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Impacts of Climate Change on Flow Regimes in Central Norway

Ganesh Hiriyanna Rao Ravindra

Hydropower Development
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Supervisor: Knut Alfredsen, IBM

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Master's Thesis

Impacts of climate change on Flow Regimes in Central Norway

A thesis submitted in fulfilment of the requirements for the M.Sc. degree in Hydropower Development

Under
Faculty of Engineering Science and Technology
Department of Hydraulic and Environmental Engineering
Trondheim, June 2017

Author:
Ganesh Hiriyanna Rao Ravindra

Supervisor:
Professor Knut Alfredsen

DECLARATION OF AUTHORSHIP

I, Ganesh Hiriyanna Rao Ravindra hereby declare that this master's thesis titled "**Impacts of climate change on flow regimes in central Norway**" and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at the Norwegian University of Science and Technology.
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
3. Where I have consulted the published work of others, this is always clearly attributed.
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
5. I have acknowledged all main sources of help.
6. This thesis is based on work done by myself with the guidance of my supervisor Professor Knut Alfredsen.

Signature: Ganesh Hiriyanna Rao Ravindra

Date and Place: June 2017, Trondheim, Norway

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Ganesh Ravindra

NTNU
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Science and Technology

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

M.Sc. THESIS IN
HYDROPOWER DEVELOPMENT

Candidate: Ganesh Ravindra

Title: Impacts of climate change on flow regimes in central Norway.

1 BACKGROUND

The effects of a changing climate on water resources is a major concern today, and current scenarios show large temporal and spatial effects on water resources. The effect on floods is of interest in many engineering applications since infrastructure designed today should have a life time that will be influenced by the farthest climate scenarios available today. Currently, the small catchment floods and floods from short duration precipitation is of particular focus based on recent flooding episodes. Predicting floods based on downscaled climate data has been difficult, and various techniques have been used. Further, changes in flow regimes are important for both use of water and for the environment and needs attention. In this project a selected number of catchments in middle Norway will be studied for flow regime alterations.

2 MAIN QUESTIONS FOR THE THESIS

The main questions for the thesis can be stated as follows:

1. Select some study catchments in the Trondheim region with long observed data series that make it possible to calibrate a hydrological model and do flood frequency analysis if necessary. Collect the discharge data and perform a flood frequency analysis on the data
2. Set up and calibrate a hydrological model for the study catchments. The calibration should be evaluated both for general good fit and fit to flood peaks. If necessary alternative calibration strategies could be used to focus on the models ability to reproduce floods. The model setup should involve an evaluation if gridded or point gauge precipitation should be used. Evaluate the parameter uncertainty in the model calibration.
3. Select a number of RCM datasets from the CORDEX database, clip them to the catchment and bias correct the data using observed precipitation and temperature (gridded or gauged). Compare the downscaled temperature and precipitation with the observed values.
4. Simulate the historical period of each bias corrected RCM and evaluate the results against the observed floods using the parameter sets from 2). Perform a flood frequency analysis on the simulated flood levels and compare them to the observed

floods. Evaluate discrepancies between this and the study in 1). Further, compute the hydrological indices for the simulated flood regime.

5. Downscale the future scenarios using the same strategy as for the historical period, and simulate the future floods using the hydrological model and the parameter sets from 2). Perform a flood frequency analysis on the downscaled data. Compute the hydrological indices for the simulated future flood regime.
6. Compare the flow hydrographs by computing hydrological indexes from the control period and the future scenarios. Evaluate changes in the flood regime for each catchment, and compare the flood regimes for the current period and the future period.
7. Compare the high flood periods of the future with the observed period. Are there any indications that we see a change in the frequency of high flows? Evaluate the precipitation data to see if there is a change in high precipitation events. Further, short duration precipitation from the GCM could be evaluated for the same purpose.

3 SUPERVISION, DATA AND INFORMATION INPUT

Professor Knut Alfredsen will be the formal supervisor the thesis work and assist the candidate to make relevant information available.

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

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

4 REPORT FORMAT AND REFERENCE STATEMENT

The thesis report shall be in the format A4. It shall be typed by a word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary, a table of content, a list of literature formatted according to a common standard and other relevant references. A signed statement where the candidate states that the presented work is his own and that significant outside input is identified should be included.
The report shall have a professional structure, assuming professional senior engineers (not in teaching or research) and decision makers as the main target group.

The thesis shall be submitted no later than 11th of June 2017.

Trondheim 05th of January 2017

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Knut Alfredsen

Professor

"To myself I am only a child playing on the beach, while vast oceans of truth lie undiscovered before me"

-Sir Isaac Newton

ABSTRACT

The phenomenon of climate change has had widespread impacts on the climatic and ecological setup of the globe ranging from rapid melting of polar ice caps to startling changes in weather patterns around the planet. From a hydrological standpoint, climate change has had a pronounced impacts on precipitation patterns which has posed a mammoth challenge for the water dependent infrastructures such as domestic water supply systems, storm water drainage systems and the hydropower industries across the globe.

This project aims to add and to strengthen the findings of previous works carried out in the fields of flood frequency analysis and hydrological regimes in a future climatic setup in central Norway. Discerning the future flood patterns in select catchments of central Norway can provide valuable information and insight for decision makers and planners to evaluate and if necessary, modify the existing design of key protective infrastructures such dams, culverts and storm water drainage systems. Furthermore, the findings of the project could help hydropower planners in designing modifications to the existing reservoir operation and power production schemes to cope with the changes imparted to the natural hydrological regime by climate change. Also, the project aims to work towards discerning possible changes to flow regimes in the region which can validate and also strengthen the findings of earlier works.

The project aims at understanding the changes imparted to the natural hydrological regimes in select catchments of central Norway such as Hagabru, Krinsvatn and Svartjonbekken. The chosen catchments represent variability in size, hypsography and distance from the coast and these parameters greatly influence the hydrological regime features of these catchments such as precipitation pattern, snow melt features, seasonality and also influence flow response characteristics.

Upon investigation of the retrieved historical observed discharge time series for these catchments, it was evident that climate change impacts on the annual natural flow regime were already observable. Further, the process of hydrological model calibration for these catchments provided an insight into the complexities in model calibration for the purpose of flood frequency analysis as the project findings showed that a hydrological model calibrated to obtain a general good fit for water balance underperformed when employed for the purpose of flood frequency analysis and vice-versa.

The process of climate data downscaling was particularly challenging and initial analysis revealed that the GCM simulated temperature time series exhibited a high degree of correspondence with the observed temperature time series. But, the GCM simulated precipitation data had a poor correspondence with the observed data which necessitated implementation of a downscaling technique. A new method of precipitation downscaling was devised termed ‘Antinoise Downscaling’ which helped correct systematic biases within the GCM simulated precipitation data series.

Finally, the calibrated hydrological models for the various catchments were employed to simulate flow regimes in a future time period (2051-2099) to get an insight into the possible ramifications to the natural flow regimes in the catchments with the downscaled GCM precipitation and temperature data series as input.

The results of the investigation revealed that the stream flow pattern would be strongly influenced with exponential reduction in spring flood peak magnitudes. A more evenly distributed flow volumes were projected and also, significant reduction in the amount of available snow cover was projected. A new methodology was implemented for the purpose of analysis of the changes imparted to the flow regimes termed ‘Flow Regime Modification Indices’. Also, a new methodology termed ‘The 1-Year approach’ aimed at obtaining swift graphical estimates of possible changes imparted to the natural flow regimes has been introduced in this study.

Flood frequency analysis was carried out over the historical observation period and also over the future simulation period. The results obtained suggested that the flood magnitudes of respective return periods would be reduced in the future simulation period in all the modeled catchments on an annual basis and also as spring floods.

ACRONYMS AND ABBREVIATIONS

CERFACS- Centre Europeen Recherche Et De Formation Avancee En Calcul Scientifique

CNRM- Centre National De Recherches Meteorologiques

CORDEX- Coordinated Regional Climate Downscaling Experiment

ENSEMBLES- Ensemble Based Predictions of climate change and their impacts

GCM-General Circulation Model

IPCC- Intergovernmental panel on climate change

M.a.s.l- Meters above Sea Level

MOCH- Met Office Hadley center

NASA- National Aeronautics and Space Administration

NVE- Norwegian Energy and Water Resources Directorate

PEST -Parameter Estimator

RCM- Regional Climate Model

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1.0 INTRODUCTION

Climate change has been one of the most widely debated topics in recent years. With over 97% of the scientific community in consensus with the existence of the phenomenon, the science has gained widespread popularity among the general public and also with the governing bodies of various nations **[1]**.

One of the first publications to quantify this effect is presented in **Figure 1.1**. Also known as the 'hockey stick model', the report stirred a widespread controversy and faced severe criticism but was later independently corroborated by various organizations such as NASA and other European agencies. The findings present a startling trend of average global temperature anomaly over the past several centuries. Remarkably, average global temperature has been constant or has had a gradual cooling trend over the past 900 years. In just the past few decades, anthropogenic climate perturbations in the form of carbon emissions due to exponential growth in fossil fuel usage across the globe has magnified the greenhouse effect on a massive scale which has resulted in increasing average global temperatures by extraordinary amounts.

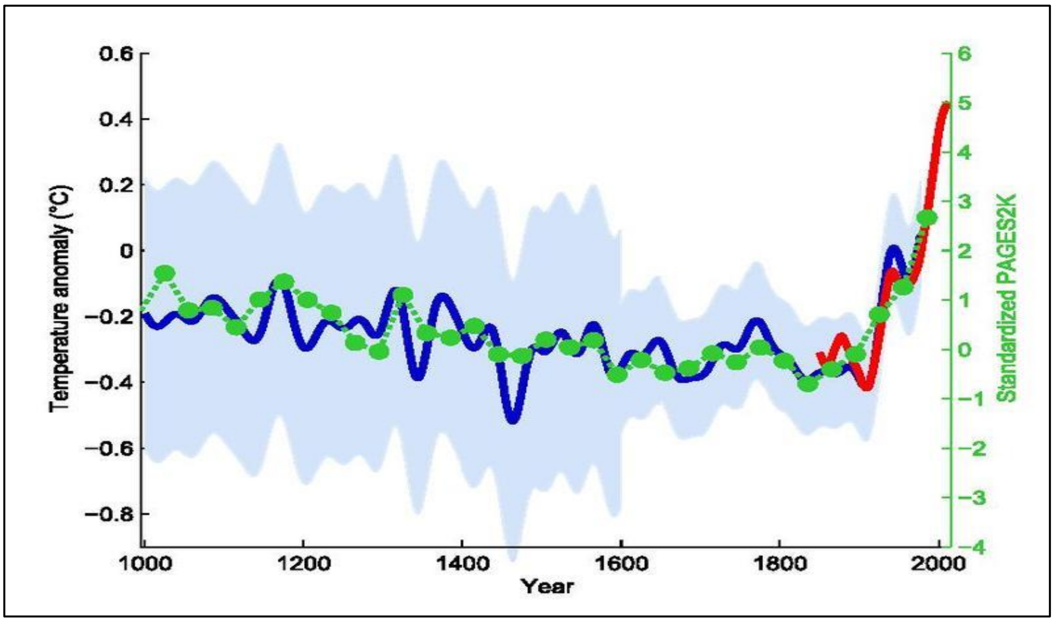


Figure 1.1: 'Hockey stick' global temperature climate model [2]

It is fascinating to note that the upward trend of the curve has an inception at about the same time as the discovery of crude oil by humanity. Since then, increase in population and a craving for sophisticated lifestyle has resulted in consumption of mammoth amounts of fossil fuels resulting in emission of absurd amounts of carbon into the atmosphere. The oceans act as massive carbon sinks and thereby are a stabilizing element in nature. But, we are far exceeding their stabilizing capacity in turn adding excess carbon into the atmosphere annually. As of 2015, the average global temperature anomaly had hit an all-time high of 0.87 ºC **[3]**.

Even minute variations in this parameter can have widespread impacts on global environmental setting. This phenomenon has already had multitudes of noticeable impacts ranging from vanishing coral reefs, more violent and more frequent natural calamities such as floods and typhoons and most importantly, rapid depletion of polar ice caps resulting in rising sea levels. Numerous cities located on coastlines are at grave risk of inundation and cities such as Miami, Florida in the USA and Venice, Italy are already spending millions of dollars annually for protection of their coastline infrastructure. Island nations such as Kiribati and Palau have faced the brunt of climate change leaving these places devastated driving the indigenous communities out of their homes.

The concept of ‘Climate refugees’ has surfaced in recent years and has given rise to numerous conflict scenarios in various regions of the globe. It is quite interesting to note that as the planet warms, we would find the “wet regions getting wetter and the dry regions getting drier” **[4]**. This would exacerbate the spatial and temporal precipitation variability challenges leading to stress on water dependent sectors especially in tropical regions. In contrast, the same phenomenon would pose a very different challenge on wet regions in the form of rapid high volume precipitation events necessitating modifications to flood management and storm water drainage systems and also on other water dependent activities such as hydropower and water supply operations.

From a hydrological standpoint, the most prominent effect of climate change include impact on the amount, timing and the form of precipitation events resulting in adverse impacts such as floods and droughts. These impacts have been observed and well documented in multitudes of research journals. Variation to hydrological regimes can have significant impacts on water dependent socio-economic activities such as water supply, irrigation and hydropower production. It is a well-known fact that the first signs of climate change are predominantly more visible in sensitive ecosystems such as that found in Norway. Hence, this project is aimed at understanding the impacts of climate change on hydrological regimes in select catchments of central Norway. The study incorporates investigation into the changes observed in hydrological regimes over the decades and also an attempt at simulating possible future scenarios to discern possible ramifications of climate change impacts on hydrological features of these catchments which can have profound impact on hydropower production scenario and also on aquatic ecosystems. Emphasis is laid on comprehending climate change impacts on alterations to hydrological regimes through the implementation of a new hydrograph shape analysis technique termed ‘Flow Regime Modification Indices’ on the annual hydrographs. Also, flood frequency analysis employing available historical time series data and also simulations from a hydrological model with input as downscaled climate data from global and regional climate models was carried out.

2.0 STUDY OBJECTIVES AND METHODOLOGY

2.1 OBJECTIVES

1. Selection of study catchments which can accurately represent variability in size, location and hypsography as these parameters greatly influence the hydrological regime features of the catchments such as precipitation pattern, snow melt features, seasonality and also influence flow response characteristics.

2. Obtaining historical observations on discharge, precipitation and temperature data series for these catchments to carry out investigations on flood frequency and changes to hydrological flow regimes to get an insight into the possible impacts of climate change on these features over the observation period.

3. Calibration and evaluation of a hydrological model (HBV model) for the selected catchments to obtain different parameter sets which can give a general good fit for water balance over the observation period and also to arrive at good agreement with the observed flood frequency characteristics and also to perform an uncertainty evaluation of the model outputs.

4. Obtaining global circulation model simulated CORDEX climate data for the catchments over the historical observation period and also future time periods and furthermore, evaluation of the obtained historical data for good agreement with the observed climate data and application of downscaling strategies if deemed necessary and calibration of the hydrological models with downscaled climate data.

5. Forecasting future runoff scenarios employing the downscaled CORDEX climate data to assess the hydrological regime features in a future climatic setting in the identified catchments to juxtapose the findings with the observed historical patterns.

6. Arriving at possible recommendations for key hydro dependent infrastructures such as the hydropower industry and storm water drainage systems to facilitate their preparation towards a different hydrological setting.

2.2 CLIMATE CHANGE IMPACT STUDY METHODOLOGY

Study of impacts of climate change on regional hydrological features is a multidisciplinary task requiring expertise in various areas such as hydrology, water resources engineering, meteorology, numerical modeling and even social Anthropology. This process can be often demanding in terms of data requirements and can also be intuitionally challenging as the processes involve uncertainties at every stage of investigation. The primary stages of investigation are depicted in **Figure 2.1** below.

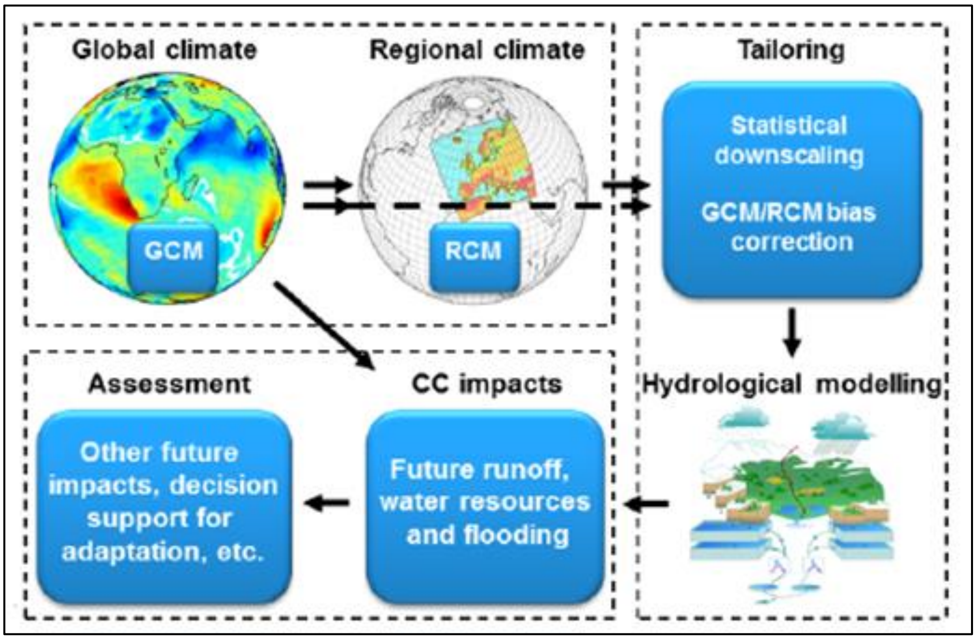


Figure 2.1: Stages of climate change impact investigations [5]

The investigation stages can be broadly classified as:

1. Climate Modelling and Downscaling
2. Hydrological Modelling

Climate change impact assessment often demands simulation of future hydrological scenarios employing a hydrological model based on acquired climatic data from Global and Regional climatic models. The obtained results can be further assessed and presented for decision making purposes in key governmental sectors such as agriculture, food security, disease prevalence, population vulnerability, hydropower generation and domestic water supply **[6]**.

The following sections succinctly present the main aspects and uncertainties involved in the above mentioned study stages to give the reader an overview of the complex nature of climate change investigations.

2.3 CLIMATE MODELLING AND DOWNSCALING

Hydrological investigations of climate change impacts primarily requires good quality data on daily time series of precipitation (Pr) and temperature (Tas) over the study catchments. Ideally, data series covering historical periods and also future emission scenarios would be required. The historical data series would facilitate validation of the calibrated hydrological model with observed data series and would also help in finding and implementation of the right downscaling strategy.

The challenge with hydrological investigation of climate change impacts is that '*Readily available climate change projections are provided at global and continental scales for the end of the 21st century* **[7]**' but, hydrological data series at much finer resolution are required to arrive at results of reasonable accuracy and validity which can facilitate decision making in specific hydro dependent sectors. Global Circulation models (GCMs) are advanced numerical tools describing global climatic scenarios employing vast amount of real-time input data from dedicated satellites orbiting the globe. '*They describe atmospheric, oceanic and biotic processes, interactions and feedbacks*' **[8]**. '*A GCM is composed of many grid cells that represent horizontal and vertical areas on the Earth's surface. In each of the cells, GCMs compute the following: Water Vapor and cloud atmospheric interactions, direct and indirect effects of aerosols on radiation and precipitation, changes in snow cover and sea ice, the storage of heat and moisture, and large-scale transport of heat and water by the atmosphere and oceans* **[9]**'. **Figure 2.2** accurately represents the structure of computation methodology adopted by majority of the GCMs.

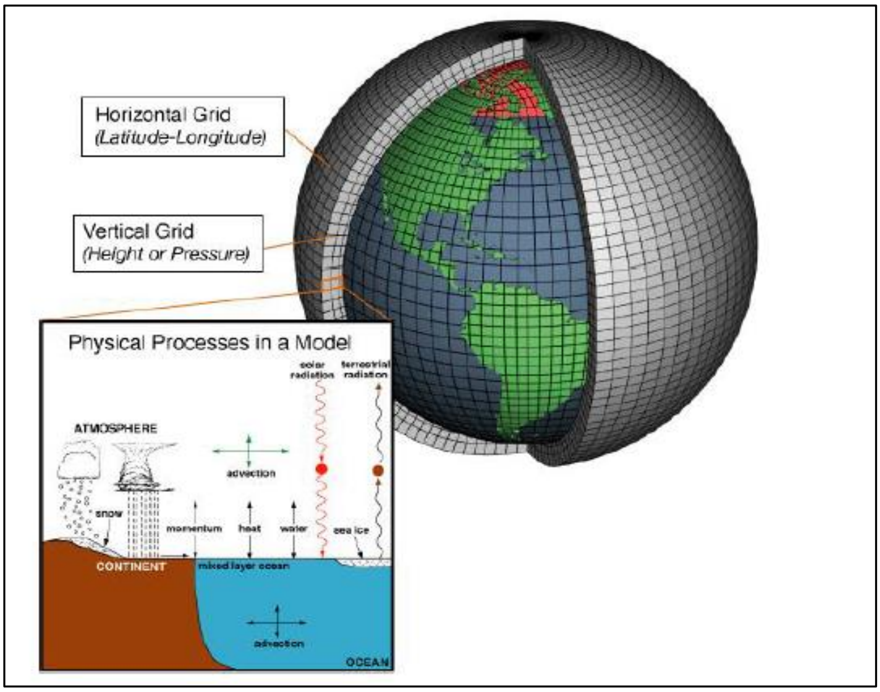


Figure 2.2: Conceptual Structure of a GCM [36]

The major shortcoming with employing GCM data for hydrological investigations is that the spatial resolution of most GCMs is in the order of 100-500 Km **[10]** due to limitations on computing resources and input data. But, hydrological models are calibrated for catchments of much smaller sizes and hence, GCMs can easily overlook fine details of '*landscape features such as mountains, water bodies, infrastructure, land-cover characteristics, and components of the climate system such as convective clouds and coastal breezes having much finer resolution* **[11]**'. These parameters can greatly influence the accuracy and temporal variability of the precipitation and temperature time-series. Furthermore, the data obtained from GCM is usually dependable at temporal scales of monthly means and longer **[12]**.

To address this major issue, a technique known as Downscaling has been developed which helps increase the accuracy of climate data on a finer special resolution. Details into some of the prominent aspects of climate data downscaling are presented in the following section.

2.4 CLIMATE DATA DOWNSCALING TECHNIQUES

The principle objective of climate data downscaling techniques are to obtain coherent and accurate climate data series at a much finer resolution when compared to the data obtained from Global Circulation models(GCMs). '*The derivation of fine-scale climate information is based on the assumption that the local climate is conditioned by interactions between large-scale atmospheric characteristics (Circulation, Temperature, moisture etc.) and local features (Water bodies, mountain ranges, land surface properties etc.)*' **[13]**. **Figure 2.3** shows the downscaling process working principle. It is worth noting that downscaling techniques and especially Dynamic Downscaling techniques attempt at obtaining climate data at sub-grid scales of the driving GCM models which can add accuracy to the climate data obtained by the GCM at a much finer resolution.

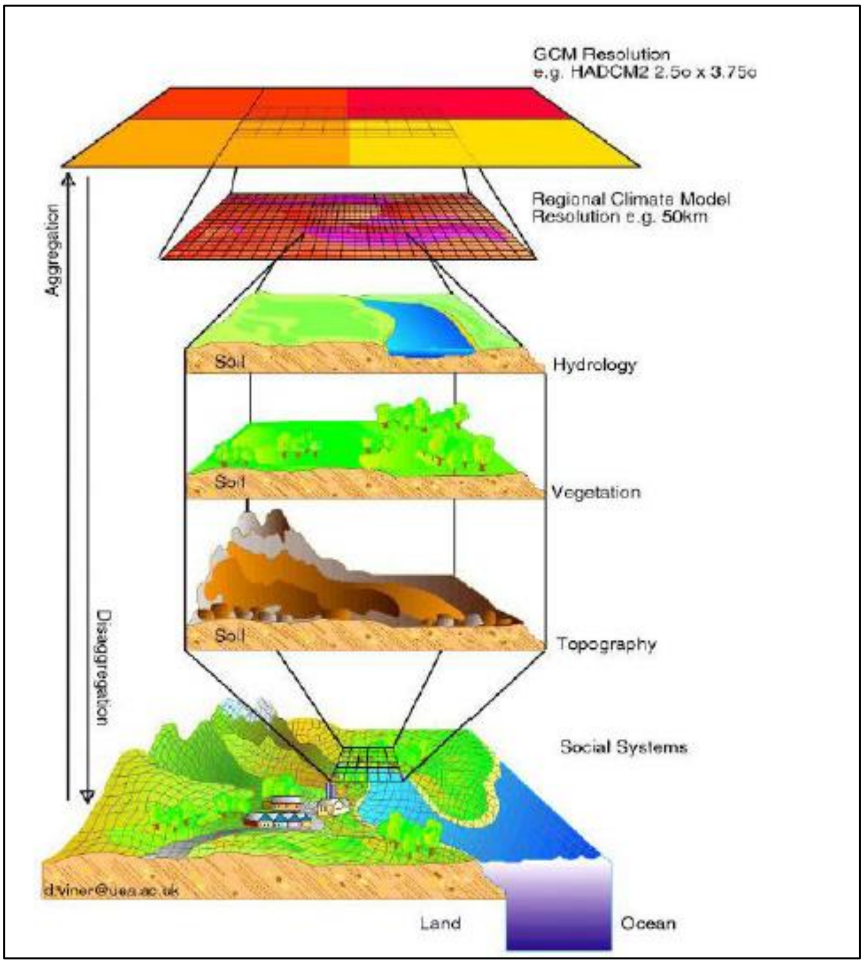


Figure 2.3: Concept of Spatial Downscaling [35]

Downscaling techniques are directed at obtaining better representation of the spatial and temporal aspects as the driving GCMs are usually designed to function at much coarser scales. '*Temporal downscaling refers to the derivation of fine-scale temporal GCM output (eg., Daily rainfall sequence from monthly or seasonal rainfall amounts) and Spatial downscaling refers to the method used to derive finer-resolution spatial climate information from coarser resolution GCM output (eg., 500 kilometers grid cell GCM output to a 20 kilometer resolution)'* **[14]**.

Dynamical downscaling deals with incorporation of a Regional climate model (RCM) on a sub grid level of the parent GCM. That is, RCMs can derive climate data to a finer resolution compared to the driving GCM. '*RCMs take the large scale atmospheric information supplied by the GCM output at the lateral boundaries and incorporate more complex topography, the land-sea contrast, surface heterogeneities, and detailed descriptions of physical processes in order to generate realistic climate information at a spatial resolution of approximately 20-50 kilometer* '**[15]**. Numerous RCMs have been independently developed and are being employed in various fields of scientific research. PRUDENCE (Europe), ENSEMBLES

(Europe), CLARIS (South America), NARCCAP (North America), CORDEX (Africa) are some of the well-established RCMs.

Some of the prominent shortcomings of dynamical downscaling are:

1. Although RCMs can derive climate data to a finer resolution, they are still bound to inherit some systematic biases which needs further processing and corrections and also, the output quality of an RCM is directly linked to the output quality of the driving GCM.
2. Dynamical downscaling can be data intensive and demanding in terms of requirement of computational power.
3. *'Most RCMs also do not accurately simulate extreme precipitation-a systematic bias that can worsen as the resolution is increased. Statistical bias corrections often need to be performed to better match the model output to the observations'* **[37].**

Statistical downscaling aims at deriving an empirical relationship between the GCM output data with the observed climate data at the desired location/station. Hence, statistical downscaling can yield site specific datasets. This method is computationally much more efficient and less data intensive when compared to dynamical downscaling. This method also eliminates the need for a RCM which simplifies the entire process. '*However, this approach relies on the critical assumption that the relationship between present large-scale circulation and local climate remains valid under different forcing conditions of possible future climates'* **(Zorita and Von Storch, 1999).**

The most important feature of statistical downscaling is that it is computationally convenient and is ideal for usage of institutions without access to sophisticated RCM capabilities. Statistical downscaling is broadly divided into three categories:

1. Linear Methods
2. Weather Classifications
3. Weather Generators

Linear methods are intended to arrive at linear relationships with the GCM output data and the observed climate data at the station which can be helpful in elimination of systematic biases. Weather classification deals with establishment of an atmospheric 'State' based on large scale weather patterns. The state predictions of GCMs are correlated with historical observed state to discern numerical relationships. Weather Generators are used to derive temporally finer resolution data (eg. Daily data from monthly series) from coarse GCM data employing statistical analysis.

Dynamical-Statistical downscaling is a hybrid approach incorporating the essence of both the dynamical and statistical downscaling methodologies. The GCM output data series is first processed to a spatially finer resolution employing a validated RCM. Further, the RCM output data is processed employing statistical tools to further eliminate systematic biases. This method is often known to give satisfactory results with reduced computational requirements.

Currently, there are no standardized international guidelines or national government specifications which provide researchers with assistance to choose the right models to obtain data sets and to choose ideal downscaling techniques.

2.5 UNCERTAINTIES INVOLVED IN CLIMATE MODELING AND DOWNSCALING

There are four main sources of uncertainty in climate projection:

1. *Uncertainty in future levels of anthropogenic emissions and natural forcings (eg., Volcanic eruptions)*
2. *Uncertainty linked to imperfect model representation of climate processes*
3. *Imperfect knowledge of current climate conditions that serve as a starting point for projections*
4. *Difficulty in representing interannual and decadal variability in long-term projections* **[16]**

Complex numerical models such as the Global Circulation models are inevitably based on some assumptions and simplifications at various stages of conceptualization and computation. These assumptions add inherent biases and uncertainties to the model output. Albeit most of the processes represented in GCMs are well documented, it is unrealistic to represent every fine details in the computations due to limitations on data availability and also due to limitations in computational capabilities. RCMs mitigate these uncertainties to a certain extent but there will always be uncertainties present in terms of model representation of global climatic processes and regional details such as orography and land use changes.

