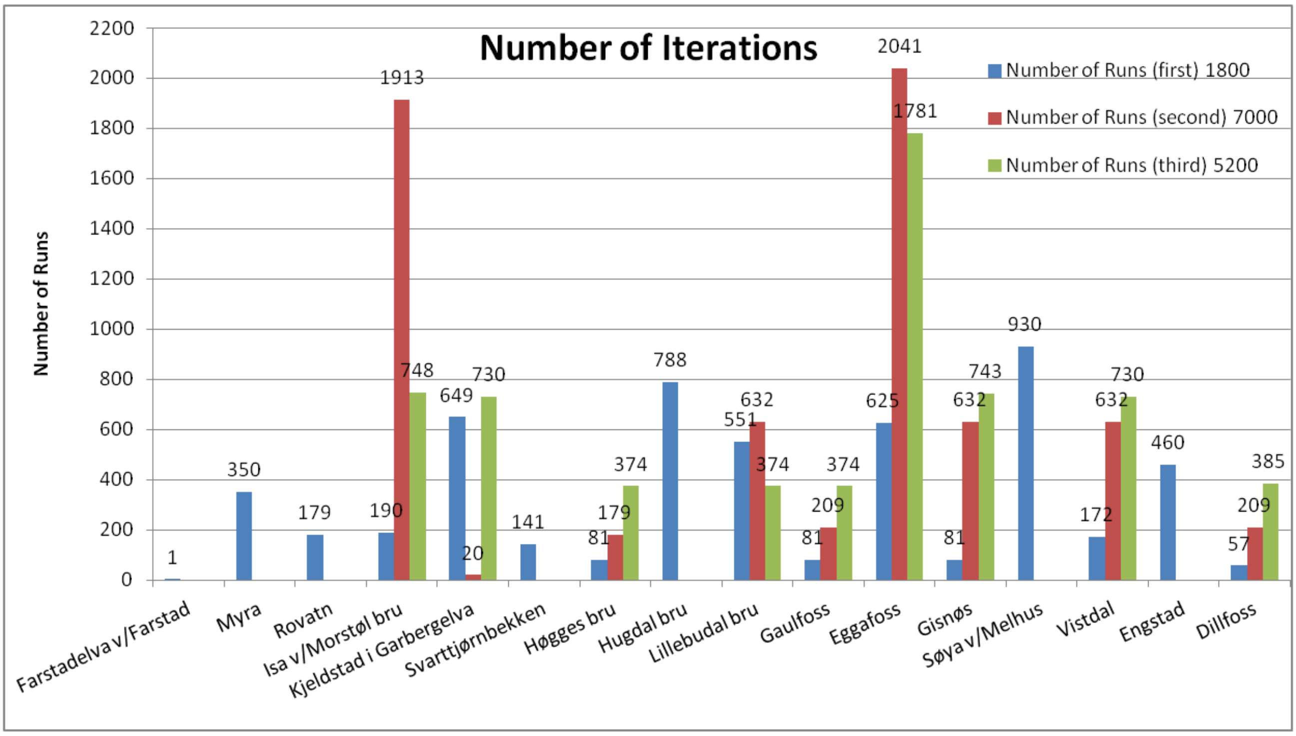


Figure 7-12 Necessary number of model calibration with ENKI

From the graph it is seen that for achieving best R^2 ENKI model should run about 2000 iterations.

Table 7-5 Calibration parameters for ENKI model

Parameters	***Routine***	***Distribution***	***Value Range***	***Best set of Parameters (average)***		
				First Case	***Second Case***	***Third Case***
PrecGrad	IDWPrec	Uniform	from 0 to 8	6.195	3.645	2.330
MaxIntDist	IDWPrec	Constant	500000	500000	500000	500000
MaxIntStats	IDWPrec	Constant	25	25	25	25
Tnugget	BayesTkrig	Constant	0.2	0.2	0.2	0.2
Tsill	BayesTkrig	Constant	10	10	10	10
Trange	BayesTkrig	Constant	80000	80000	80000	80000
Tzscale	BayesTkrig	Constant	20	20	20	20
PriSDtgrad	BayesTkrig	Constant	0.2	0.2	0.2	0.2
TX	PCorrMap2	Uniform	from -2 to 4	0.158	0.728	-0.482
PcorrRain	PCorrMap2	Uniform	from 0.8 to 1.9	1.143	1.570	raster map
PcorrSnow	PCorrMap2	Uniform	from 0.75 to 2	0.875	1.013	raster map
ConstantHumidity	ConstValue	Constant	78	78	78	78
Constwind	ConstValue	Constant	1.2	1.2	1.2	1.2
LandAlbedo	PristleyTaylor	Constant	0.25	0.25	0.25	0.25
PTalpha	PristleyTaylor	Constant	1.26	1.26	1.26	1.26
Windscale	GamSnow	Uniform	from 1 to 10	8.810	3.266	3.885
Windconst	GamSnow	Constant	1	1	1	1
MaxLWC	GamSnow	Constant	0.1	0.1	0.1	0.1
SurfaceLayer	GamSnow	Constant	30	30	30	30
Maxalbedo	GamSnow	Constant	0.9	0.9	0.9	0.9
Minalbedo	GamSnow	Constant	0.6	0.6	0.6	0.6
FastDecayRate	GamSnow	Constant	5	5	5	5
SlowDecayRate	GamSnow	Constant	15	15	15	15
ResetSnowDepth	GamSnow	Constant	20	20	20	20
GlacierAlb	GamSnow	Constant	0.4	0.4	0.4	0.4
fieldcap	HBVSoil	Uniform	from 50 to 500	383.026	448.685	420.507
LP	HBVSoil	Constant	0.9	0.9	0.9	0.9
BETA	HBVSoil	Uniform	from 1 to 5	1.408	1.657	1.357
k2	HBVResponse	Uniform	from 0.15 to 0.6	0.229	0.249	0.394
k1	HBVResponse	Uniform	from 0.01 to 0.25	0.124	0.164	0.189
k0	HBVResponse	Uniform	form 0.001 to 0.1	0.051	0.044	0.020
perc	HBVResponse	Uniform	from 0.5 to 2	1.944	0.672	0.789
Rtreshold	HBVResponse	Uniform	from 5 to 30	20.851	13.904	11.536
lakep	HBVResponse	Constant	0	0	0	0

The following hydrographs graphically represent the results after applying average set of parameters from second calibration.

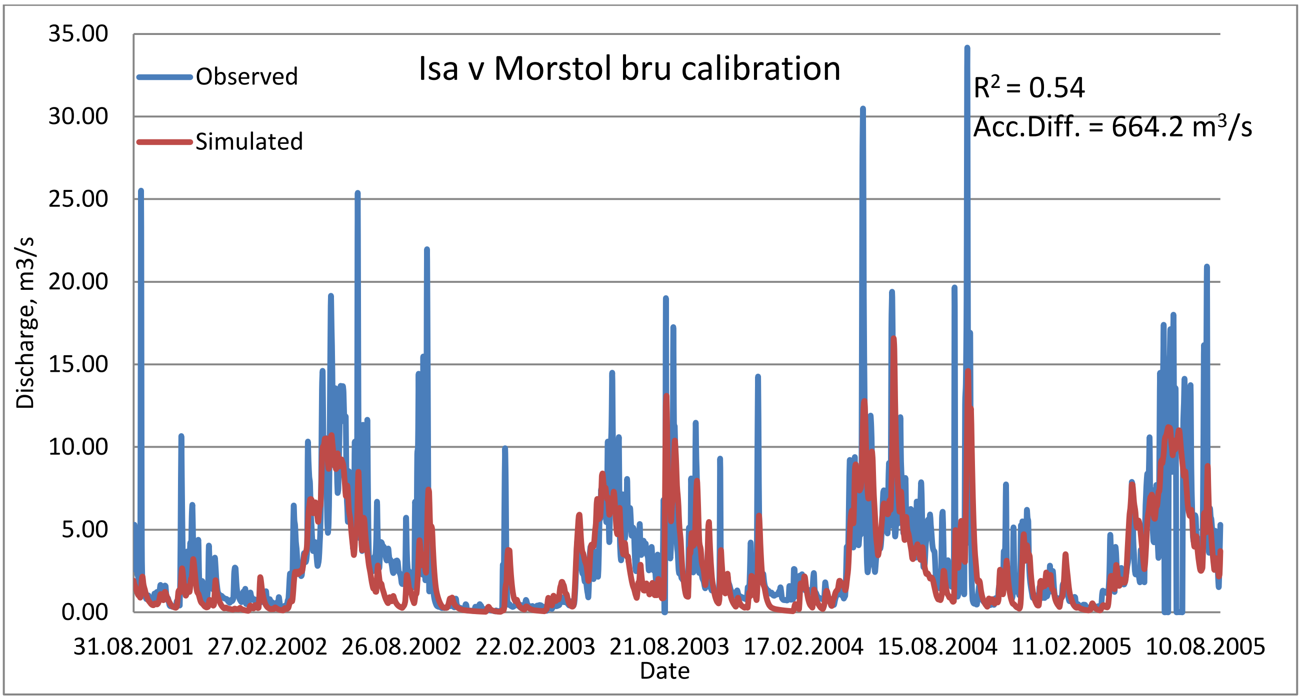


Figure 7-13 Isa v Morstol bru catchment calibration

For Isa v/Morsol bru catchment the model was able to represent relatively good fit of simulated hydrograph. In general, the pattern is repeating the observed hydrograph. The peaks of spring snowmelt and autumn rainfalls are missing.

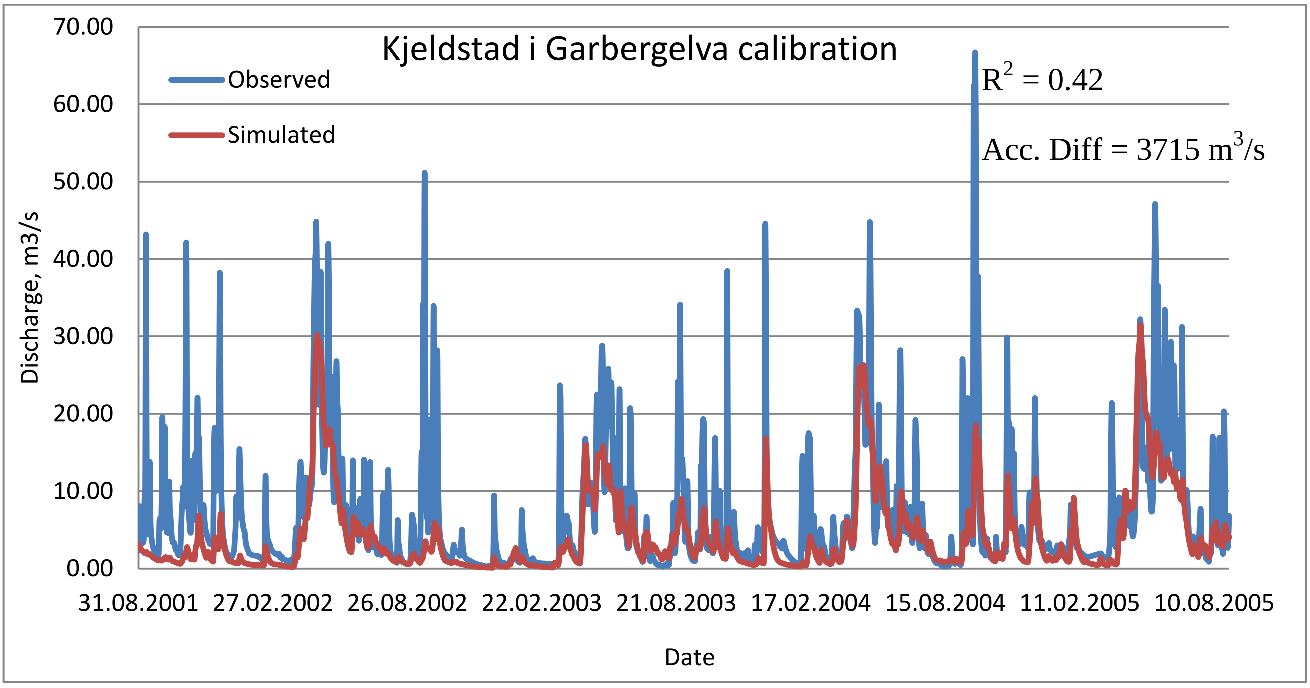


Figure 7-14 Kjeldstad i Garbergelva catchment calibration

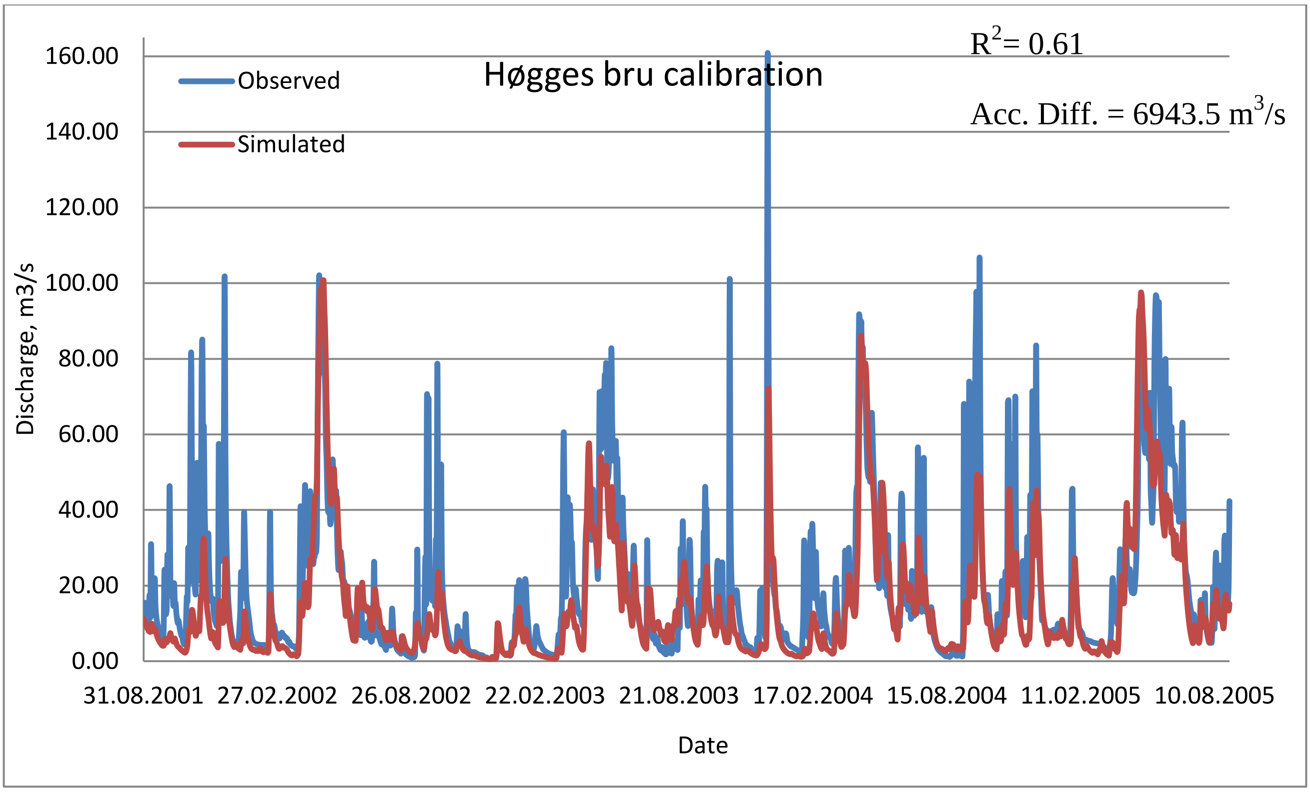


Figure 7-15 Høgges bru catchment calibration

From above hydrographs it can be concluded that ENKI model is able to estimate good fit of observed and simulated graphs. The pattern of predicted flow is follows the observed one. The low flow is repeating the observed hydrographs, but the peaks are not reaching the top values, some of the peaks are missing.

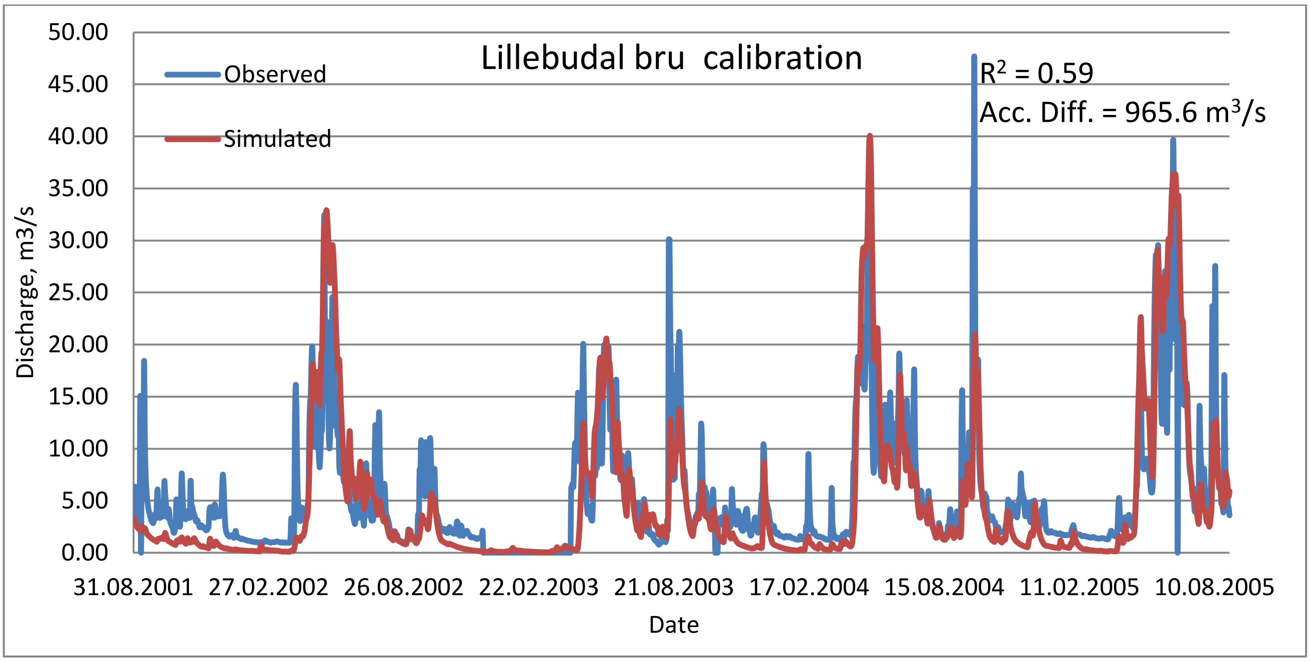


Figure 7-16 Lillebudal bru catchment calibration

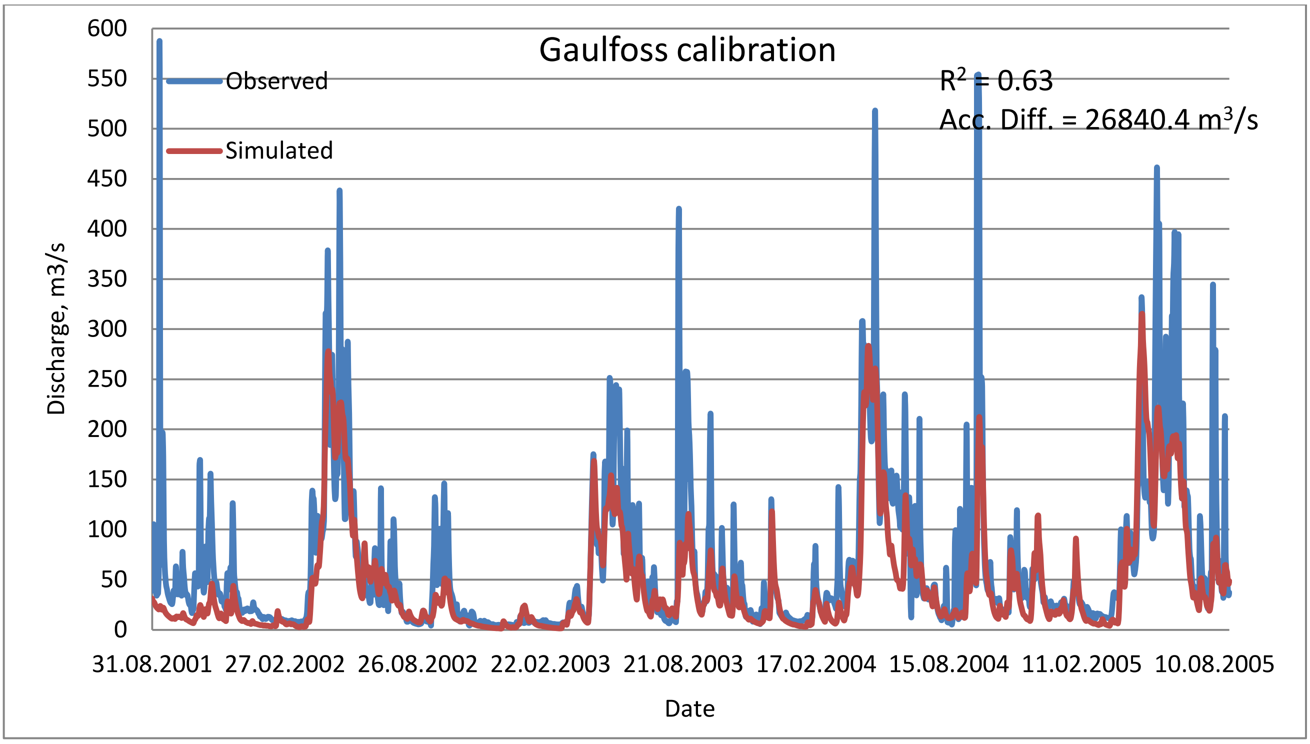


Figure 7-17 Gaulfoss catchment calibration

For Lillibudal bru catchment the model showed better fit for peaks, but for low flow period the simulated runoff is slightly lower.

For Gaulfoss catchment the simulated runoff follows the observed one. Most of the spring snowmelt and autumn peaks are not repeating the observed hydrograph.

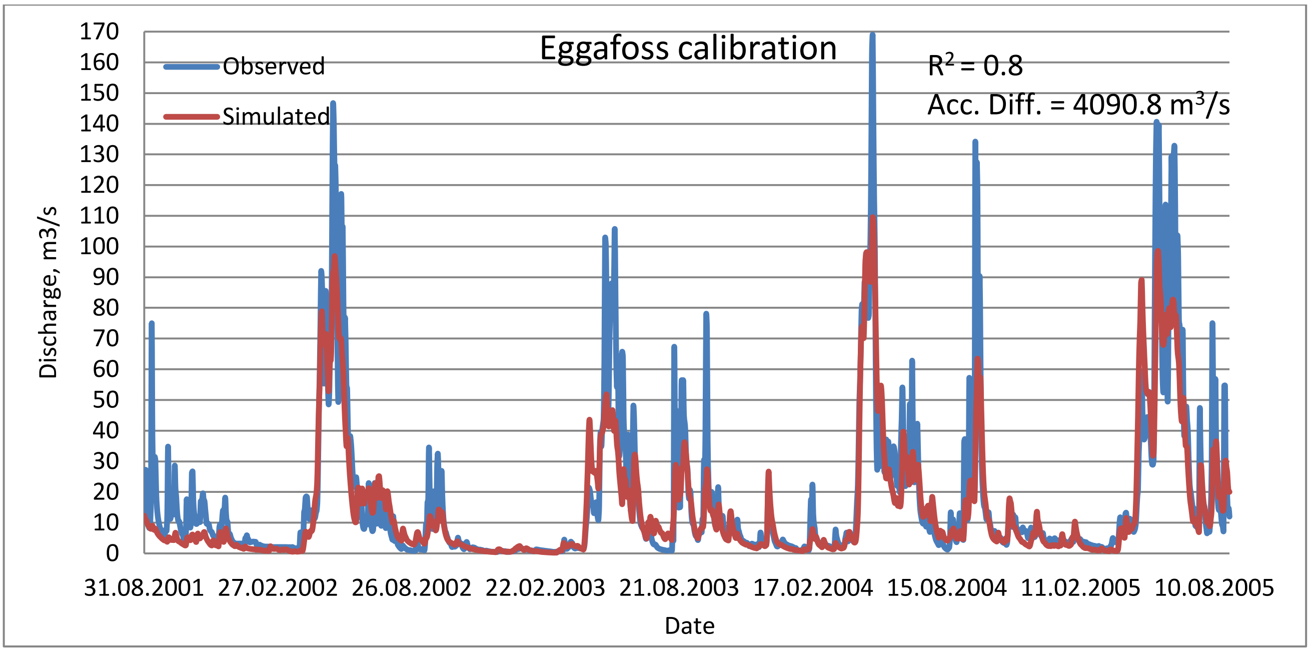


Figure 7-18 Eggafoss catchment calibration

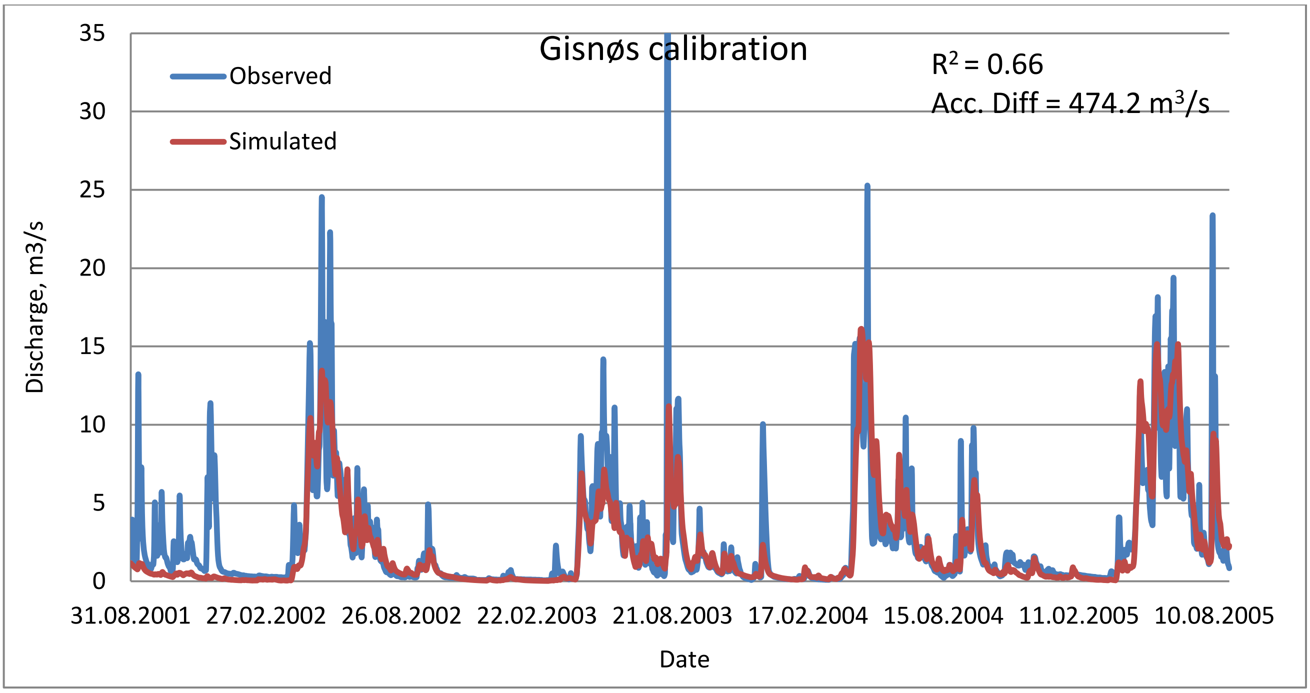


Figure 7-19 Gisnøs catchment calibration

The model was able to estimate good simulated value of flow for Eggafoss catchment. Most of the peaks are follows the observed hydrograph, except extremely high ones mostly during spring snowmelt.

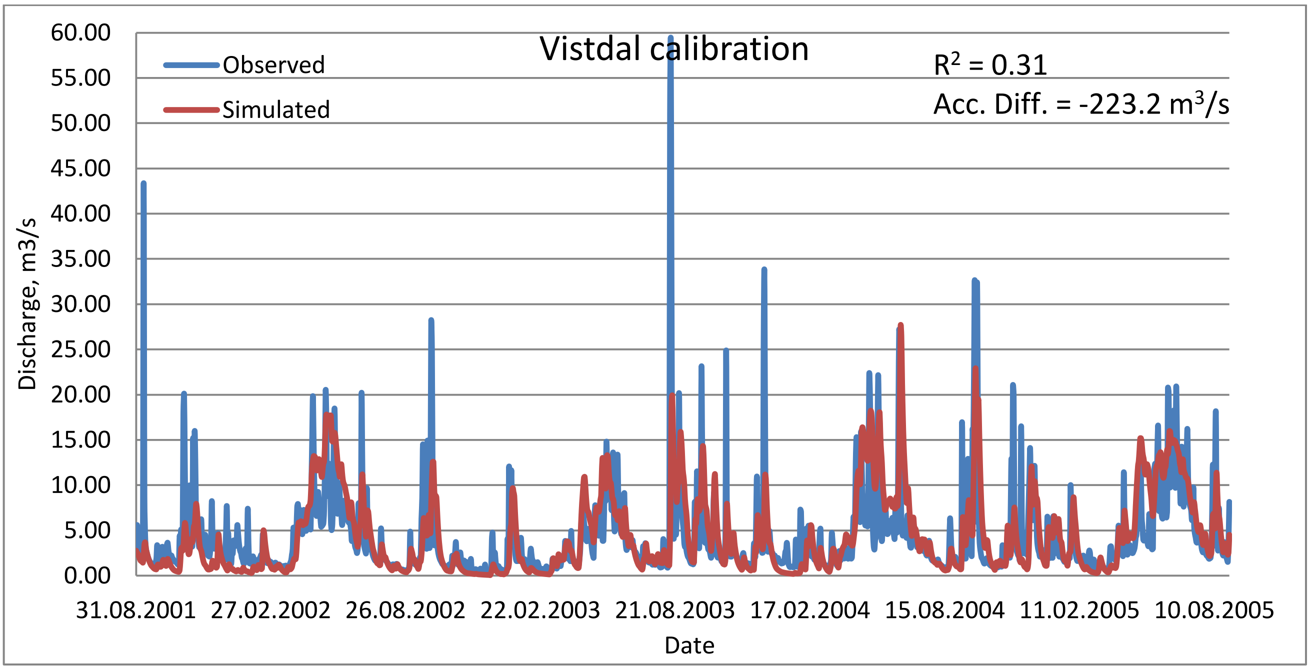


Figure 7-20 Vistdal catchment calibration

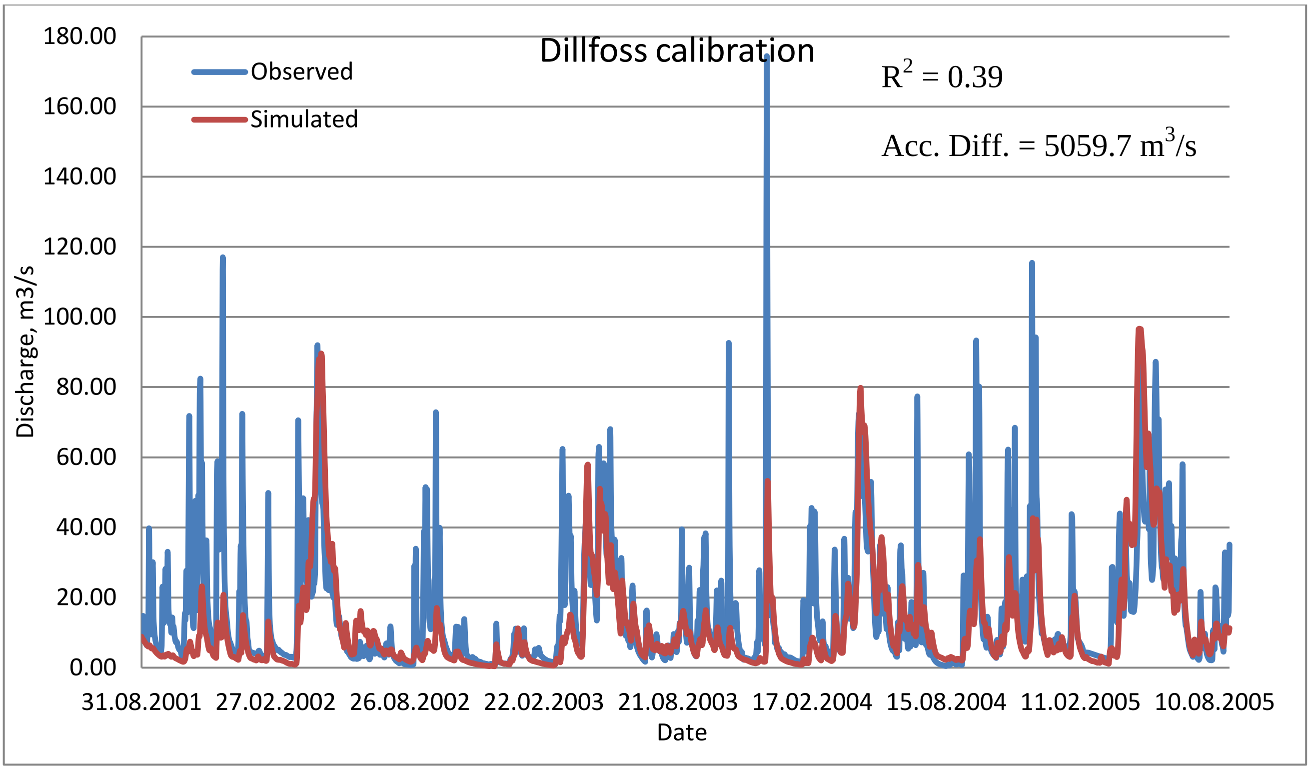


Figure 7-21 Dillfoss catchment calibration

For all of the catchments the starting conditions are poor that is why the simulated and observed hydrographs shows such a large variability in results.

It can be concluded from above results that the model is able to predict good fitted parameters for large catchments better than for smaller ones.

7.4.2 SECOND CASE VALIDATION RESULTS

As was mentioned in above chapters the period from 31/08/2005 to 31/08/2011 have been used for validation of the model.

The values of R^2 for individual and average set of parameters for validation are shown in Table 7-7. The graphical representation of individual and average R^2 for validation is shown in Figure 7-22.

Table 7-6 Validation results, second case

	R2	
Name of the Station	***Best individual validaton***	***Average individual validation***
Isa v/Morst?l bru	0.575	0.515
Kjeldstad i Garbergelva	0.582	0.548
Høgges bru	0.666	0.634
Lillebudal bru	0.569	0.409
Gaulfoss	0.720	0.745
Eggafoss	0.805	0.811
Gisnøs	0.661	0.624
Vistdal	0.392	0.296
Dillfoss	0.516	0.523
Average		***0.58335***

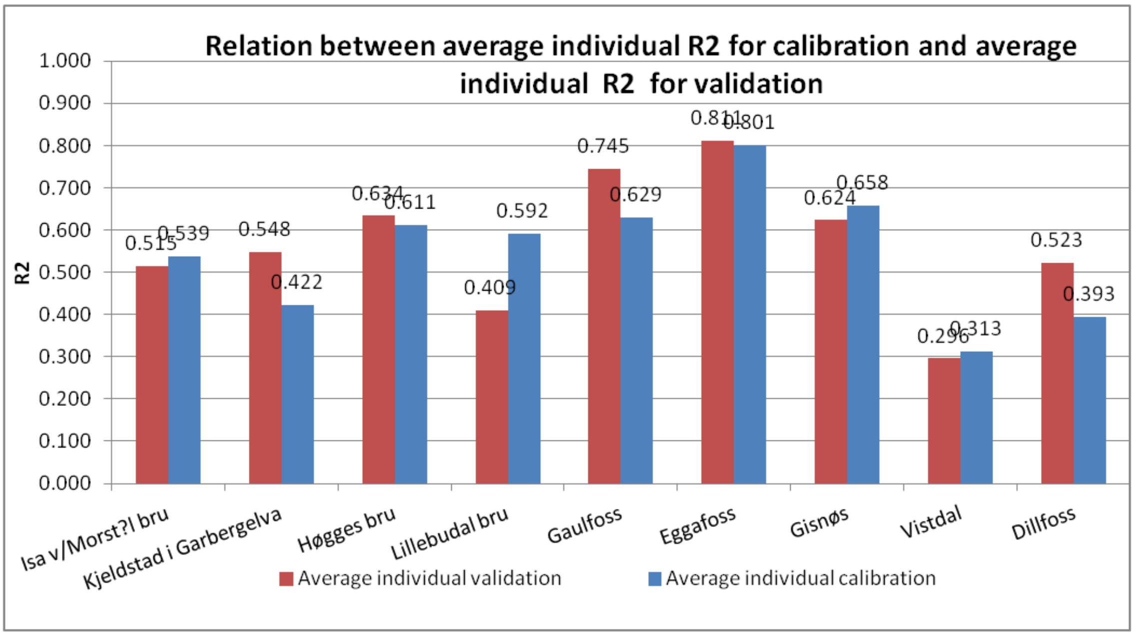


Figure 7-22 Relation between individual R^2 for calibration and for validation

From the chart above it should be concluded that the model worked good for validation period. For some of the catchments the R^2 value is even higher compare to R^2 for calibration.

Following hydrographs shows graphical representation of model validation.

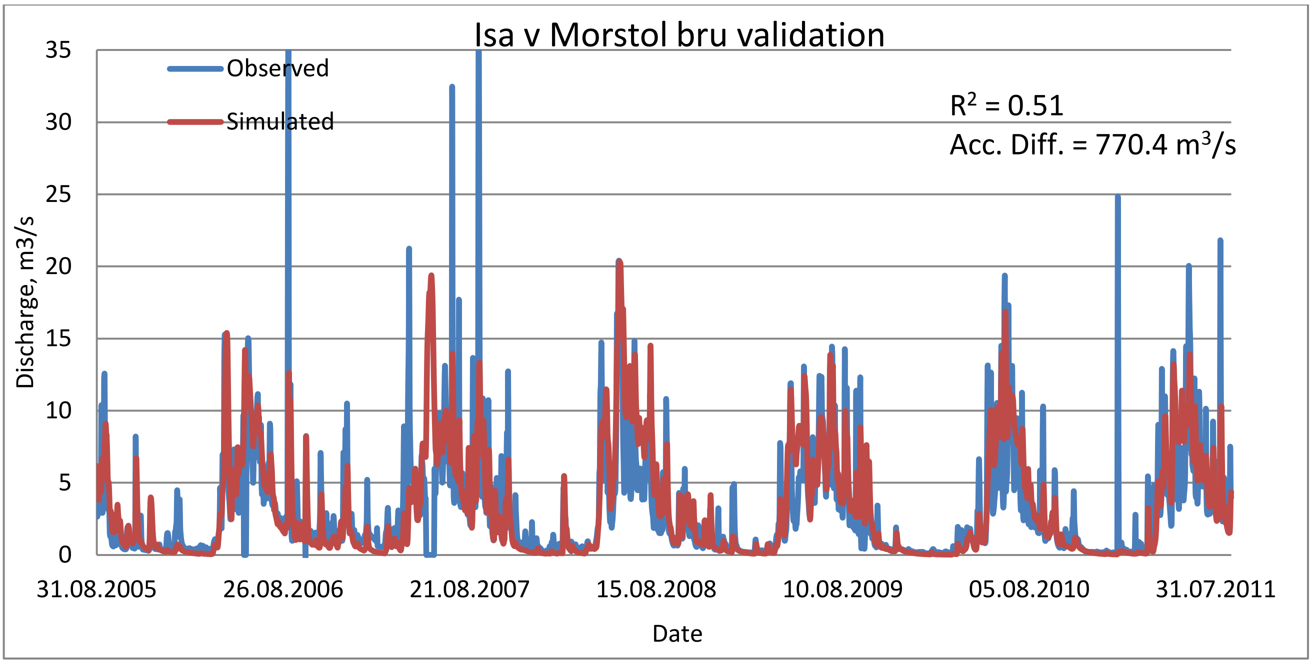


Figure 7-23 Isa v Morstol bru catchment validation

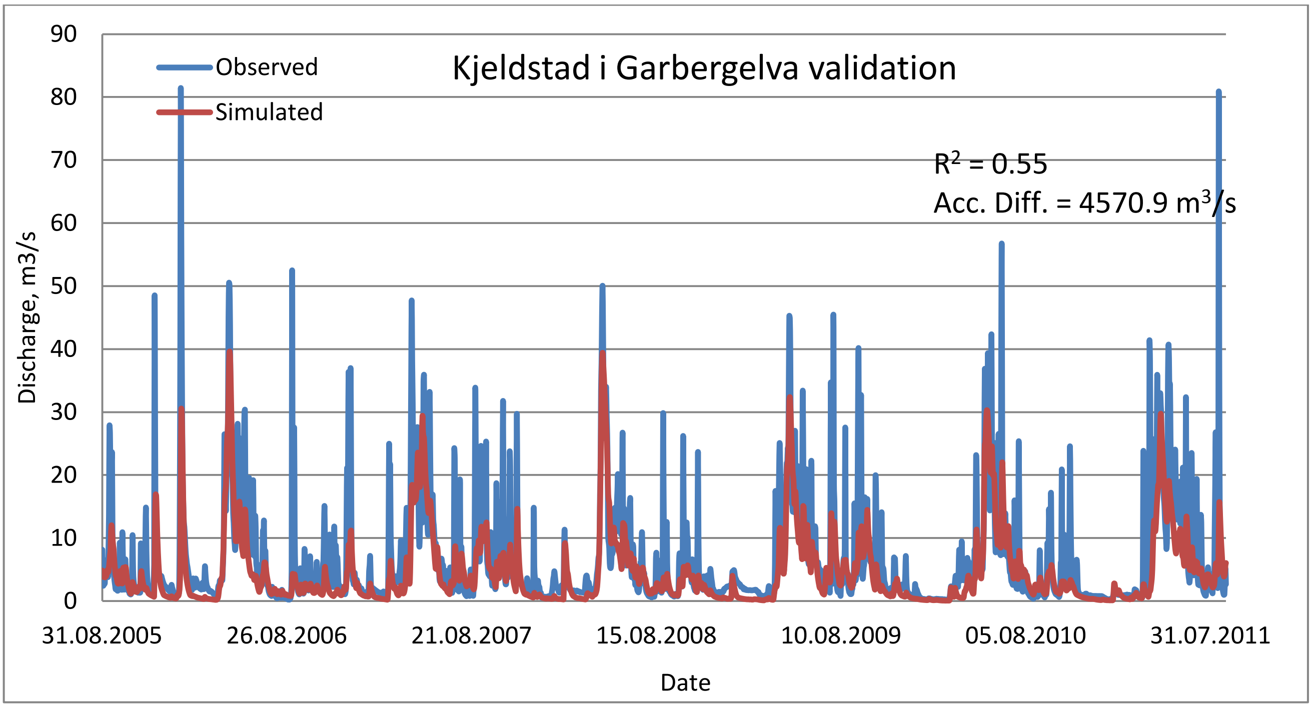


Figure 7-24 Kjeldstad i Garbergelva catchment validation

The model established good fit of simulated hydrograph for Isa v/Morsol bru catchment. The pattern of simulated graph is repeating the observed hydrograph. The extremely high peaks in autumn 2006 and 2007 and in spring 2011 are missing.

The model showed good fit of low flow during validation for Kjeldstad i Garbergelva catchment. The simulated hydrograph is not caching high peaks, but follows the pattern of measured hydrograph.