One of the most important aspects of climate modeling which imparts uncertainty to model output is the representation of current and future state of carbon emissions on a global scale. Qualitative and Quantitative representation of current climatic conditions and prediction of possible future scenarios are highly dependent upon multitudes of socio-technical scenarios such as national economy, development of green technology and governing policies. Hence, it is always advised to consider multiple possible scenarios as this can give a sense of variability in model output which can greatly facilitate researchers and policy makers in the process of decision making. Almost all of the GCMs and RCMs are designed to foresee multiple emission scenarios and an ensemble analysis would be highly informative.

It is important to understand that uncertainties are vital in scientific research as it gives a picture of possible spectrum of future trends which can provide valuable input to draw preparation plans especially for sectors such as hydropower industry and storm water drainage systems. Hence, multi-model and multi-emission scenario study would be idyllic.

2.6 HYDROLOGICAL MODELING

A Hydrological model may be defined as a mathematical tool employed to obtain a quantitative description of the numerous complex hydrological phenomenon taking place within a specified catchment area leading to runoff generation at an outlet location. Most if not all hydrological models work on the principle of the "System Concept". A system may be defined as a set of interconnected parts, the combination of which forms a whole.

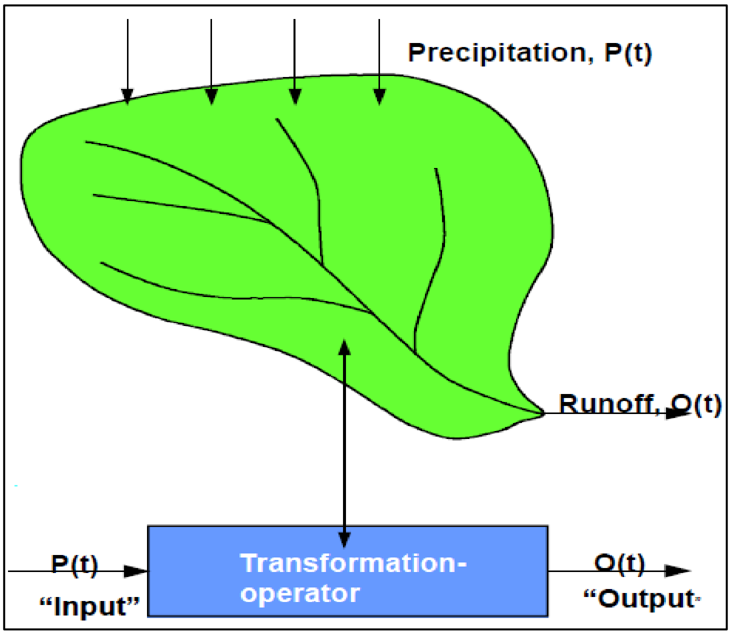


Figure 2.4: Illustration of the system concept of a hydrological model [17]

'*A Hydrological system can be defined as a structure or volume in space, surrounded by a boundary that accepts water and other inputs, operates on them internally and produces an output* **[18]**'.

Various hydrological processes such as precipitation, evaporation, snow melt and infiltration are represented through mathematical equations aimed at producing accurate runoff generation characteristics of the defined catchment.

Hydrological models are predominantly classified based on three major criteria:

1. *Spatial Variation (Lumped or distributed)*
2. *Randomness (Deterministic or Stochastic)*
3. *Time Variability (Time-dependent or Time-Independent)* **[19].**

Lumped models consider the entire catchment as a single integral entity and all the process computations are performed employing simplified mathematical equations considering them as uniformly distributed over the predefined catchment boundary. This is a simplified approach which provides adequately accurate results for most practical applications such as flood forecasting, reservoir routing and so on.

However, oversimplification of these features might render the model ineffective for specialized research applications such as pollutant transport studies, studies related to movement of storms within the catchment boundary and study of localized floods. These research areas demand a model with much finer special resolution.

Distributed models were developed to address this longstanding shortcoming of lumped models. The catchment is further subdivided into uniform grids and detailed computations of complex hydrological phenomenon are carried out within each grid cell. A form of flow routing is implemented within the catchment to obtain the flow path from one grid cell to another and the cumulative runoff is obtained at the outlet cell.

The feature of randomness adds the attribute of considering the probability of occurrence of an event in time. **Deterministic models** are non-probabilistic in their approach that a particular set of inputs would yield the same outputs irrespective of when the computation was carried out. But, **stochastic models** consider a form of probability distribution within the model to discern the most probable output at certain given point in time.

Variability in time refers to the condition if the same processes take place in every location of the catchment. For instance, in distributed models, a grid cell situated at a higher elevation might be receiving precipitation whereas a grid cell located at a lower location might receive no rainfall at this particular instance. This is due to the fact that even meteorological data is fed to the model as distributed data. As can be deduced, lumped models cannot have time variability as a feature since this is exclusive to distributed models.

2.7 The HBV Model

The HBV model (Hydrologiska Byrans avdeling for Vattenbalans) was first conceptualized by Dr Sten Bergstrorm at the Swedish Meteorological and Hydrological Institute (SMHI). It is a linear deterministic lumped model and is considered the standard hydrological model in various countries such as Norway and Sweden for multitudes of commercial and academic applications.

The most attractive features of the HBV model are its attributes of simplicity and user-friendliness and yet its ability of efficiently reproducing complex hydrological process states within the calibrated catchment to a high degree of accuracy.

Some salient features of the HBV model are:

1. The HBV model is a linear hydrological model with an exception of the soil moisture routine. That is, majority of the equations employed are linear in nature.

2. It is a lumped model which signifies that the entire defined catchment is considered as a single entity with all the hydrological processes considered to be uniformly distributed over the catchment area with the exception of the snow routine which is distributed.
3. *'The HBV model is a conceptual model, meaning that it is based on some considerations of the physical structure and processes in the catchment*'.

4. *'It is a deterministic model meaning that two equal sets of inputs will always yield the same output, if run through the model from identical start conditions and with identical model parameters***'**.

The major applications of the HBV model are as follows:

1. *Runoff forecasting*
2. *Flood forecasting*
3. *Generation of runoff series from meteorological data*
4. *To fill in missing runoff observations* **[20].**

2.8 MODEL STRUCTURE OF THE HBV MODEL

The HBV model comprises of four major routines and each routine is designated at handling a particular hydrological process computation and the output generated by a routine is passed on to the subsequent routine in the hierarchy for further processing and this process culminates in the generation of cumulative runoff from the model. Each of the routines and also description of the input data requirements are briefly presented in this discussion. Reference is made to the book on 'Hydrology'-Book number seven in the Hydropower Development series for detailed description of the HBV model within the chapter of 'Hydrological Modeling'.

The primary input data requirements for the HBV model include:

1. Catchment characteristics.
2. Precipitation, Air-Temperature time-series measured at uniformly distributed locations within the catchment and Discharge time series measured at the catchment outlet.

The various catchment specific features such as the Catchment area, Hypsographical distribution, Lake Area percentage and so on need to be provided as inputs to the model. These can be conveniently obtained by various mapping services such as that offered by the NVE or can also be the result of a short field survey.

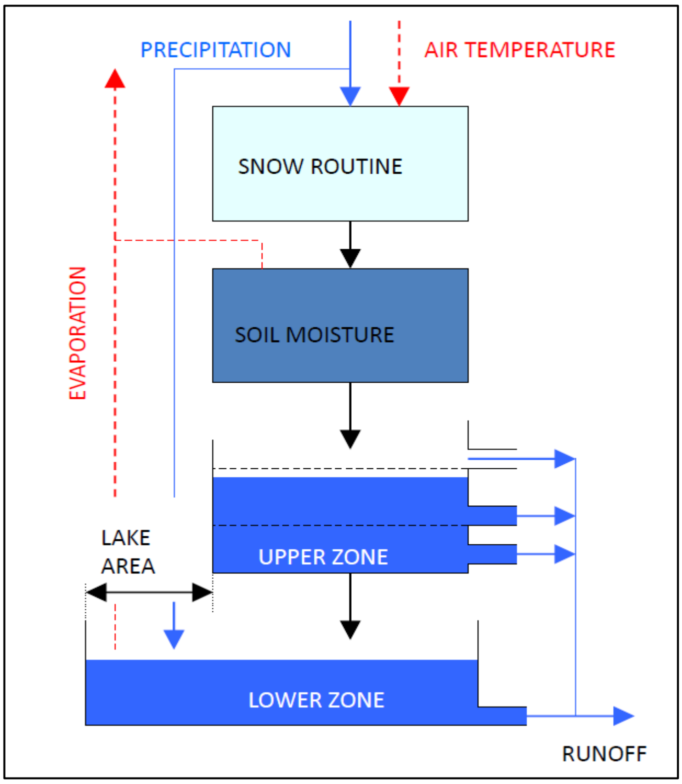


Figure 2.5: Illustration of the structure of the HBV model [21]

Daily time-series of Precipitation, Temperature and Runoff from the catchment need to be obtained for the purpose of calibration and validation of the effectiveness of the hydrological model outputs. They need to be of the same time span and the obtained data needs to undergo an evaluation to discern the validity of the data (That is, to evaluate the data for gaps, errors or unphysical values and trends). Further, the obtained Precipitation and Temperature data needs to be corrected for errors and biases and also, point measurements of Precipitation and Temperature need to be converted to area values as per the following equations:

$$P_{area} = \mathbf{P_{obs}} * RCORR * SCORR * (1 + PGRAD * (H_{area} - H_{obs})/100) \ldots\ldots\ldots\ldots\ldots(1)$$

$$T_{area} = \mathbf{T_{obs}} + TCGRAD * (H_{area} - H_{obs})/100) \quad \text{(Days without Precipitation)} \ldots\ldots\ldots(2)$$

$$T_{area} = \mathbf{T_{obs}} + TPGRAD * (H_{area} - H_{obs})/100) \quad \text{(Days with Precipitation)} \ldots\ldots\ldots\ldots(3)$$

Where,

RCORR, SCORR = precipitation correction factors for rain, snow.

PGRAD = precipitation increase coefficient with elevation [%/100 meter].

TCGRAD = temperature lapse rate with elevation on clear days [˚C/100 meter].

TPGRAD = temperature lapse rate with elevation on cloudy days [˚C/100 meter].

H_{area}=Average elevation of the catchment

H_{obs}=Elevation of the observation stations

Since the Precipitation and Temperature gauging stations can be located at a different elevation compared to the average elevation of the catchment, the data needs to be adjusted as the Temperature and Precipitation have a strong tendency to vary with altitude. The precipitation usually has an increasing trend with altitude in Norway and the term PGRAD is designated to account for this variation. The temperature generally has a reducing trend with elevation and the terms TPGRAD and TCGRAD are employed to adjust for this trend depending on the climatic condition of the day as the term tends to vary with cloud cover. In addition, the monthly potential evapotranspiration values need to be provided as an input which is a function of seasonal temperature. This can be obtained by employing standard equations such as the Penman formula or can also be obtained from previous literature for the region.

Also, the catch efficiency of the precipitation gauging station plays a major role in obtaining accurate precipitation values for the day at the gauging location. The term RCORR is adopted for this purpose and the value fir this parameter is higher for snow precipitation when compared to rain as snow catch efficiency is generally lower and is strongly influenced by climatic conditions such as wind speed.

2.9 THE SNOW ROUTINE

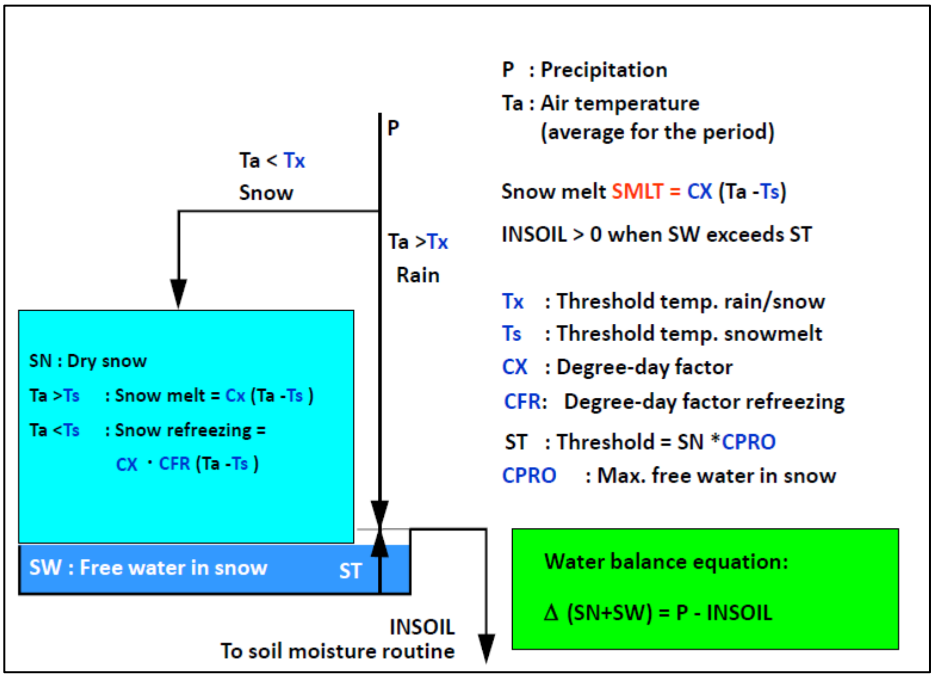


Figure 2.6: Illustration of the structure of the snow routine in the HBV model [22]

Snow hydrology is predominantly important for the generation of spring floods resulting from snow melt. Since most of the runoff in cold weather countries arrives as spring flood, snow hydrology is well defined and incorporated within the HBV model.

As previously stated, the HBV model is a lumped model that is, the entire catchment is considered a single integral unit. But, the snow routine within the HBV model is distributed. It is subdivided into various elevation zones. This is to account for the elevation dependent features of snow hydrology such as increasing precipitation with increasing altitude and decreasing snow melt with increasing altitude due to lower air temperatures. Provision is also made to accommodate for uneven distribution of snow within each elevation zone.

Depending upon the set threshold temperature and the air temperature on that particular day, the model receives either snow or rain as input precipitation. Snow precipitation enters the snow routine and rain precipitation is passed onto the soil moisture routine bypassing the snow routine. Process computations are carried out within each elevation of the snow routine in accordance with the equations presented in **Figure 2.6**. This is to quantify the process of interconversion of dry snow to liquid water and vice-versa. The resultant output from the snow routine is passed onto the soil moisture routine.

2.10 THE SOIL MOISTURE ROUTINE

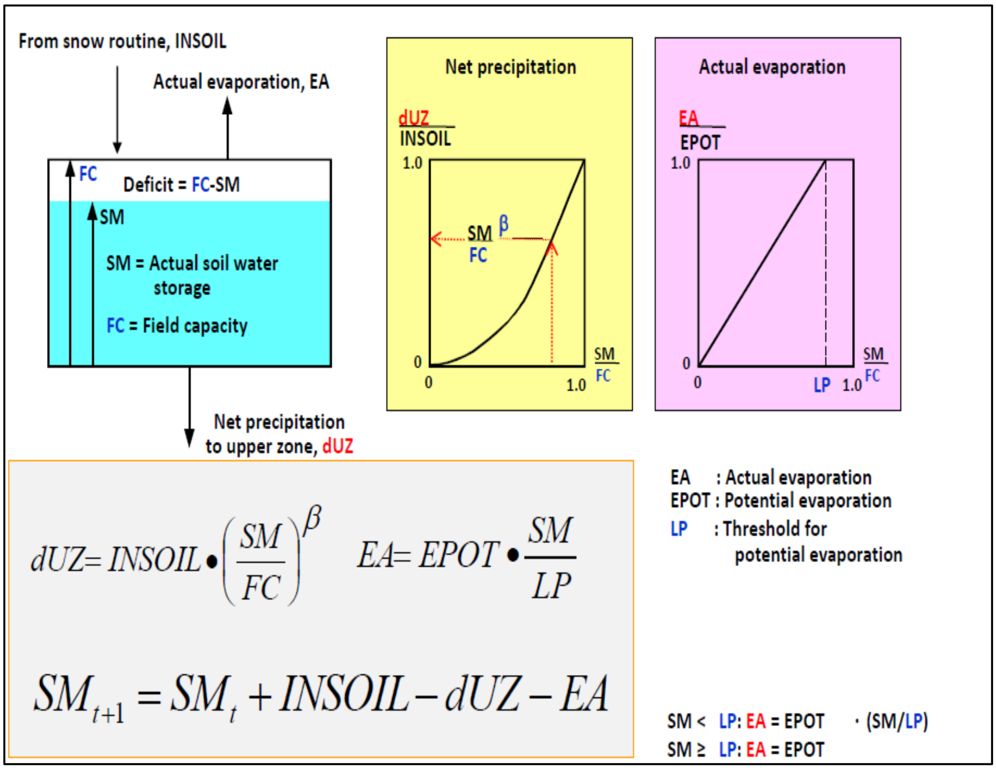


Figure 2.7: Illustration of the structure of the soil moisture routine in the HBV model [23]

The soil moisture routine receives precipitation as either the snow routine output or as direct precipitation depending upon the set threshold temperature and the air temperature on that particular day. The incoming precipitation is subdivided into soil storage (as soil moisture) and outflow to the upper zone (duZ) based on two equations as presented in the figure 8. It was stated earlier that the HBV model is linear with the exception of the soil moisture routine.

This is due to the fact that β takes up values other than 1 (generally 2 or 3) which makes this routine non-linear. Actual evapotranspiration is also removed from this routine as a linear function of the soil storage.

2.11 THE FLOW RESPONSE ROUTINES

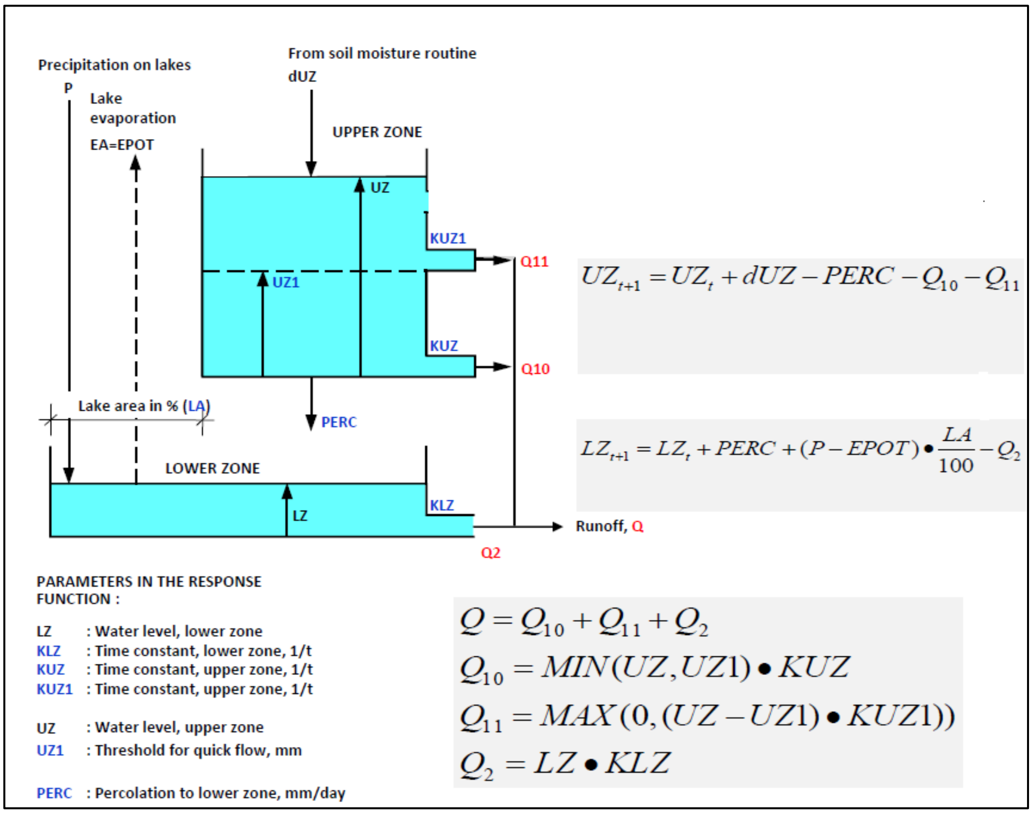


Figure 2.8: Illustration of the structure of the Flow Response routines in the HBV model [24]

The two linear tanks handle the flow response characteristics of the model. They are termed the upper tank and the lower tank. The upper tank deals with features contributing to the 'quick response' in the generally observed hydrograph patterns. These include overland flow and also ground water through superficial flow channels. The lower tank deals with the features contributing to slow flow response (Base Flow) such as lakes and deep ground water flow.

The upper zone receives input from the soil moisture routine (duZ). The process computations are described in **Figure 2.8**. The resulting output from the various outlets of the upper and lower tanks are calibrated through iterative adjustments of parameters such as KUZ1, KUZ2 and KLZ to accurately reproduce the observed hydrograph. An important thing to note is that the evapotranspiration computed from the lower zone is the Potential Evapotranspiration or the Lake Evaporation.

2.12 CALIBRATION OF THE HBV MODEL

The various hydrological routines represented in the HBV model are governed by simplified mathematical equations. These equations comprise of numerous process parameters and constants as described in the previous discussions. These parameters can be broadly classified as:

1. Confined Parameters
2. Semi-Confined Parameters
3. Free Parameters

Confined parameters are inherent catchment characteristics such as the catchment Area, Hypsographical distribution, Lake Area percentage and so on which are constants for a particular defined catchment. These parameters need to be provided as an input to the model. These parameters can be generally obtained from various mapping services or through field surveys.

Semi-Confined parameters are regional hydro-meteorological variables of the catchment under considerations. These include parameters such as the precipitation gradient (PGRAD), temperature gradient (TPGRAD and TCGRAD), Snow distribution parameters, Potential Evapotranspiration and so on. These parameters are usually obtained from literature review of previous investigations within the catchment or may need to be obtained through field measurements.

Free parameters are of particular interest in this section as they are the result of calibration within the HBV model. Process Parameters and coefficients such as Field Capacity in the soil moisture routine, Degree-Day factor in the snow routine and the various coefficients within the Flow-Response routine belong to this category. These parameters need not be provided as definitive inputs but are calibrated within the model to obtain optimal efficiency.

As can be inferred from the above discussion, calibration may be defined as the process of arriving at the most apt set of free parameters to obtain the best overall fit for the observed and simulated discharges. Within the HBV model, the efficiency is quantified using the Nash-Sutcliffe efficiency criteria:

$$R^2 = 1 - \frac{\sum (Q_S - Q_o)^2}{\sum (Q_o - \overline{Q})^2} \qquad \text{.................................(4)}$$

Where, $\mathbf{Q_S}$=Simulated discharge (m^3/s)

$\mathbf{Q_O}$=Observed discharge (m^3/s)

$\overline{\mathbf{Q}}$=Mean of observed discharges (m^3/s)

The R^2 value can vary from -∞ to +1 and the value +1 indicates perfect fit between the observed and the simulated discharges and a lower value signifies discrepancies between the model output and the observed discharge time-series.

The calibration process is subdivided into manual and automatic calibrations. Manual calibration is considered obsolete due to its numerous disadvantages such as inability of handling large amount of data, excessive time consumption and reduced efficiency due to manual errors and limited capabilities to achieve the best possible parameter set.

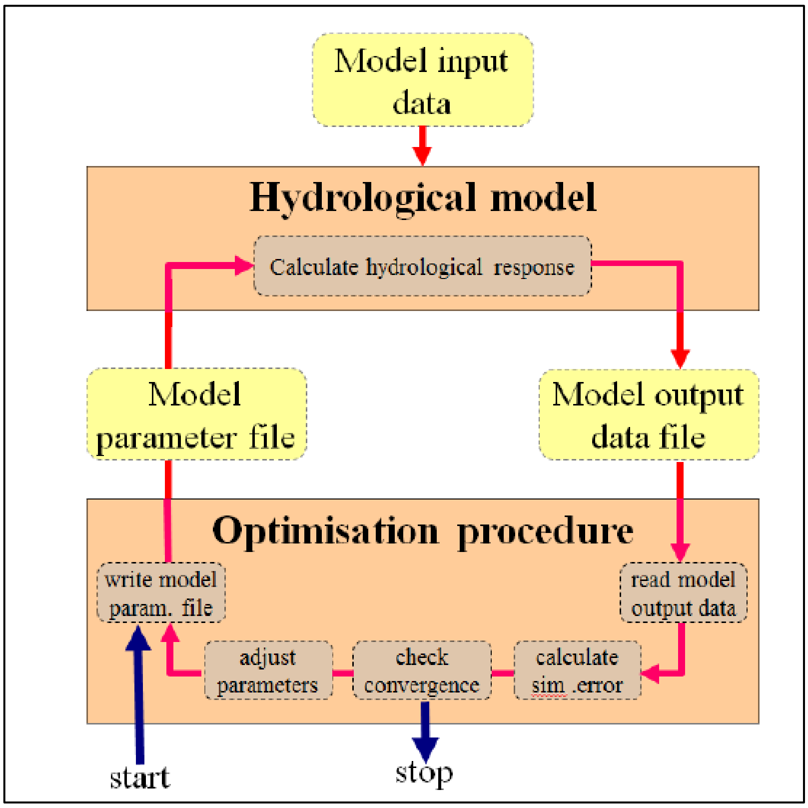


Figure 2.9: Structure of the calibration loop within the HBV model [25]

The process of automatic calibration within the HBV model is described in the **Figure 2.9** above. '*Basically, hydrological model calibration is a trial and error procedure, where free parameters are chosen, model simulation performed and the computed and observed runoff compared* **[26]**'. The fundamental objective of the calibration process is to carry out large number of iterative computations to arrive at the best possible model efficiency or in other words, to find the highest point on the response surface in the parameter space.

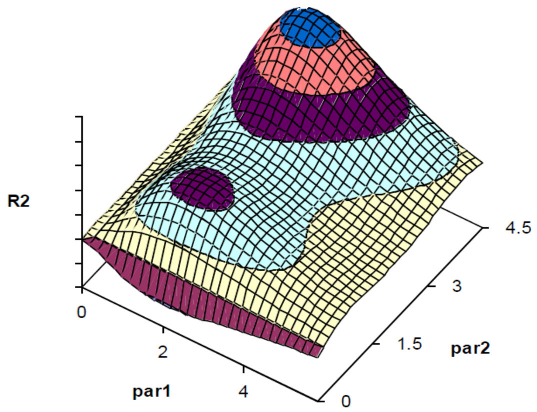


Figure 2.10: Parameter space and response surface in the HBV calibration process [27]

As can be inferred from the above depicted **Figure 2.10**, parameter space is the three dimensional space made up by the two parameters under consideration as the X and the Y axes and the model efficiency criteria as the Z axis.

Various methods of search are available to accomplish this task such as the direct search method, gradient search method and also probabilistic search algorithms. The PEST (Parameter Estimator) model optimizer is the most commonly employed tool for calibration of numerical models. It works on the principle of Gauss-Marquardt-Levenberg algorithm which is a robust gradient search method.

2.13 UNCERTAINTY EVALUATION AND THE CONCEPT OF EQUIFINALITY

The fundamental drawback of the automatic calibration process described earlier is that the calibration might end up at local maxima on the response surface as the termination point is strongly influenced by the set initial conditions.

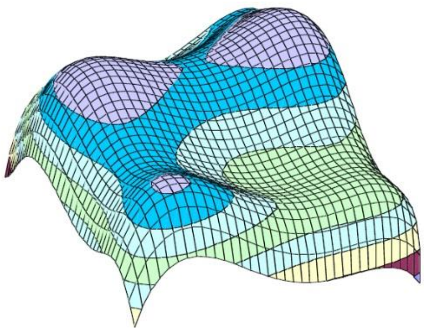


Figure 2.11: Response surface with multiple maxima [28]

Hence, an uncertainty always exists regarding the obtained evaluation from the PEST optimization loop. And also, two or more parameter sets can produce the same model efficiency within the HBV optimization loop and this effect is known as Equifinality or multimodality. So, it is always advised to carry out a Monte-Carlo type of calibration to obtain multiple parameter sets to expand the uncertainty horizon by evaluating the model performance under different parameterization conditions.

3.0 CATCHMENT CHARACTERISTICS, DATA RETRIEVAL AND EVALUATION

3.1 CATCHMENT CHARACTERISTICS

The process of selection of study catchments is perhaps the most important stage of any investigation. The chosen catchments should provide a sufficiently broad sample space in order for the results of the investigation to be of value. That is, the chosen catchments should incorporate features such that any observable trends in a certain parameter across the selected catchments could be termed a definitive result rather than a coincidence. Hence, variability in catchment characteristics play a major role in validating the project outcomes.

The most prominent features to be considered are:

1. **Variability in catchment size:** Catchment size can have significant influence over hydrological features such as flow response of the catchment to incoming precipitation and snowmelt outflow. Smaller catchments tend to produce rapid runoff generation patterns when compared to a larger catchment. Also, since the flow path length of the stream flow tends to be longer in a larger catchment, hydrological features such as the time of concentration (T_C) and lag in reaching peak discharges tend to be longer when compared to a smaller catchment. Furthermore, presence of flow dampening features such as large lakes can have significant impact on flow response in smaller catchments when compared to larger catchments. Hence, the chosen catchments should represent large scale variation in size to discern observable trends incorporating all the above mentioned features.

2. **Variability in Catchment Location:** The choice of location of the catchment plays a prominent role in obtaining and validating trends in hydrological features. For instance, a catchment located on the coastline would have a significantly different climatic domain representing strong variability in the amount and form of precipitation, trends in air temperature, evapotranspiration, specific runoff and even vegetation when compared to an inland catchment.