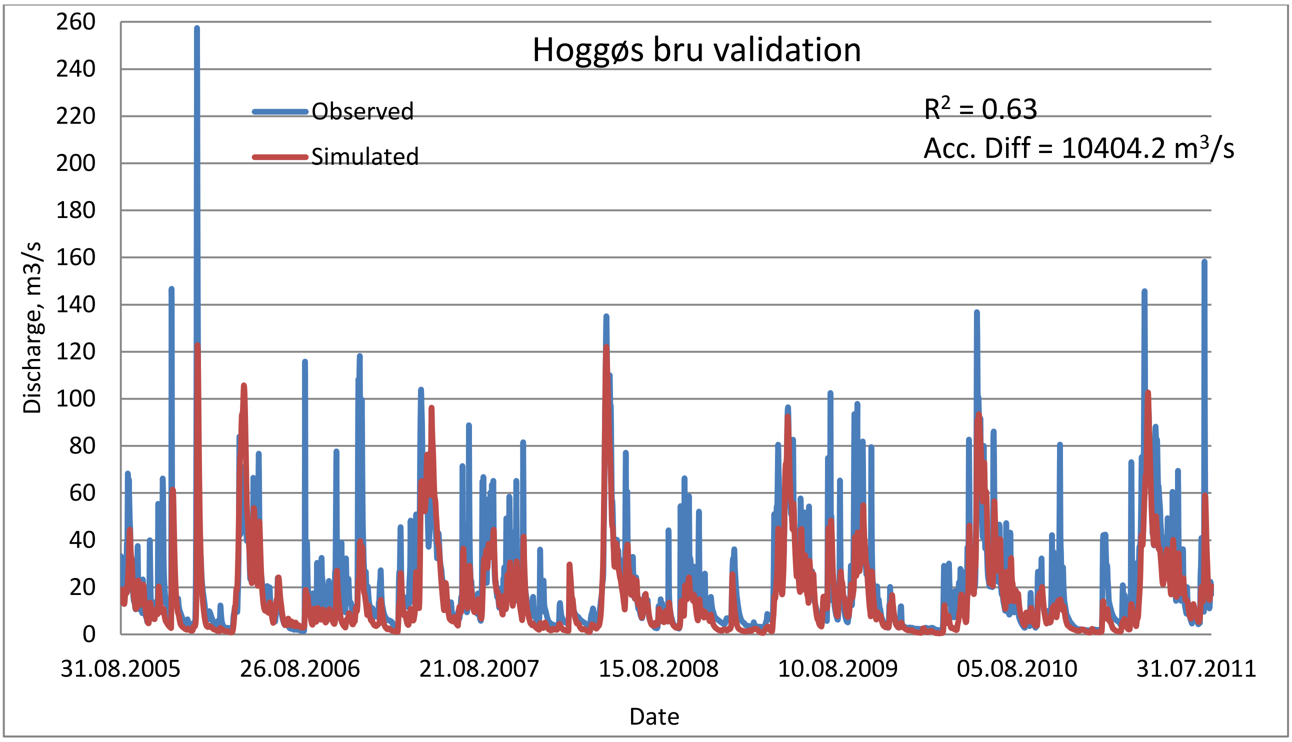


Figure 7-25 Hoggøs bru catchment validation

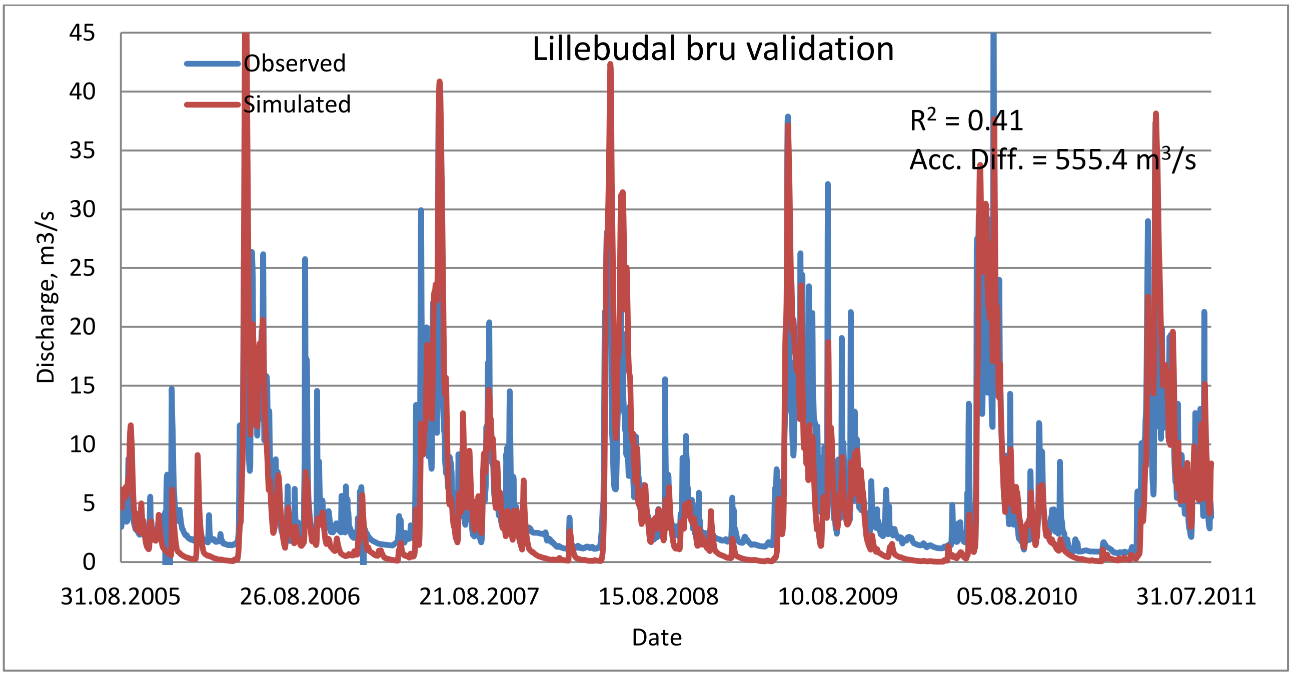


Figure 7-26 Lillebudal bru catchment validation

As concluded for calibration, the validation of Lillibudal bru catchment the model showed better fit for peaks, but for low flow period the simulated runoff is also lower.

For Høgges bru the pattern of predicted runoff is following the observed one. The low flow periods are repeating the observed hydrograph, but some of the peaks are missing.

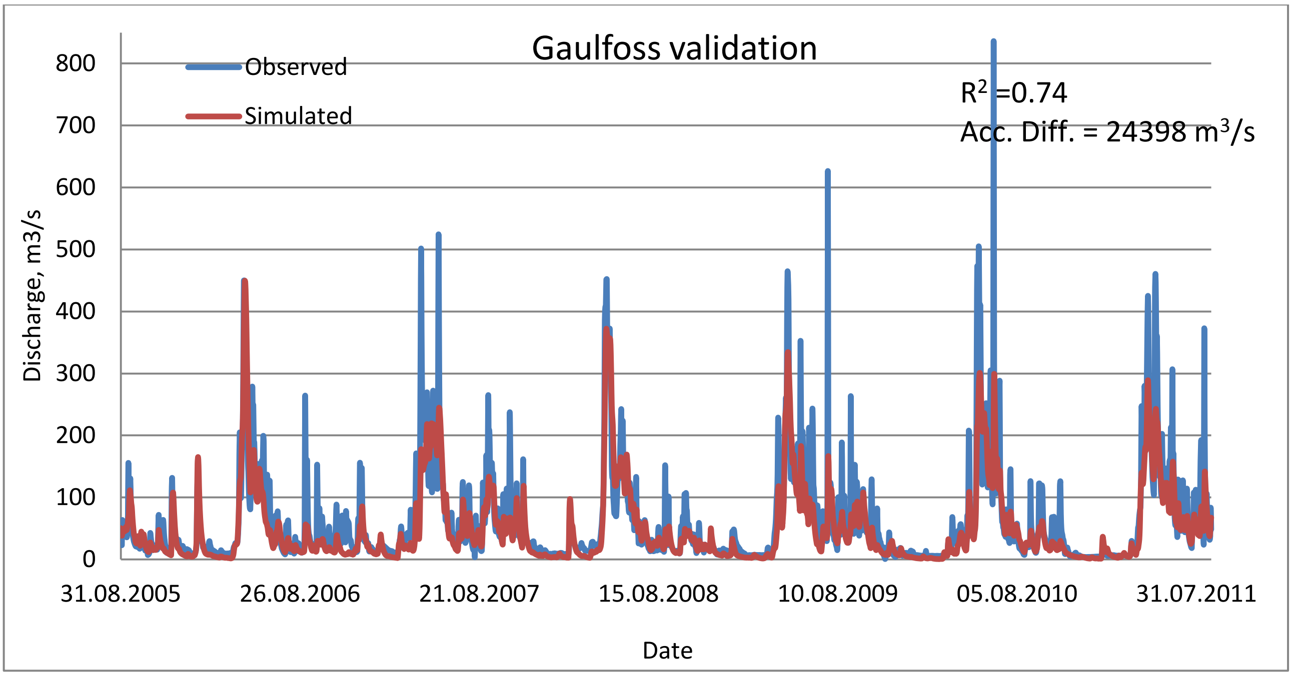


Figure 7-27 Gaulfoss catchment validation

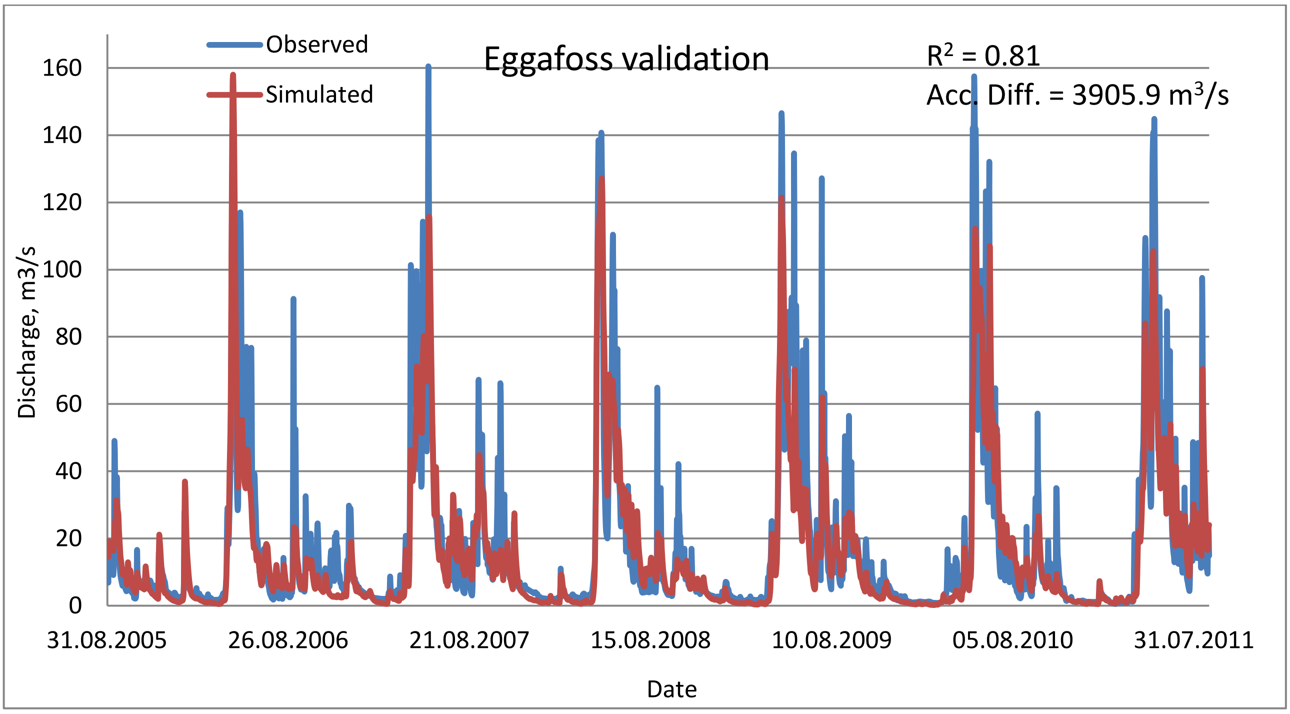


Figure 7-28 Eggafoss catchment validation

For Gaulfoss and Eggafoss catchments the model established best fit of simulated runoff during validation. The hydrographs are follows the observed ones. Some of extremely high peaks are not reaching the values of observed hydrograph.

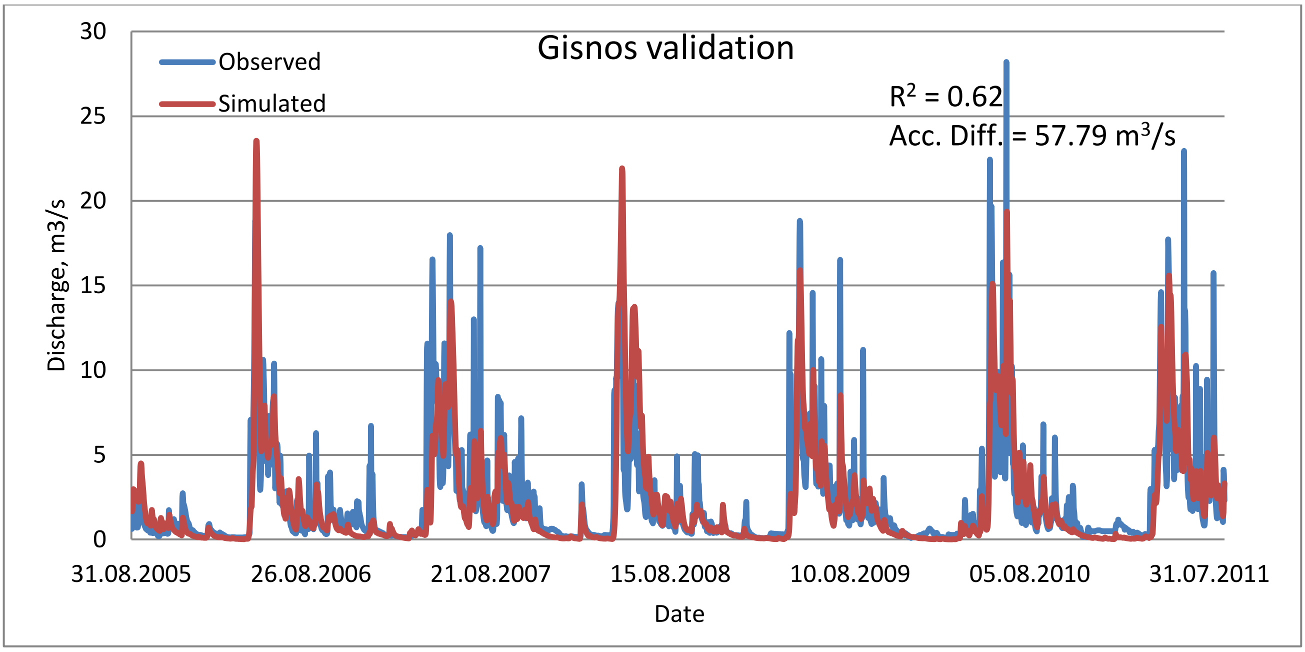


Figure 7-29 Gisnos catchment validation

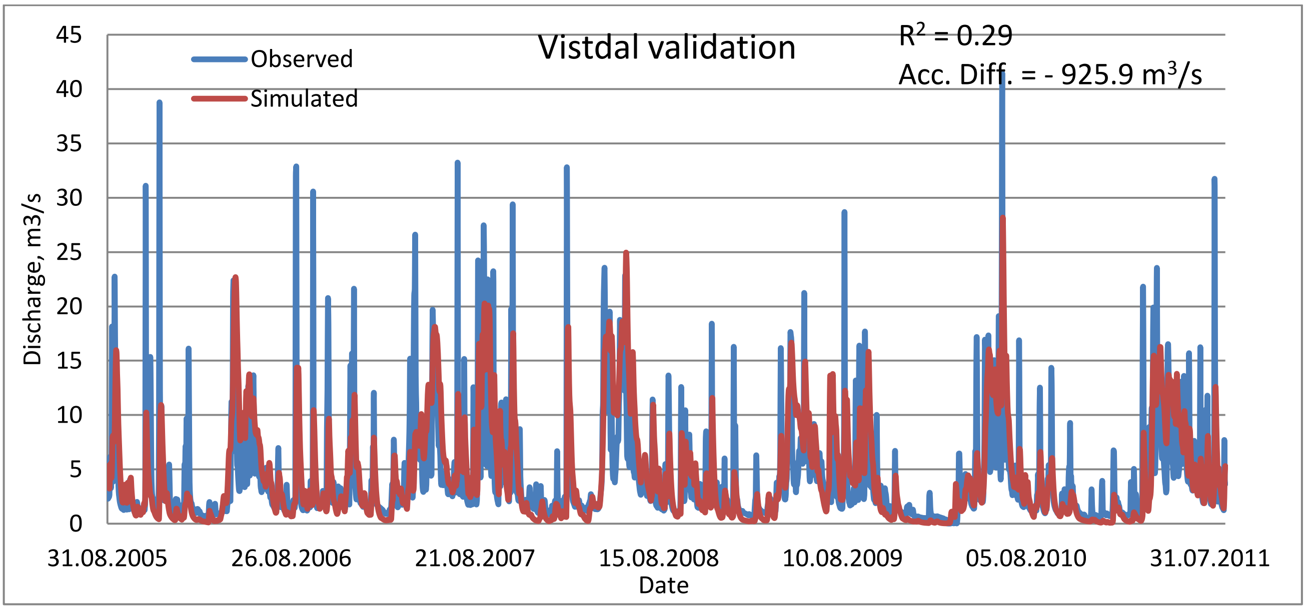


Figure 7-30 Vistdal catchment validation

The Nash efficiency value for Vistdal catchment during validation showed lower value, compare with R^2 for calibration. The pattern of simulated hydrograph follows the observed one, but high peaks are missing.

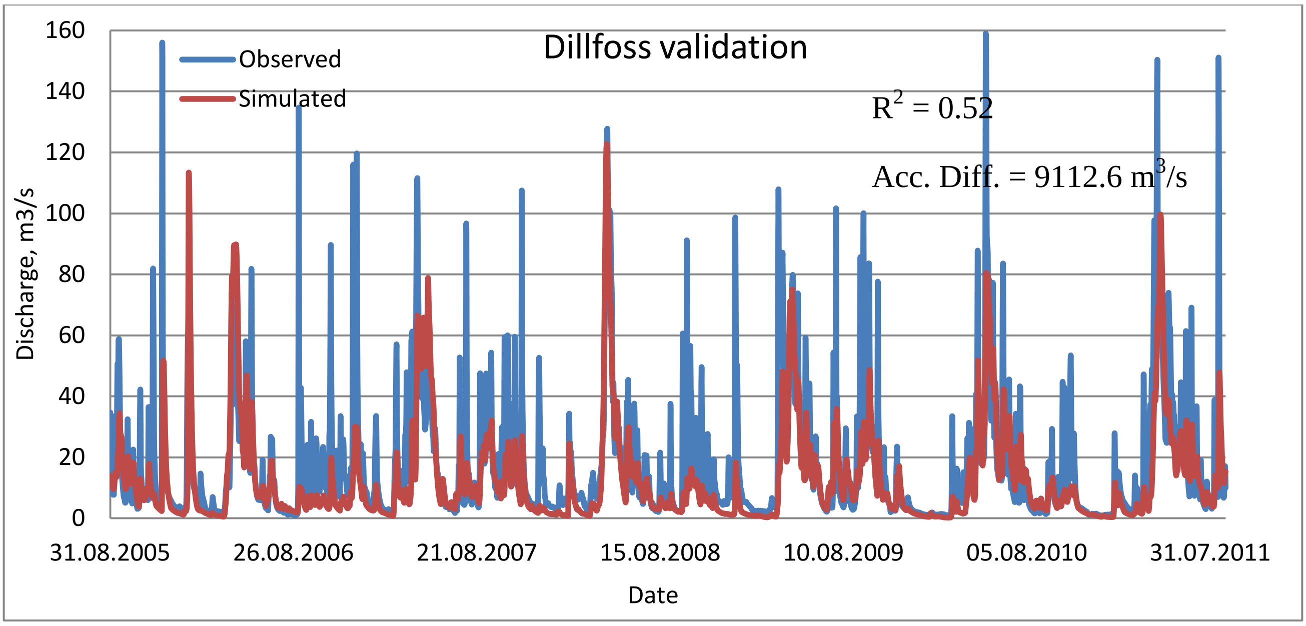


Figure 7-31 Dillfoss catchment validation

The R^2 value for Dillfoss catchment shows better result for validation period. It might due to better fit of simulated hydrograph in the beginning of validation period.

For all of the catchments the hydrographs showed good fit during starting period. It should be concluded that model established good results from validation. The model can be applied for further extracting of simulated runoff for Sweco catchments.

The summary of calibration and validation of the model is shown in Table 7-8.

Table 7-7 The summary of calibration and validation of ENKI model

	R2			
Name of the Station	***Best individual calibration***	***Best individual validaton***	***Average individual calibration***	***Average individual validation***
Isa v/Morst?l bru	0.621	0.575	0.539	0.515
Kjeldstad i Garbergelva	0.606	0.582	0.422	0.548
Høgges bru	0.683	0.666	0.611	0.634
Lillebudal bru	0.611	0.569	0.592	0.409
Gaulfoss	0.717	0.720	0.629	0.745
Eggafoss	0.852	0.805	0.801	0.811
Gisnøs	0.674	0.661	0.658	0.624
Vistdal	0.375	0.392	0.313	0.296
Dillfoss	0.469	0.516	0.393	0.523
Average			**0.550950667**	***0.58335***

7.5 EXTRACTING RUNOFF DATA SERIES FOR SWECO CATCHMENTS

The regional set of parameters from second calibration with average R^2 = 0.55 have been applied for extracting runoff data series for Sweco catchments.

The values of R^2 from extracting of Sweco catchments are represented in Table 7-9.

Table 7-8 Results of R^2 for extracted Sweco catchments

Station Name	R^2	***Acc. Diff., m³/s***	***Catchment area, km²***
Usma	**0.38**	2361.25	69.70
Vassdalselva	**0.21**	147.10	16.90
Malmedalselva	**-12.79**	-2713.50	29.70
Skorgeelva	**-0.23**	-395.50	42.30
Erga	**0.33**	1669.30	26.70
Eidaa	**-0.31**	2410.30	17.30
Tangvella	**0.09**	1702.70	33.90

The variability of R^2 for Sweco catchments is from -12.79 to 0.38. The reasons of such high variability can be the location, the size of the catchments or errors in input data.

The Malmedalselva catchment showed worst result of Nash efficiency. The reason might be the close location to the coastal line. It should be noted that Malmedalselva catchment locates close to Farstadelva v/Farstad which showed worst result of R^2 after first calibration and has been excluded from second calibration.

The catchments located in coastal zone obtain worser value of R^2 compare to catchments located in inland climatic zone (Figure 7-9). The graphical presentations of predicted and measured hydrographs are shown in below figures.

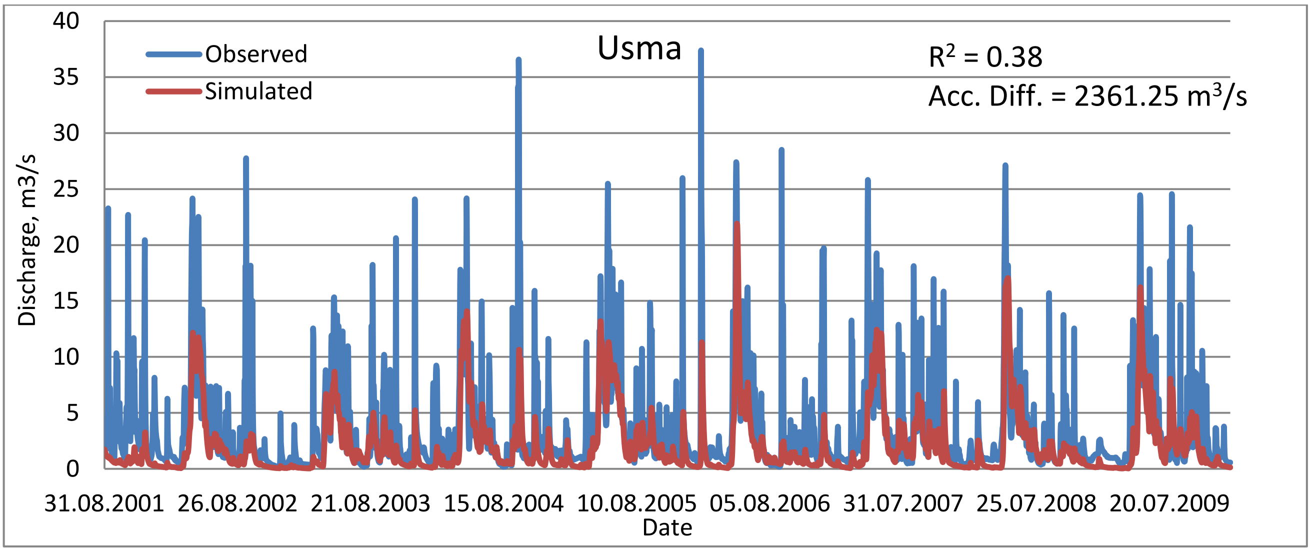


Figure 7-32 Extracted and observed runoff for Usma catchment

The model was able to estimate the largest R2 value for Usma catchment from all other extracted Sweco catchments. The catchment also has largest area and locates in inland climatic zone (Figure with excluded catchments). The predicted flow shows less water than measured. Most of high peaks are not reaching the top values. In general simulated flow follow the pattern of observed one.

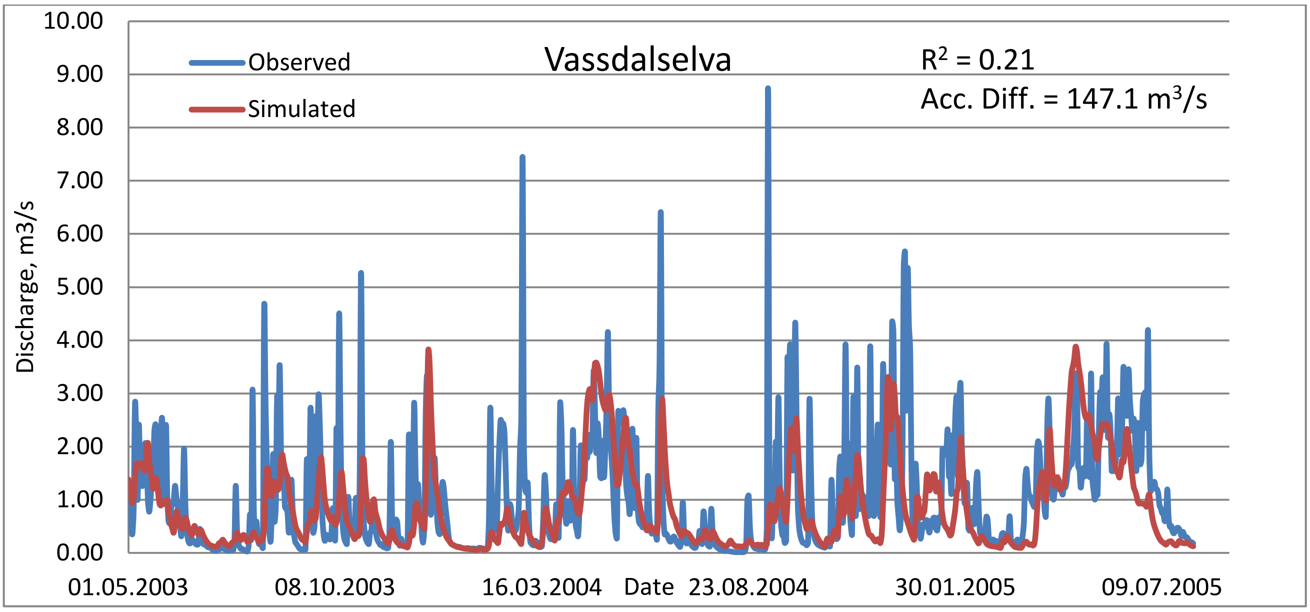


Figure 7-33 Extracted and observed runoff for Vassdalselva catchment

The model produced simulated flow for Vassdalseva with $R^2 = 0.21$. The simulated flow is underestimated. Simulated flow better follows low flow periods. Most of high peaks are missing.

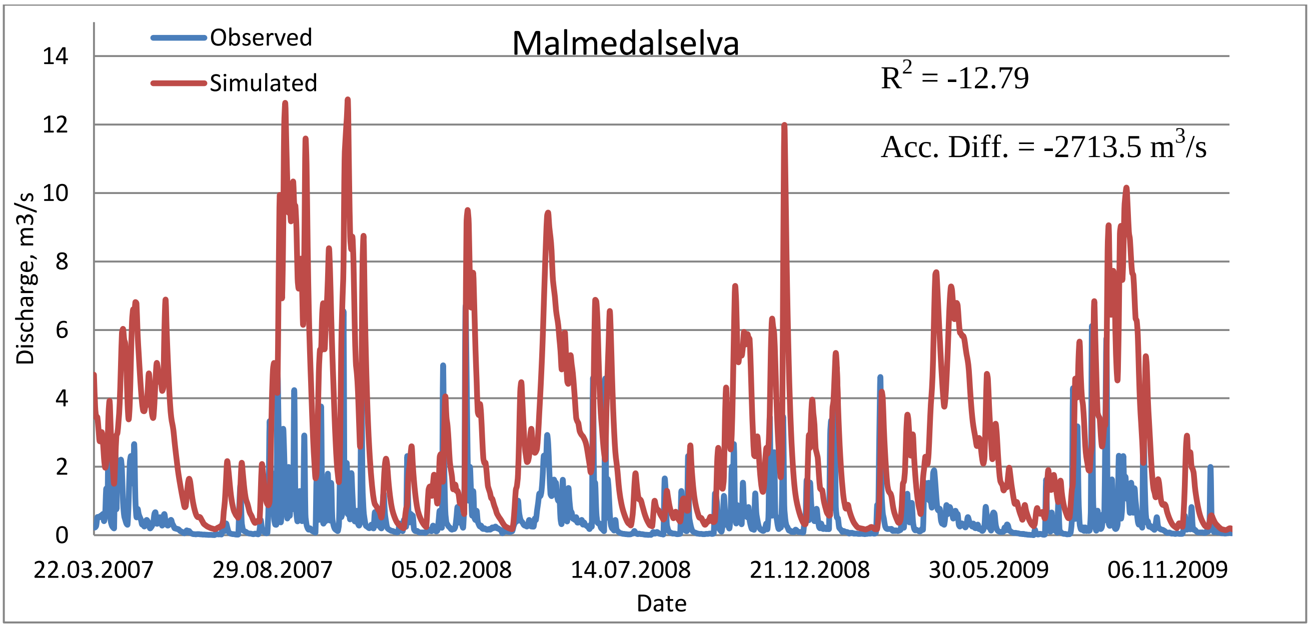


Figure 7-34 Extracted and observed runoff for Malmedalselva catchment

Extracted simulated flow for Malmedalselva catchment showed lowest R^2 value. The simulated flow is underestimated. But the pattern of low and high flow is follows the observed hydrograph with certain shift in time.

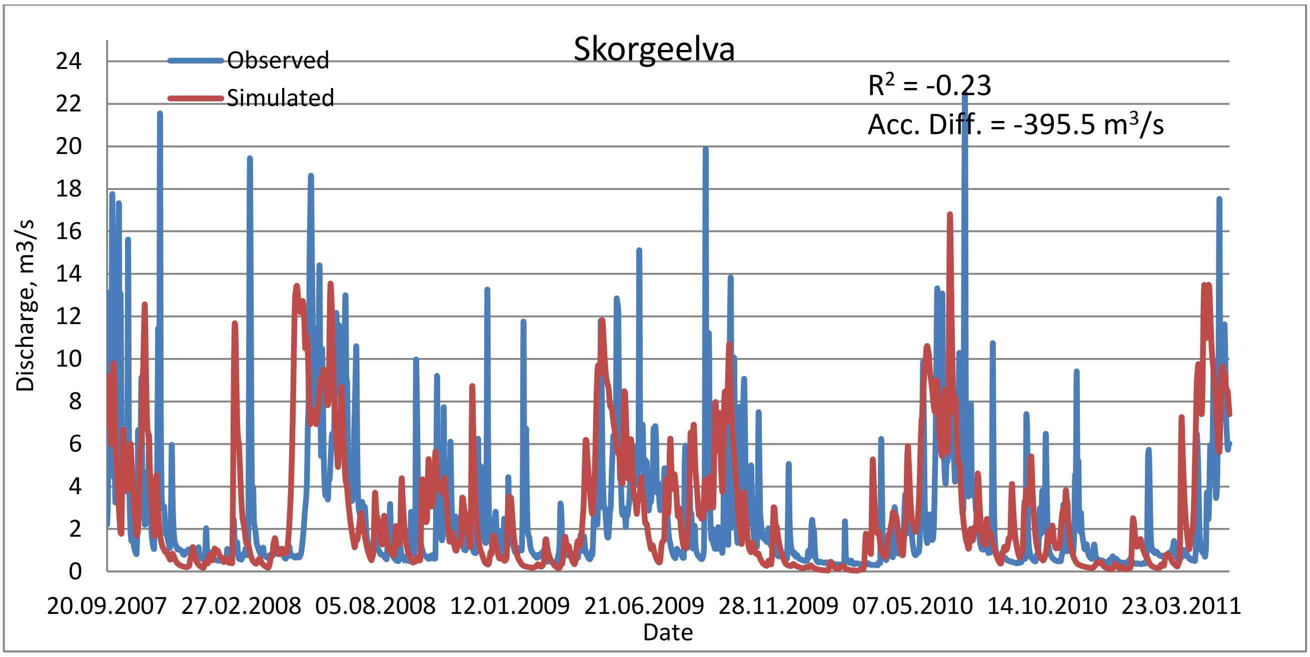


Figure 7-35 Extracted and observed runoff for Skorgeelva catchment

The model estimated simulated flow for Skorgeelva with R^2= -0.23. The hydrographs of simulated and observed flow are matching quite well, but with some shift in time. Most of the peaks, except extremely high ones are follow the observed hydrograph.

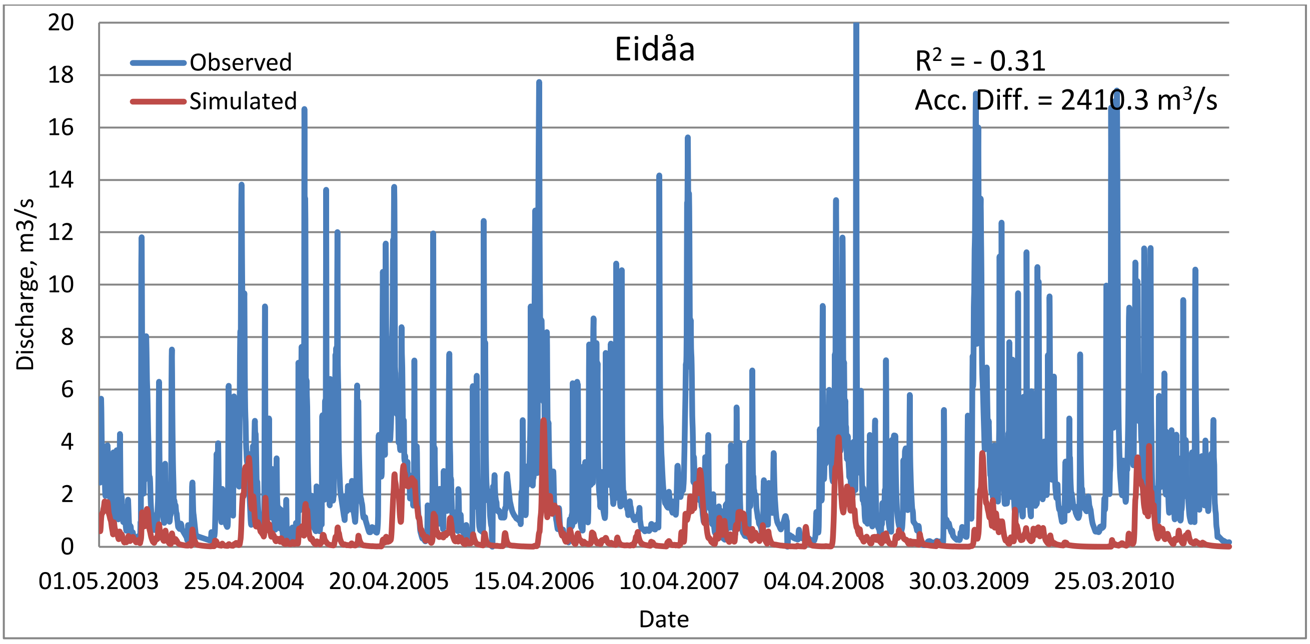


Figure 7-36 Extracted and observed runoff for Eidåa catchment

The simulated flow for Eidåa catchment is underestimated. The model established much less water than in observed one. The simulated pattern of low and high flow is follows the observed hydrograph.

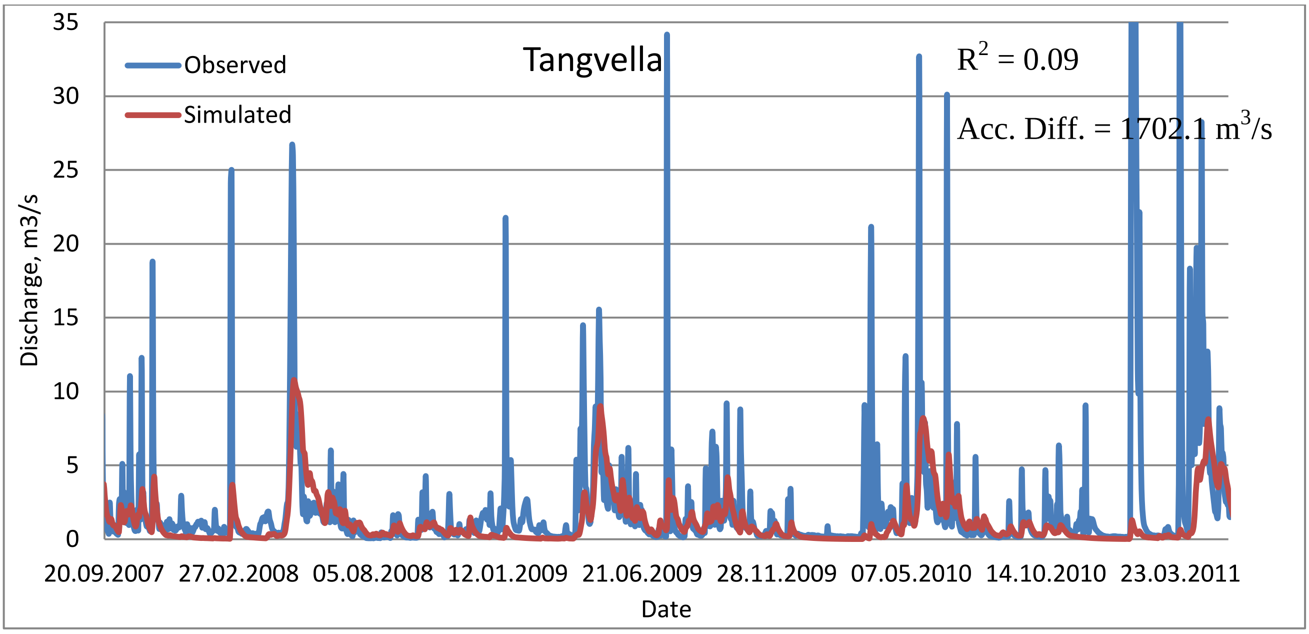


Figure 7-37 Extracted and observed runoff for Tangvella catchment

The extracted simulated flow for Tangvella catchment has low Nash efficiency value R^2 = 0.09. Predicted flow is underestimated. The simulated hydrograph repeats quite well the observed one. Some of the peaks are follows the natural flow. The extremely high peaks are missing.

The Nash efficiency has quite low values for extracted Sweco catchments. Further analysis of applicability of the regional modeling with ENKI has been carried out. The extracted runoff from regional modeling is compared with scaling approach.

7.5.1 COMPARISION OF EXTRACTED DATA SERIES FOR SWECO CATCHMENT WITH SCALING METHOD

The data series for scaling method have been used from NVE catchments previously utilized for calibration in this project. The location and area of NVE catchments are taking into consideration.

The catchments taken for scaling approach with all necessary characteristics are tabulated in Table 7-10.

Table 7-9 Summary for scaling approach

Station Name, SWECO catchments	***Scaled Station name, NVE catchments***	***SWECO Catchment area,km2***	***NVE Catchment area,km2***	***SWECO Specific Runoff, l/s/km2***	***NVE Specific Runoff, l/s/km2***	***Scaling factor***
Usma	Kjeldstad i Garbergelva	69.70	144.92	51.55	46.73	0.53
Vassdalselva	Søya v/Melhus	16.90	137.29	61.82	78.14	0.10
Malmedalselva	Farstadelva v/Farstad	29.70	24.14	17.12	45.39	0.46
Skorgeelva	Isa v/Morstøl bru	42.30	44.26	85.75	110.05	0.74
Erga	Gisnås	26.70	94.32	61.57	26.46	0.66
Eidaa	Gisnås	17.30	94.32	135.80	25.22	0.99
Tangvella	Kjeldstad i Garbergelva	33.90	144.92	58.32	46.37	0.29

Graphical representation of observed, simulated and scaled hydrographs and duration curves is performed below.

7.5.1.1 COMPARISION OF USMA RUNOFF DATA SERIES

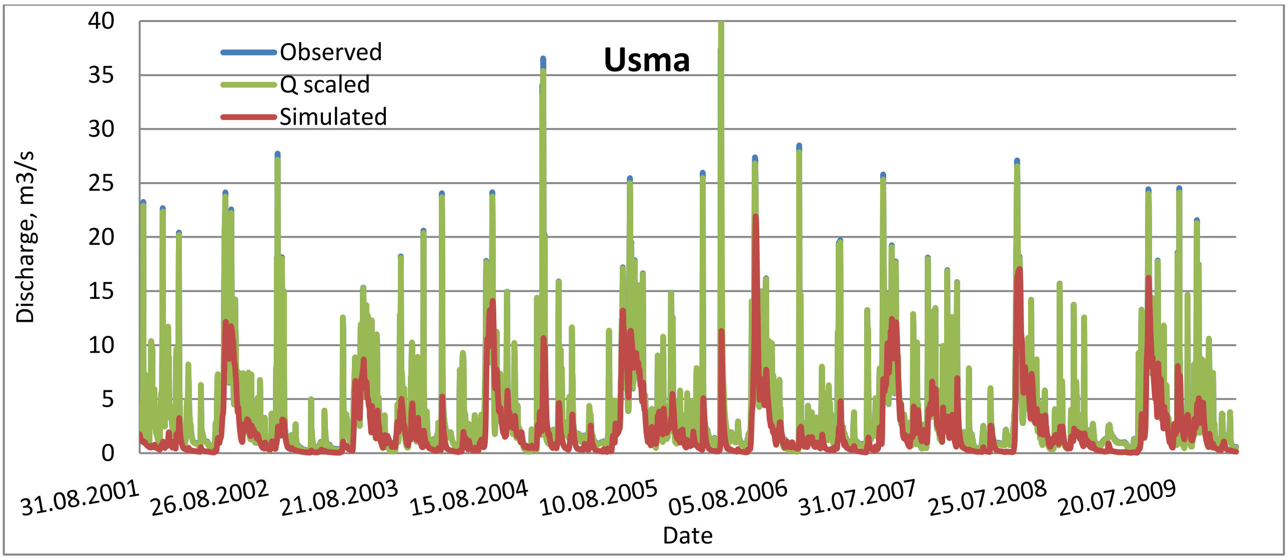


Figure 7-38 Simulated, observed and scaled hydrographs for Usma catchment

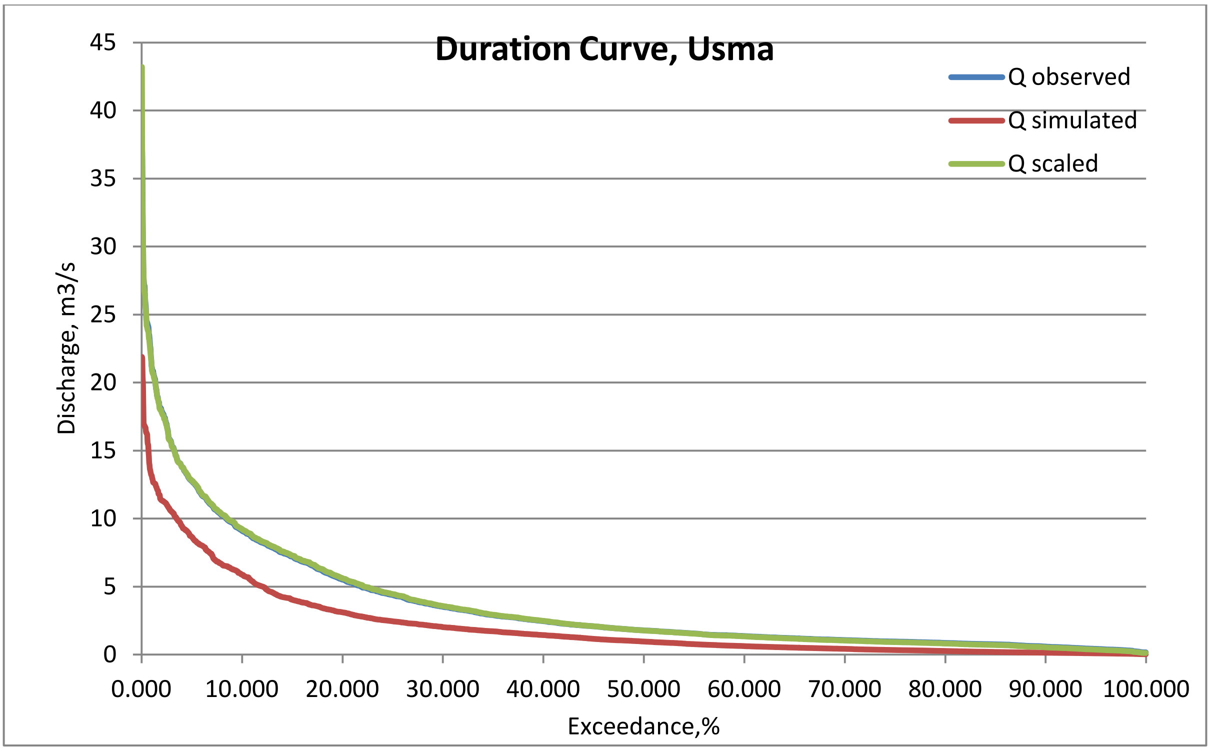


Figure 7-39 Duration curves for Usma catchment

Hydrographs of scaled and observed runoff for Usma catchment are identical. According to duration curve, 50 % of the time simulated runoff shows twice less water than observed and scaled runoff. Application of regional modeling with ENKI for Usma catchment will lead to large uncertainty during planning stage for small hydropower plants. For Usma catchment scaling approach should be utilized to estimate runoff.