3. **Variability in catchment hypsography:** The hypsography of the study catchment plays a dominant role in controlling key factors responsible for the generation of runoff such as the amount of snow precipitation, snow accumulation and depletion trends. Since the upper elevation zones of the catchment tends to receive much larger quantity of snow precipitation, in turn leading to higher spring floods, catchment hypsography plays a prominent role in the process of classification of catchments based on their hydrological regime. Furthermore, vegetation is also highly dependent upon hypsography as the lower elevation zones tend to be much more densely vegetated compared to elevation zones further up in the catchment.

The study catchments for this research project were chosen in accordance with the preceding discussions. Catchments of central Norway such as Hagabru, Krinsvatn and Svartjonbekken were chosen as these catchments were ideally poised to demonstrate variation in catchment size, location and also hypsographic distribution.

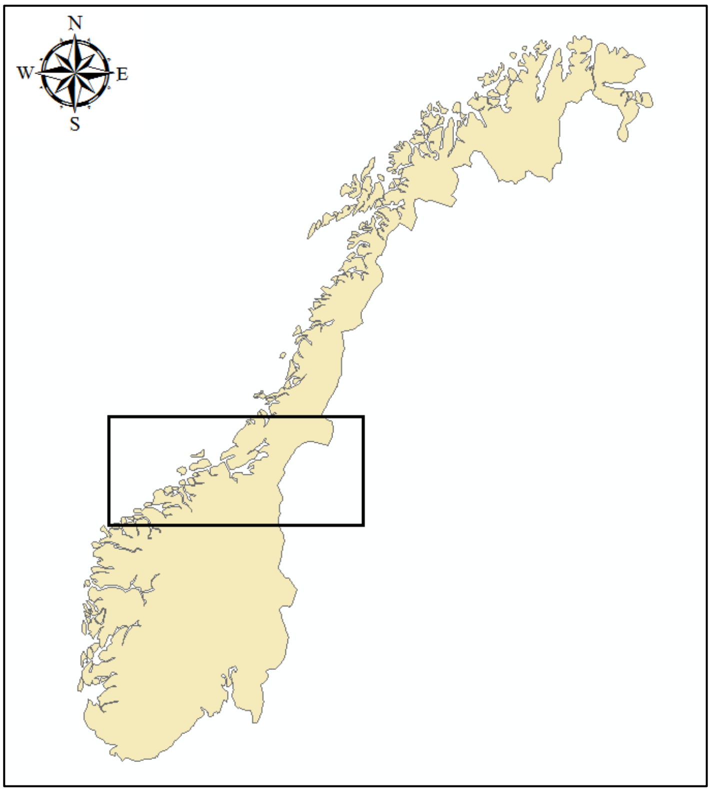


Figure 3.1: Study catchment location within central Norway

Hagabru was the largest catchment chosen (3060 Km^2) while Svartjonbekken (3.7 Km^2) was the smallest chosen catchment and Krinsvatn (206.4 Km^2) represents a catchment of intermediate size. Further, Krinsvatn can be classified as a coastal catchment whereas Hagabru is a catchment located inland and Svartjonbekken is located in an intermediate location. Finally, Krinsvatn is a low lying catchment with hypsographical distribution between the elevations of 87 m.a.s.l and 627 m.a.s.l whereas the hypsography of Hagabru catchment is concentrated at a much higher altitudes (up to 1325 m.a.s.l) while Svartjonbekken is situated at an intermediate elevation range.

Details regarding the catchment characteristics, retrieval and evaluation of data for hydrological model operation for the respective catchments have been discussed in the following sections.

3.1.1 HAGABRU CATCHMENT CHARACTERISTICS

Hagabru is a catchment of central Norway located between the coordinates of 62° 55' 53.94" N 10° 00' 10.91" E, 62° 49' 18.91" N 11°36'22.90"E, 62°55'04.36"N 11°10'27.92"E and 62°43'28.60"N 10°59'57.56"E. With a catchment area of 3060 Km^2, Hagabru was the largest of the chosen catchments in size. It is an inland catchment with a moderately steep topography. The governing hydrological features of the catchment are depicted in **Figure 3.2** and the hypsographical distribution of the catchment is presented in **Figure 3.3**. As can be observed, the catchment is void of significant dampening agents such as lakes or natural reservoirs and any influence of regulations on discharge were ruled out. Also, being an inland catchment, Hagabru receives comparable amounts of winter and summer precipitations.

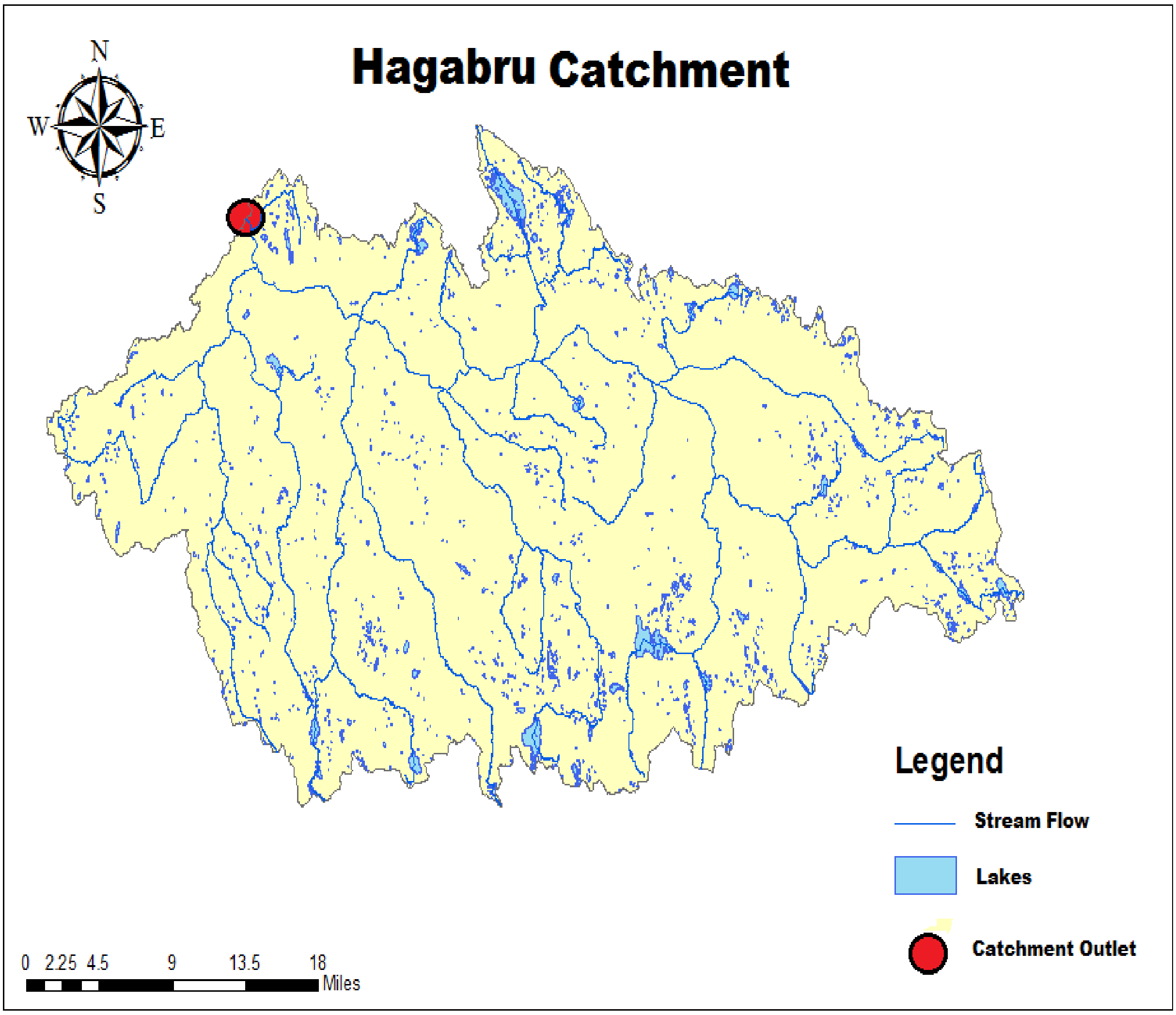


Figure 3.2: Major hydrological features of Hagabru catchment

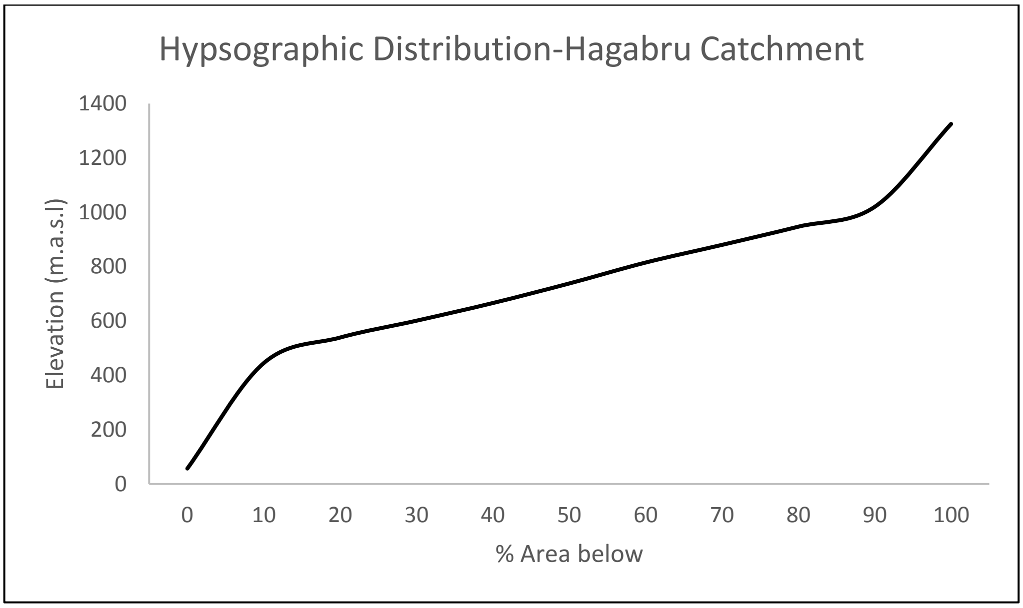


Figure 3.3: Hypsographical distribution of Hagabru catchment

The most prominent catchment features and climatic parameters are presented in **Table 3.1** and reference is made to **Appendix 1** for further details into the catchment characteristics.

Table 3.1: Key catchment characteristics of Hagabru catchment

Catchment Area	3059.7 Km^2
Specific Runoff	27.1 l/(s*Km^2)
Annual Precipitation	920 mm
Annual Winter Precipitation	505 mm
Annual summer Precipitation	416 mm
Lake Area %	0 %
Annual average air Temperature	0.6°
Summer Average air Temperature	6.9°
Winter Average air Temperature	-3.9°

3.1.2 KRINSVATN CATCHMENT CHARACTERISTICS

Krinsvatn is a catchment of central Norway located between the coordinates of 63° 48' 12.48" N 10° 13' 37.14" E, 63° 53' 38.4" N 10°38'47.73"E, 63°34'45.82"N 10°10'38.45"E and 63°53'37.17"N 10°16'34.94"E. With a catchment area of 206.4 Km^2, Krinsvatn can be classified as a catchment of intermediate size. It is a catchment located on the west coastline of Norway with a moderately steep topography. The governing hydrological features of the catchment are depicted in **Figure 3.4** and the hypsographical distribution of the catchment is presented in **Figure 3.5**. The Lake area percentage for Krinsvatn catchment is higher in comparison with Hagabru catchment hinting at possible dampening influences but existence of flow regulation infrastructure was ruled out. Also, Krinsvatn being a coastal catchment receives most of its incoming precipitation during the winter season as snow precipitation. This could be very significant for studying the impacts of climate change in a future climate setting as a warmer atmosphere can have significant impacts on snowpack features for Krinsvatn catchment leading to significant impacts on hydrology of Krinsvatn.

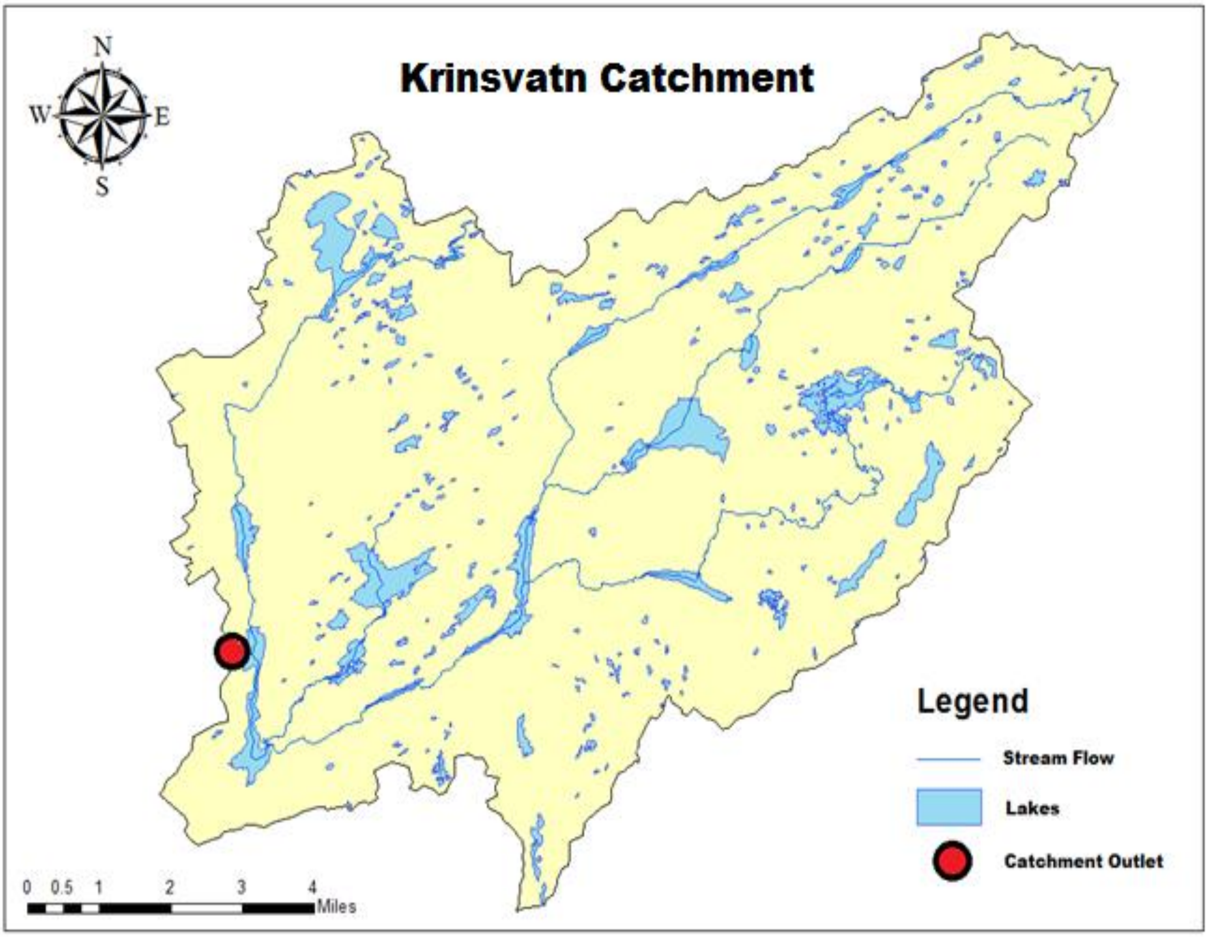


Figure 3.4: Major hydrological features of Krinsvatn catchment

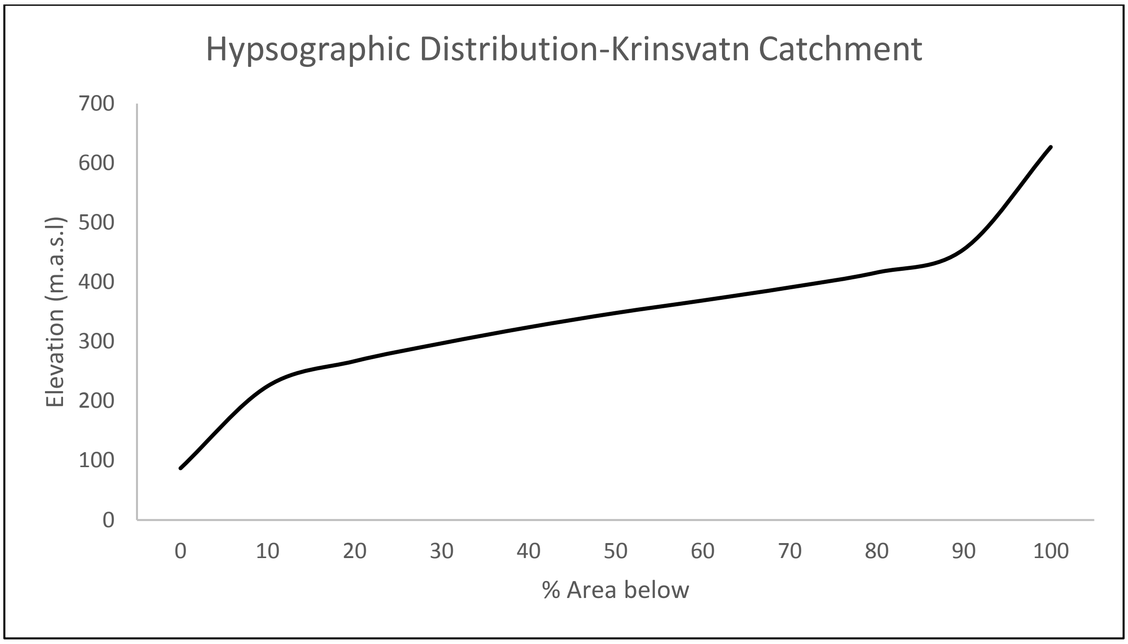


Figure 3.5: Hypsographical distribution of Krinsvatn catchment

The most prominent catchment features and climatic parameters are presented in **Table 3.2** and reference is made to **Appendix 2** for further details into the catchment characteristics.

Table 3.2: Key catchment characteristics of Krinsvatn catchment

Catchment Area	206.4 Km^2
Specific Runoff	63.8 l/(s*Km^2)
Annual Precipitation	1783 mm
Annual Winter Precipitation	1171 mm
Annual Summer Precipitation	612 mm
Lake Area %	1.1 %
Annual average air Temperature	4.1°
Summer Average air Temperature	9.5°
Winter Average air Temperature	0.3°

3.1.3 SVARTJONBEKKEN CATCHMENT CHARACTERISTICS

Svartjonbekken is a catchment of central Norway located between the coordinates of 63° 17' 52.81" N 10° 38' 52.85" E, 63° 19' 13.4" N 10°38'58.22"E, 63°18'46.58"N 10°40'12.79"E and 63°18'41.11"N 10°38'32.70"E. With a catchment area of 3.7 Km^2, Svartjonbekken was chosen to represent catchments of small sizes. It is a catchment located at an intermediate location between Krinsvatn and Hagabru catchments and hence can be classified as an inland catchment. The governing hydrological features of the catchment are depicted in **Figure 3.6** and the hypsographical distribution of the catchment is presented in **Figure 3.7**. Svartjonbekken is a noted catchment for its rapid runoff generation feature due to its small size and this catchment could be particularly interesting to study the impacts of climate change on flood frequency in a future climate setting.

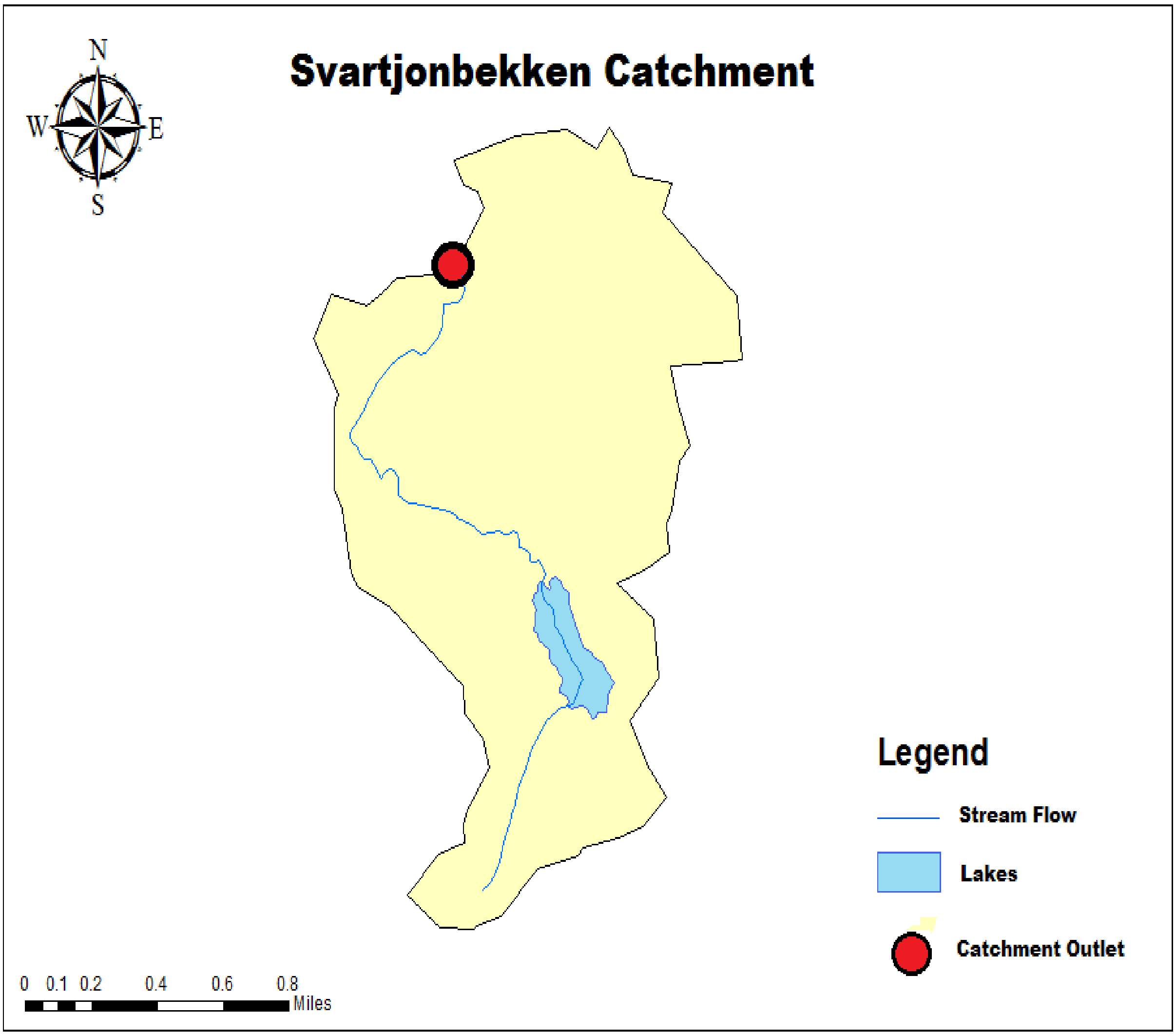


Figure 3.6: Major hydrological features of Svartjonbekken catchment

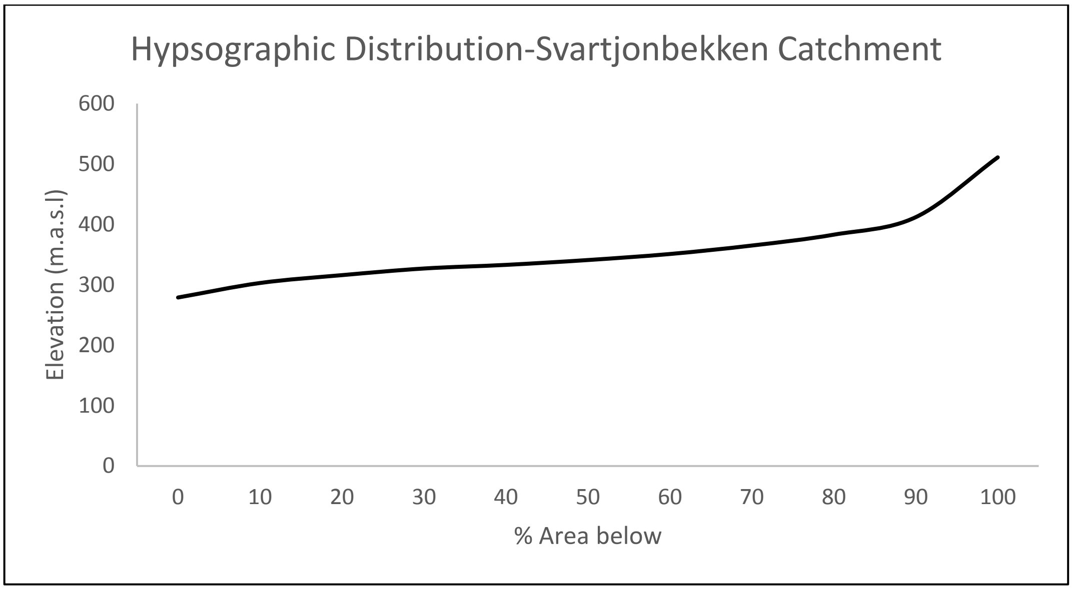


Figure 3.7: Hypsographical distribution of Svartjonbekken catchment

The most prominent catchment features and climatic parameters are presented in **Table 3.3** and reference is made to **Appendix 3** for further details into the catchment characteristics.

Table 3.3: Key catchment characteristics of Svartjonbekken catchment

Catchment Area	3.7 Km^2
Specific Runoff	27.8 l/(s*Km^2)
Annual Precipitation	999 mm
Annual Winter Precipitation	565 mm
Annual Summer Precipitation	434 mm
Lake Area %	0.7 %
Annual average air Temperature	3.5°
Summer Average air Temperature	9.6°
Winter Average air Temperature	-0.9°

3.1.4 COMPARATIVE STUDY OF CATCHMENT CHARACTERISTICS

Some of the most important catchment characteristics as far as this research project is concerned are briefly discussed in the following points:

1. The variability in size of catchments has been represented to a great extent with the choice of catchment size varying from 3.7 Km^2 to 3060 Km^2.
2. The hypsographical features of the catchments are also disparate with Krinsvatn representing a low lying catchment and Hagabru representing a catchment with broad hypsographical distribution while Svartjonbekken can be considered to be situated at an intermediate elevation zone.
3. It is clearly evident from the previously presented catchment features that location plays a prominent role in discerning key climatic parameters. Since Krinsvatn is a coastal catchment, it receives much higher amounts of annual precipitation due to a warmer climate (As a result of energy transfer from the Gulf currents) whereas the amount of annual precipitation decreases progressively moving inland due to much colder temperatures.
4. The above mentioned effect also influences the specific runoff of the catchments with Krisvatn having the highest value due to its coastal climatic setting.
5. Finally, the location also influences the form of precipitation as it can be inferred from the presented data that Krinsvatn receives almost twice the amount of summer precipitation (Rain) as winter precipitation (Snow) whereas Svartjonbekken and Hagabru receive comparable amounts of winter and summer precipitation.

3.2 DATA RETRIEVAL AND EVALUATION

The fundamental input requirements for the purpose of HBV calibration includes:

1. Observed historical discharge (Runoff) time series
2. Observed historical precipitation and temperature time series
3. Global circulation model simulated precipitation and temperature time series over the historical observation time period
4. Global climate model simulated precipitation and temperature time series over a future time period based on an assumed emission scenario.

The observed historical discharge (Runoff) time series for the catchments were obtained from the NVE Hydra database. Runoff observations were available for Hagabru catchment from 1908-2015, from 1916-2015 for Krinsvatn catchment and from 1973-2015 for Svartjonbekken catchment. It is worth noting that the obtained records were of natural stream flow and effect of regulation was ruled out. Availability of such a long time series was ideal to effectively carry out long term trend analysis of the natural flow regime and the flood frequency analysis. The retrieved data was evaluated for gaps and unphysical values and a visual inspection was carried out to rule out any unphysical trends. The results of the evaluation suggested that the data was of very good quality void of any gaps or unusual trends. The accumulated plot for the observed discharge over the years for the catchments was plotted and has been presented in **Figure 3.8** to **Figure 3.10**. As can be inferred, the linear trend of the accumulated plot demonstrates excellent data quality.