7.5.1.2 COMPARISION OF VASSDALSELVA RUNOFF DATA SERIES

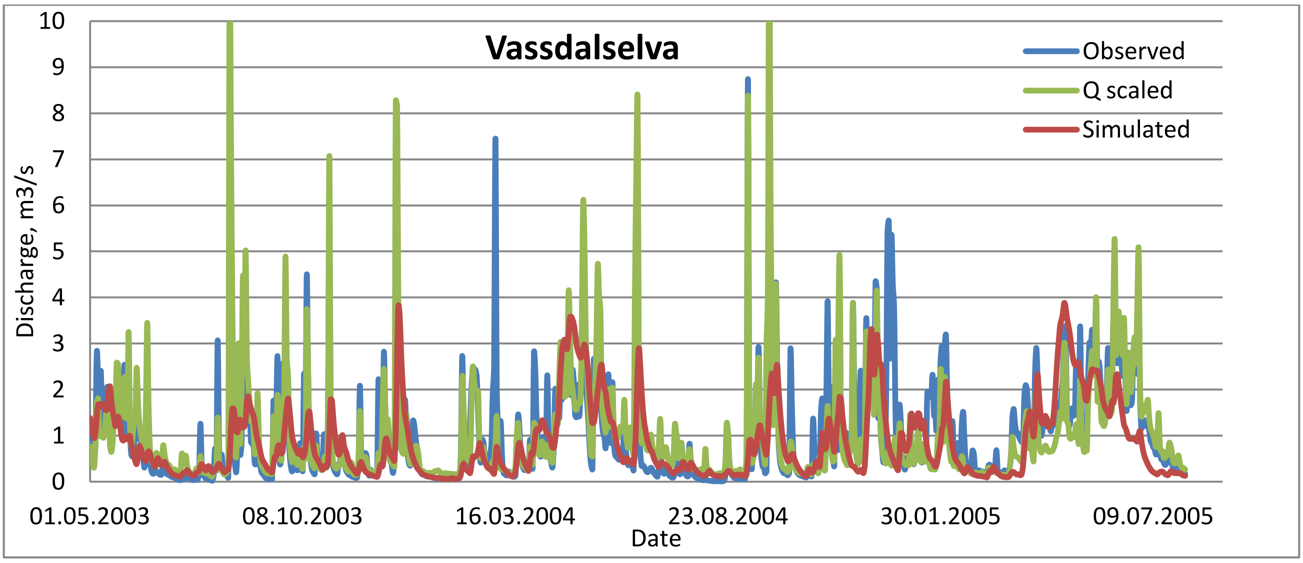


Figure 7-40 Simulated, observed and scaled hydrographs for Vassdalselva catchment

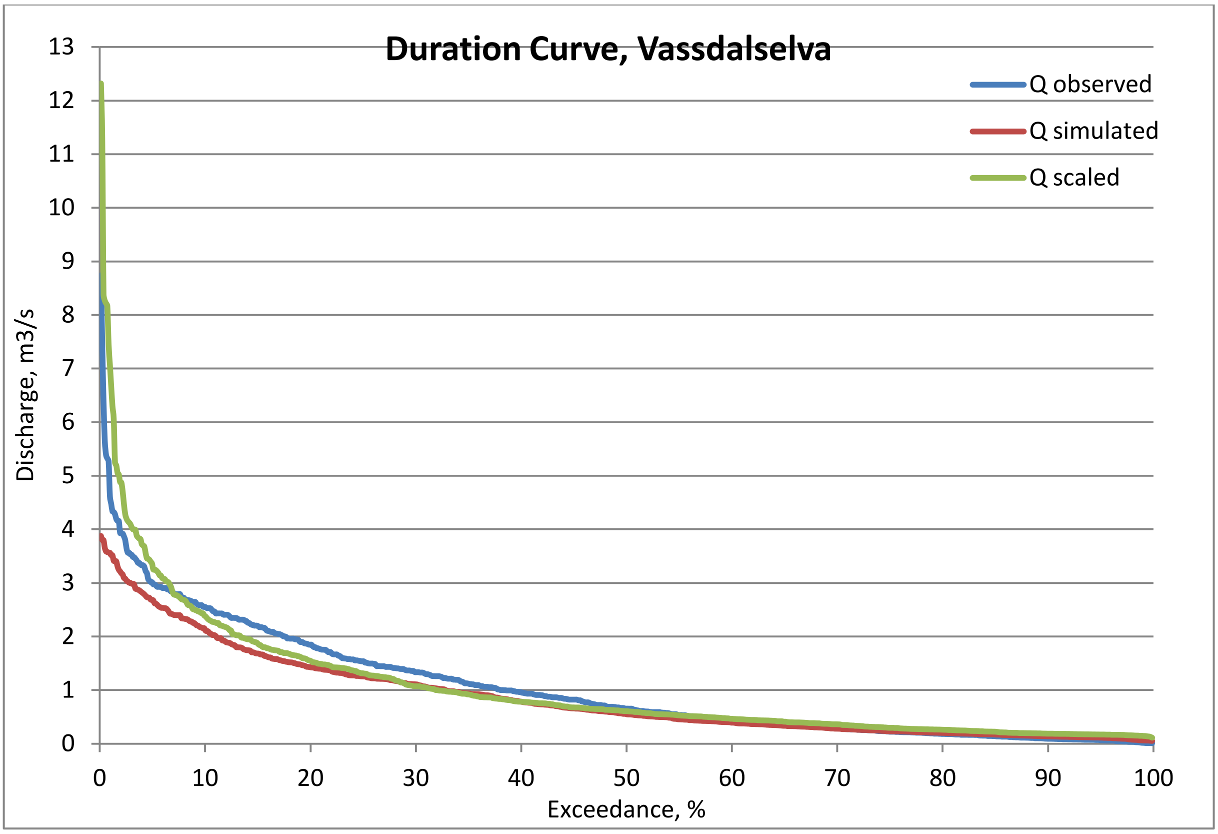


Figure 7-41 Duration curves for Vassdalselva catchment

Hydrographs of scaled and observed runoff for Vassdalselva catchment are similar. Some of the peaks of scaled runoff are overestimated. The duration curve shows similar pattern, except for period of 5 % of the time where scaled runoff shows much higher value and simulated runoff shows twice less water than measured discharge. For low flow period the simulated, scaled and observed runoff are identical. Using regional modeling with ENKI for Vassdaselva catchment is applicable for small hydropower plants planning, only if the high flow during snowmelt and autumn periods will be planned to spill.

7.5.1.3 COMPARISION OF MALMEDALSELVA RUNOFF DATA SERIES

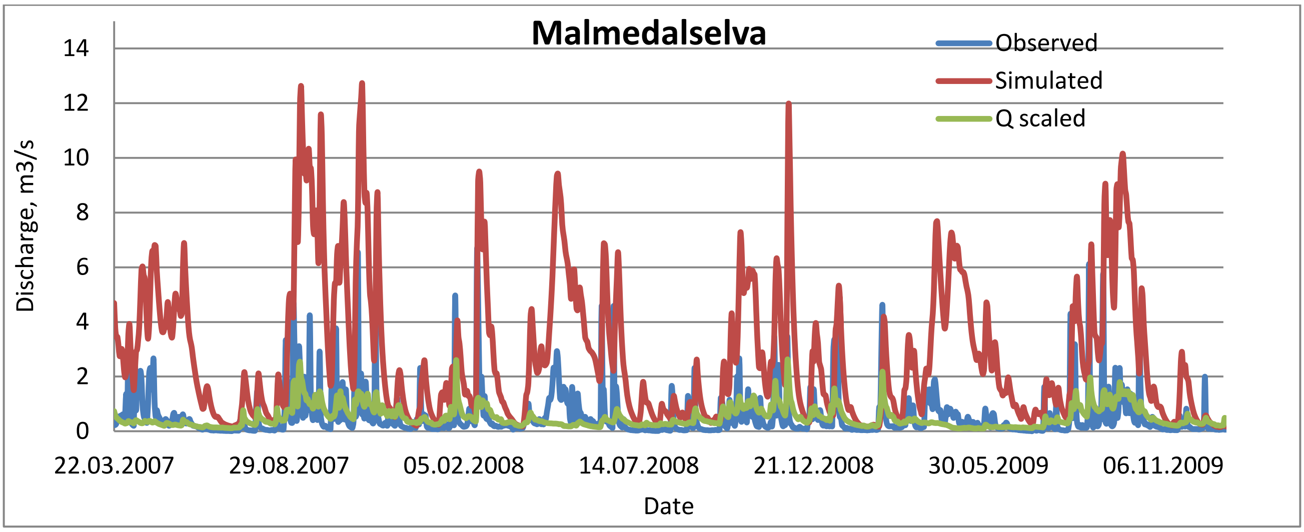


Figure 7-42 Simulated, observed and scaled hydrographs for Malmedalselva catchment

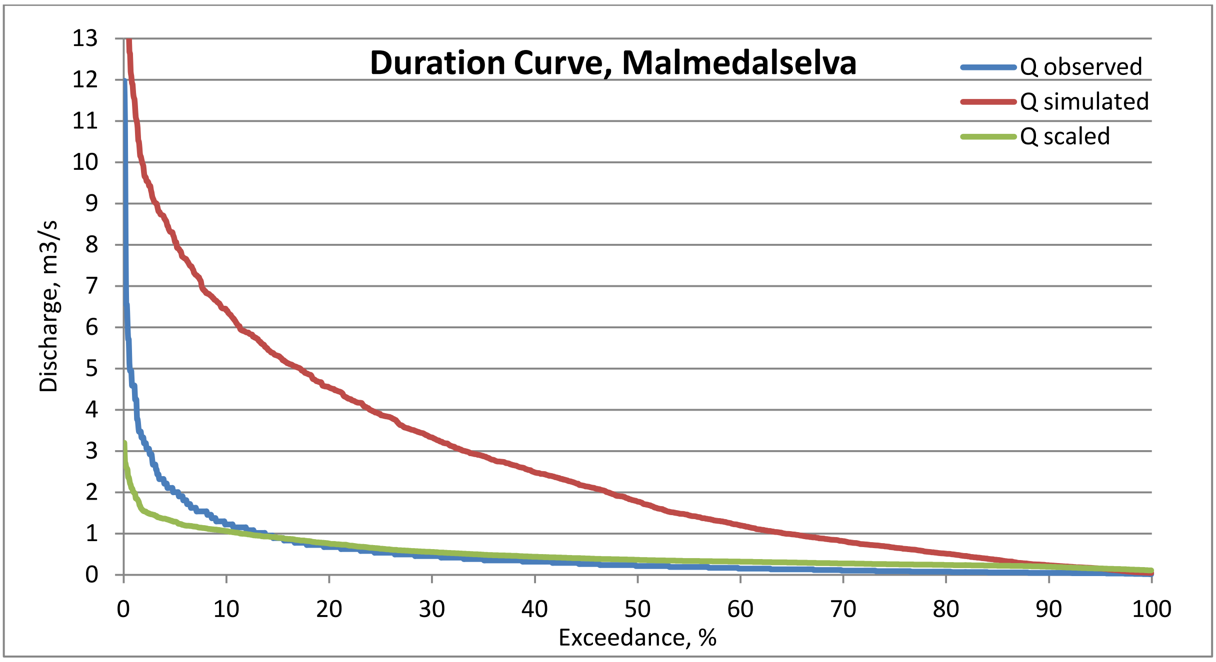


Figure 7-43 Duration curves for Malmedalselva catchment

Duration curve of simulated runoff for Malmedalselva catchment shows significant difference and not follows the pattern of duration curve for observed runoff. Duration curve of scaled runoff is close to observed one. 5% of the time scaled flow has four times less water than observed runoff. During low flow period the scaled runoff is overestimated. Applicability of regional modeling with ENKI for Malmedalselva catchment will lead to completely wrong results of estimating runoff. Scaling approach should be utilized for estimating discharge.

7.5.1.4 COMPARISION OF SKORGEELVA RUNOFF DATA SERIES

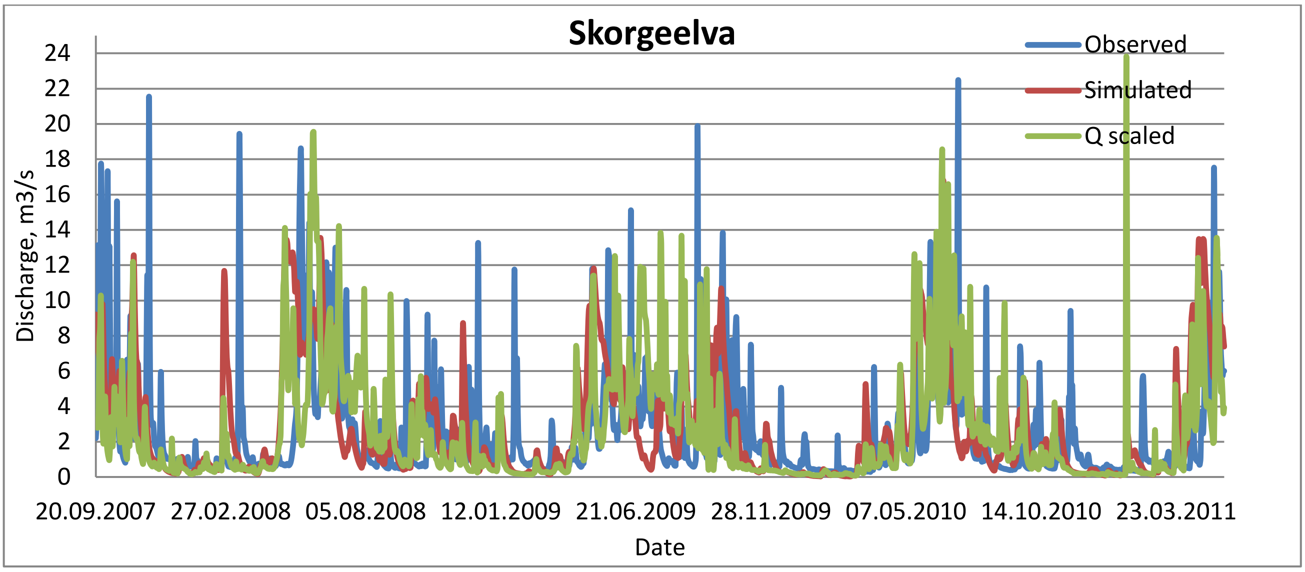


Figure 7-44 Simulated, observed and scaled hydrographs for Skorgeelva catchment

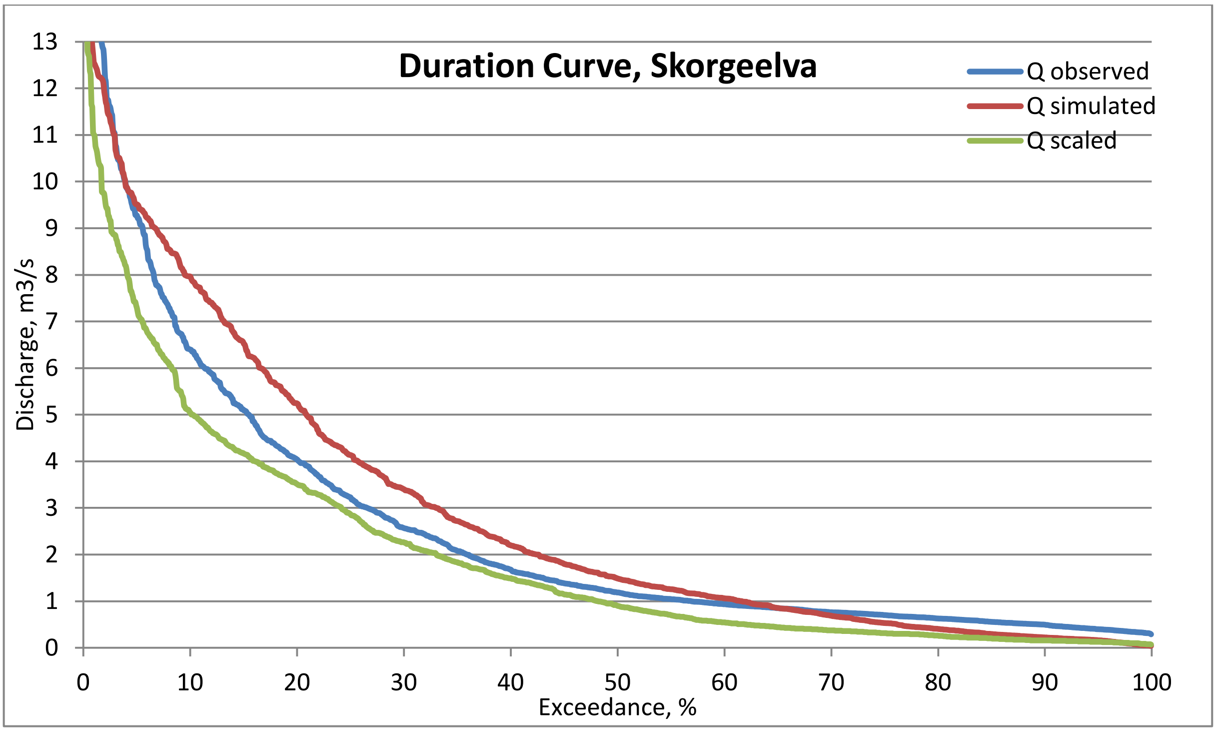


Figure 7-45 Duration curves for Skorgeelva catchment

Duration curve of simulated runoff for Skorgeelva catchment shows more water for 50 % of the time. During low flow period simulated flow is underestimated. Duration curve of scaled runoff shows less water than observed one. Application of regional modeling as well as scaling approach might be used for estimating runoff for Skorgeelva catchment, but uncertainty should be taken into consideration.

7.5.1.5 COMPARISION OF ERGA RUNOFF DATA SERIES

Duration curves of scaled and observed discharge are identical. The duration curve for simulated runoff shows less water. Application of regional modeling with ENKI for Erga catchment will lead to large uncertainty during planning stage for small hydropower plants. Scaling method should be used for estimation discharge for Erga catchment.