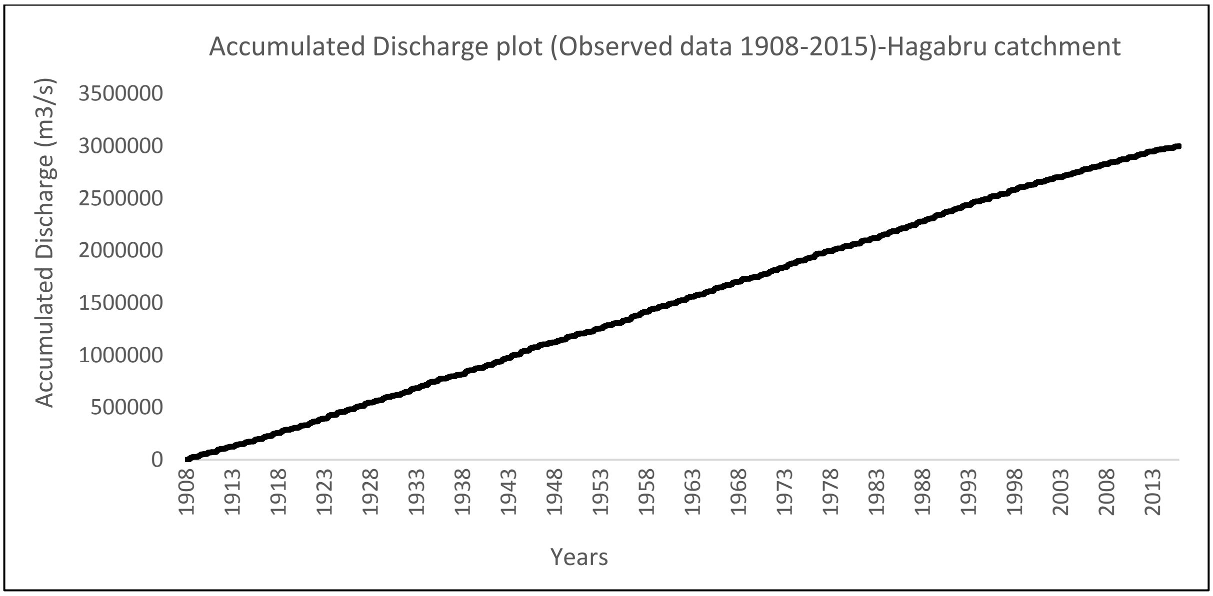


Figure 3.8: Accumulated discharge plot for Hagabru catchment

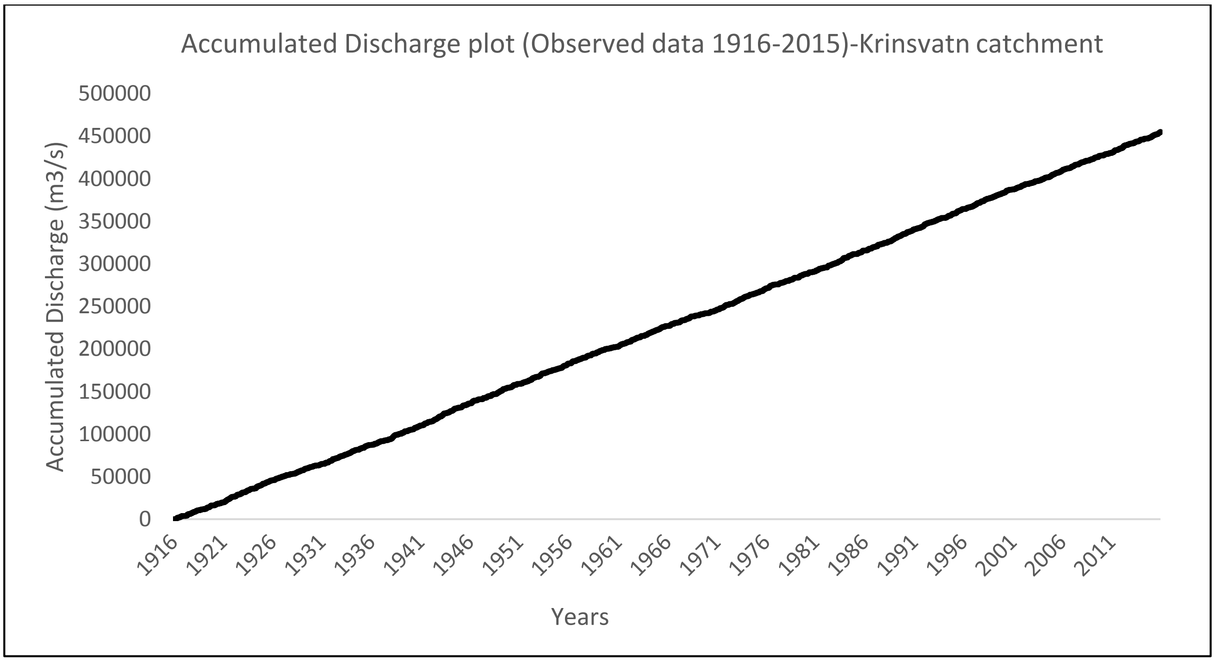


Figure 3.9: Accumulated discharge plot for Krinsvatn catchment

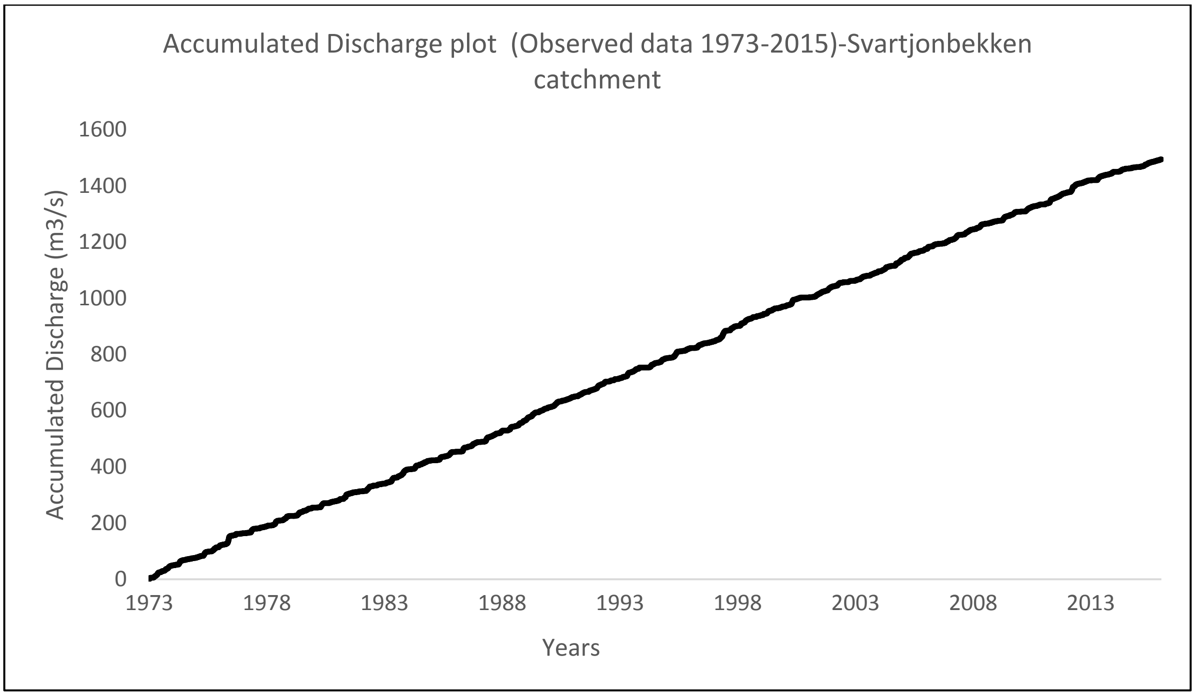


Figure 3.10: Accumulated discharge plot for Svartjonbekken catchment

The generally employed methodology for obtaining areal values for precipitation and temperature has been to retrieve observed data series from multiple climate data gauging stations within the catchment and in turn to implement the Thiessen Polygon technique to convert point measurements to areal values. This approach can have some drawbacks such as non-uniform distribution of gauging stations within the catchment leading to difficulty in application of the Thiessen polygon method resulting in limited accuracy of obtained data. Hence, to obtain data of good quality and accuracy, the gridded climate data maps prepared and maintained by the Norwegian Meteorological Institute was employed. To begin with, a pre-prepared gridded map of observed Precipitation and Temperature data over the time period of 1957-2015 was obtained for Norway in its entirety. Further, an R-script intended at delineating the grids encompassed by the catchment from the national map was used. The obtained grids (1Kmx1Km) within the study catchments have been presented in **Figure 3.11** to **Figure 3.13**.

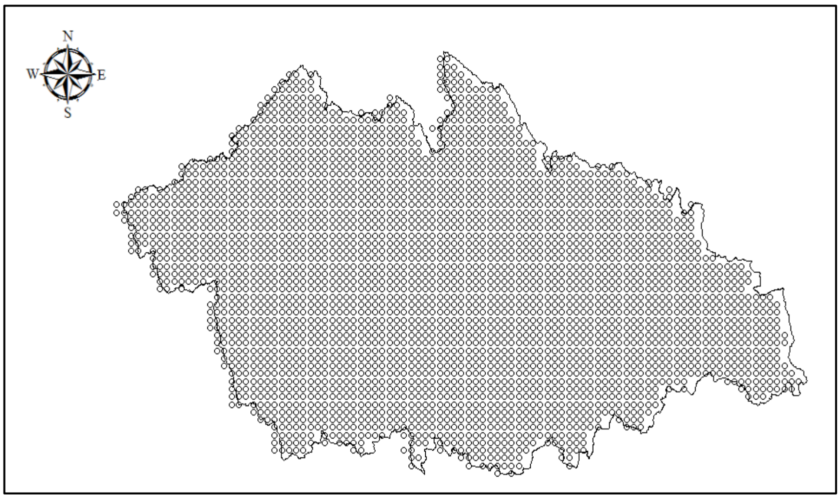


Figure 3.11: Grid network for observed climate data within Hagabru catchment

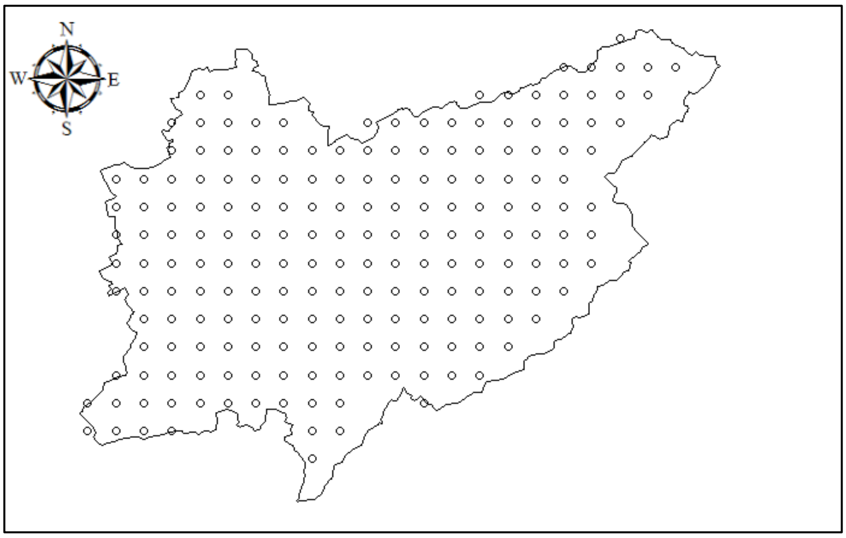


Figure 3.12: Grid network for observed climate data within Krinsvatn catchment

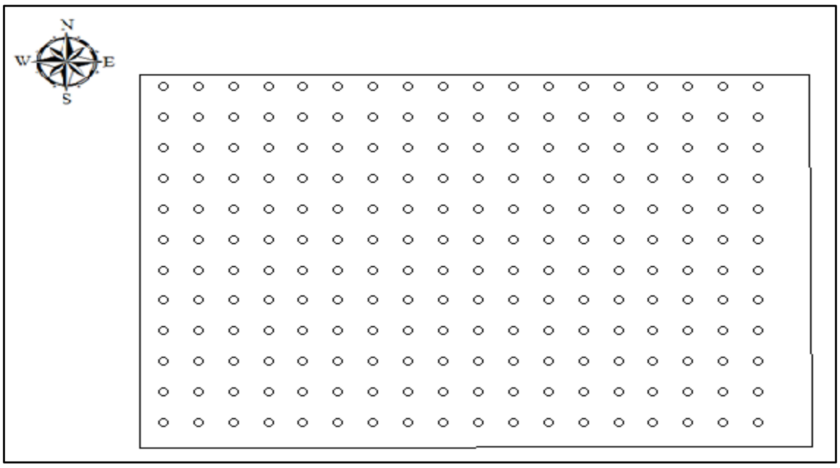


Figure 3.13: Grid network for observed climate data within Svartjonbekken catchment

It is worth noting that the grid network for Svartjonbekken has been presented as rectangular. This is due to the fact that since Svartjonbekken is a catchment of just 3.7 Km^2, the process of identification of grids becomes challenging as the resolution of the available map is comparable with the size of the catchment. Hence, a much larger rectangular area of 200 Km^2 was employed to obtain the data with Svartjonbekken placed at the center of the above depicted rectangular area. Further, three grid point were identified within the boundary of Svartjonbekken from the grid network presented in **Figure 3.13**.

The areal values for precipitation and temperature were considered to be the average of the respective values within all the obtained grids. The data was further evaluated for gaps and unphysical values and trends. The accumulated plots for the areal precipitation and temperature time series have been presented in **Figure 3.14** and **Figure 3.15**.

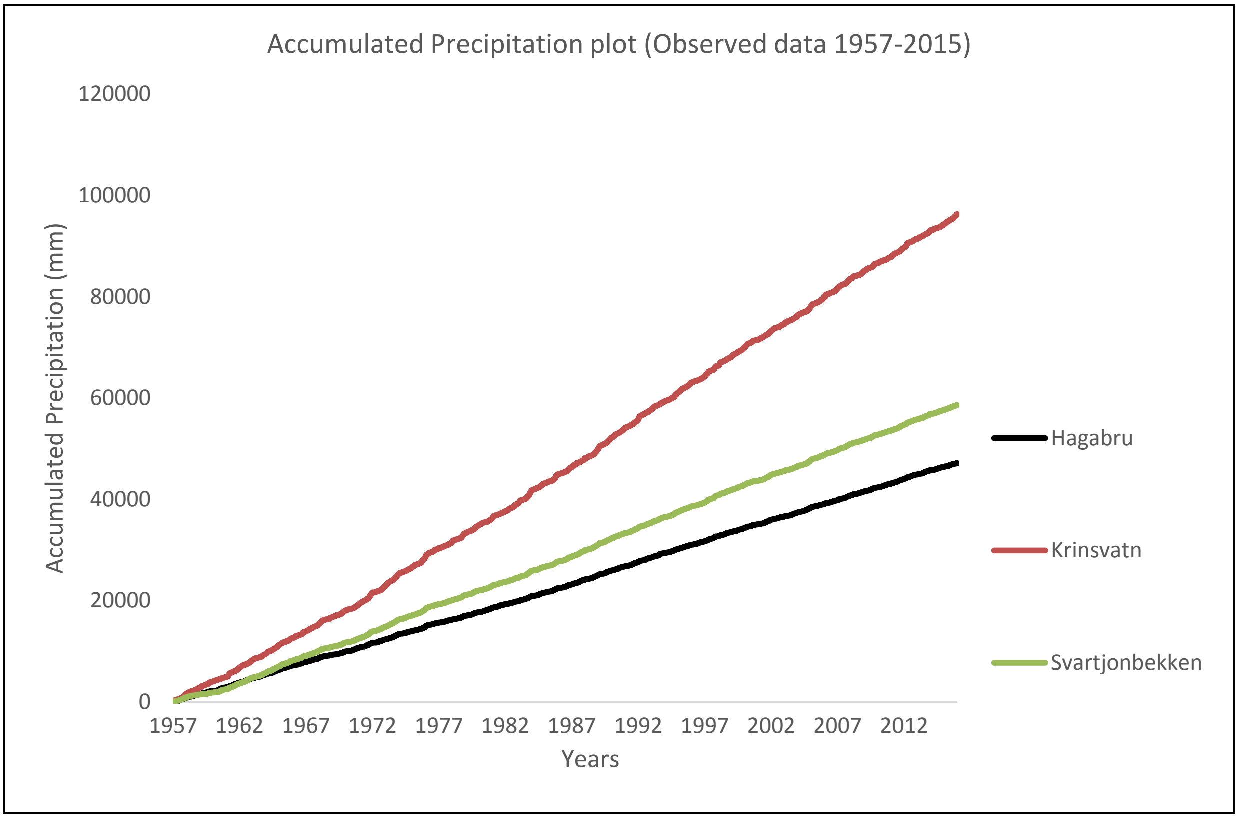


Figure 3.14: Accumulated precipitation plot for historical observed data

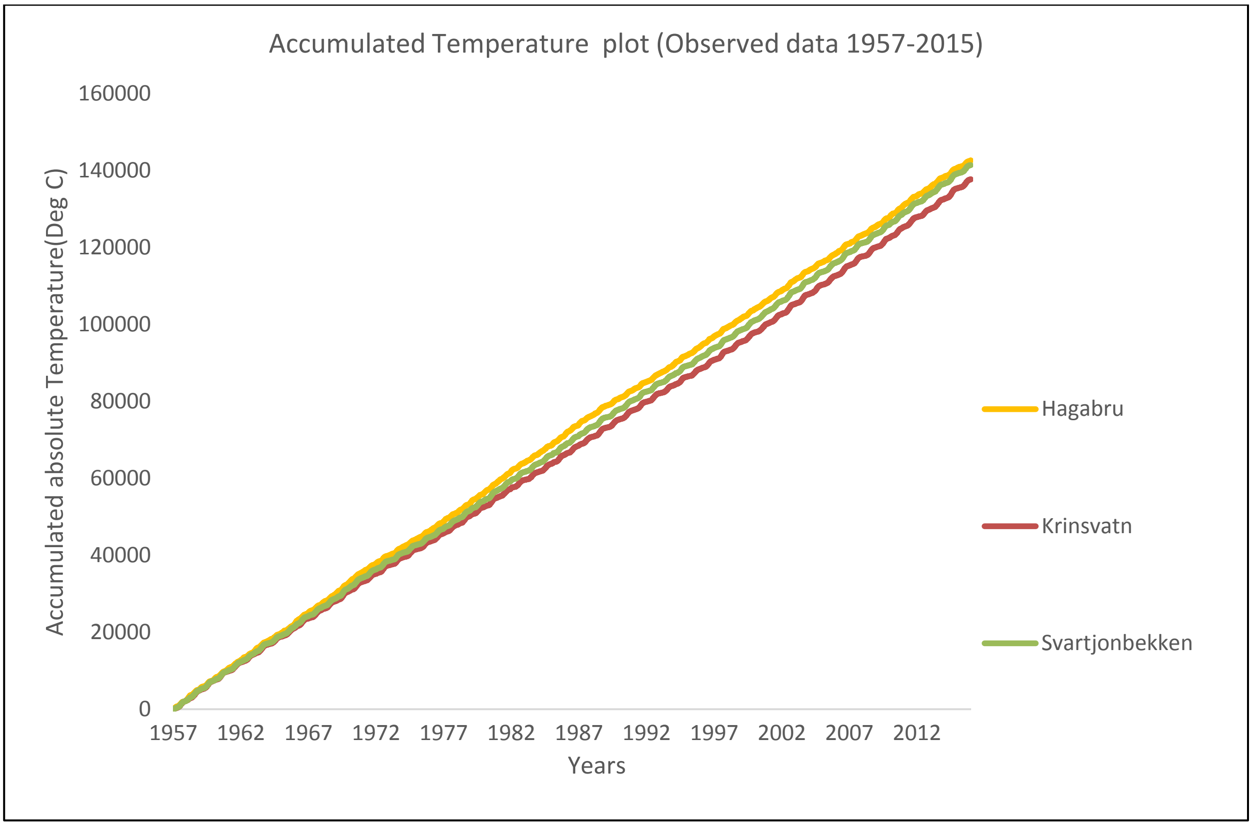


Figure 3.15: Accumulated absolute temperature for historical observed data

As can be observed from the depictions, the data was of very good quality and the availability of data over a long time period facilitated the process of HBV model calibration and validation.

Global circulation model climate data was required for the following purposes:

1. The GCM simulated historical precipitation and temperature time series were required for evaluation of the simulated data for good correspondance with observed historical data for identification of ideal downscaling techniqes.
2. The GCM simulated historical precipitation and temperature time series were required for calibration of the HBV model to obtain suitable parameter sets which can reproduce the runoff time series and especially the flood peaks to a high degree of accuracy.
3. GCM simulated climate precipitation and temperature time series over a future time period serves as input for the calibrated HBV model to simulate future runoff scenarios.

CORDEX (Coordinated Regional Climate Downscaling Experiment) climate data was obtained from two different models over the time period of 1956-2099. The details of the employed models are presented in **Table 3.4**.

Table 3.4: Details of the employed GCM models

Model Name	CNRM-CM5	HADGEM2-ES
Developing Agency	CNRM-CERFACS	MOCH
Model Domain	EUR-11	EUR-11
Greenhouse gas emission scenario	Rcp85	Rcp85
Internal Initial model condition	r1i1p1	r1i1p1

As can be observed, CORDEX data sets for two different climate models were obtained for a single high emission scenario of RCP85. The process of obtaining climate model data sets and further delineating the data sets for the study catchments was an extremely time consuming task and hence, the number of data sets obtained was limited to the above mentioned two models. Addition of a multi model multi scenario ensemble could be looked into in future versions of this work. As far as this study is concerned, primary emphasis has been laid on the process of hydrological modeling and analysis of flow regime alterations.

The obtained data was gridded with a grid size of 12Kmx12Km uniformly distributed over the entirety of the continent of Europe. Further, an R-Script with the objective of delineating the required grids within the catchments under consideration from the vast network was implemented. The resultant plot of the obtained grid network within the study catchments have been presented in **Figure 3.16** to **Figure 3.18**.

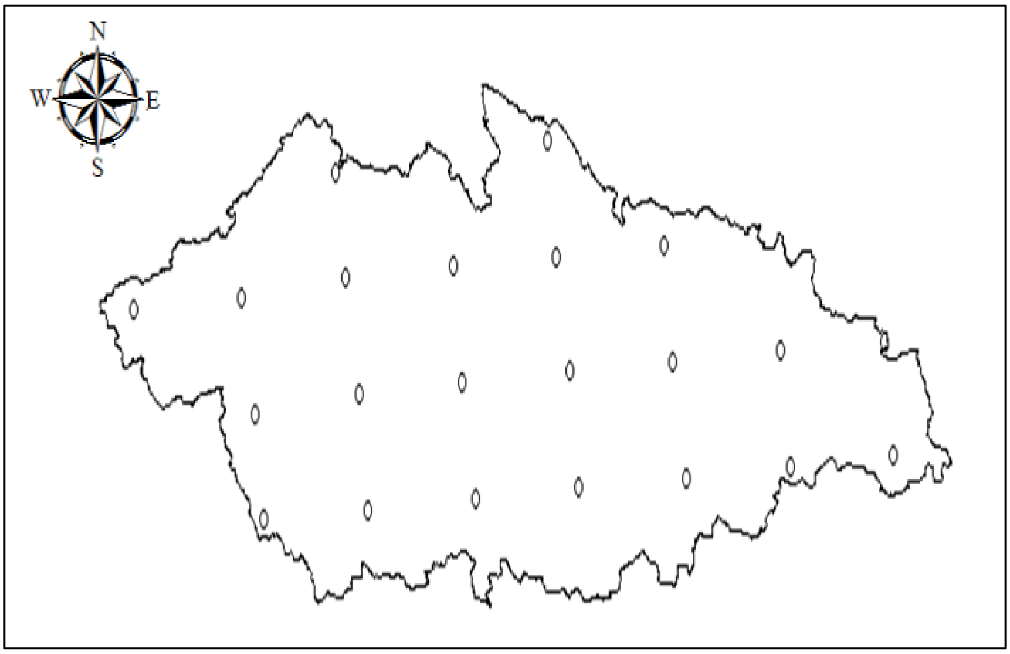


Figure 3.16: Grid network for GCM simulated climate data within Hagabru catchment

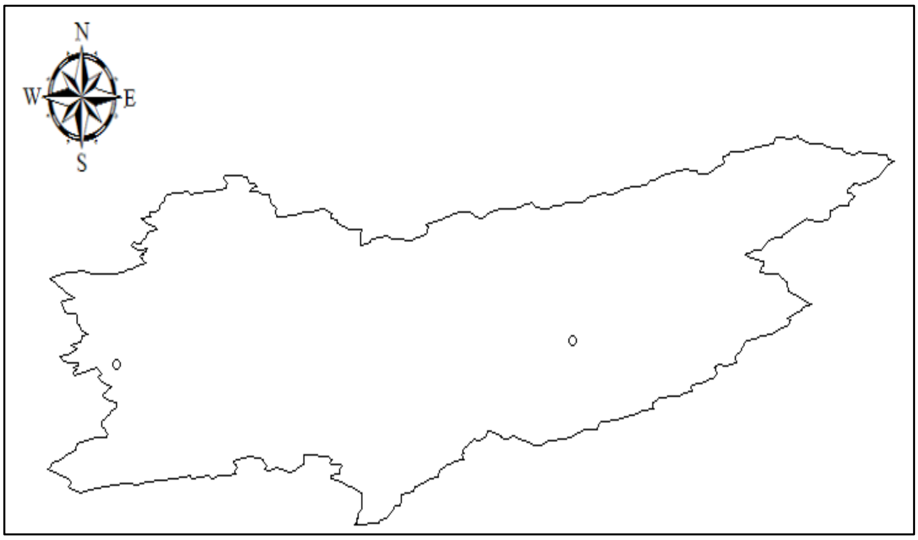


Figure 3.17: Grid network for GCM simulated climate data within Krisvatn catchment

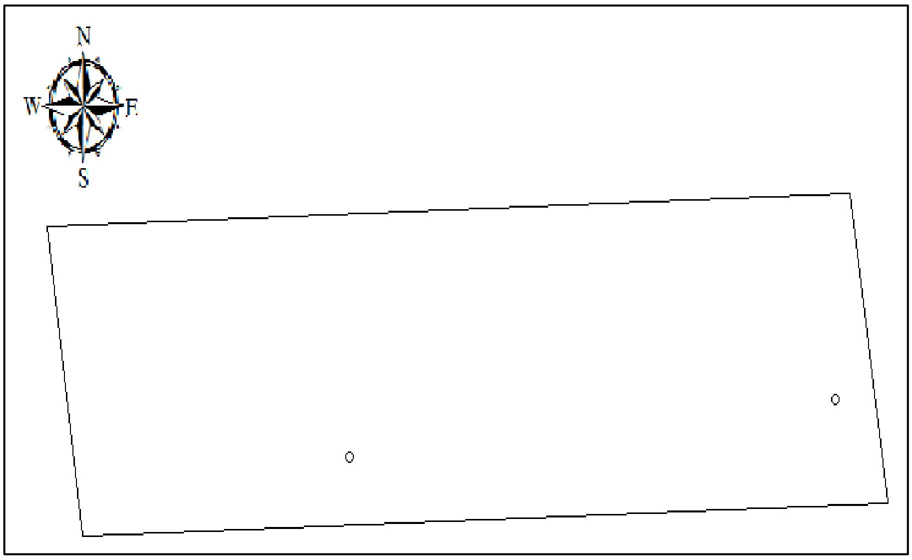


Figure 3.18: Grid network for GCM simulated climate data within Svartjonbekken catchment

A juxtaposition of **Figure 3.11** to **Figure 3.13** with **Figure 3.16** to **Figure 3.18** revealed that the grid network distribution within the catchment was much finer in the observed climate data obtained from the Norwegian Meteorological Institute when compared to the data obtained from the GCM simulated data.

The average values of the delineated gridded data was employed as areal input for the HBV model. The results of data quality evaluation for the obtained climate data from the two different GCMs have been presented in **Figure 3.19** and **Figure 3.20**. The two models are identified with the acronyms of their respective developing agencies ('CNRM' and 'MOCH') consistently throughout this report.

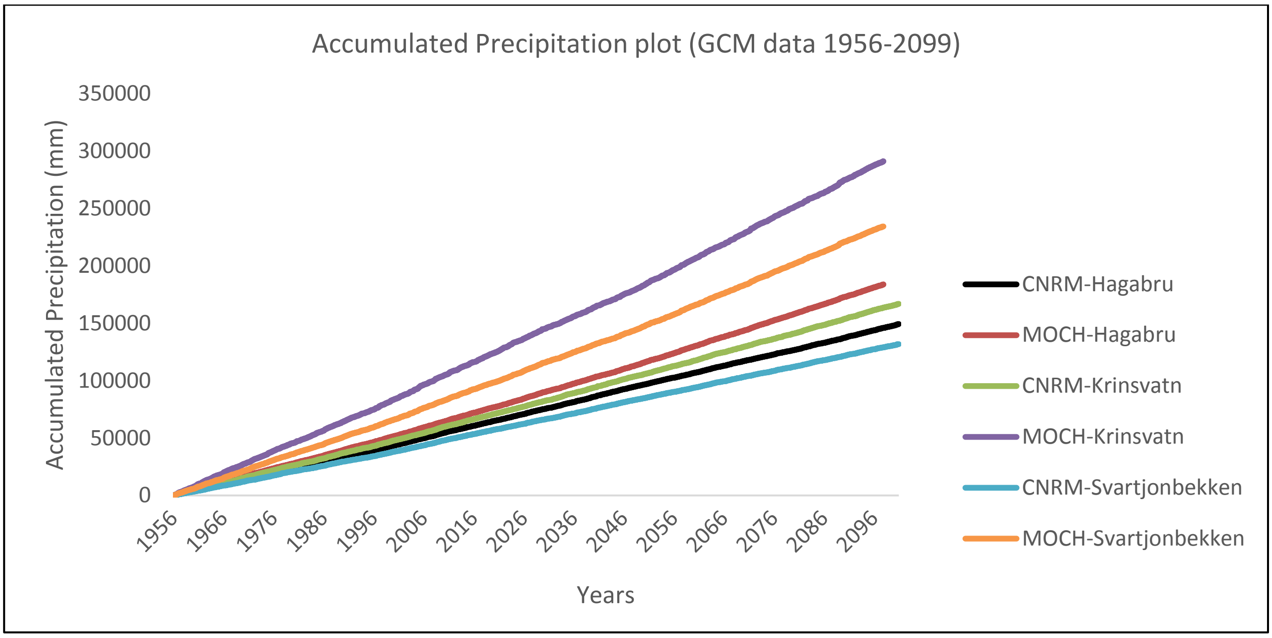


Figure 3.19: Accumulated precipitation plot for GCM simulated data

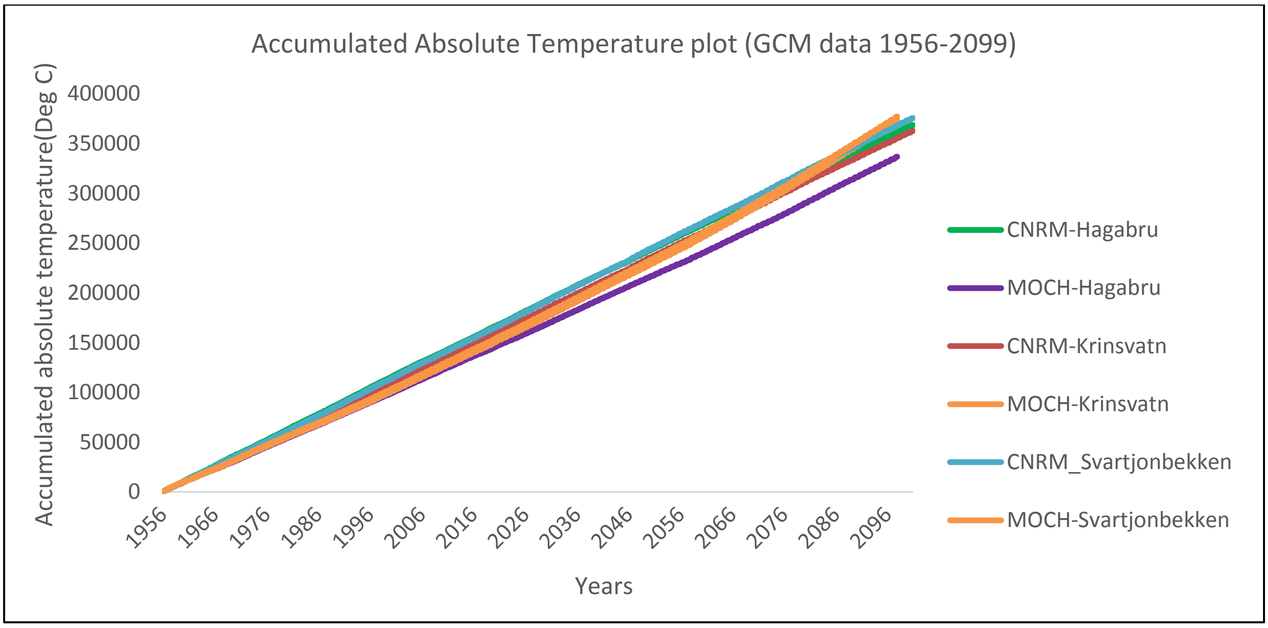


Figure 3.20: Accumulated absolute temperature for GCM simulated data observed data

A very interesting observation was made with the above depicted plots. It could be observed that the difference between the accumulated plots between models for a particular catchment was minimal with accumulated temperature plots but was seen to be significant with accumulated precipitation plots. This hints at the internal discrepancies between GCM precipitations data between different models. CNRM model was much drier internally when compared to MOCH model. This is essentially the reasoning behind going for a multi model ensemble analysis.