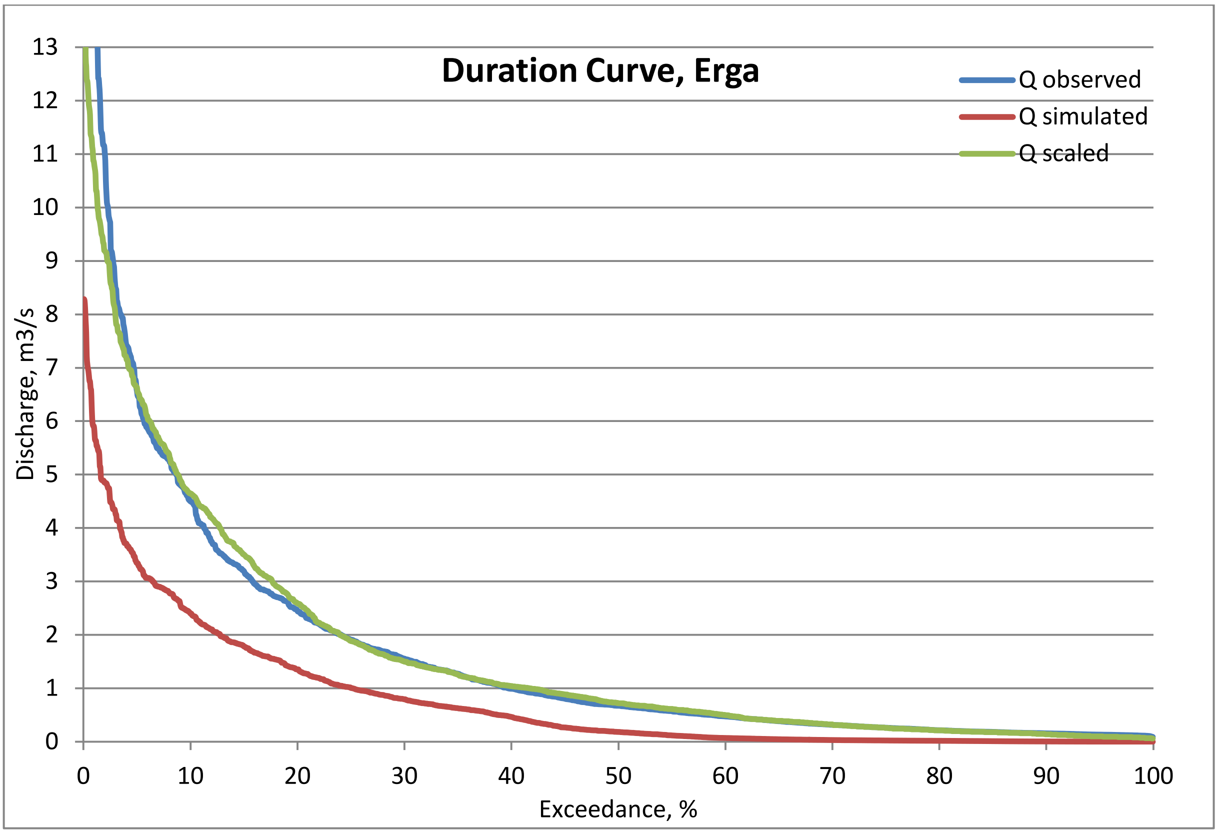


Figure 7-46 Duration curves for Erga catchment

7.5.1.6 COMPARISION OF EIDÅA RUNOFF DATA SERIES

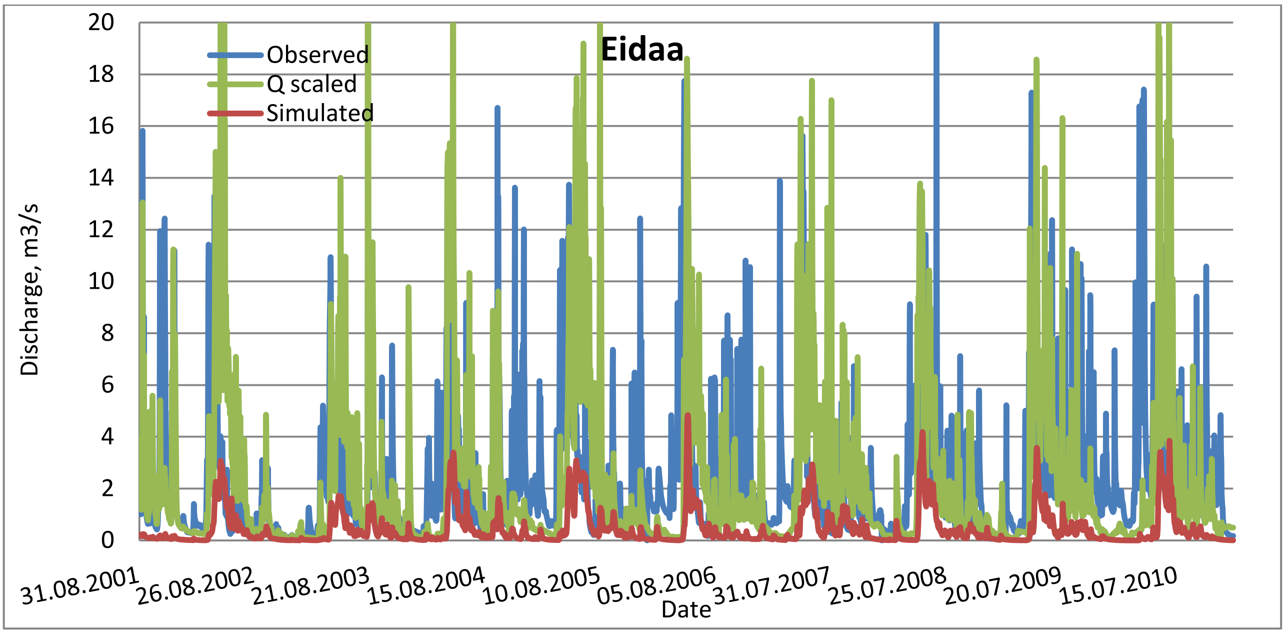


Figure 7-47 Simulated, observed and scaled hydrographs for Eidaa catchment

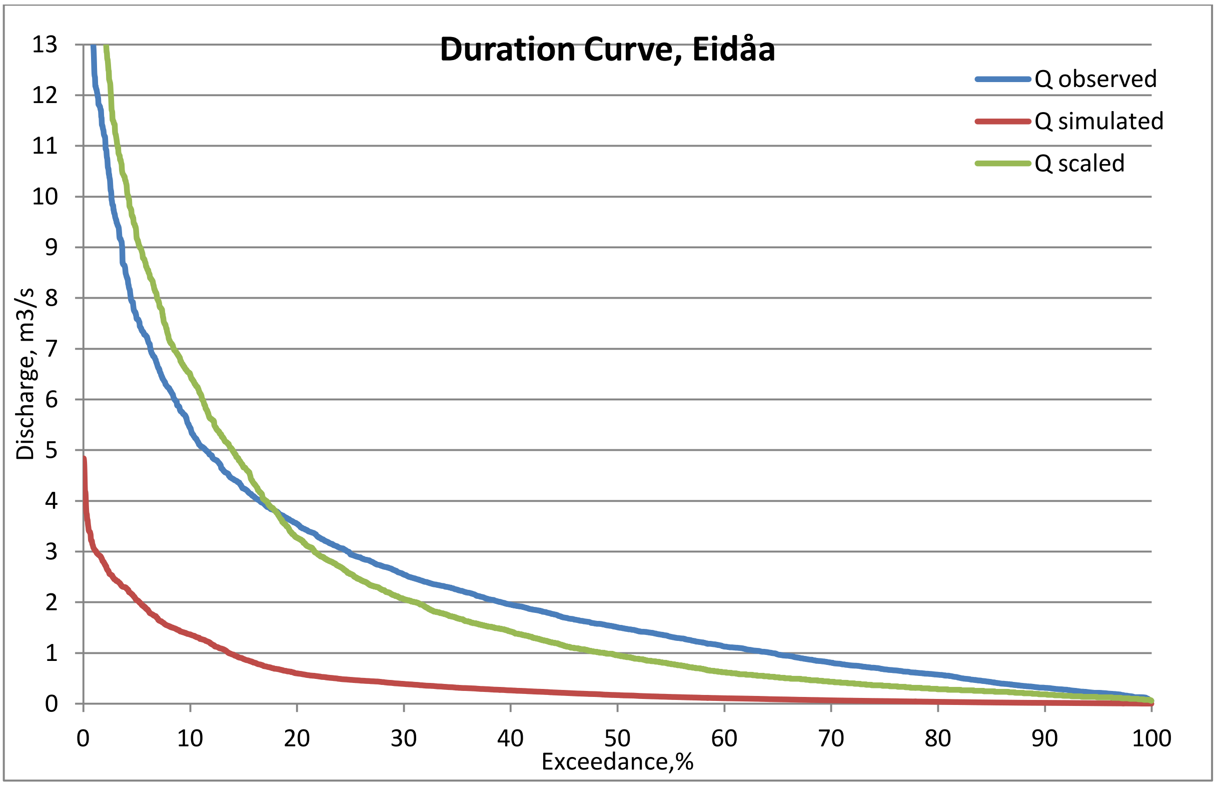


Figure 7-48 Duration curves for Erga catchment

Duration curve of simulated runoff for Eidåa catchment shows more than three times less water than observed runoff. Duration curve of scaled runoff is close to observed one. During low flow period the scaled runoff is underestimated. Regional modeling with ENKI for Eidåa catchment is not applicable. Scaling approach should be utilized for estimating discharge.

7.5.1.7 COMPARISION OF TANGVELLA RUNOFF DATA SERIES

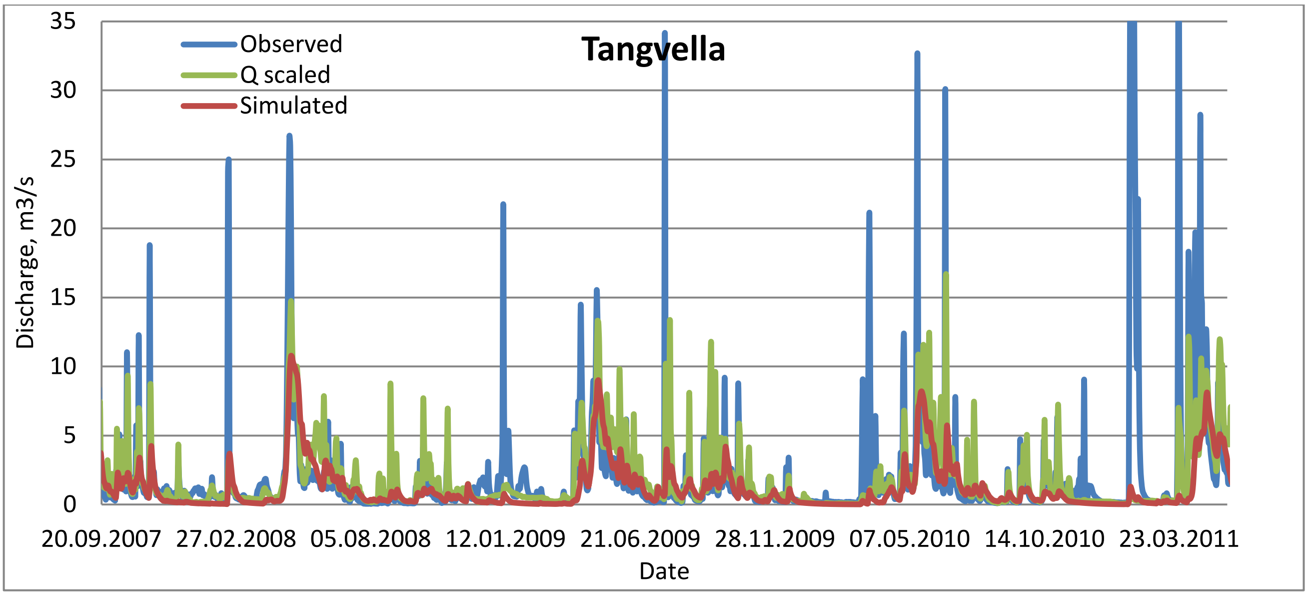


Figure 7-49 Simulated, observed and scaled hydrographs for Tangvella catchment

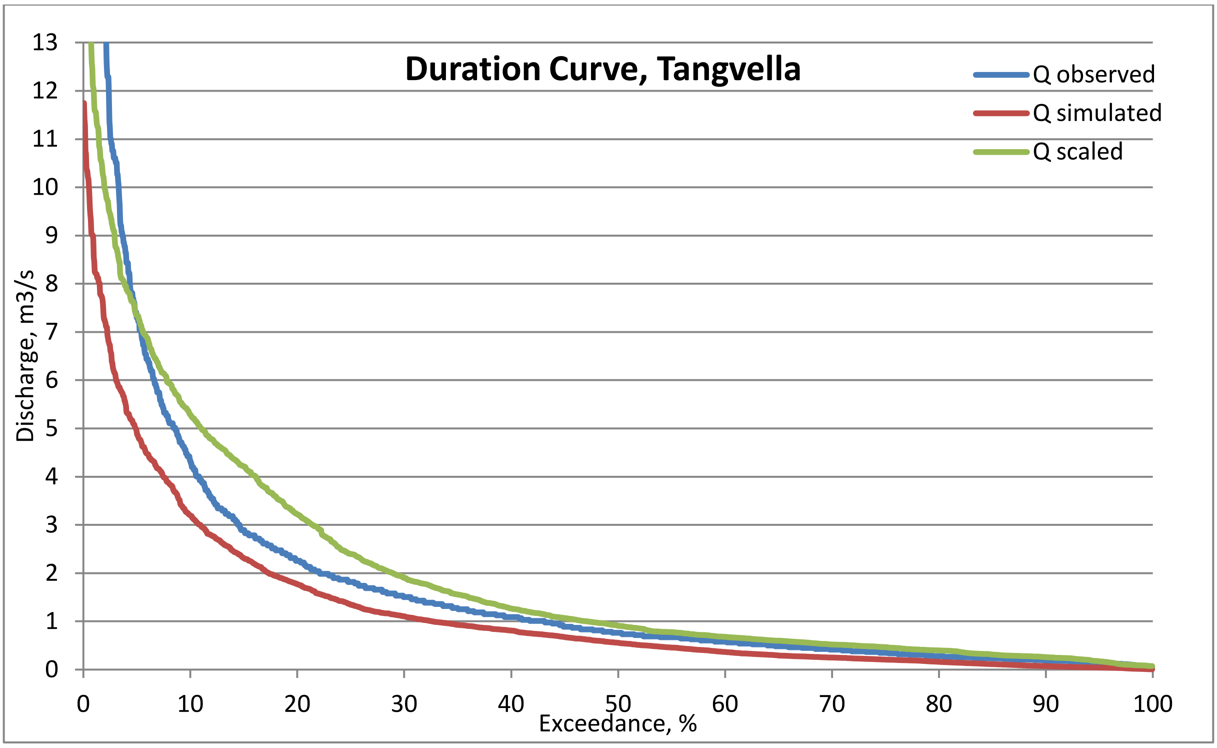


Figure 7-50 Duration curves for Erga catchment

Hydrographs of scaled and observed runoff for Tangvella catchment are similar, except extremely high peaks. Duration curve of simulated flow shows slightly less water than observed one. In general simulated and scaled duration curve are follows the pattern of observed flow. For low flow period the scaled and observed runoff are identical. Using regional modeling with ENKI for Tangvella catchment is applicable, but uncertainty should be taken into consideration. Scaling approach will lead to more accuracy in estimating runoff for Tangvella catchment for small hydropower planning.

Comparison of ENKI regional modeling with traditional scaling method for estimating runoff data series for Sweco catchments lead to the conclusion that scaling approach is able to estimate more accurate runoff data series.

7.6 COASTAL ZONE CALIBRATION

In order to try to achieve better results for calibration over coastal climatic zone the decision was made to run another calibration over the catchments, lying near the coastal line. New input parameters have been implemented into ENKI model including runoff and precipitation data series only located within coastal zone. The temperature data series have been used as for all other calibration cases. The range of parameters was kept the same as well. The results from coastal zone calibration is tabulated in Table

Table 7-10 Coastal zone calibration results

Station Name	***Individual R2***	***Individual R2***	***R2 (First Case)***
Farstadelva v/Farstad	-0.669	n/a	-0.242
Myra	0.289	0.289	0.277
Rovatn	0.158	0.158	0.302
Isa v/Morstål bru	0.633	0.633	0.634
Søya v/Melhus	0.327	0.327	0.268
Vistdal	0.326	0.326	0.372
Average	***-0.069***	***0.155***	***0.150***

The average value of Nash efficiency for coastal zone calibration is R^2 = - 0.069. Excluding from calculation of average value of R^2 for Farstadelva v/Farstad the average R^2 is 0.155. The results from coastal zone calibration did not improved compare to first case of calibration. Such results are not applicable for further extraction of runoff data series for Sweco catchments.

The reason of such low results might be the difficult precipitation pattern along the coastal zone. In order to improve the calibration the area of study region should be reduced, the input data series should be long and representative for the region. It can be implemented and checked in further studies.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The regional modeling using ENKI is carried out for the study area in order to obtain regional set of parameters to estimate runoff for ungauged catchments. The regional set of parameters was calibrated from historical climatic and runoff data. All necessary hydro-meteorological and geographical input data have been collected, processed and converted to ENKI readable format. The ENKI model has been set-up. Three cases of calibration have been carried out to obtain the best regional set of parameters for the entire study area and extracted simulated runoff are compared with the observed runoff values of Sweco catchments. Applicability of ENKI regional modeling has been compared to scaling approach.

The first case of calibration was done including all the catchments; the calibrated period is from 2001 to 2005. The results showed variability of R^2 from -0.24 to 0.85 for individual calibration. The catchments with small area and coastal zone location showed low R^2 values. The lowest R^2 belongs to Farstadelva v/Farstad catchment located in coastal zone with area of 24.14 km^2. The second largest catchment Eggafoss with area of 653.9 km^2 and inland location have been calibrated with result of R^2 = 0.85.The reasons of such high variability might be the size of the catchments, its location, errors in input parameters, low number and not equally distribution of meteorological data. The regional set of parameters for the first case of calibration resulted in Nash efficiency of 0.15 which is comparatively very low.

To improve the Nash efficiency a second calibration run was done. In this case the catchments which were giving poor R^2 values have been omitted. The range of calibrated parameters has been expanded. The model runs over 7000 iterations over 9 catchments. The variability of R^2 for second case is from 0.375 for Vistdal catchment to 0.85 for Eggafoss catchment. The regional set of parameters has been improved and resulted in R^2 = 0.55. Validation of the model has been carried out for the period from 2005 to 2011 and resulted with regional value of R^2 = 0.583, which proves that the model is applicable for predicting runoff.

The third case of calibration have been set identical to second one, the only difference is that the PcorrRain and PcorrSnow parameters were performed as raster maps with best values from first case of individual calibration. Those two parameters are ones of the most influencing in spatial interpolation of precipitation. Two raster maps have been prepared in GIS and converted to Idrisi format. The regional set for the third case of calibration resulted in R^2 = 0.452.

The regional set of parameters with R^2 = 0.55 obtained from second case of calibration has been used for extraction runoff data series for Sweco catchments. The Nash efficiency for simulated runoff from Sweco catchments resulted with low R^2 values. The variability of R^2 is from -12.79 to 0.38. The reasons of such results can be the small size of Sweco catchments (area is from 16.9 km^2 to 69.7 km^2), errors in input data or the location of the catchments. The catchments located in coastal zone obtain worser value of R^2 compare to catchments located in inland climatic zone.

Coastal climatic zone calibration have been done as one more try in order to achieve better results over the catchments, lying near the coastal line. New input parameters have been implemented into ENKI model including runoff and precipitation data series only located within coastal zone. The temperature data series and range of parameters have been used as for all other calibration cases. The results showed variability of R^2 from -0.669 (for Farstadelva v/Farstad catchment) to 0.633 (for Isa v/Morstål bru catchment). The R^2 of coastal climatic zone regional best set of parameters resulted in 0.069. Excluding Farstadelva v/Farstad catchment from average calculation of regional parameters, the regional R^2 value becomes 0.155 which is very low. The calibration results for coastal climatic zone have not been improved compare with results from first case of calibration. The reason of such low results might be the difficult precipitation pattern along the coastal zone.

The comparison of estimating runoff for Sweco catchments using regional modeling with ENKI and scaling method have been carried out. The runoff data series for scaling method have been used from NVE catchments previously utilized for calibration in this project. The location and area of NVE catchments have been taking into consideration. The hydrographs and duration curves have been drown to see the relation between simulated, scaled and observed runoff for Sweco catchments. The conclusion from the analysis is that the scaling approach is able to estimate more accurate runoff data series for small catchments in comparison with regional modeling with ENKI method.

The overall conclusion is: the application of regional modeling with ENKI within selected study region able to estimate good simulated runoff for large catchments. For estimating runoff within small catchment the traditional scaling approach will lead to higher accuracy of data compare with application of regional modeling.

8.2 RECOMMENDATIONS

The runoff estimation using ENKI model has been carried out for ungauged catchments for selected study area. However, the results are not satisfactory for small catchments which can be improved in further studies. Following points are recommended:

- The size of the region selected for regional modeling with ENKI should be chosen such that the best parameter set can be obtained.
- Climatic conditions within the region should be homogeneous.
- The input data series for regional modeling should be long enough and well distributed in order to be representative of the whole region.

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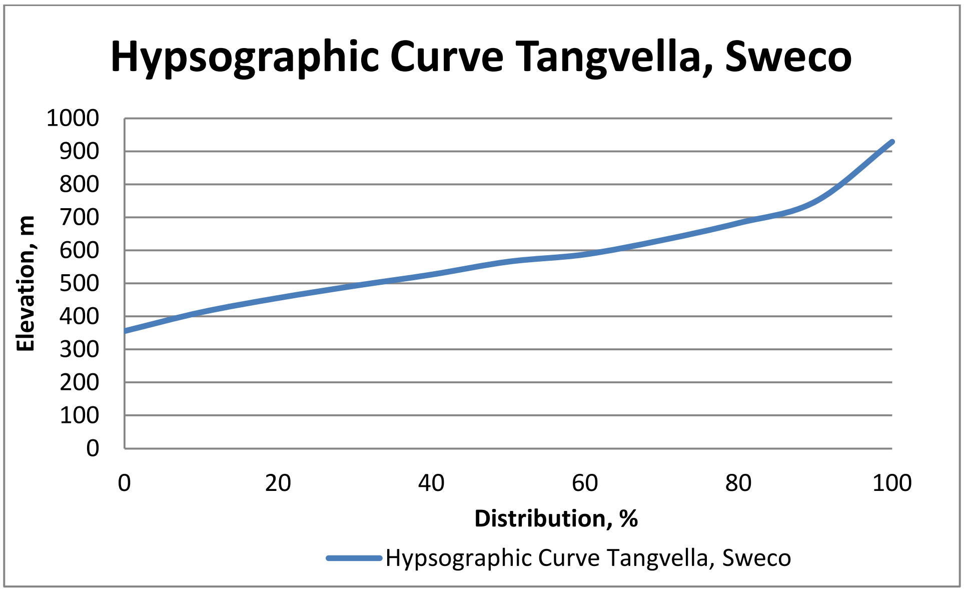
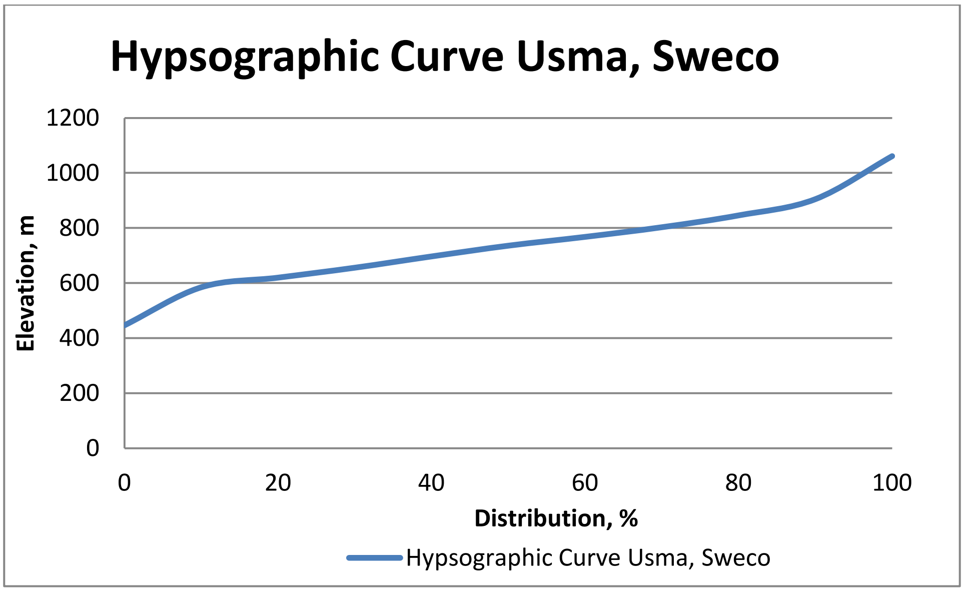
10 APPENDICES