4.0 FINDINGS FROM HISTORICAL OBSERVED DATA

4.1 TEMPERATURE CHANGE SIGNAL OF CLIMATE CHANGE

The entire concept of climate change essentially revolves around the phenomenon of a warming atmosphere. Prior to carrying out investigations into the impacts of climate change on regional hydrology, it was very essential to establish the existence of the phenomenon. The daily average temperature time series for the three study catchments have been presented in **Figures 4.1 through 4.3**.

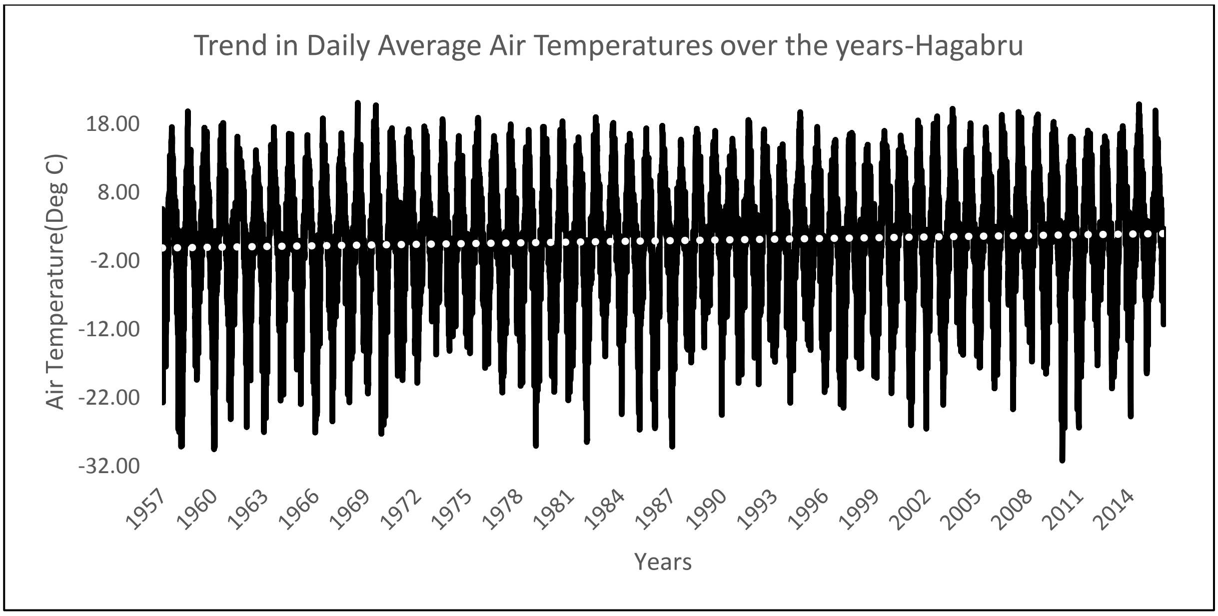


Figure 4.1: Trend in Daily Average Air Temperatures over the years-Hagabru catchment

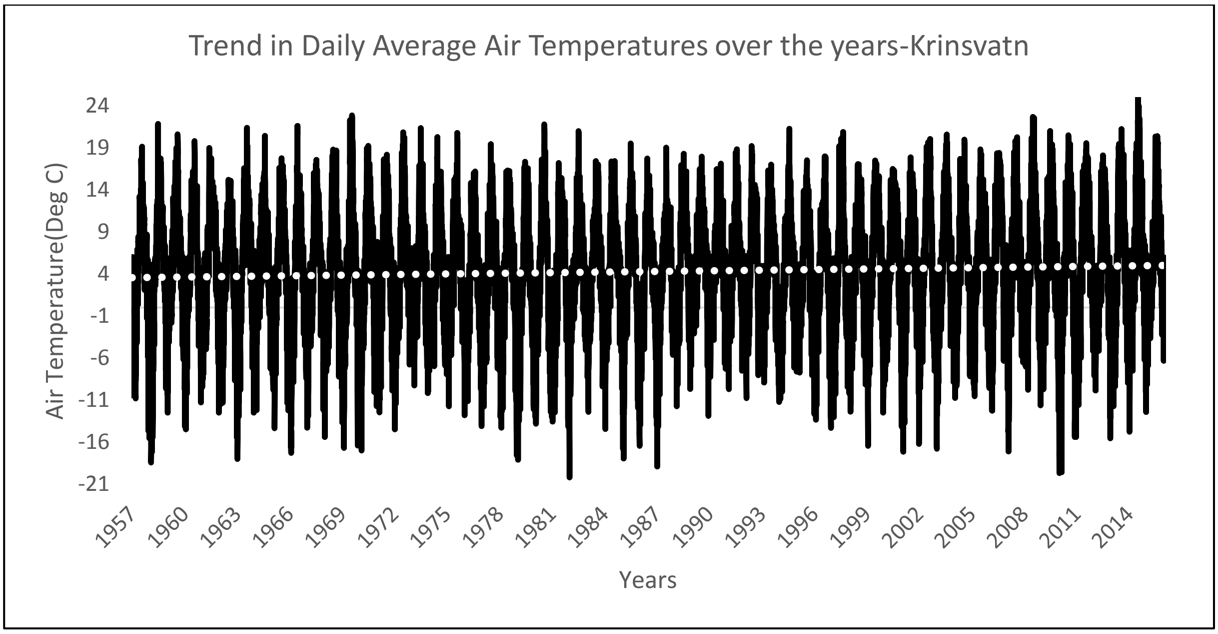


Figure 4.2: Trend in Daily Average Air Temperatures over the years-Krinsvatn catchment

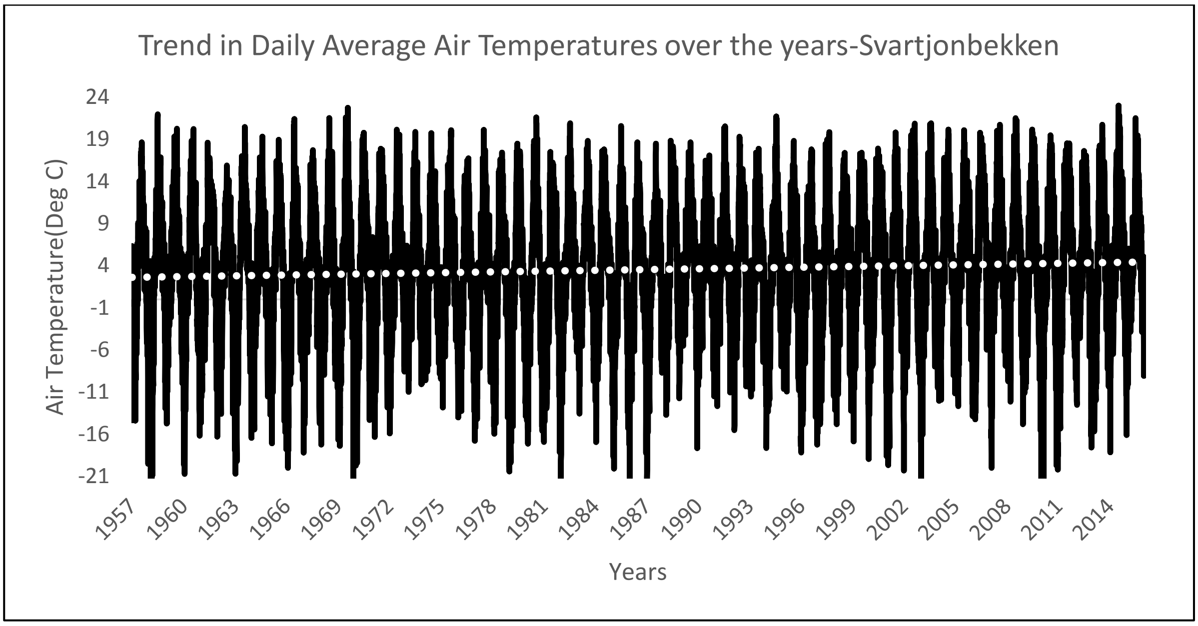


Figure 4.3: Trend in Daily Average Air Temperatures over the years-Svartjonbekken catchment

It was clearly evident that there was a small but gradual increase in slope of the average temperature trend lines over the decades in all of the catchments under consideration. Although an increasing trend was observed over the time period of 1957-2015, a clear delineation point in time for the inception of the effects of climate change was not possible to be established with the above presented plots. Hence, a graphical representation of average annual temperatures was plotted and has been presented in **Figure 4.4** and it was concluded from the depiction that the annual average temperature trend took a drastic upward turn at the end of the 1980's signaling the inception of observable impacts of climate change.

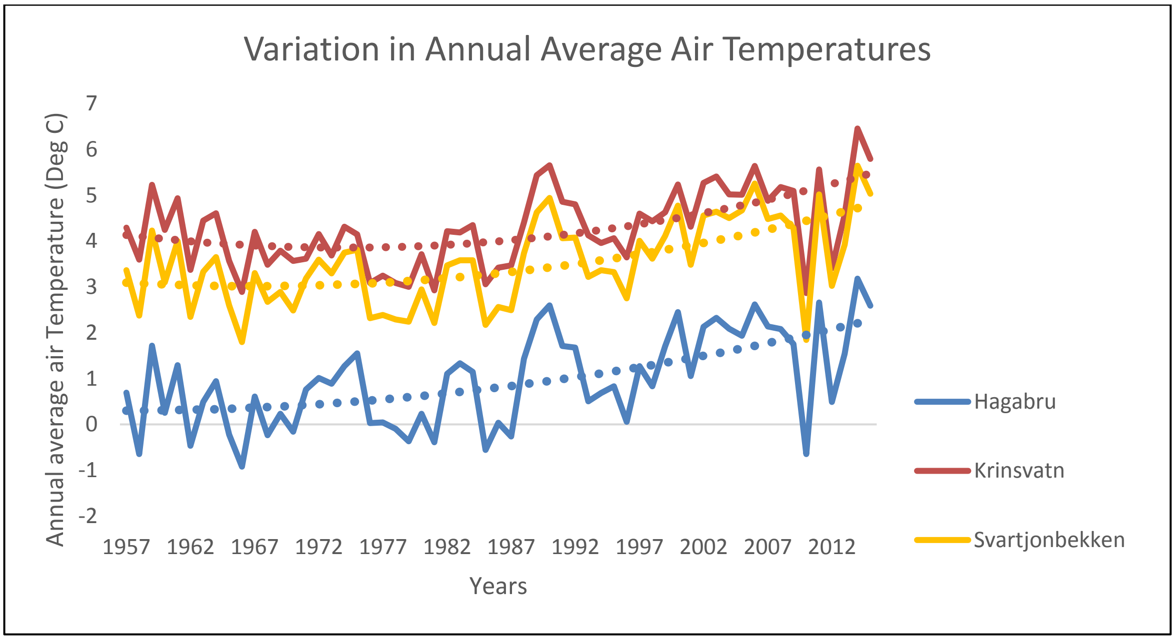


Figure 4.4: Variation in average annual air temperatures over the years

It was fascinating to note that the obtained trends had a striking resemblance with the average simulation output of numerous global circulation models as published by the Intergovernmental Panel on Climate change which has been presented in **Figure 4.5**.

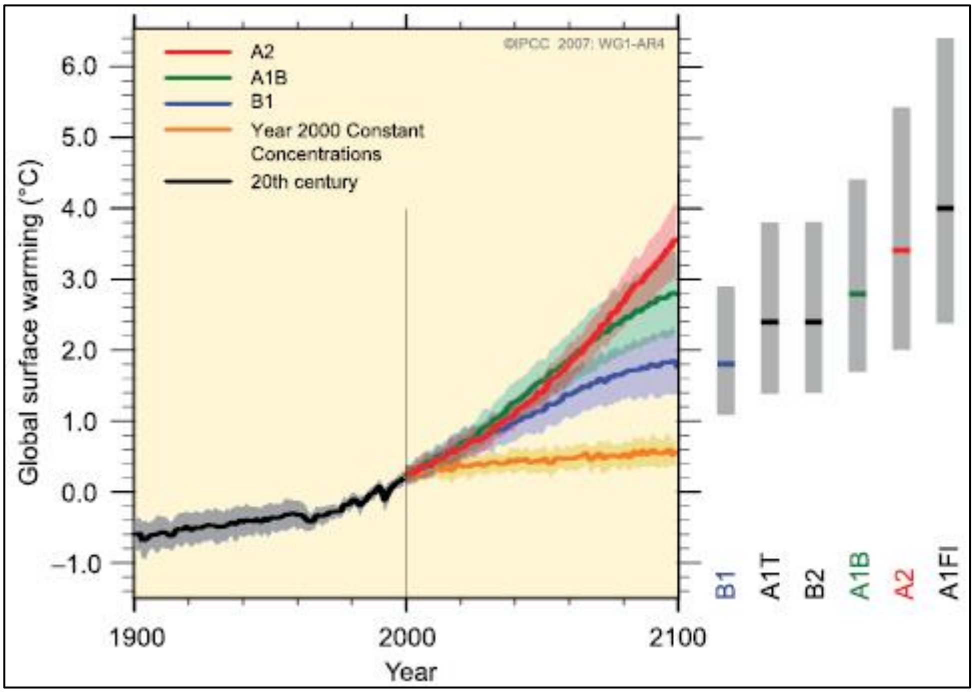


Figure 4.5: GCM Global surface warming temperature projections [29]

Since the GCM simulations were based on global greenhouse gas emission scenarios, the obtained results were conclusive evidence that the observed effect was due to pollution induced global warming rather than a natural anomaly. Hence, it could be concluded from the discussion that the impact of climate change in enhancing air temperatures was observable at the study locations.

4.2 VARIATIONS IN NATURAL FLOW REGIME

The primary objective of this research project was to fathom the possible impacts of climate change on the natural hydrological regimes of the study catchments. This inevitably includes the study of variations in annual hydrograph trends and the flood frequency features in a future climatic setting. Literature review of previous climate change impacts investigations carried out in the region suggested that studies had predominantly focused on simulating a future hydrological setting with global circulation model climate data as input. This approach provides valuable insight into possible impacts of climate change on future hydrological regimes and in turn, on hydropower production and storm water drainage systems. But, dedicating resources to investigate the impacts already visible at present times would be very relevant for climate studies as this would serve as a baseline for future comparisons and would also provide additional data facilitating reclassification of hydrological regimes mapped out in previous decades. Hence, investigation was carried out to a certain extent to look for any possible trends in hydrological regime changes in the selected catchments making use of available observed discharge data series over the past decades.

Efforts were made to investigate changes in annual hydrograph trends by comparing daily average hydrographs over the decades through division of available datasets into specific intervals. Flood frequency analysis was also carried out to determine any possible trends in flood frequency and magnitude changes in the same specified time intervals. The autumn and spring flood characteristics were also studied to look for any existing trends as these are the key features which help us fathom possible impacts of climate change on regional hydrology at present times.

4.2.1 TRENDS IN ANNUAL HYDROGRAPH PATTERNS

Discharge data was available for Hagabru catchment over the period 1908-2015 and from 1916-2015 for Krinsvatn catchment. The available data was divided into uniform intervals and average hydrographs were prepared over these specific time periods. The observed trends in annual hydrographs at Hagabru and Krinsvatn catchments up to the year 1970 have been presented in **Figure 4.6** and **Figure 4.7**. Since discharge data was available for Svartjonbekken over the time period of 1973-2015, it was not possible to carry out similar investigation for Svartjonbekken catchment.

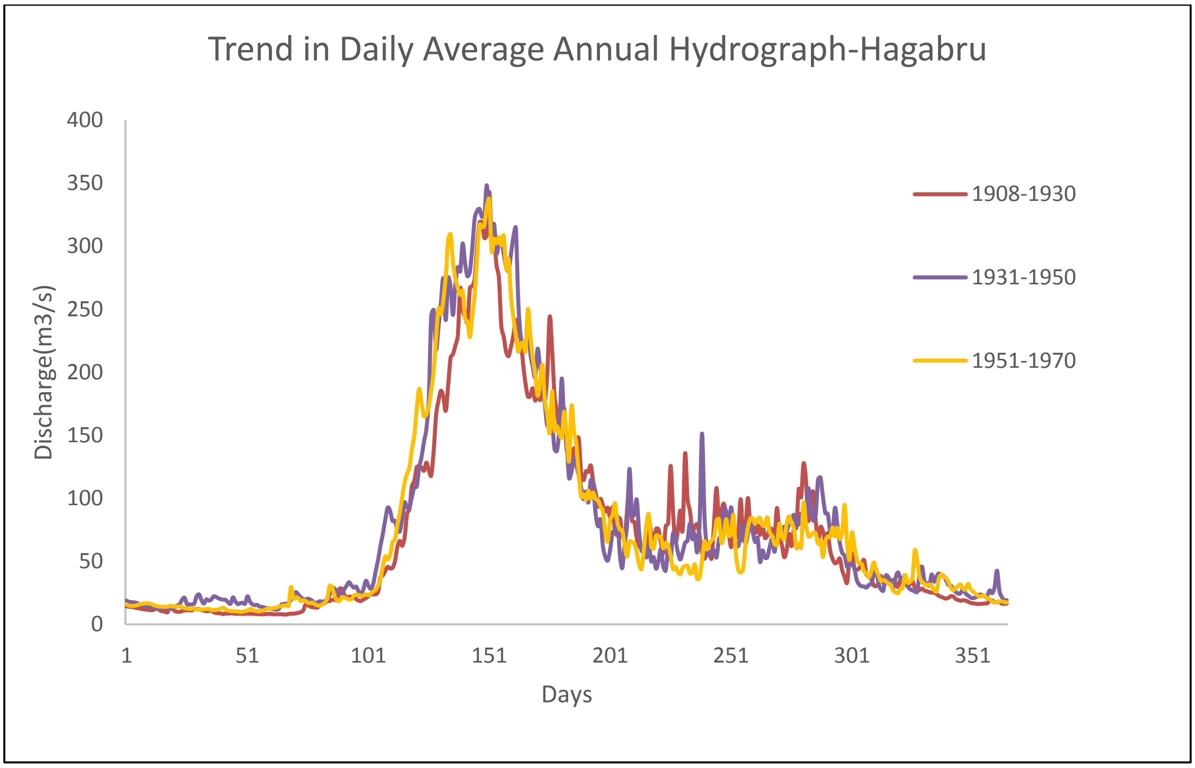


Figure 4.6: Trend in daily average annual hydrograph up to the year 1970-Hagabru catchment

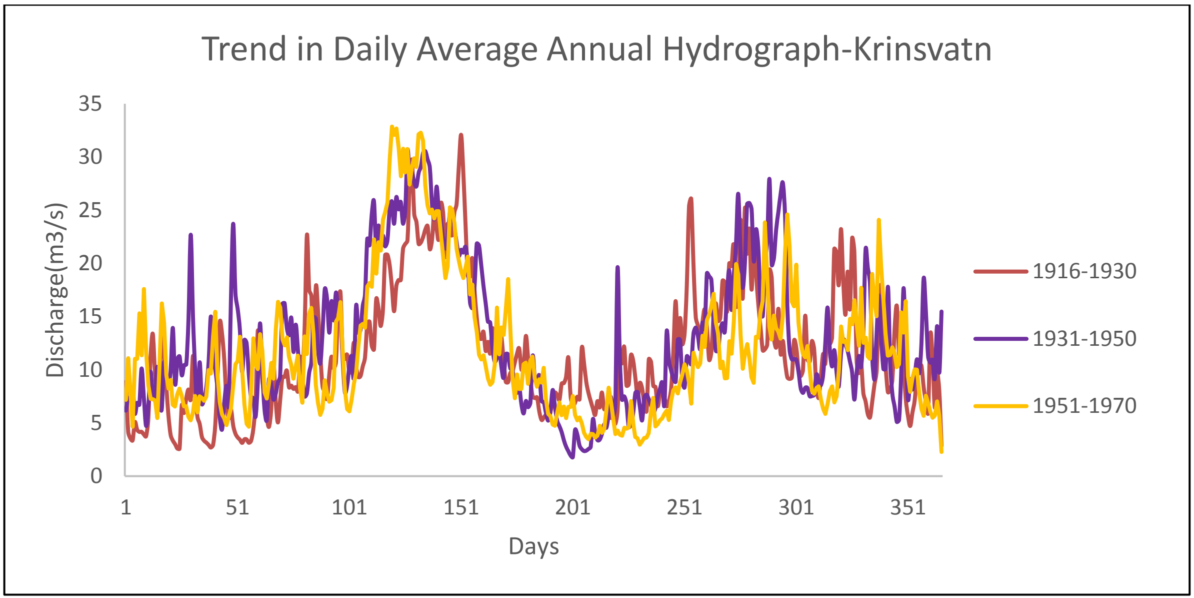


Figure 4.7: Trend in daily average annual hydrograph up to the year 1970-Krinsvatn catchment

It was remarkable to note that the average annual runoff patterns averaged over the decades were found to be consistent with minimal deviations from one another until the year 1970. This suggested consistent and unaltered hydrological regimes at the study catchments until 1970. Further, **Figure 4.8** to **Figure 4.10** depict the trends in annual average hydrographs over the time periods 1971-1990 and 1991-2015 for Hagabru and Krinsvatn catchments and over the time periods 1973-1990 and 1991-2015 for Svartjonbekken catchment. The average historical hydrographs up to the year 1970 were overlaid with the plots for Hagabru and Krinsvatn catchments but this was not possible for Svartjonbekken due to unavailable data.

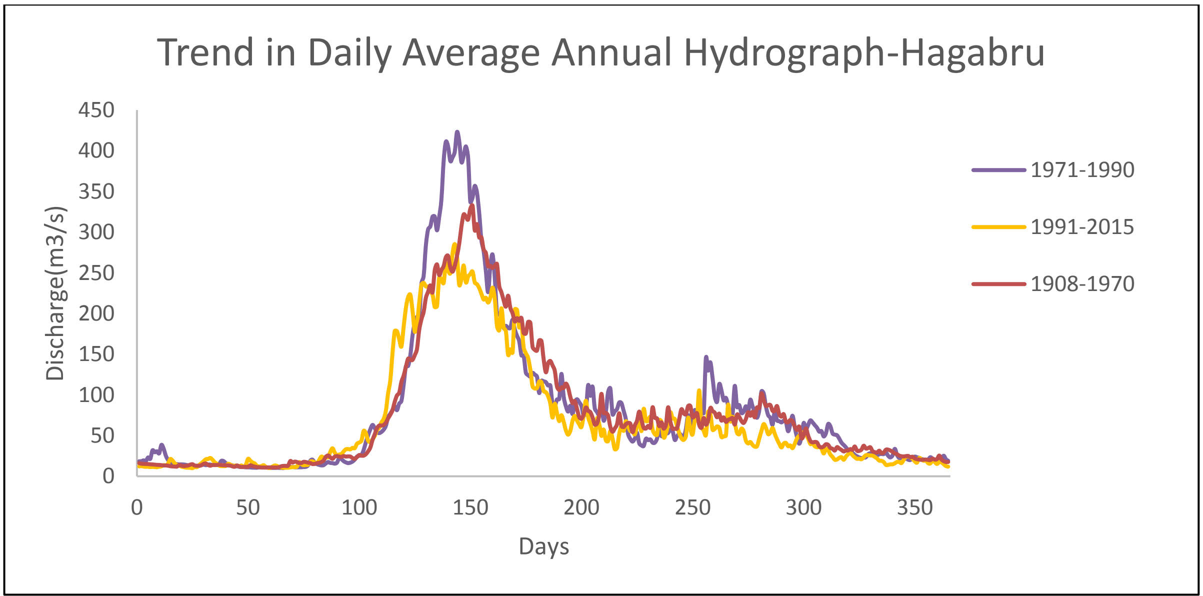


Figure 4.8: Trend in daily average annual hydrograph (1970-2015)-Hagabru catchment

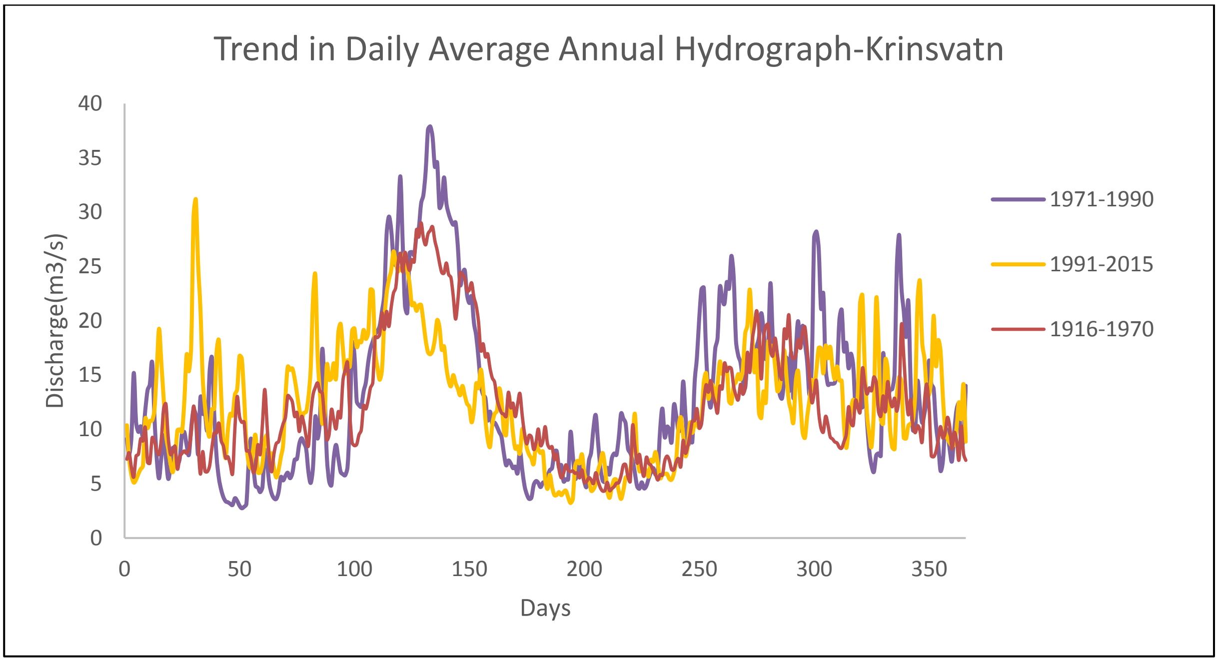


Figure 4.9: Trend in daily average annual hydrograph (1970-2015)-Krinsvatn catchment

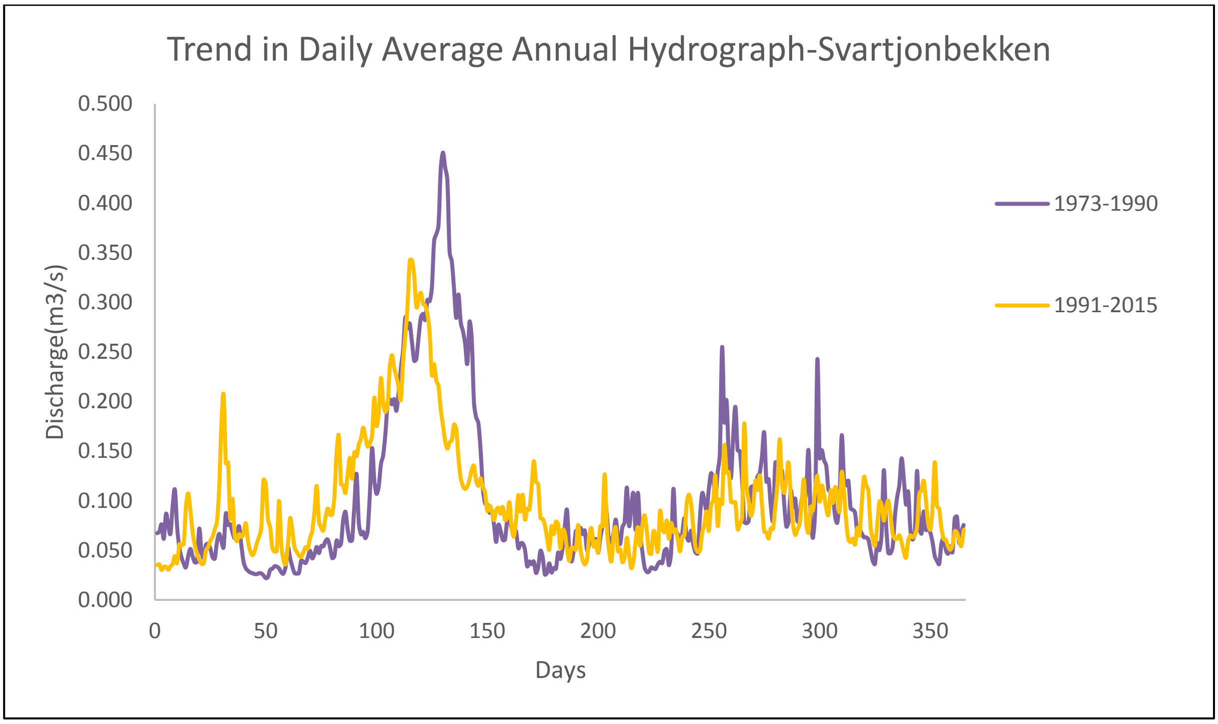


Figure 4.10: Trend in daily average annual hydrograph (1970-2015)-Svartjonbekken catchment

It was fascinating to note that significant changes to the natural flow regimes were observable over the time periods 1970-1990 and 1991-2015 when compared to the consistent trends presented in **Figure 4.6** and **Figure 4.7** for Hagabru and Krinsvatn catchments. Similar trends were also observed at Svartjonbekken catchment over the time periods 1973-1990 and 1991-

2015. The spring flood peak magnitudes were observed to be undergoing drastic changes over the decades with a significant increase over the period 1970-1990 and a significant reduction over 1990-2015. An earlier onset of spring floods were also observed over the period 1990-2015. A reduction in magnitude of spring floods and an earlier onset of the same are considered hallmarks of climate change impact on hydrology as far as cold weather countries are considered where snowmelt floods tend to dominate the runoff generation process.

The results were corroborated by an earlier work carried out at the NVE which stated "*In all the three periods, a signal towards earlier snowmelt floods was clear, as was the tendency towards more severe summer droughts in southern and eastern Norway. These trends in streamflow result from changes in both temperature and precipitation but the temperature induced signal is stronger than precipitation influences. This is evident because the observed trends in winter and spring, where snowmelt is the dominant process, are greater than the annual trends* **[30]**". Further, **Figures 4.11** to **4.13** clearly show that the amount of winter precipitation closely followed the observed trend in annual hydrograph with increased amounts of precipitation over the period 1970-1990 and a reduction over the period 1991-2015. Hence, it could be concluded that the observed impact to annual hydrographs was influenced by a precipitation and a temperature signal at the study locations as corroborated by the present discussion and also the observed increasing trend in temperature.

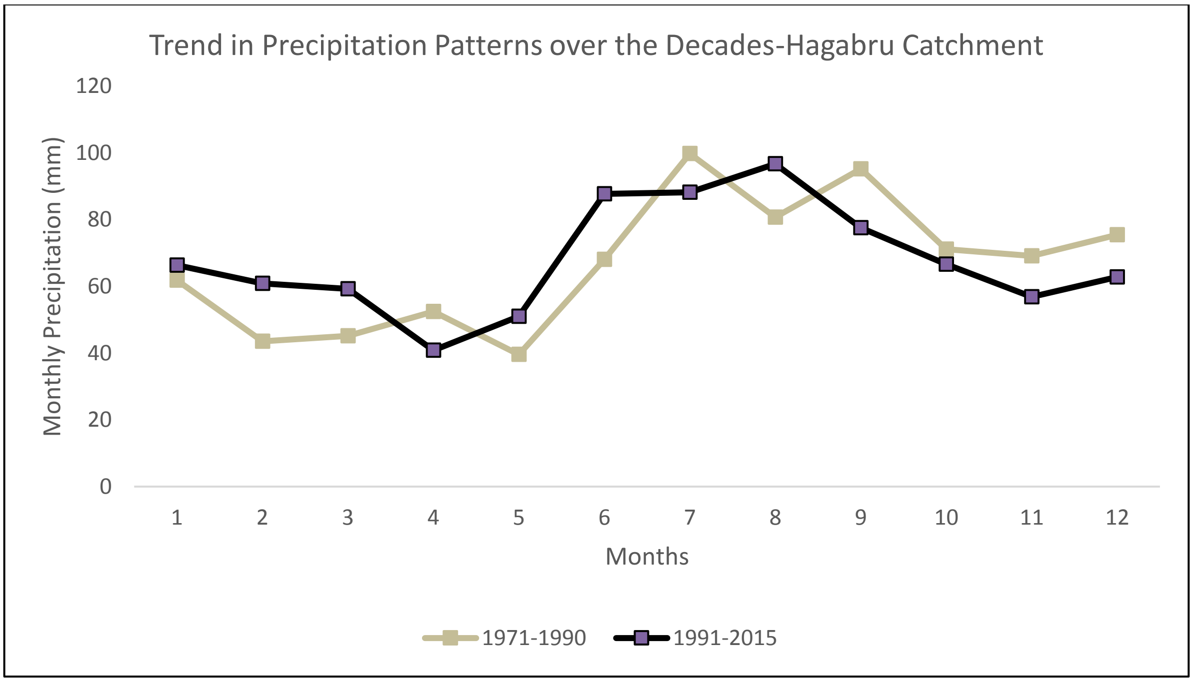


Figure 4.11: Trend in precipitation pattern over the decades – Hagabru catchment

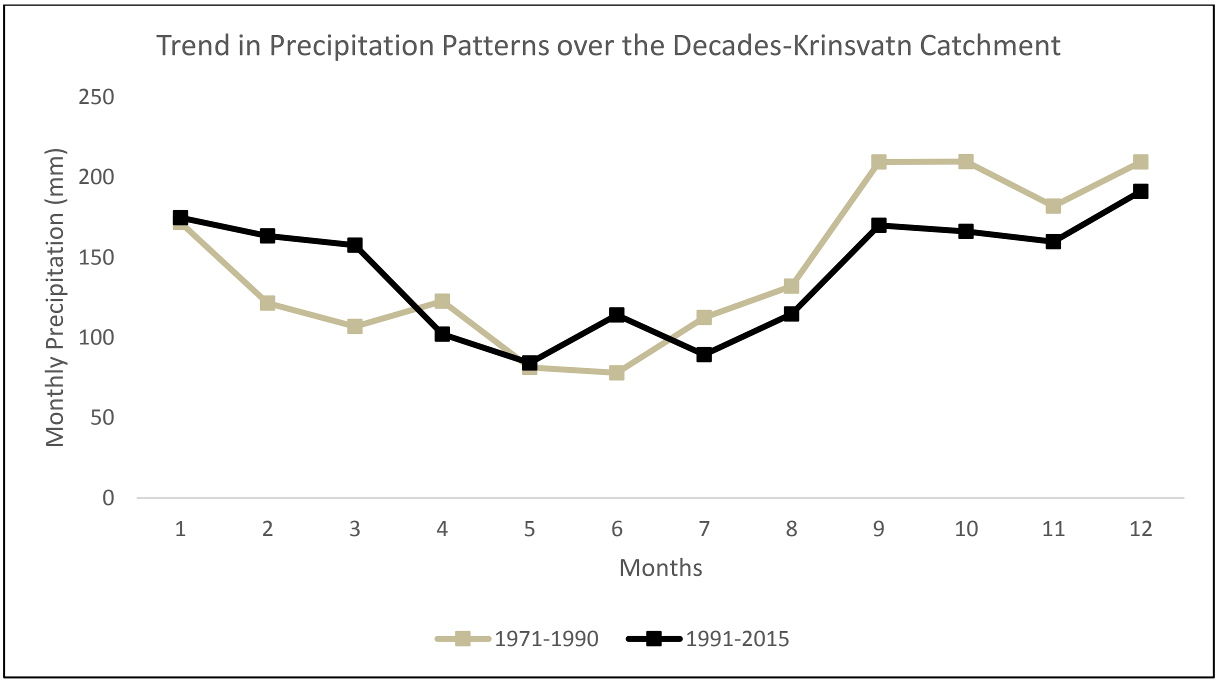


Figure 4.12: Trend in precipitation pattern over the decades– Krinsvatn catchment

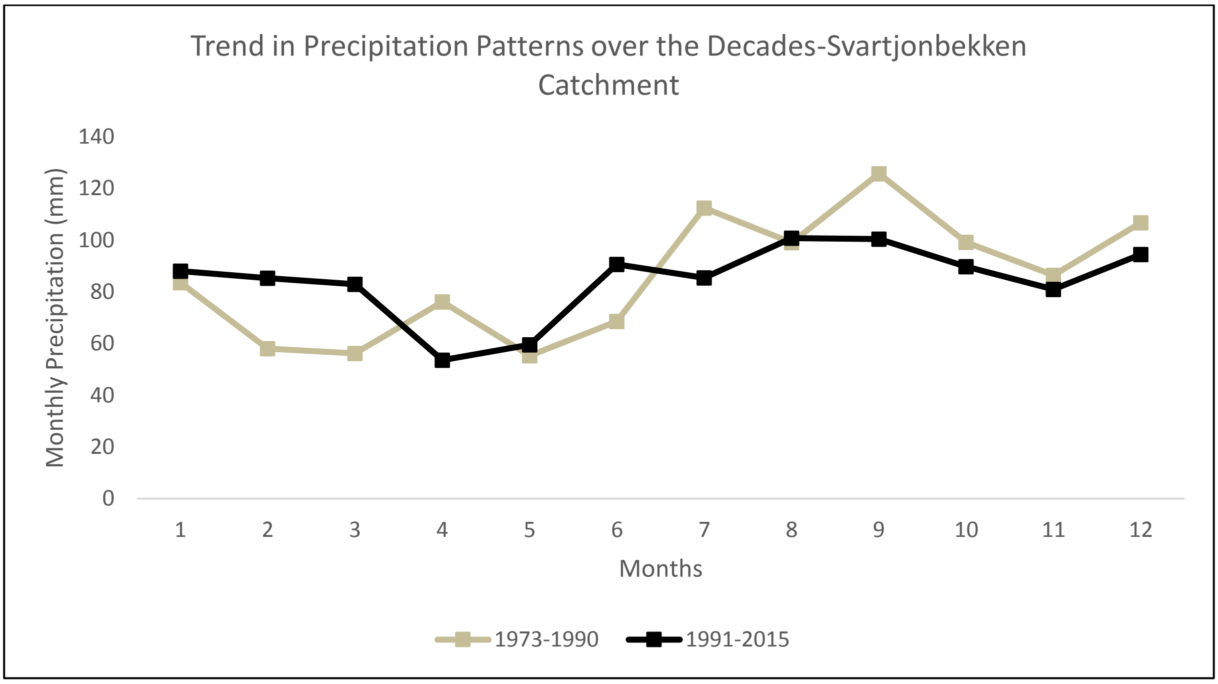


Figure 4.13: Trend in precipitation pattern over the decades – Svartjonbekken catchment

4.2.2 FLOOD FREQUENCY ANALYSIS

As standard practice, flood frequency analysis was carried out in accordance with the graphical probability plotting technique also known as Log-Normal plotting. This method has a unique advantage of giving the user better control over the outcome since the best fitting trend line is usually drawn in accordance with the situation at hand. Results were also compared with other techniques such as the Gumbel distribution and since the results closely resembled one another, the plotting position technique was adopted as standard practice for this project. The procedure of the plotting position technique is as follows:

1. Sort the respective flood values in descending order
2. Rank the data with the highest value given a rank of '1' and the lowest value given a rank as the total number of data elements (n)
3. Plotting position P(g) is computed as per the equation:

   $$P(g) = \frac{1}{T} = m/(n+1) \quad \text{……………………..(5)}$$

   Where, m= Rank

   n= Total number of data elements

   T= Return Period
4. Plot the data on probability chart with the discharge values on the Y-axis and the Log (T) values on the X-axis
5. A best fitting trend line is drawn for the data

4.2.2.1 ANNUAL MAXIMUM FLOOD FREQUENCY ANALYSIS

Flood frequency analysis was one of the primary focus areas for this project. Study of variation in historical flood frequency trends and comparison of the historical trends with the future projected trends would be valuable information for key storm water drainage infrastructure design and maintenance. Hence flood frequency analysis was carried out on an annual basis and also on seasonal basis. Annual maximum flood values were employed for annual flood frequency analysis in accordance with the previously described procedure and spring flood frequency analysis was carried out by employing the flood peak within the first 300 days of the calendar year and autumn flood frequency analysis was carried out by employing flood peak within the latter 165 days of the calendar year. This was to accurately capture the flow regime trends observed in the selected Norwegian catchments. The discussions on annual flood frequency analysis are presented in this section and seasonal food frequency analysis has been discussed in the following sections of the report.

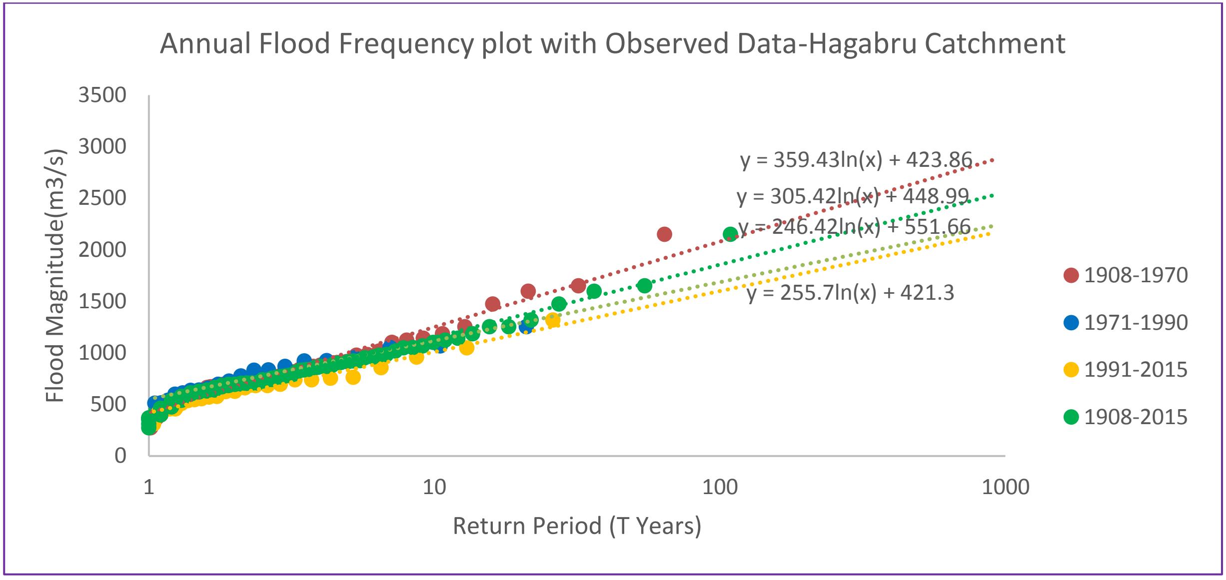


Figure 4.14: Annual Flood frequency probability plotting with observed data –Hagabru catchment

Discharge data series was available for Hagabru catchment from the year 1908 to 2015. This provided immense amount of data over a very long period which greatly facilitated the hydrological investigations. Probability plotting was carried for specific periods as designated in **Figure 4.14**. From the obtained results, it was clearly evident that the flood magnitudes of the respective return periods had been steadily dropping over the decades. The influence of the high magnitude flood which occurred in the catchment in the year 1940 on the trend line was looked into. The procedure was repeated excluding the flood and the above presented trend still held good with only minor variation to the slope of the trend line.

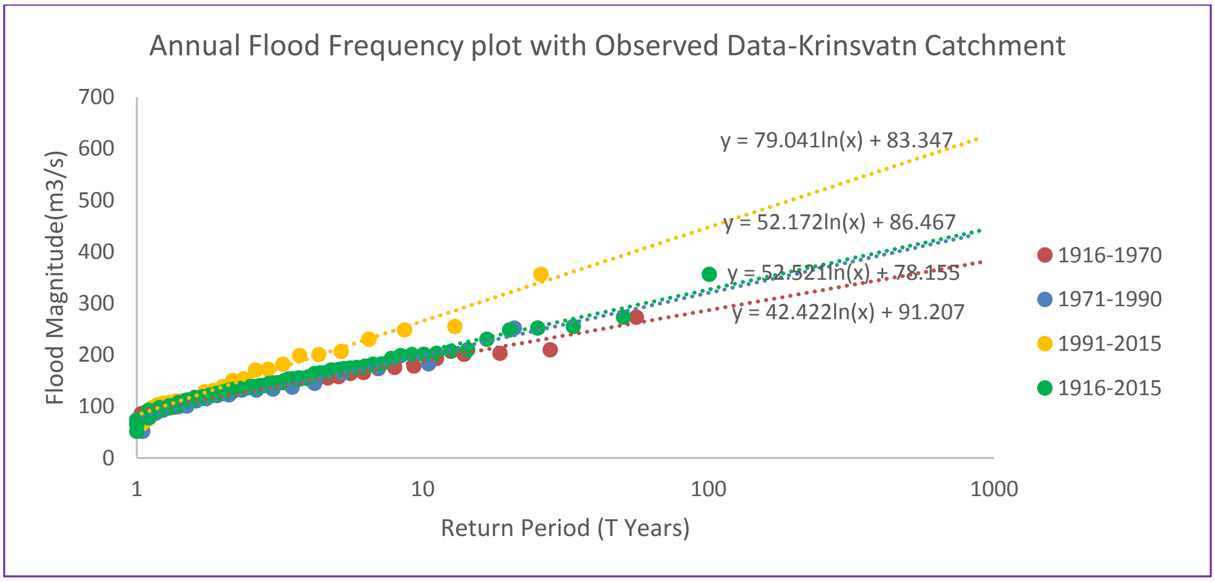


Figure 4.15: Annual Flood frequency probability plotting with observed data –Krinsvatn catchment

At Krinsvatn, discharge data series was available from the year 1916 to 2015 which was comparable to the length of time series data available at Hagabru. So, similar flood frequency analysis was carried out on the available data and the result is presented in **Figure 4.15**. It was interesting to note that the trend observed in Krinsvatn was opposite to that observed in Hagabru with the flood magnitudes of respective return periods subsequent to 1970 having a higher magnitude in comparison with the floods prior to 1970. The probability plotting of annual maximum floods over the entire period lied in the central region of the other plots.

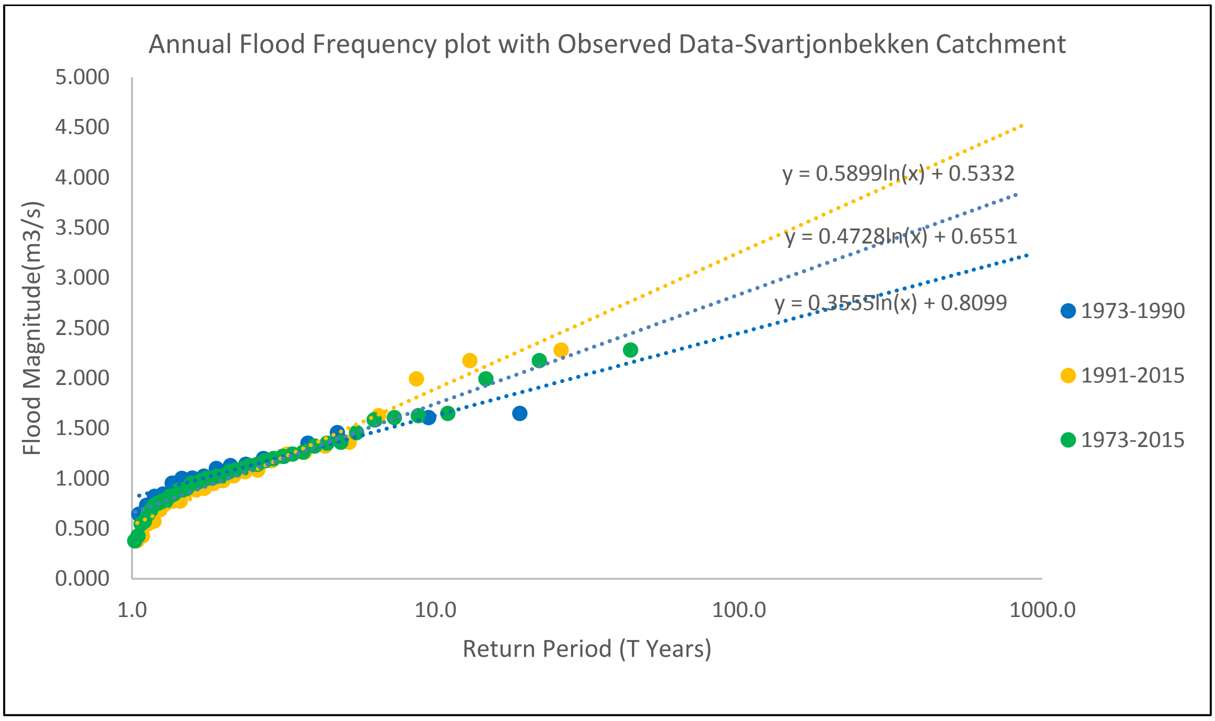


Figure 4.16: Annual Flood frequency probability plotting with observed data –Svartjonbekken catchment

Discharge data series was available for Svartjonbekken catchment only from the year 1973 to 2015. Hence, the flood frequency analysis was carried out on a much narrower time period to determine any possible similarities to the results from the other two catchments and the plotting result is presented in **Figure 4.16.** The data series was divided into intervals of 1973-1990 and 1991 to 2015 and the flood frequency analysis was carried out. The results resembled the findings of Krinsvatn catchment with the most recent floods dominating the floods prior to the year 1990.

To summarize, gradually declining annual flood frequency trends were observed in Hagabru catchment while the annual flood frequency trends in Krinsvatn and Svartjonbekken were observed to be increasing over the decades. Hence, no clear and consistent trend was observed with respect to annual flood frequency patterns over the decades as far as the study catchments were concerned. However, the amount of spread observed with respect to the flood frequency trend lines clearly suggest alterations to flood patterns in these catchments.

4.2.2.2 SEASONAL MAXIMUM FLOOD FREQUENCY ANALYSIS

It was quite essential to investigate the seasonal changes in flood frequency over the decades as climate change can have a strong seasonal impacts especially in cold climates with snow precipitation in the winter. Since warmer temperatures can result in reduced snow precipitation and also increased snow melt rates, the comparison of spring and autumn flood features becomes quite important. Seasonal maximums were found by considering the spring flood to occur within the first 200 calendar days of the year and the autumn flood to occur within the final 165 days of any calendar year.

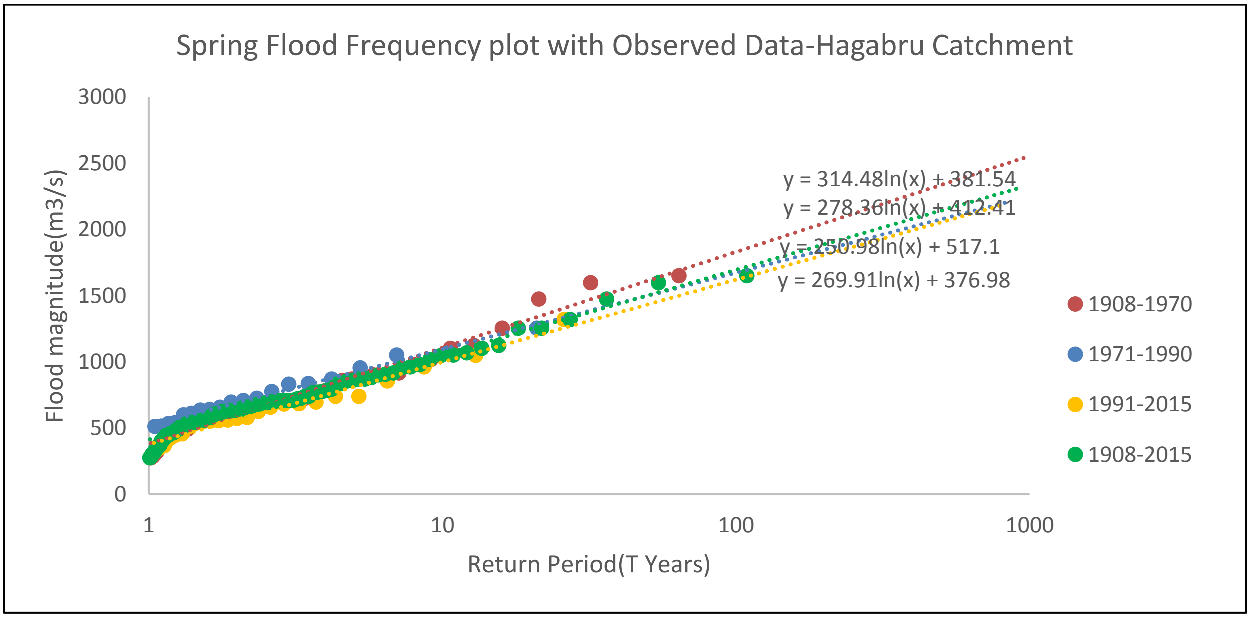


Figure 4.17: Spring Flood frequency probability plotting with observed data –Hagabru catchment

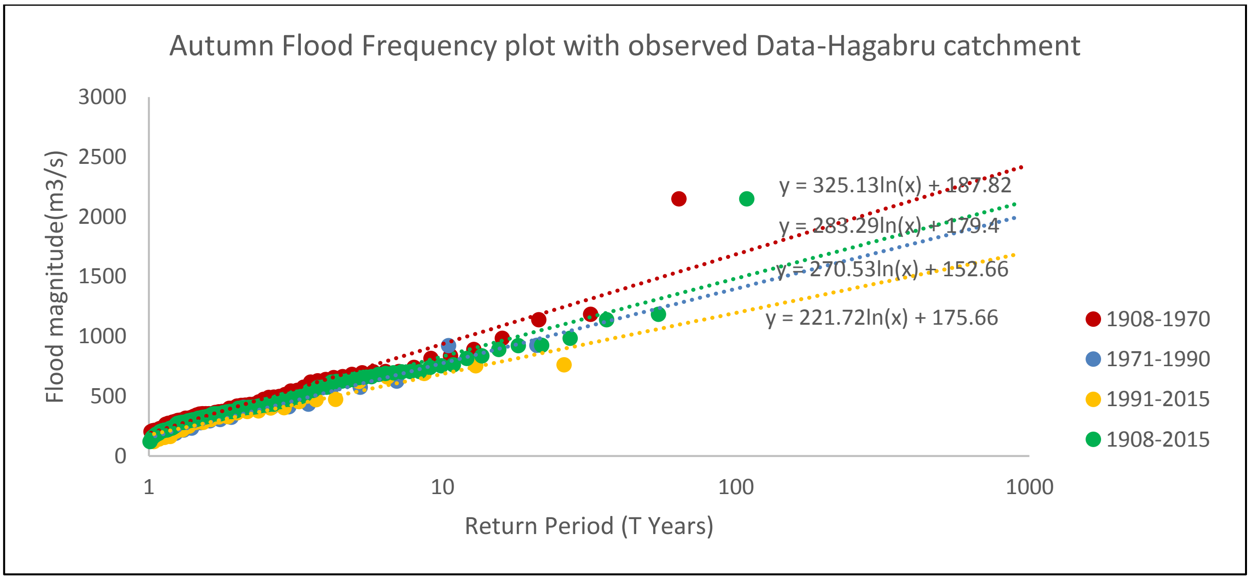


Figure 4.18: Autumn Flood frequency probability plotting with observed data –Hagabru catchment

Probability plotting for Hagabru catchment was carried out for autumn and the summer over the same time intervals as stated previously and the results of the investigations are presented in **Figure 4.17** and **4.18**. It was observed that the autumn and spring flood magnitudes subsequent to the year 1970 were observed to be consistently lower when compared to the floods prior to 1970 hinting at gradual dampening of flood magnitudes across seasons. Although the trend was noticeable in both the cases, the spread observed in case of the autumn floods was much more prominent when compared with the spring floods. Hence, it was safe to conclude that the autumn flood pattern had undergone higher level of impacts in recent decades compared to the spring floods at Hagabru catchment.