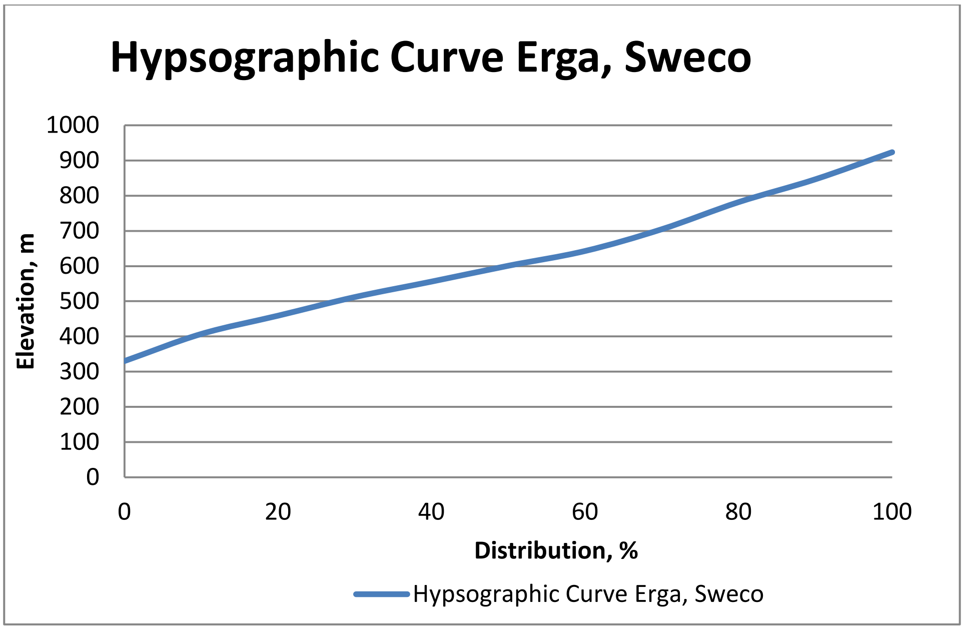
Appendix A: Hypsographic Curves

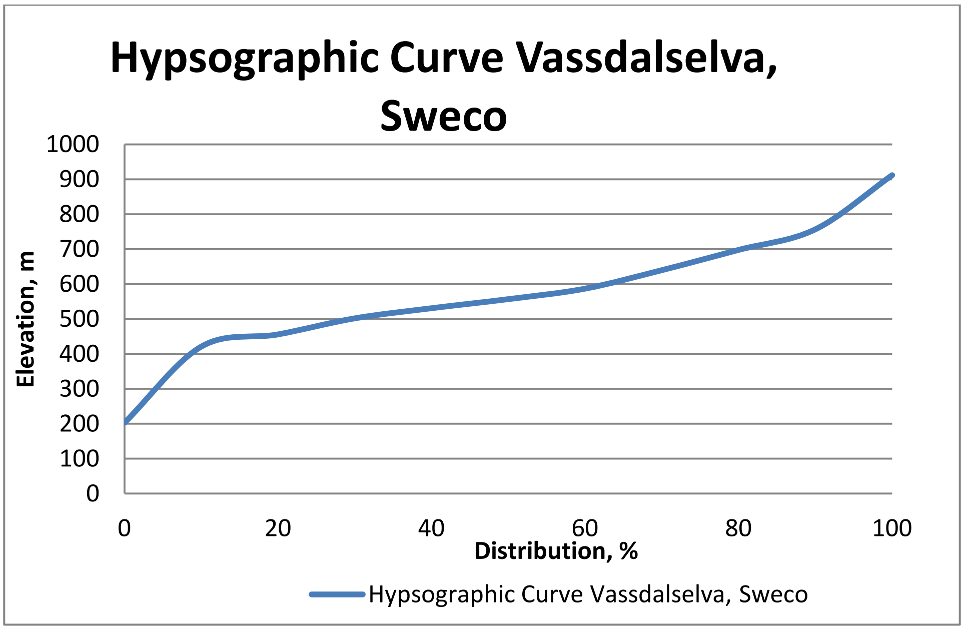
Appendix B: The script for extracting calibration results from .nc file using "R" program

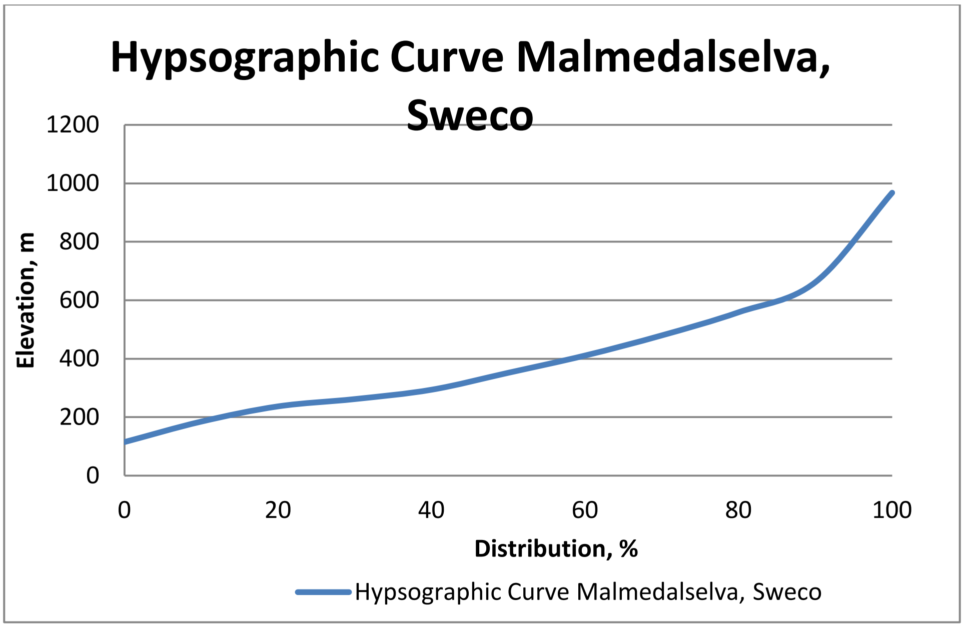
Appendix A: Hypsographic Curves

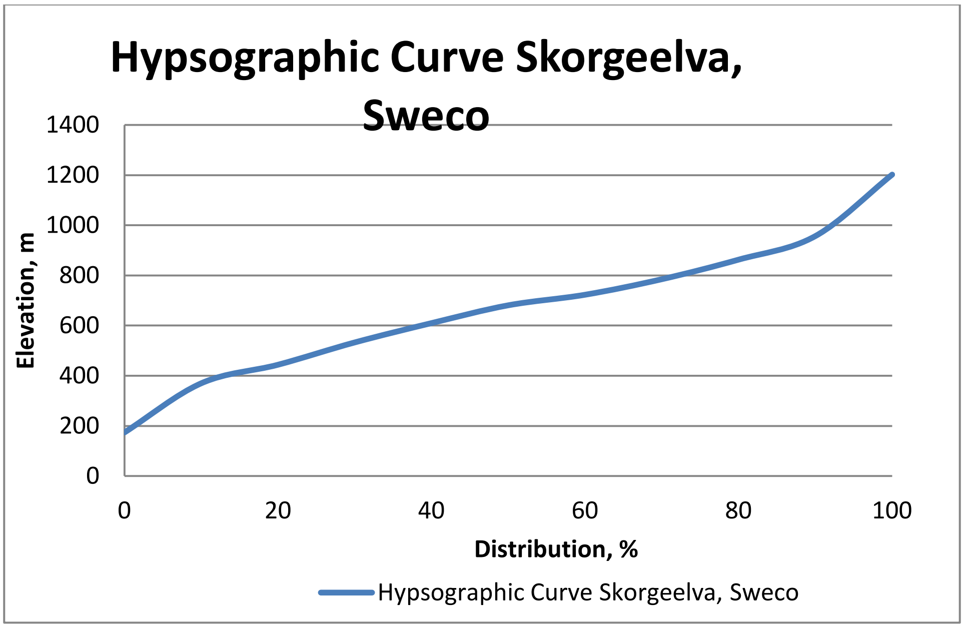


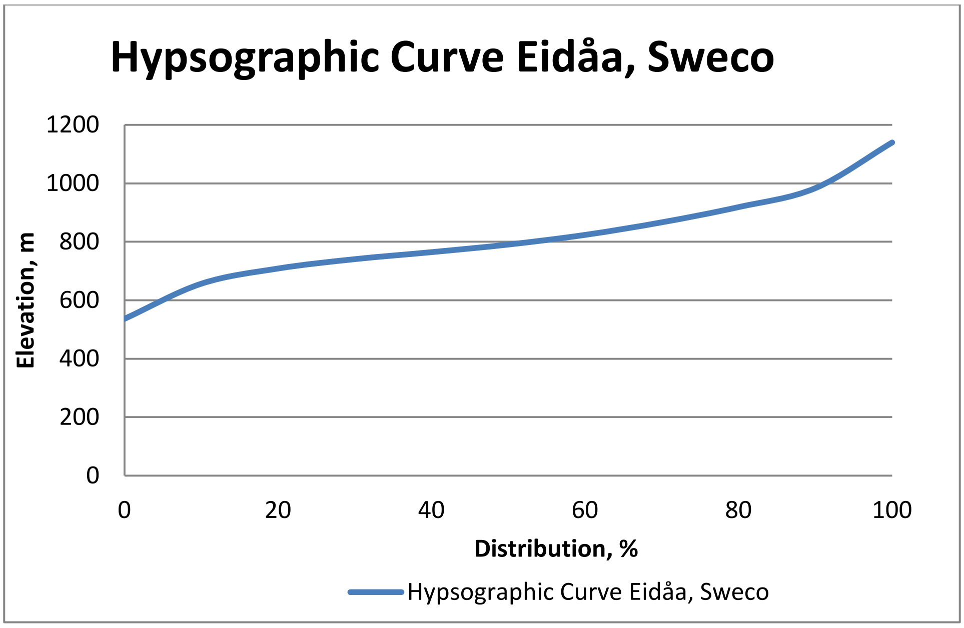


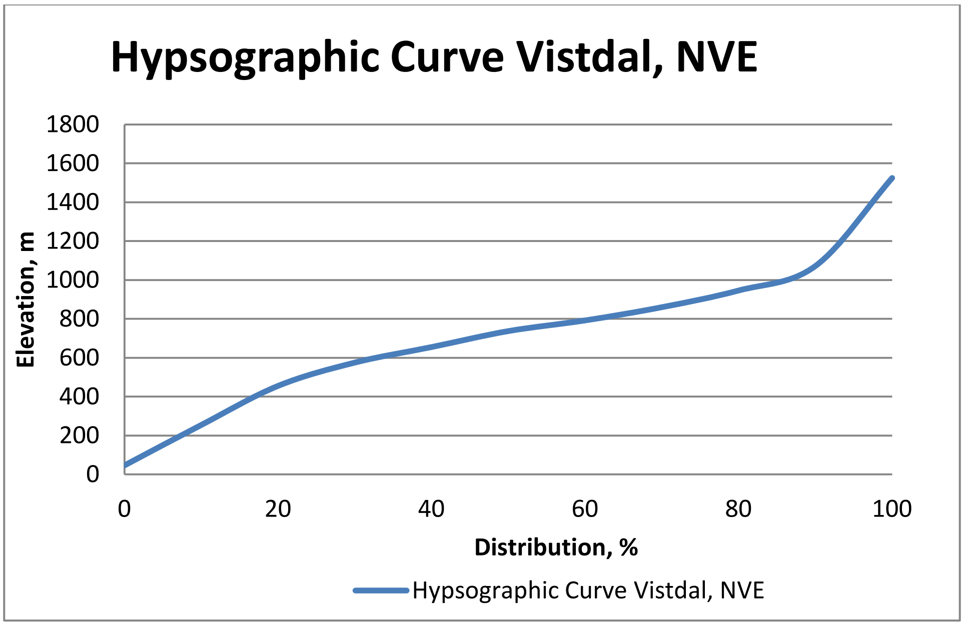

Hypsographic Curve Erga, Sweco
Elevation, m
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Erga, Sweco

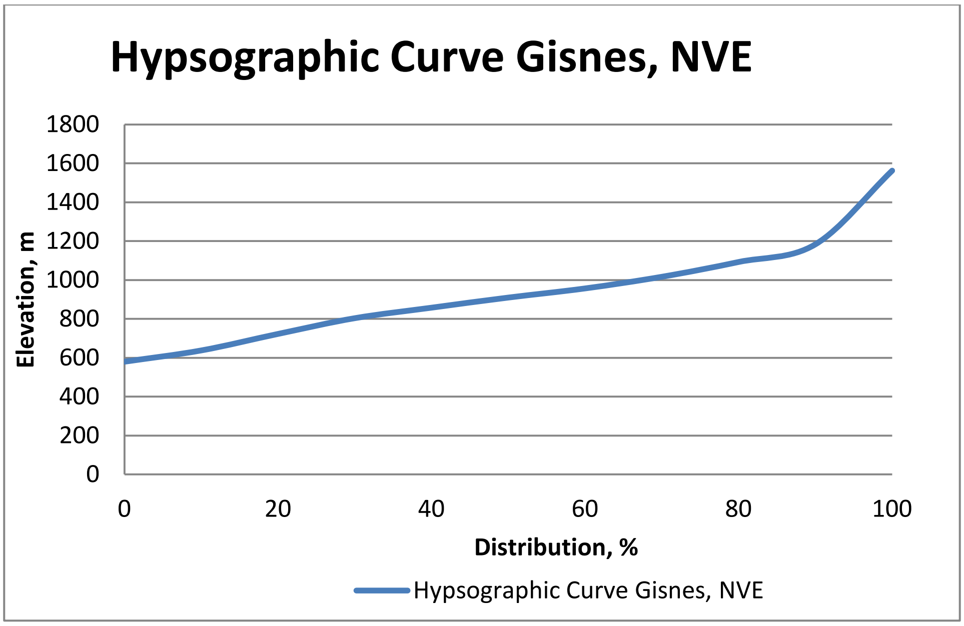

Hypsographic Curve Vassdalselva, Sweco
Elevation, m
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Vassdalselva, Sweco

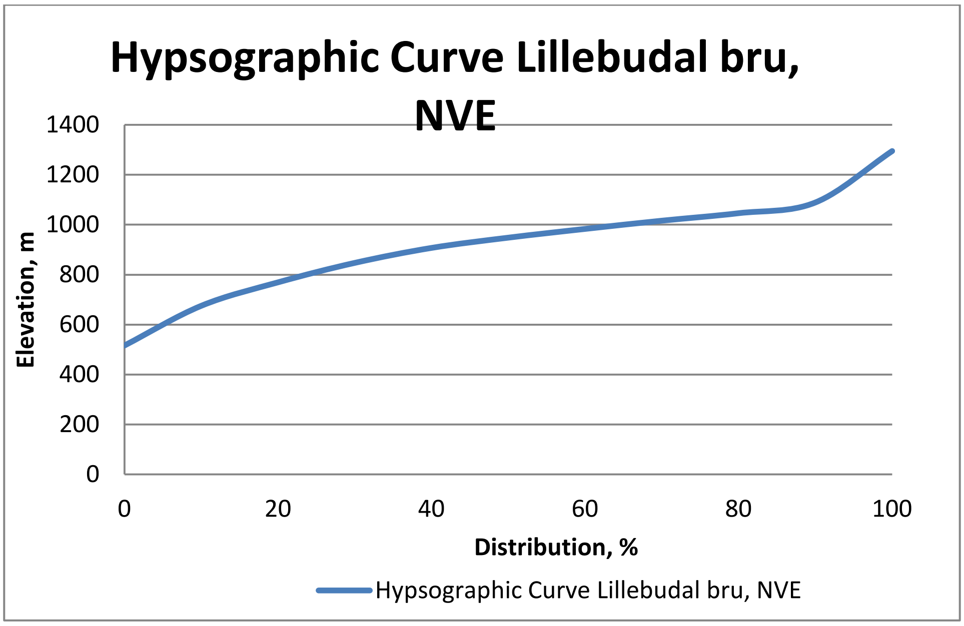

Hypsographic Curve Malmedalselva, Sweco
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Malmedalselva, Sweco

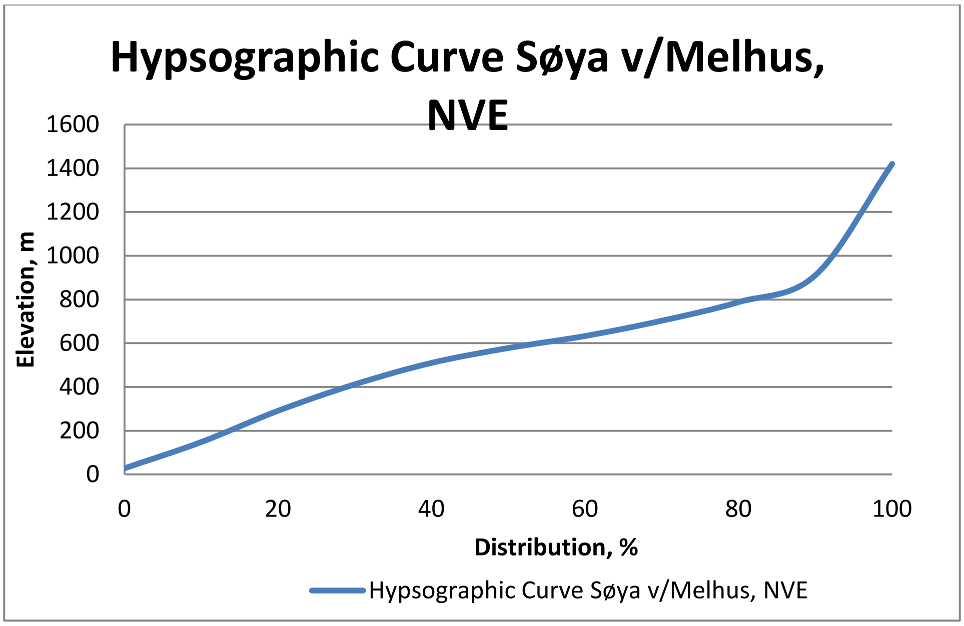

Hypsographic Curve Skorgeelva, Sweco
1400
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Skorgeelva, Sweco

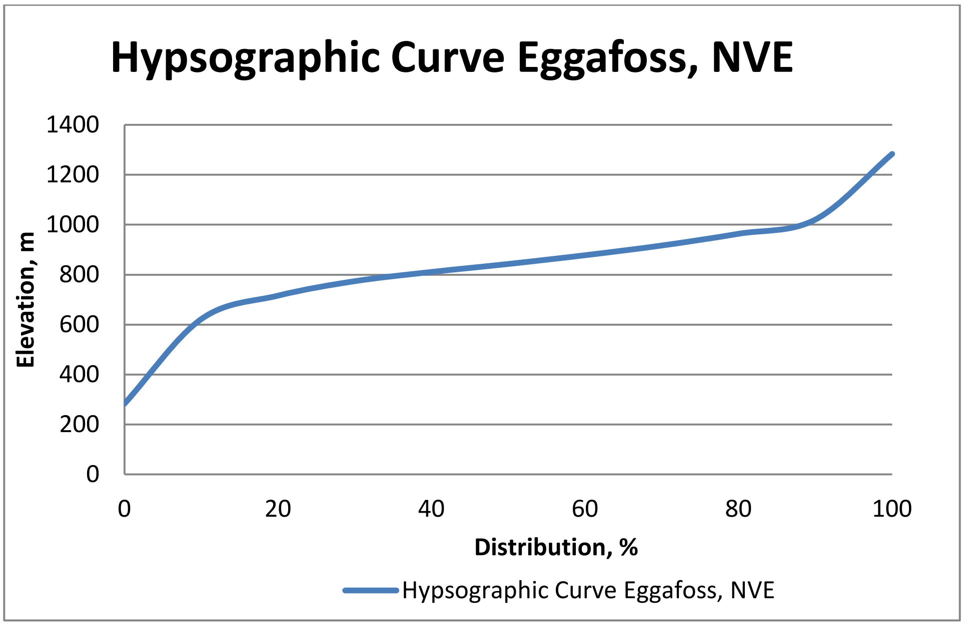

Hypsographic Curve Eidåa, Sweco
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Eidåa, Sweco

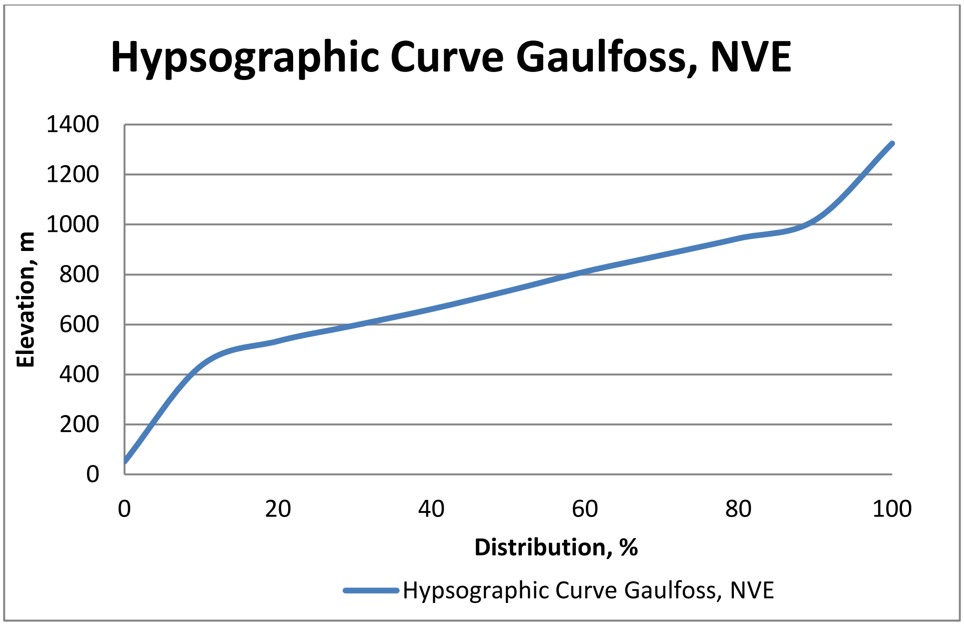

Hypsographic Curve Vistdal, NVE
1800
1600
1400
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Vistdal, NVE