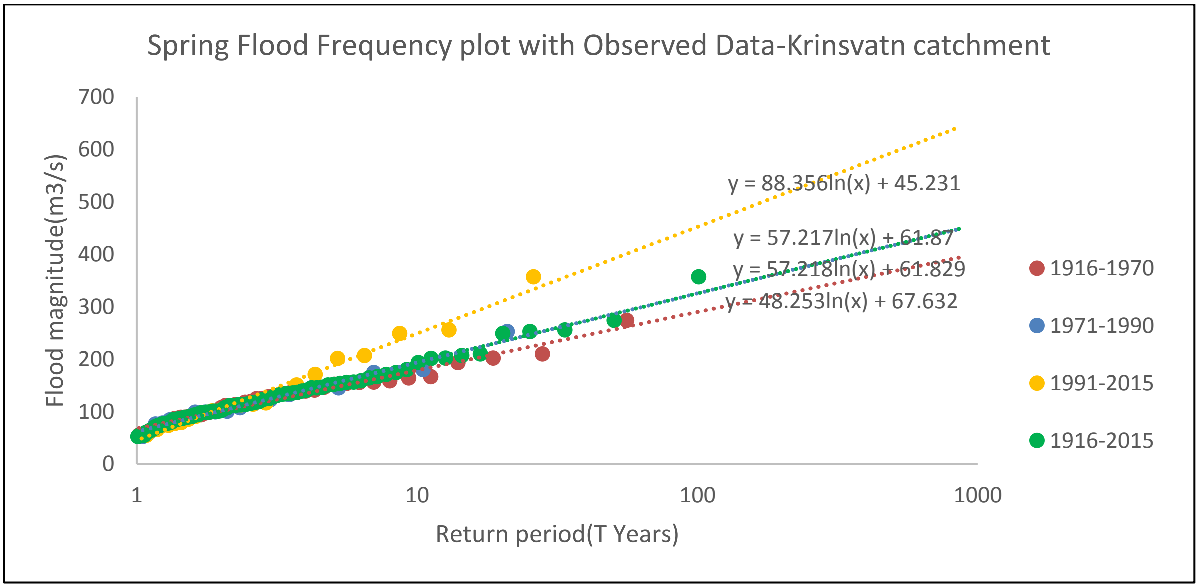


Figure 4.19: Spring Flood frequency probability plotting with observed data –Krinsvatn catchment

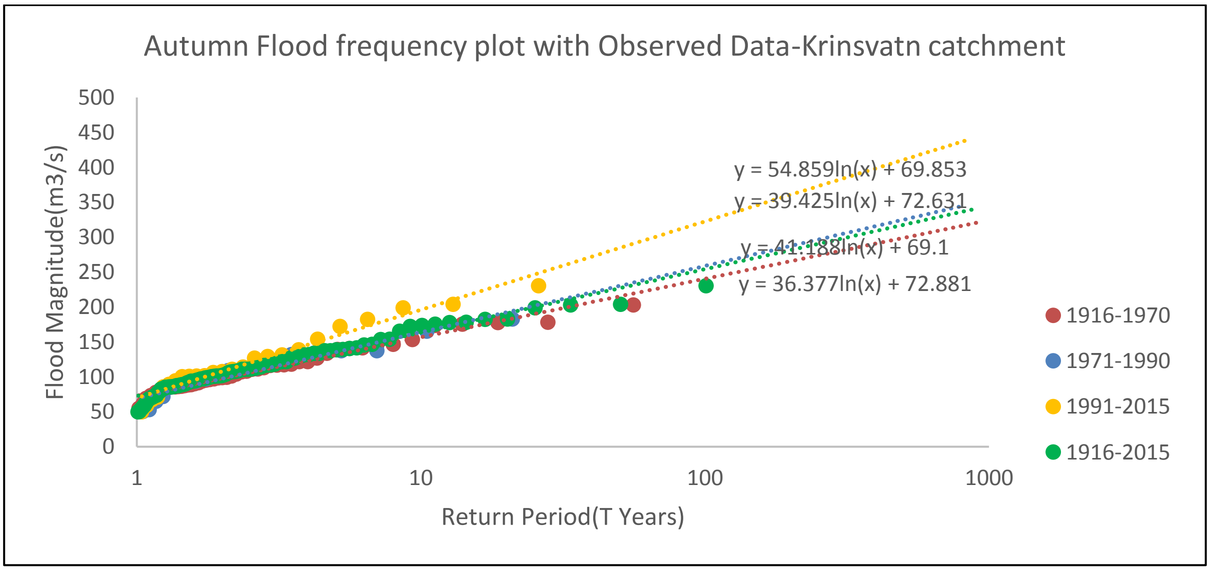


Figure 4.20: Autumn Flood frequency probability plotting with observed data –Krinsvatn catchment

Similar seasonal flood frequency analysis was carried out for Krinsvatn catchment and the results are depicted in **Figures 4.19** and **4.20**. The trends observed were quite interesting in that significant spread was observed with both the spring floods and the autumn floods. Hence, it was concluded that the spring floods and autumn floods had undergone alterations at Krinsvatn catchment. And also, the flood magnitudes of respective return periods were seen to be undergoing a gradual enhancement effect in recent decades at Krinsvatn catchment in both the seasons.

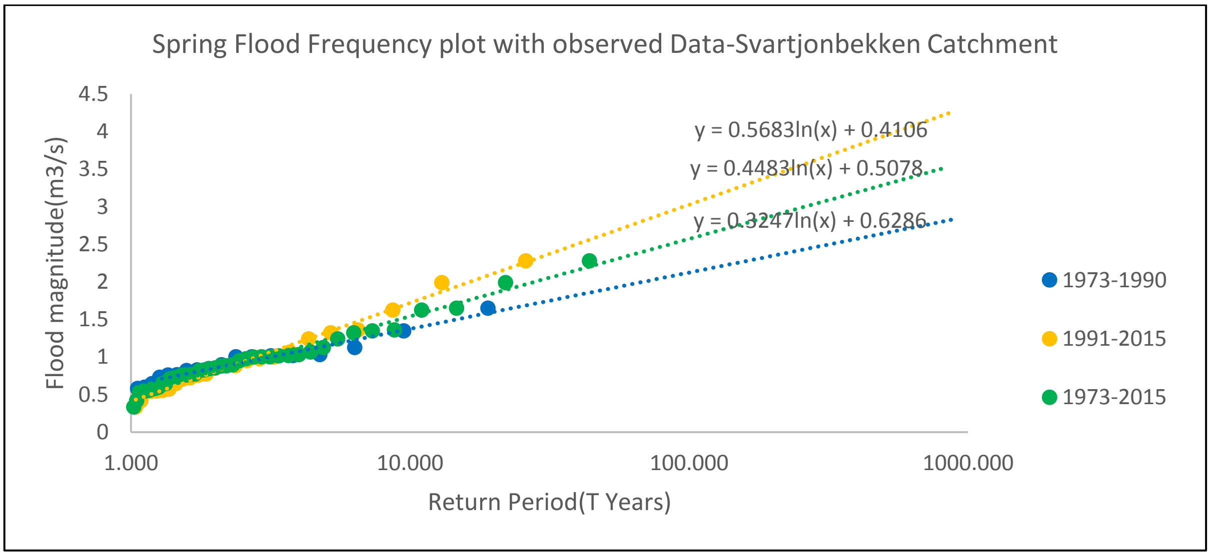


Figure 4.21: Spring Flood frequency probability plotting with observed data –Svartjonbekken catchment

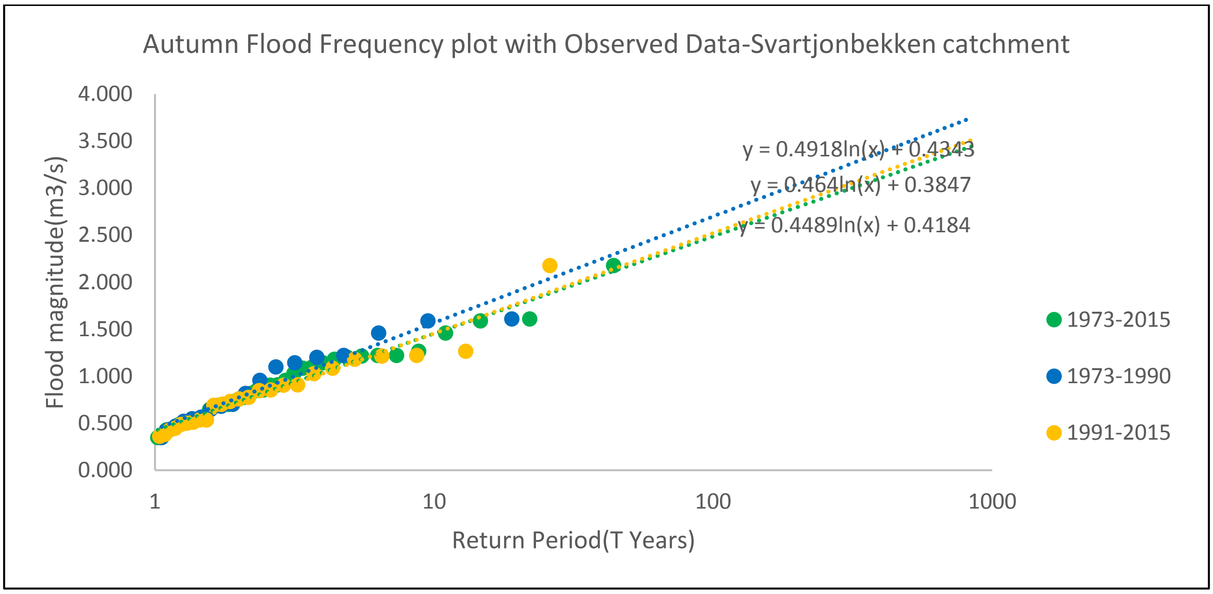


Figure 4.22: Autumn Flood frequency probability plotting with observed data –Svartjonbekken catchment

The seasonal flood frequency analysis for Svartjonbekken catchment yielded a mixed trend as can be observed from the **Figures 4.21** and **4.22**. The recent autumn floods (1990-2015) of respective return periods had lower magnitudes when compared to floods prior to 1990 whereas in the case of spring floods, the recent floods were having a significantly higher flood magnitude compared to the floods prior to 1990. Hence, no clear conclusion could be drawn with regards to climate impacts on seasonal floods in Svartjonbekken but it was still noticeable that the spring floods showed a much wider spread hinting at the fact that the spring hydrological regime might have undergone some transformation in recent decades.

To conclude, the recent floods were found to be undergoing gradual dampening in Hagabru catchment over the decades in both the autumn and the spring seasons. An opposite trend was detected at Krinsvatn catchment with increasing seasonal flood magnitudes in recent decades. A mixed trend was observed in Svartjonbekken that the spring floods were seen to be enhanced in recent decades and the autumn floods were observed to be undergoing gradual dampening in the recent decades. Hence, no conclusive trend was observable with respect to seasonal flood trends in the study catchments. But alterations to flood frequency trends were clearly observed.

5.0 CALIBRATION AND EVALUATION OF THE HBV MODEL

Study of the natural flow regimes and the flood frequency characteristics in a future climatic setting requires a calibrated hydrological model capable of accurately simulating the hydrological features at the study locations. The ability of the hydrological model to reproduce the observed historical runoff records can be considered as an evaluation criteria for discerning the validity of calibration and also the models ability of simulating the future runoff scenarios.

The following discussions describe the process of calibration of the HBV model for the study catchments with observed historical records of runoff, precipitation and temperature as input data. Also, the challenges faced with respect to the calibration process in validating the models performance and uncertainty are also discussed.

Input file for the HBV model requires runoff, precipitation and temperature time series over the same time period. Runoff data was available for Hagabru catchment over the time period 1908-2015, over the time period 1916-2015 for Krinsvatn and from 1973-2015 for Svartjonbekken. But, climate data was available over the period 1957-2015 for all the study catchments. Hence, available data over 1957-2015 was used as input for Hagabru and Krinsvatn catchments whereas 1973-2015 was used for Svartjonbekken.

Once the input files were prepared, the parameter files had to be set up for the respective HBV models. Details of confined parameters such as the catchment area, lake area % and hypsographical distribution were obtained from the catchment report generated by NEVINA, NVE. This has been presented for the study catchments in **Appendix 1** through **Appendix 3**. Also, since gridded data was employed to find the areal average precipitation and temperature series, the average elevation of the catchment (H_{50}) was considered as the elevation for the precipitation and temperature measurement stations.

Semi-confined parametric details were assumed as standards from Norwegian meteorological literatures and the input values are presented in **Table 5.1** and **Table 5.2** below. Finally, Annual Evapotranspiration values were obtained from pre prepared national maps from NVE and is presented in **Appendix 4.**

Table 5.1: Semi confined parametric details for the catchments

TCGRAD	-1 Deg C/100 m
TPGRAD	-0.5 Deg C/100 m
PGRAD	5%/100 m
LWMAX	0.07
NDAY	270
CGLAC	2
MAXUNIFORM	20 mm

Table 5.2: Snow distribution parametric details for the catchments

	Forest	Open
SMAX	1.5	2.0
S75%	1.25	1.5
S25%	0.75	0.5
SMIN	0.5	0.0

5.1 CALIBRATION DETAILS AND UNCERTAINTY EVALUATION

As concluded in **Section 4.2.1**, the hydrological regime of the study catchments have been steadily undergoing modifications. In order to obtain good quality calibration which was capable of performing in a future climate setting, decision was taken to choose recent periods for calibration of the HBV models. Hence, 1995-2000 was consistently assumed as the calibration period. 2000-2005 and 1990-1995 were employed as validation periods for the respective HBV models.

Figure 5.1 depicts the comparison between observed and simulated output for Hagabru catchment with best fitting calibration for water balance. The calibration resulted in a Nash-Sutcliffe coefficient of R^2=0.90 and an accumulated difference value of just -39 mm over the calibration period. The model also performed well over the validation period with an R^2 value of 0.80 over the simulation period 2000-2005 and an R^2 of 0.88 over 1990-1995. The models ability of accurately reproducing the recession curve and the timing of flood peaks was also observed to be of very good quality. Also, the model reproduced the observed changes in hydrography pattern over the decades to a very good extent when employed for simulations over the period of 1957-2015 as can be inferred from **Figure 5.2**. Hence, it was concluded that the model calibration with parameter set 1 met the quality requirements for good water balance. But, the resultant flood frequency analysis performed with the simulated data over the period 1957-2015 proved to be unsatisfactory as can be inferred from **Figure 5.3.**

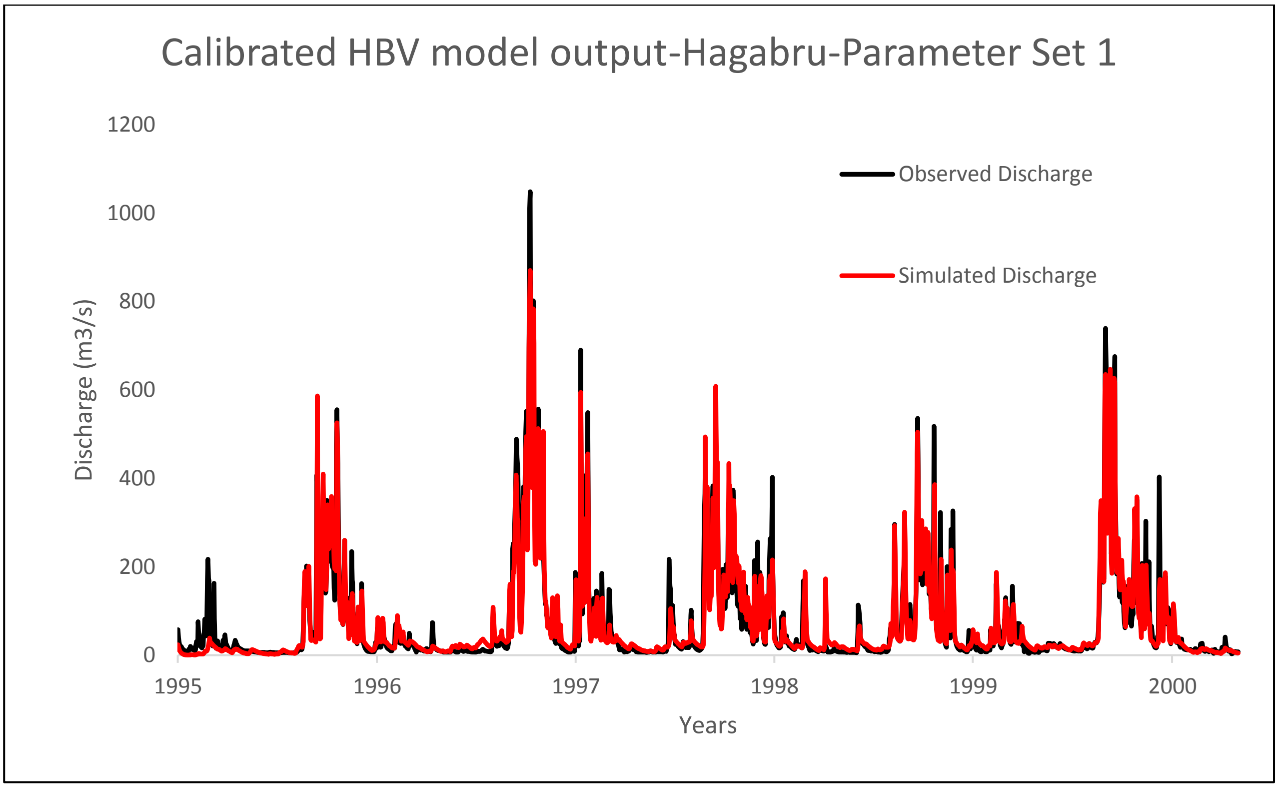


Figure 5.1: Calibrated HBV model output-Hagabru-Parameter set 1

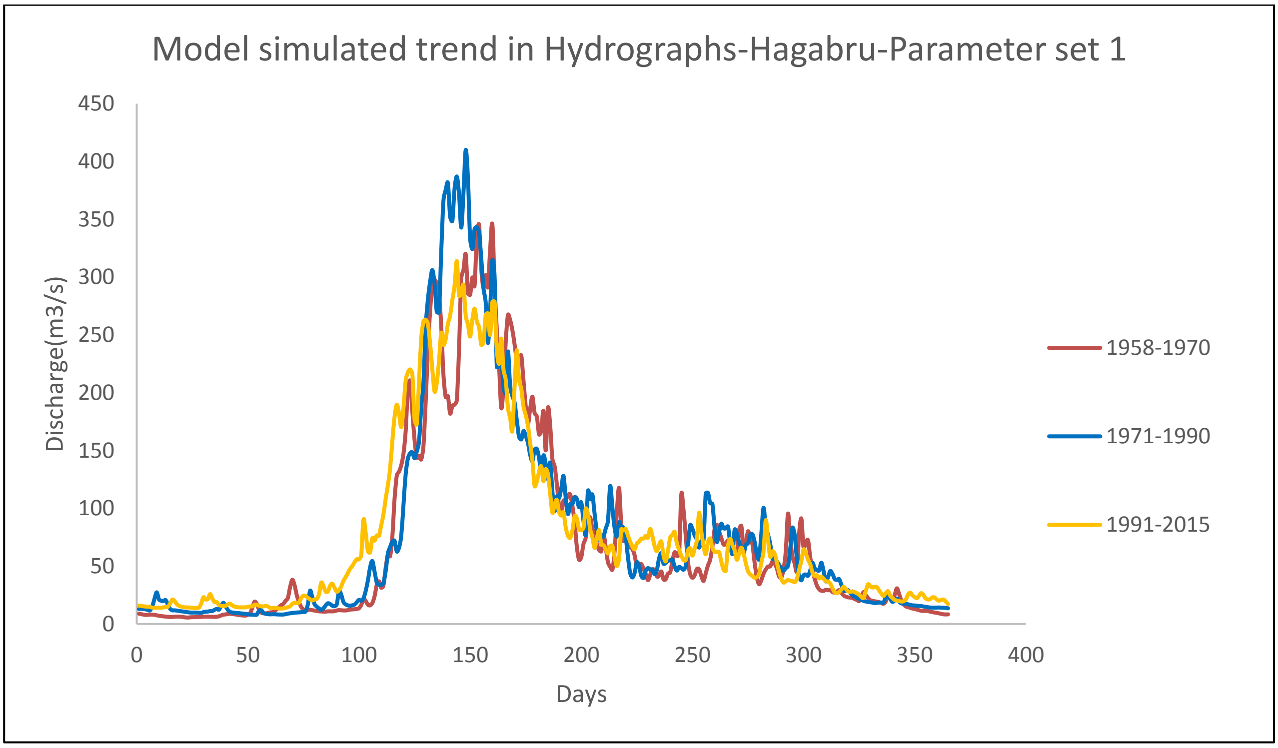


Figure 5.2: Model simulated trend in hydrographs-Hagabru-Parameter set 1

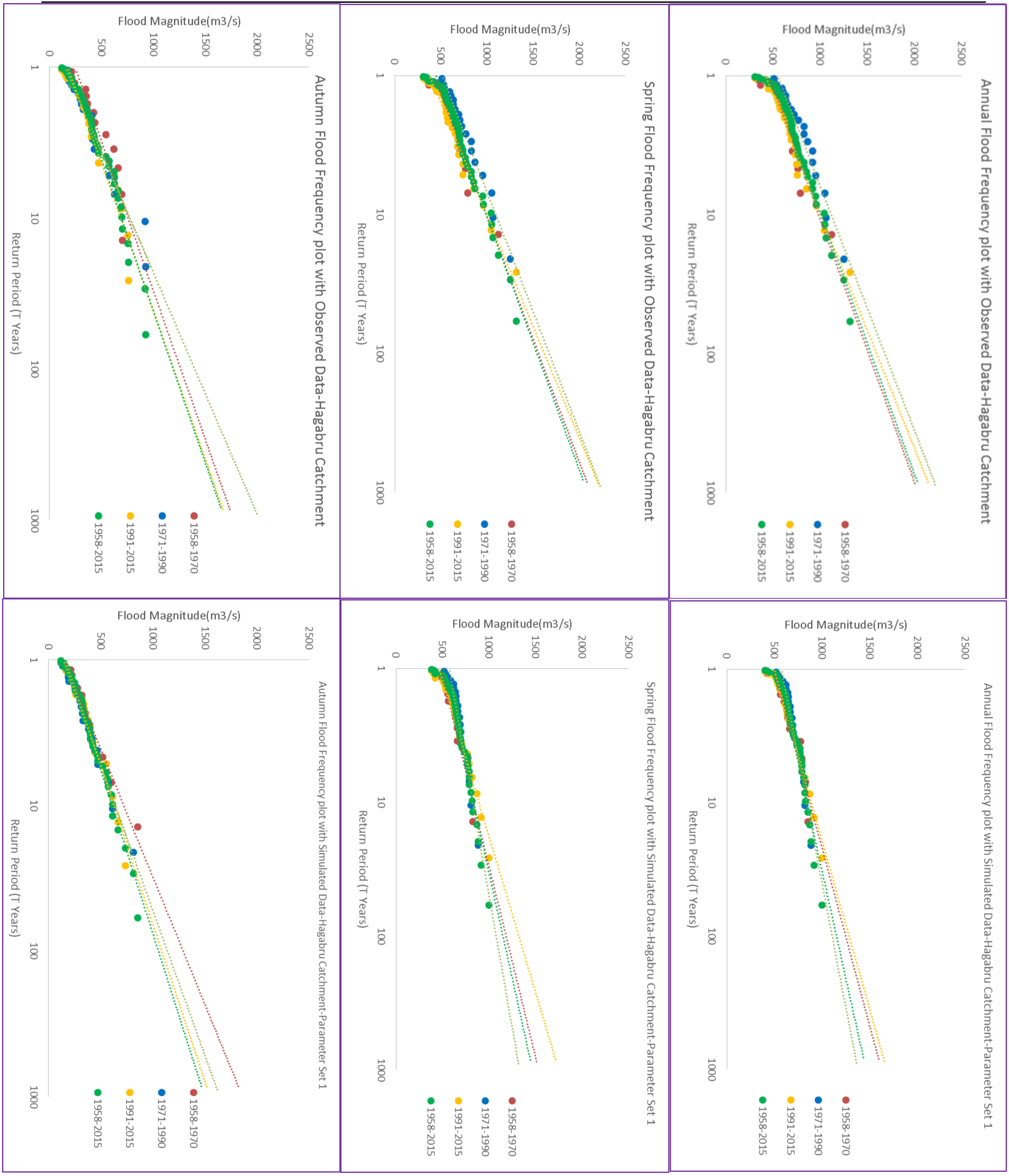


Figure 5.3: Calibrated HBV model flood frequency comparison-Hagabru-Parameter set 1

The model underestimated the flood magnitudes to a great extent which inevitably resulted in poor quality flood frequency fit on an annual basis and also on seasonal basis. The model was also unable to reproduce the variation in flood frequency characteristics over the decades. Hence, it could be concluded that the calibration with parameter set 1 was very much suitable for water balance studies but was ineffective for flood frequency analysis.

A recalibration was carried out to address this issue with scrupulous iterative approach with careful modification of parameters to come up with a parameter set capable of reproducing the flood frequency analysis to a good extent. The fundamental methodology adopted for recalibration was manual iterative parameter manipulation to come up with good fit for spring and autumn flood frequency trends. This would automatically result in a good fitting annual flood frequency trend. It was found that parameter RCORR was very sensitive with respect to autumn flood frequency trends whereas parameter SCORR and the snow routine parameters were the once in control of the spring floods while the flow response parameters such as KLZ, KUZ and so on influenced both the autumn and the spring flood generation. It was also found that spring floods were predominantly significant with respect to reproducing the annual flood frequency trends as the annual maximum floods in the study catchments were often spring floods with certain exceptions. The model output comparison with recalibrated parameter set is presented in **Figure 5.4** and the resultant flood frequency trend comparison has been presented in **Figure 5.6**. Recalibration over the period 1995-2000 resulted in an R^2 value of 0.80 and an accumulated difference value of 140 mm. Model validation over the periods 2000-2005 and 1990-1995 resulted in R^2 values of 0.67 and 0.74 respectively. It could be observed that the performance coefficients were considerably lower when compared to that obtained from parameter set 1. This was a strong indication that a hydrological model calibrated for obtaining good fit for water balance would be ineffective for flood frequency studies and vice-versa.

Further, a comparative study of the accumulated discharge was carried out to understand the behavior of the different parameter sets and the results are presented in **Figure 5.5**. It could be clearly observed that the performance of output obtained from Parameter Set 1 was superior compared to the output obtained from Parameter Set 2 that the accumulated discharge plots for the observed discharge time series and the simulated discharge time series for Parameter set 1 were in resonance with minor underestimations and this in turn resulted in an excellent accumulated difference value of just -39 mm. But, the accumulated plot for Parameter set 2 was overestimating the runoff on a consistent basis ultimately leading to a high accumulated difference value of 130 mm over the calibration period as clearly demonstrated by the plots in **Figure 5.5**.