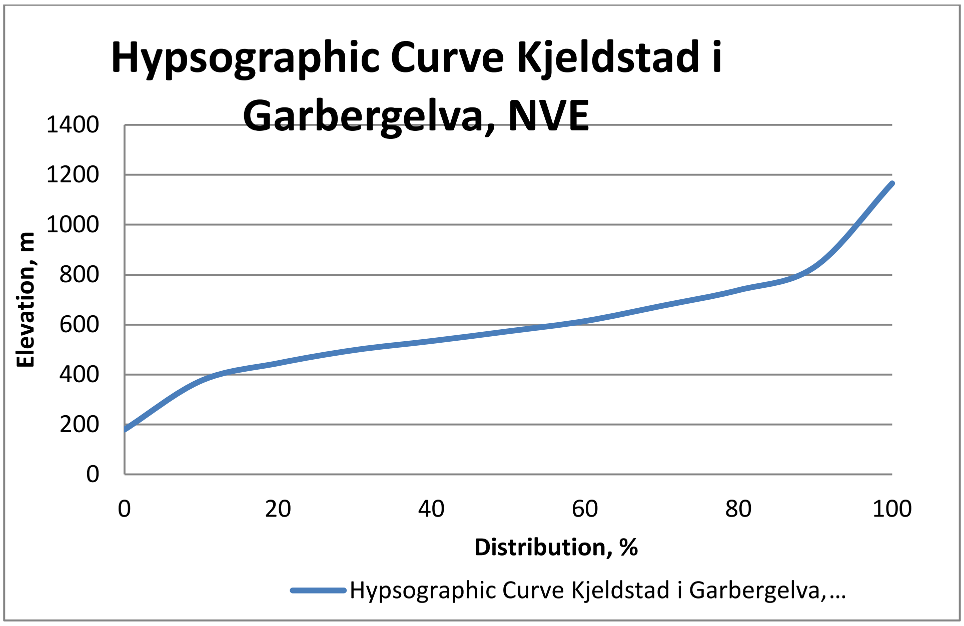

Hypsographic Curve Gisnes, NVE
Elevation, m
1800
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Gisnes, NVE

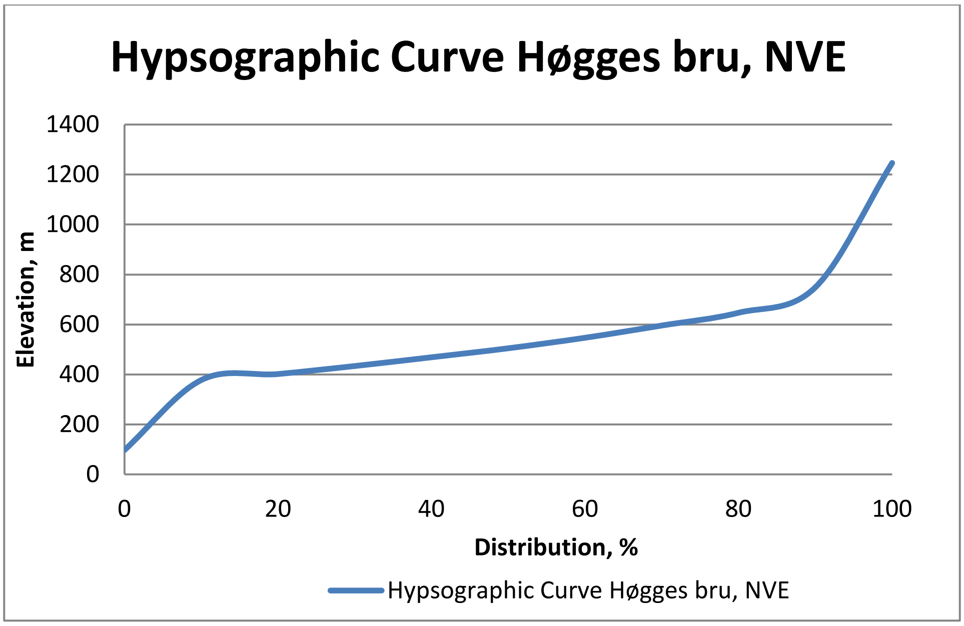

Hypsographic Curve Lillebudal bru, NVE
Elevation, m
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Lillebudal bru, NVE

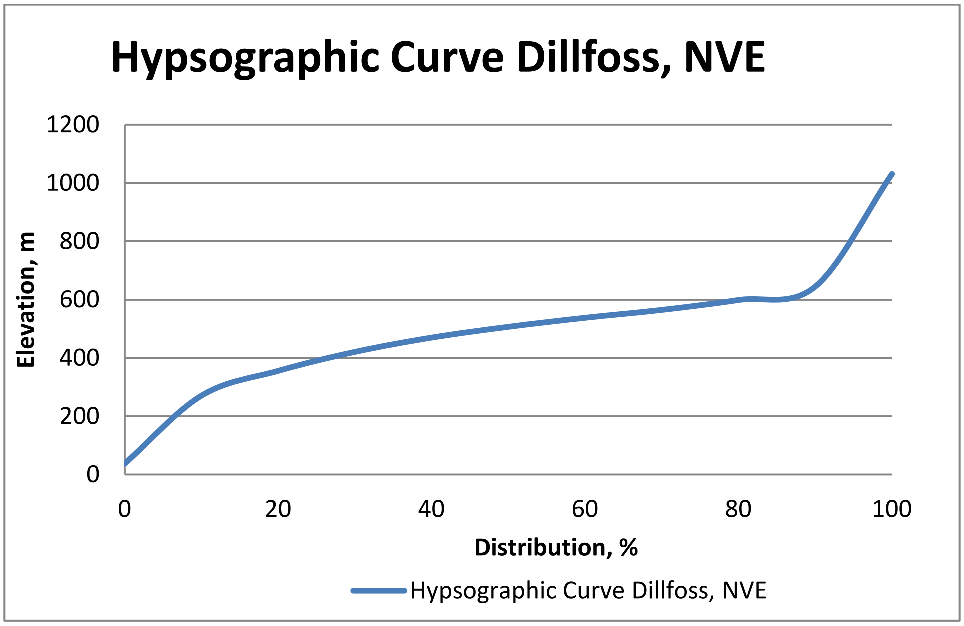

Hypsographic Curve Søya v/Melhus, NVE
Elevation, m
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Søya v/Melhus, NVE

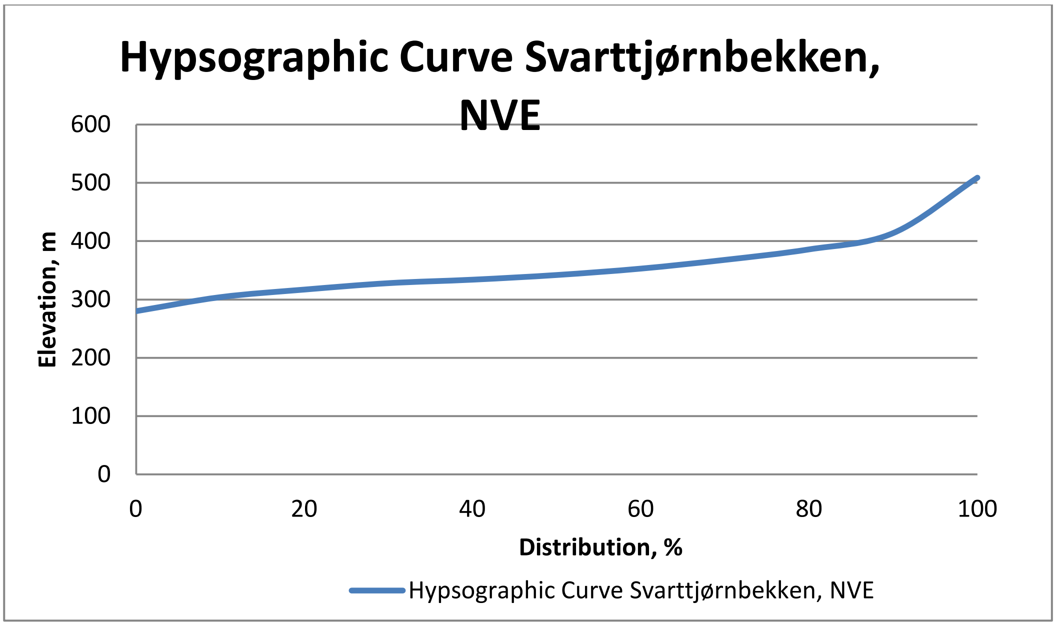

Hypsographic Curve Eggafoss, NVE
Elevation, m
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Eggafoss, NVE

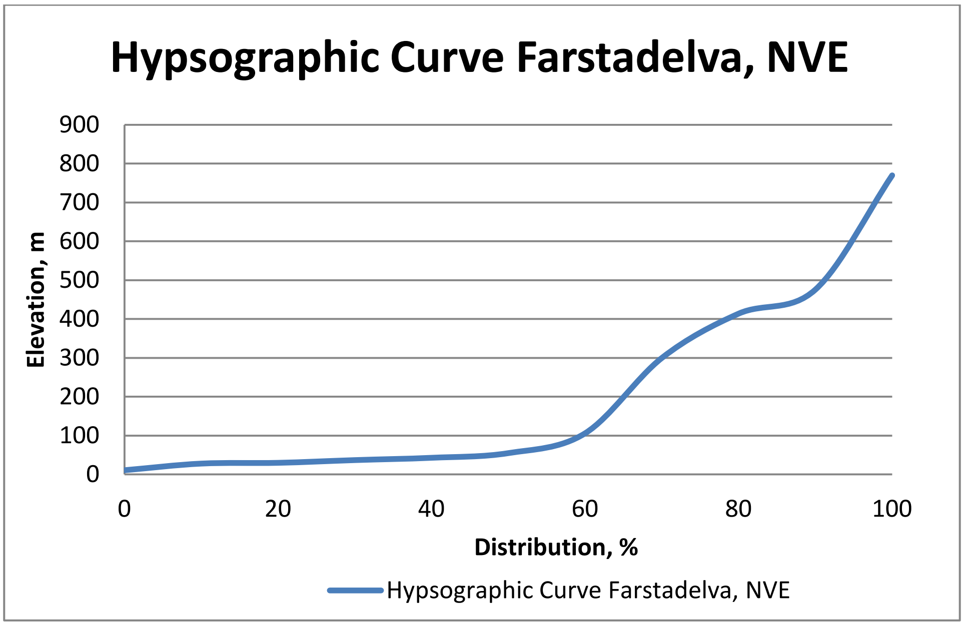

Hypsographic Curve Gaulfoss, NVE
1400
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Gaulfoss, NVE

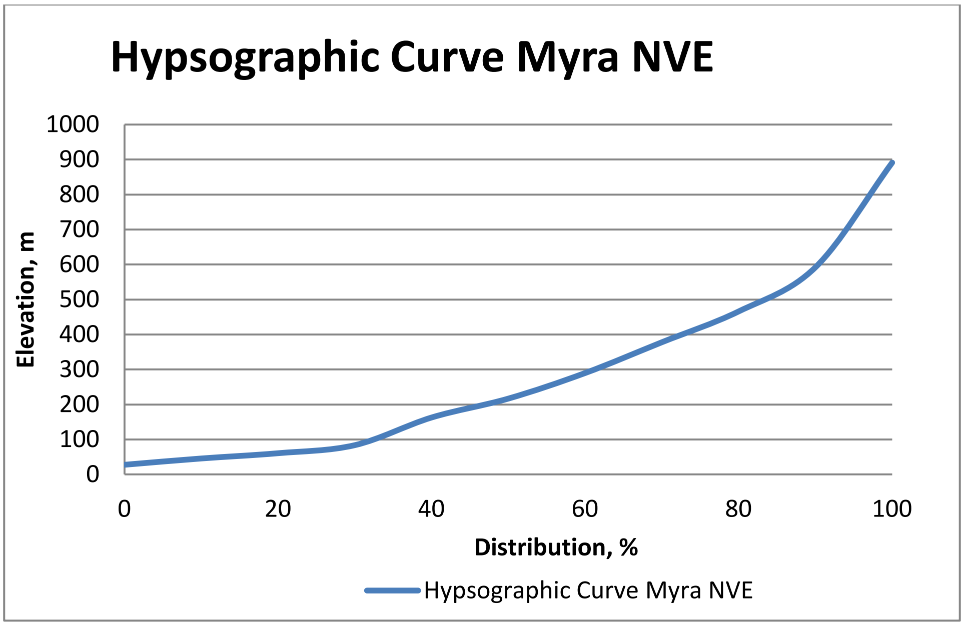

Hypsographic Curve Kjeldstad i Garbergelva, NVE
1400
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Kjeldstad i Garbergelva,...

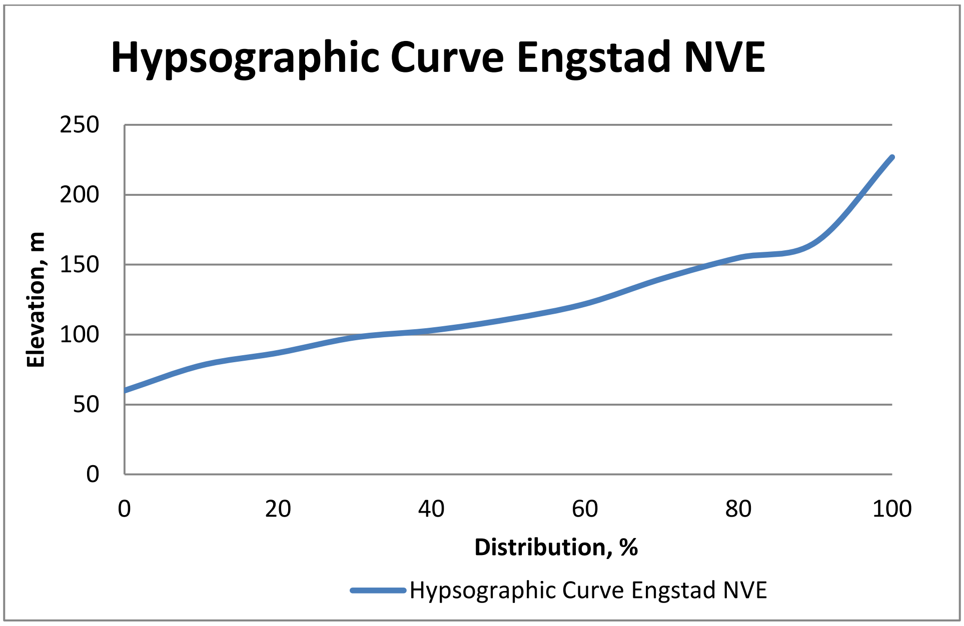

Hypsographic Curve Høgges bru, NVE
1400
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Høgges bru, NVE

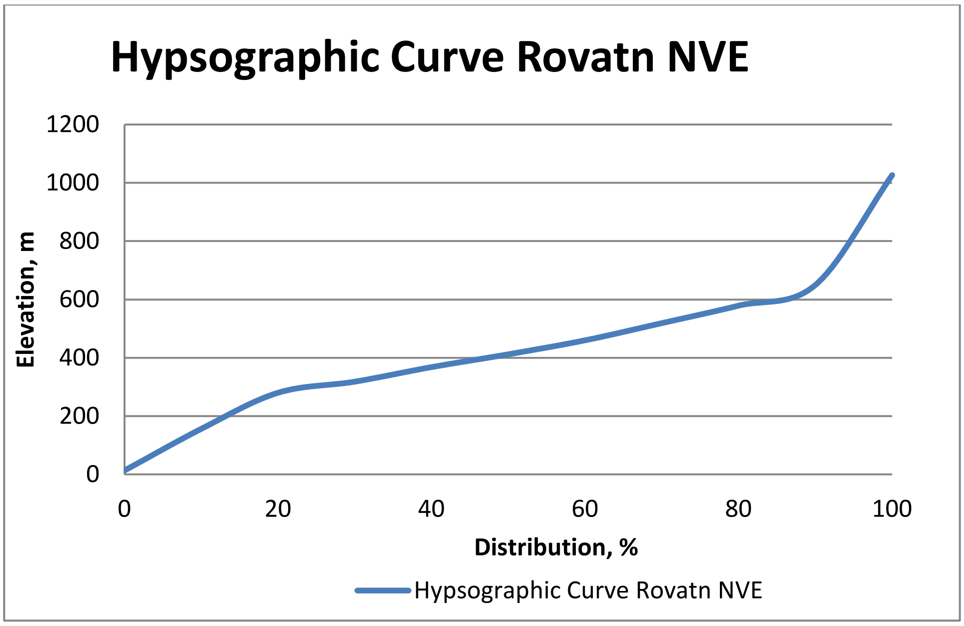

Hypsographic Curve Dillfoss, NVE
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Dillfoss, NVE

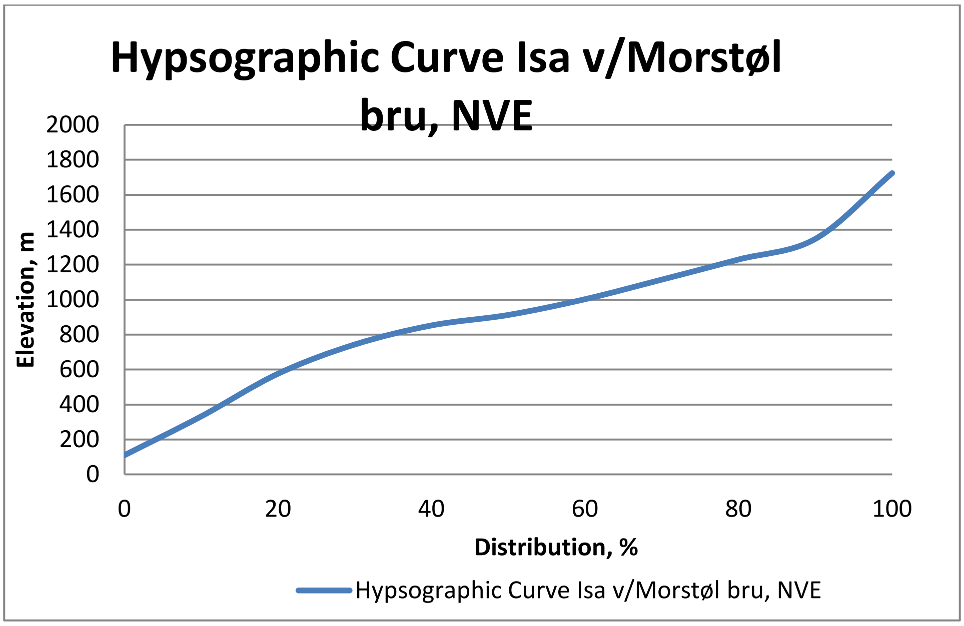

Hypsographic Curve Svarttjørnbekken, NVE
Elevation, m
600
500
400
300
200
100
0
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Svarttjørnbekken, NVE

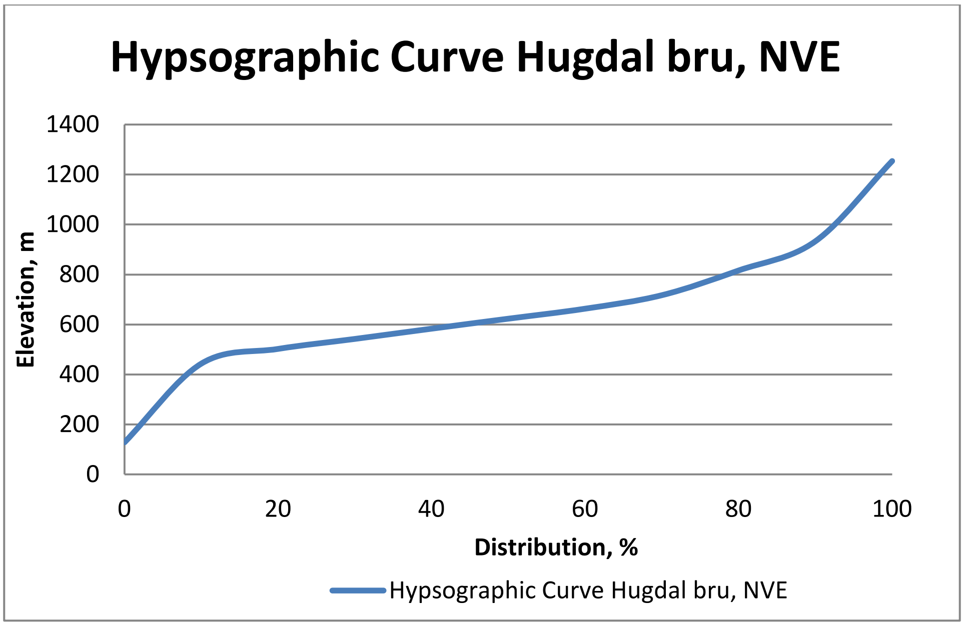

Hypsographic Curve Farstadelva, NVE
Elevation, m
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Farstadelva, NVE


Hypsographic Curve Myra NVE
Elevation, m
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Myra NVE


Hypsographic Curve Engstad NVE
Elevation, m
250
200
150
100
50
0
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Engstad NVE


Hypsographic Curve Rovatn NVE
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Rovatn NVE


Hypsographic Curve Isa v/Morstøl bru, NVE
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Isa v/Morstøl bru, NVE


Hypsographic Curve Hugdal bru, NVE
1400
1200
1000
800
600
400
200
0
Elevation, m
0
20
40
60
80
100
Distribution, %
Hypsographic Curve Hugdal bru, NVE

Appendix B: The script for extracting calibration results from .nc file using "R" program.

```
# this script reads the ENKI result file
setwd("C:\\calibration_resulrs_R)\\")
library(nvdf)


nc=open.ncdf( "FINAL_CALIBRATION_RESULTS.nc", write=FALSE, readunlim=F)
#________________________observation__________________________________________
obs=get.var.ncdf (nc, "Qstats")
data
dead(obs)
ob1=t(obs[,,1])  # first parameter set simulation
head(ob1)
#_______________________simulation results_____________________________________
data <- get.var.ncdf (nc, "Qsim")
data
head(data)
dim(data)    # 23 rivers, 2679 time steps and 1627 runs  (1627 parameter set run)
first_rn=data[,,1]
par1=(t(first_rn))
head(par1)
plot(pat1[,1] , type="1")
for ( i in 1:1627){|
first_rn=data[,,i]
par1=round((t(first_rn)),2)
head(par1)
write. table(par1, paste("Flow_for_ParSet_", i, ".txt",sep=("")))
```