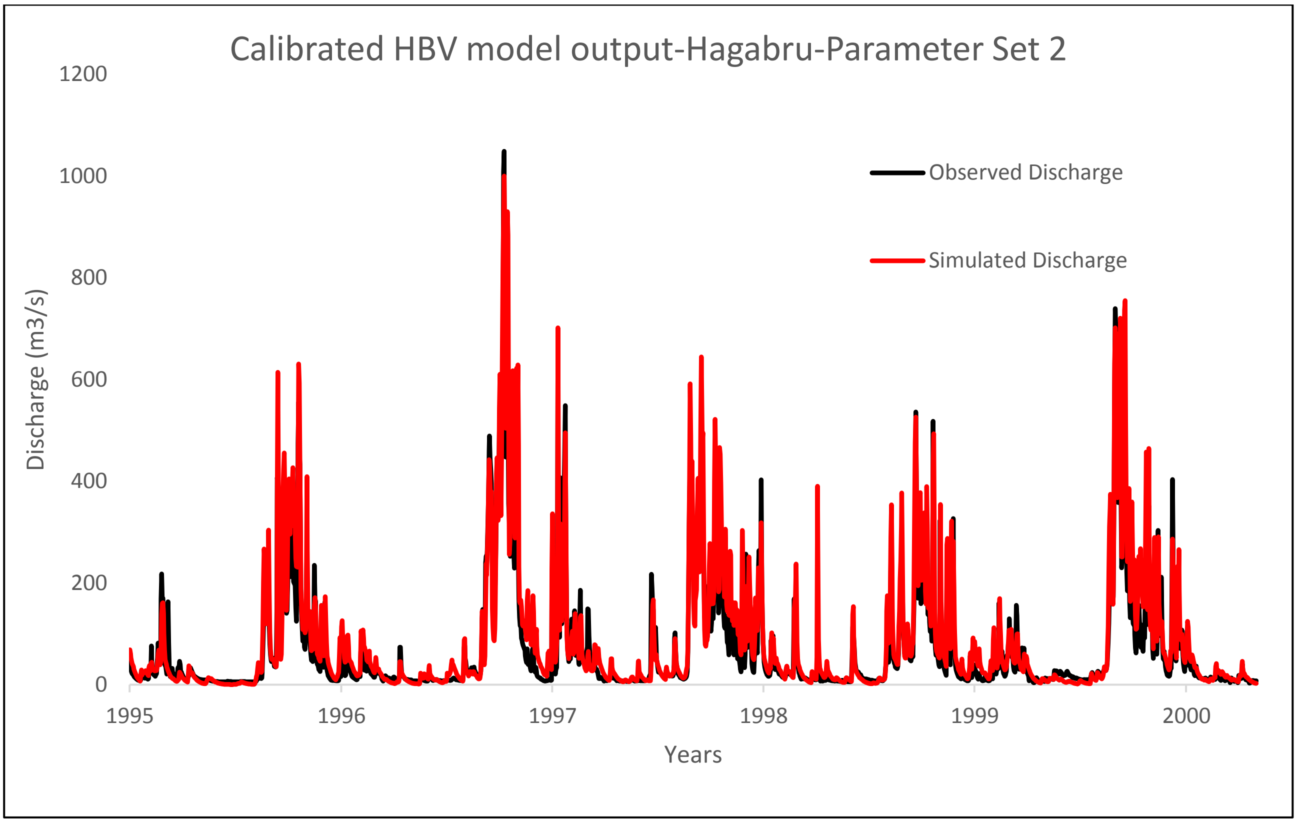


Figure 5.4: Calibrated HBV model output-Hagabru-Parameter set 2

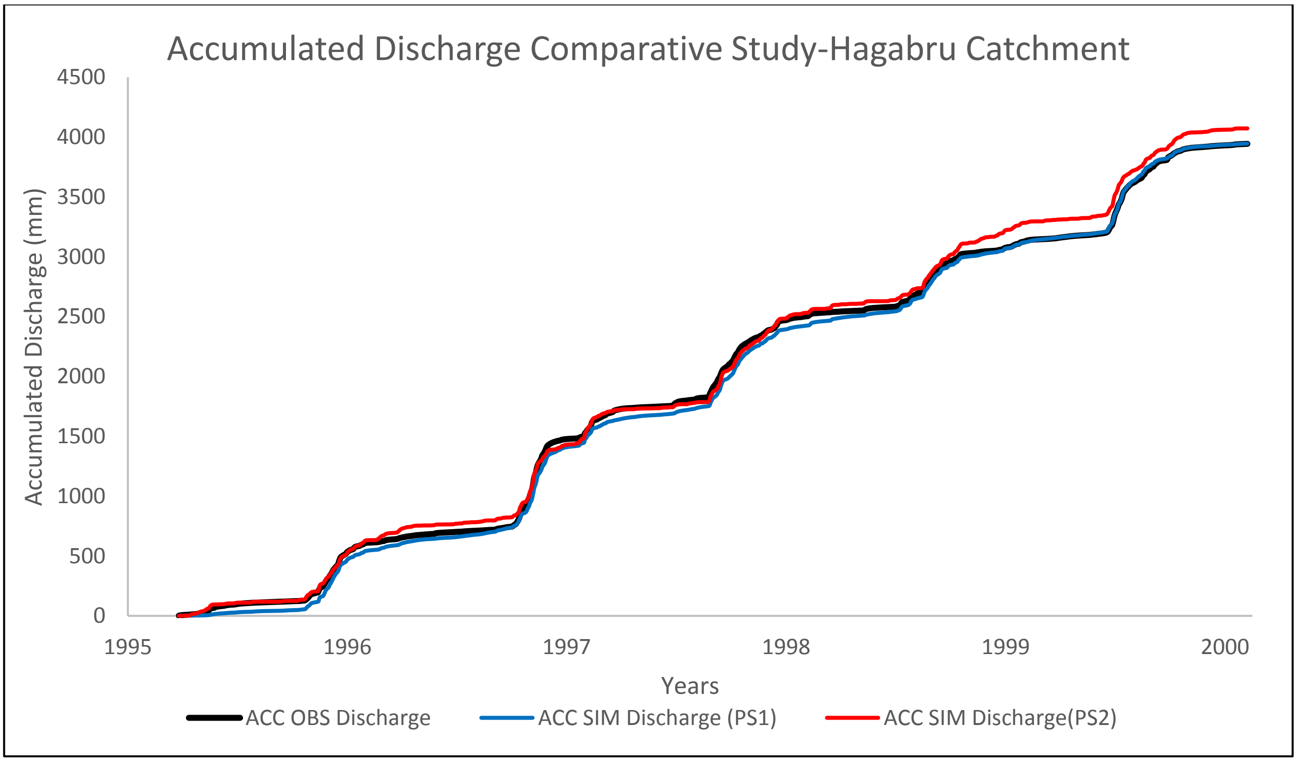


Figure 5.5: Accumulated Discharge Comparative Study-Hagabru Catchment

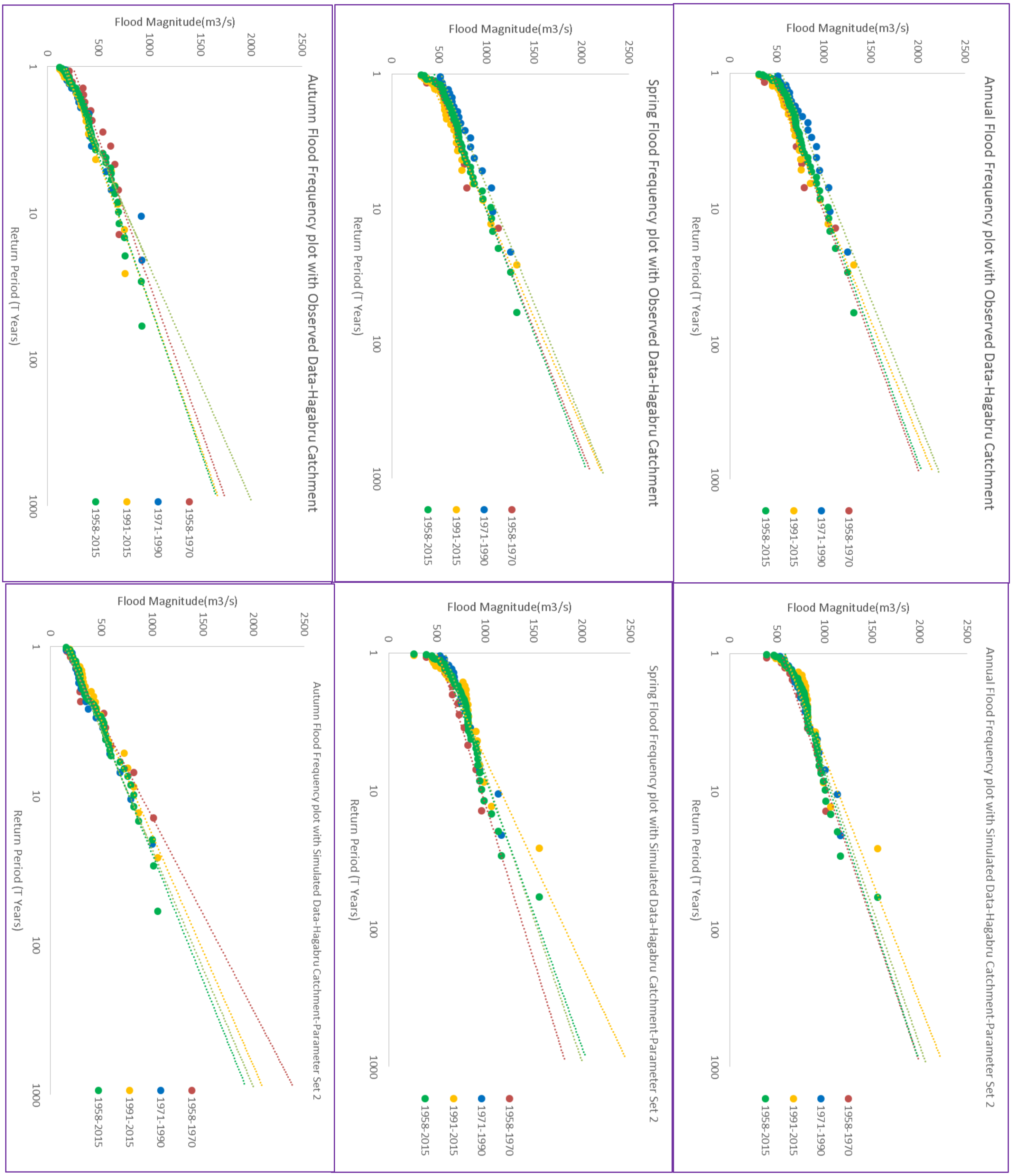


Figure 5.6: Calibrated HBV model flood frequency comparison-Hagabru-Parameter set 2

It was clearly observed that the model performance with parameter set 2 with respect to flood frequency analysis was superior to that obtained from parameter set 1. The model could capture not only the annual flood frequency trends but also the seasonal fluctuations over the decades which suggested that the calibration could be termed reliable for carrying out flood frequency analysis in a future climatic setting. The value of RCORR was changed from 0.99 within parameter set 1 to 1.30 in parameter set 2. Also, the value of SCORR was reduced from 1.3 to 0.73 within parameter set 2. This could not be concluded as an issue with input precipitation data quality but it was a necessary adjustment as the flow response and snow routine parameters were altered to obtain good fit for flood frequency as can be inferred from **Table 5.3**.

The manual calibration procedure adopted to achieve good fit for flood frequency analysis was as follows:

1. As previously stated, the parameter RCORR was found to be most influential for obtaining good fit for autumn flood frequency. Hence, RCORR was varied to obtain better fit for autumn flood frequency trends.
2. The snow routine parameters such as CX, CXN, TS, TSN were varied to obtain better fit for the spring flood frequency trends.
3. Finally, the flow response parameters were adjusted to achieve fine corrections for both the spring and autumn flood frequency trends.
4. This procedure was repeated multiple times until satisfactory fit for both the spring and autumn flood frequency trends was obtained.

An interesting finding as can be inferred from **Table 5.3** was that the parameter SCORR was reduced from 1.3 to 0.73 to obtain good fit for spring flood frequency. This was due to the internal redistribution of snow accumulation and depletion processes within the HBV model as parameters such as CX, CXN and the rest of the parameters within the snow routine were varied to compensate for the reduced SCORR value.

It is also worth noting that similar flood frequency trends could be obtained by varying only the parameters RCORR and SCORR significantly but this approach resulted in model performance with exorbitant accumulated difference values. Hence, an alternate manual calibration approach as previously described was adopted. This also hints at the uncertainty imparted by the Equifinality concept within the HBV model discussed in following sections of the report.

It was also found that obtaining good fit for autumn flood frequency floods was much more convenient with only minor adjustments required to the parameter RCORR and the flow response coefficients while the model response for obtaining good fit for spring floods was limited. This strongly points at the over parametrized nature of the snow routine within the HBV model which makes the process of manual parameter adjustments cumbersome.

Table 5.3: HBV parameter set comparison-Hagabru catchment

	Parameter set 1	Parameter Set 2
RCORR	0.995	1.30
SCORR	1.312	0.73
CX	3.572 mm/Deg C day	8 mm/Deg C day
CXN	1.915 mm/Deg C day	8 mm/Deg C day
TX	0.973 Deg C	1.226 Deg C
TS	0.484 Deg C	2.00 Deg C
TSN	-2.92 Deg C	0.08 Deg C
KUZ2	2.365 mm/day	7 mm/day
KUZ1	0.558 mm/day	3 mm/day
KUZ	0.050 mm/day	0.5 mm/day
KLZ	0.037 mm/day	0.052 mm/day

The same methodology was adopted to investigate HBV model calibration performance for Krinsvatn and Svartjonbekken catchments and the findings are presented in **Appendix 5** and **Appendix 6.** It was once again found that RCORR and SCORR were the governing parameters when it comes to obtaining good fit for flood frequency analysis. Similar trend in model performance coefficients were observed with calibration for good water balance giving higher R^2 values in comparison with calibration for flood frequency fit in all the study catchments.

Summary of the calibration results for water balance (Parameter set 1) for the study catchment are presented in **Table 5.4** and calibration results carried out for flood frequency fit are presented in **Table 5.5**.

Table 5.4: HBV model performance comparison-Parameter set 1

Catchment	R^2(Nash-Sutcliffe model coefficient)-Parameter set 1		
	1990-1995	1995-2000	2000-2005
Hagabru	0.88	0.90	0.80
Krinsvatn	0.84	0.84	0.83
Svartjonbekken	0.65	0.72	0.73

Table 5.5: HBV model performance comparison-Parameter set 2

Catchment	R^2(Nash-Sutcliffe model coefficient)-Parameter set 2		
	1990-1995	1995-2000	2000-2005
Hagabru	0.74	0.80	0.67
Krinsvatn	0.70	0.76	0.72
Svartjonbekken	0.60	0.66	0.66

5.2 UNCERTAINTY EVALUATION FOR HBV MODEL CALIBRATION

The primary uncertainty when dealing with calibration of HBV models for various purposes was whether the optimizing algorithm (PEST) was capable of coming up with parameter sets which satiate the needs of the specific task at hand. The results of the investigation carried out (**Figure 5.7** to **Figure 5.9**) clearly demonstrated the fact that a single parameter set was incapable of meeting the quality requirements for both water balance studies and flood frequency studies as far as the selected study catchments of central Norway were concerned.

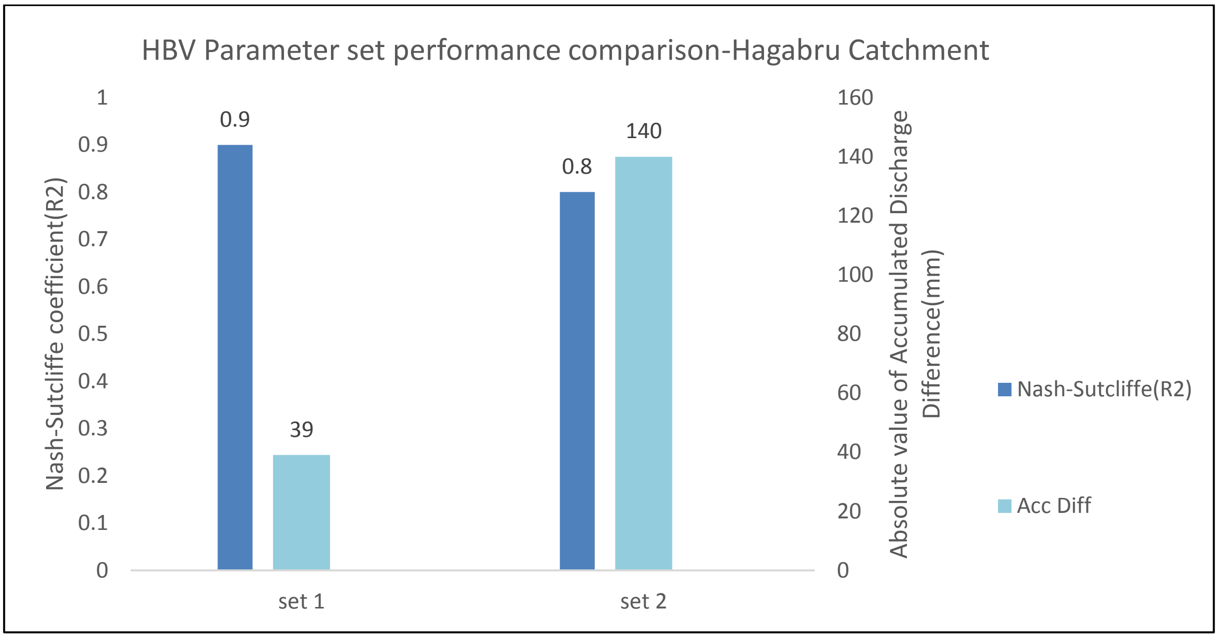


Figure 5.7: HBV model parameter set performance comparison-Hagabru catchment

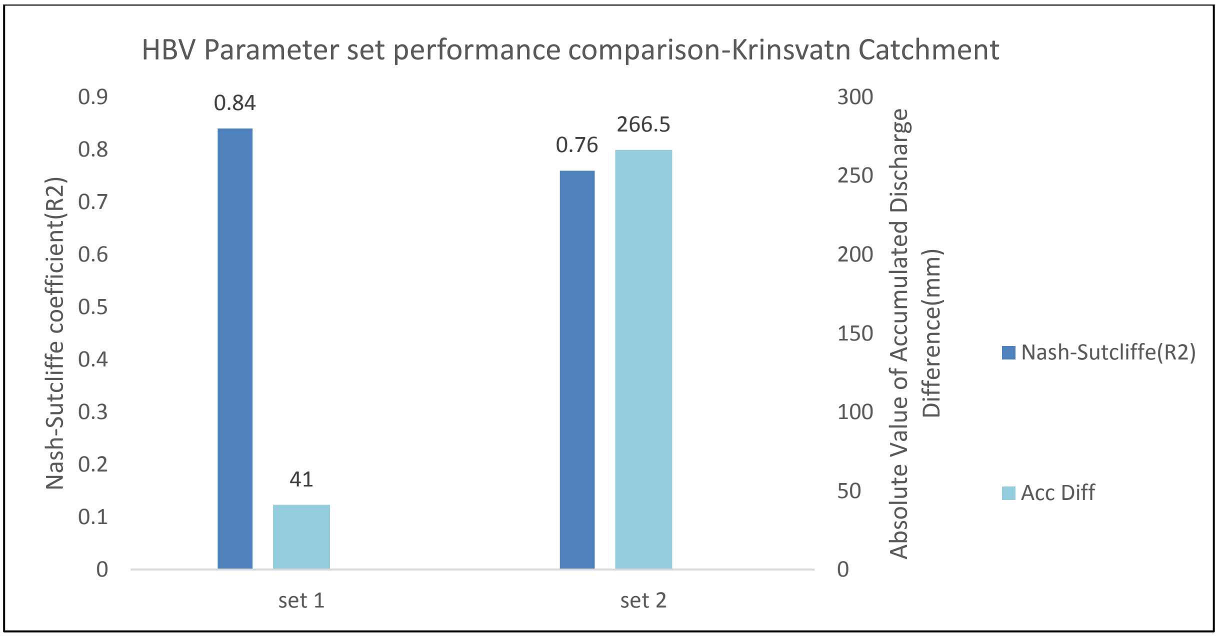


Figure 5.8: HBV model parameter set performance comparison-Krinsvatn catchment

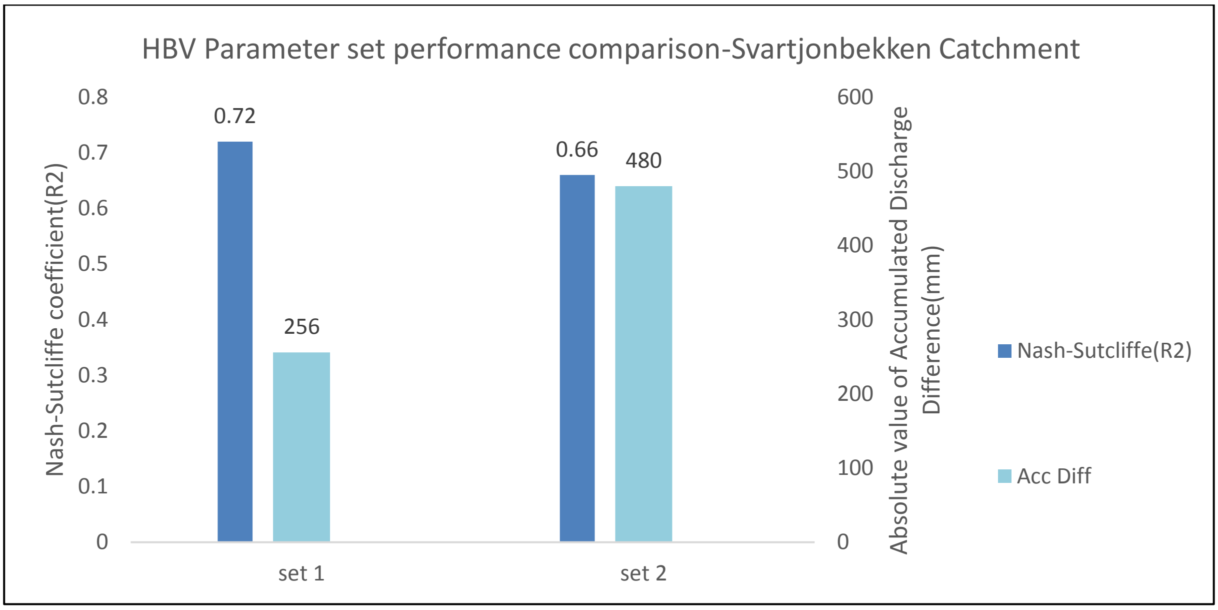


Figure 5.9: HBV model parameter set performance comparison-Svartjonbekken catchment

This leaves us with an uncertainty as to what methodology needs to be adopted for identifying ideal parameter sets for various purposes. At present, no standard guidelines are available from any established research or governmental organizations to deal with this issue. But, the NVE seems to be working with a methodology where 25 different parameter sets with comparable R^2 values are considered in a Monte-Carlo type of analysis and it is assumed that all uncertainties are evaluated within the range of these parameter sets. An excerpt from an NVE report states "*Ensemble models include 25 calibrated parameter sets for each catchment, so that uncertainty introduced by hydrological modelling can be considered* **[31]**". Further, they also state "*Model calibration was accomplished using PEST routine and 150 different best fit model parameter sets were calibrated for each catchment. The best 25 parameter sets were selected for each catchment for further use, such that for individual catchments the Nash-Sutcliffe criterion varies by no more that 2%* **[32]**".

The fundamental problem with this approach is that it considers parameter sets of comparable model efficiencies (That is with a difference of ±2%). But, the project findings clearly show that the model efficiencies can vary by much more than 2% and by as much as 20%. Hence, the approach adopted by the NVE which considers 25 different sets may still result in inaccurate flood frequency analysis. However, the approach cannot be termed ineffective as a large number of simulations are carried out which can broaden the uncertainty range with model output and a widening of search criteria from the assumed 2% can add to the validity of the approach.

The manual iterative approach adopted in this research project gives much better control over the calibration outcome when compared to the NVE approach in that it is certain that a unique parameter set capable of capturing the flood peaks can be arrived at. But, there would still be multitudes of parameter sets which could probably give similar outputs. Also, this approach inevitably inherits the disadvantage of manual HBV calibration in that it can be time consuming and the results can always be refined with effort.

An alternate solution for this issue would be the addition of a flood frequency analysis routine within the HBV model which can override the water balance calibration approach to come up with good fit for flood frequency. Research and development in this regard is highly possible and would greatly enhance and broaden the scope of applicability of the HBV model for various research and utility purposes.

5.3 HBV PARAMETER SETS UNCERTAINTY EVALUATION

The inherent uncertainty with hydrological model output is directly dependent on the reliability or confidence in the parameter sets employed for the purpose of runoff simulations. The over parameterized nature of the HBV model can lead to large uncertainties with model behavior when employed for practical applications. Also, the Equifinality effect with HBV model calibrations can add to this uncertainty.

In previous discussions, the importance of coming up with right parameter sets for different practical applications was discussed. Further detailed evaluations were carried out in this regard to ascertain the dependability of HBV model outputs for the three catchments under consideration. The Monte-Carlo approach was implemented to come up with different parameter sets of comparable model efficiencies to discern the behavior of the HBV model and to delineate the uncertain sections of the hydrograph. This would give a much better understanding and serve as a caution as to which sections of the hydrographs need special attention to determine the validity of model output.

Monte-Carlo calibrations were carried out to come up with ten different parameter sets of comparable model efficiencies for each of the catchments. The parameter set selection criteria was that the Nash-Sutcliffe model efficiency criterion (R^2)>0.7 for Hagabru and Krinsvatn catchments and R^2>0.60 for Svartjonbekken catchment considering that the best fit model efficiencies obtained were 0.90,0.84 and 0.75 for Hagabru, Krinsvatn and Svartjonbekken catchments respectively. The calibration periods for the catchments were maintained from the previous discussions (1995-2000) for all the study catchments.

Further, annual hydrographs were constructed by employing the simulated discharges for each of the chosen parameter sets. That is, 30 different hydrographs were constructed for the three study catchments. The obtained ensemble plots gave exhaustive amount of information as to which sections of the hydrographs were more uncertain.

Finally, to determine the confidence or reliability with the HBV model outputs, plots consisting of 95% confidence intervals about the ensemble means juxtaposed with the observed daily mean discharges were constructed. These plots once again provided valuable information regarding model behavior in simulations of the seasonal fluctuations in runoff generation patterns. **Figure 5.10** through **Figure 5.12** depict the investigation results obtained as described previously for the three study catchments.

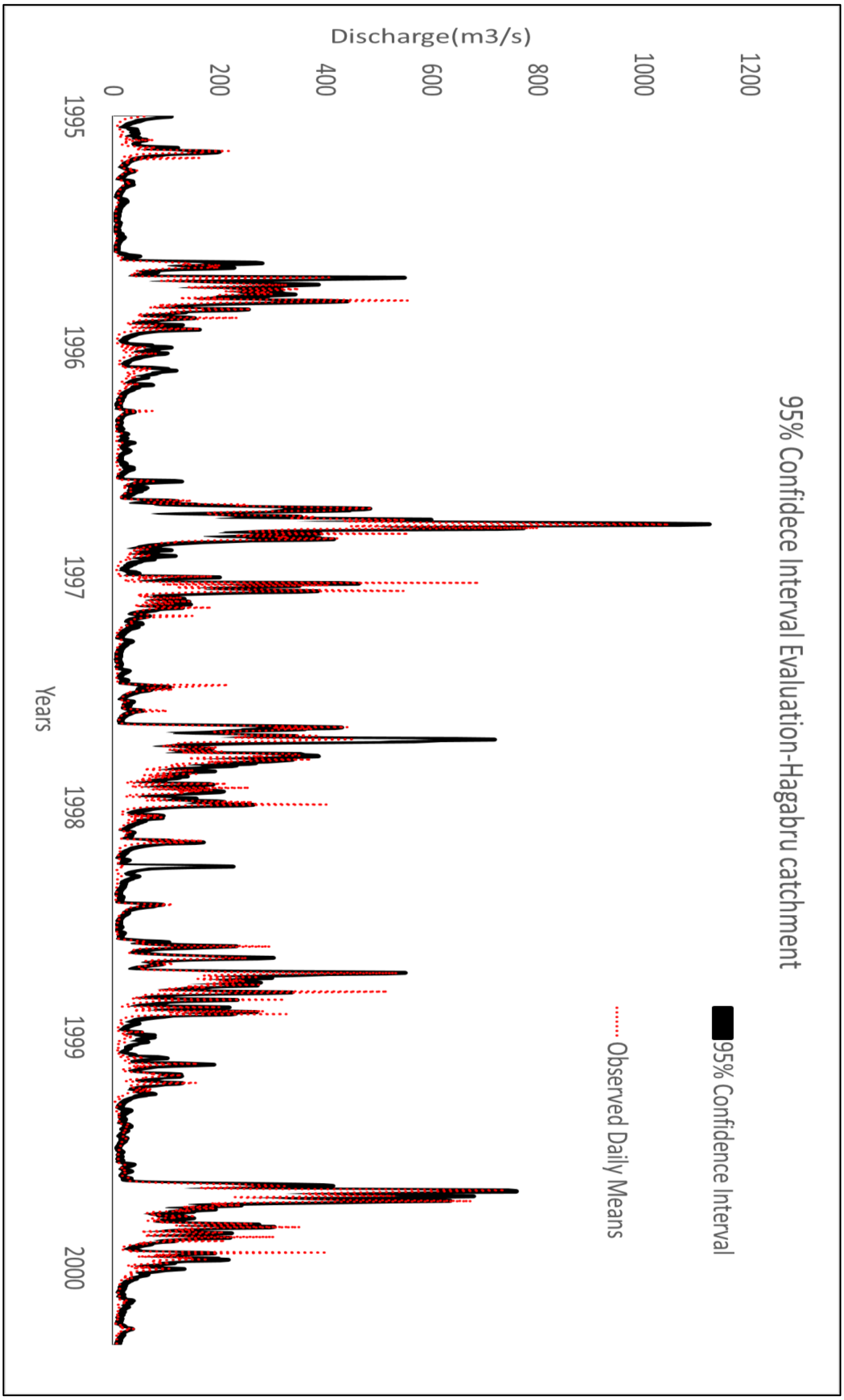


Figure 5.10: 95% Confidence Interval Evaluation-Hagabru catchment

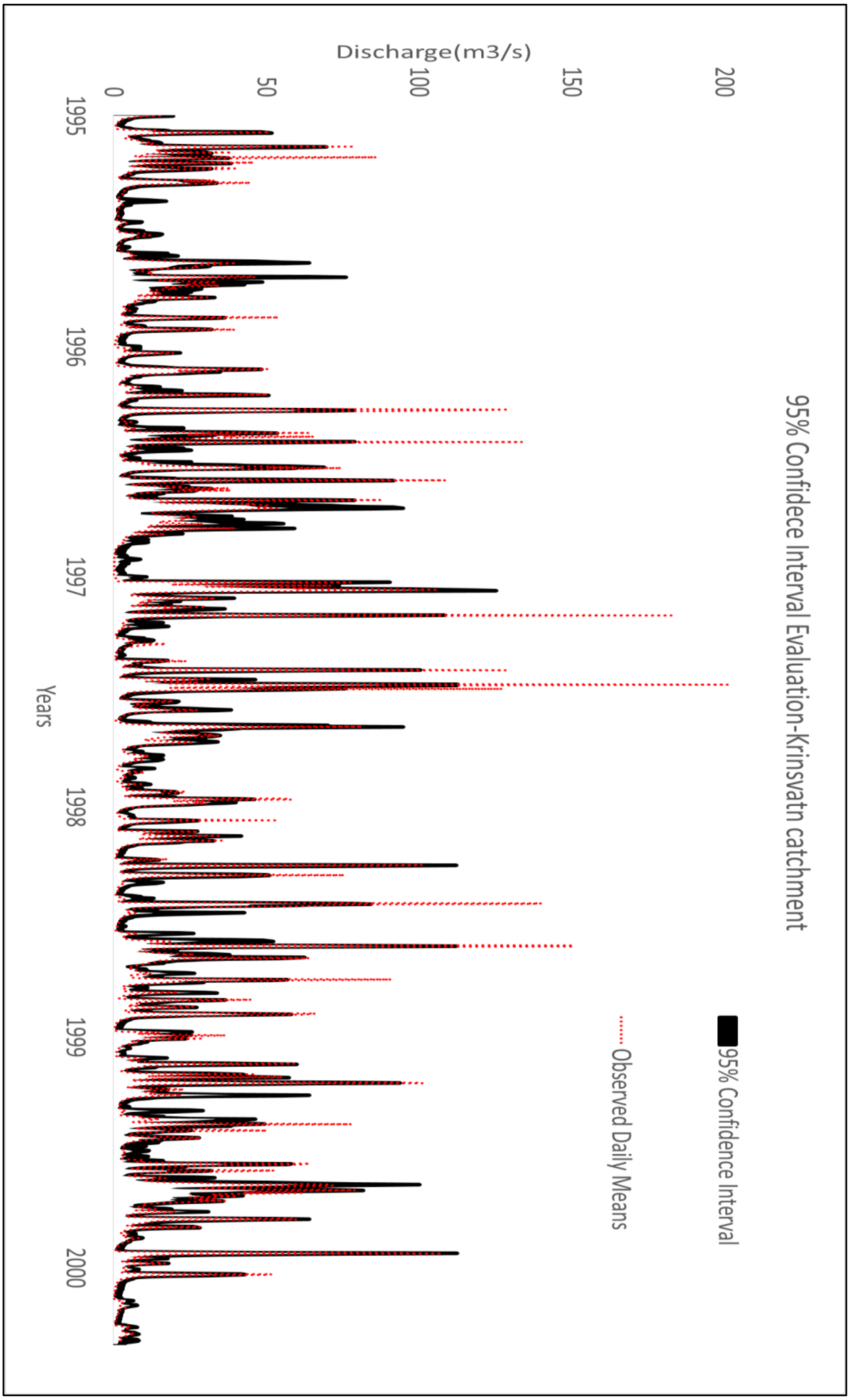


Figure 5.11: 95% Confidence Interval Evaluation-Krinsvatn catchment

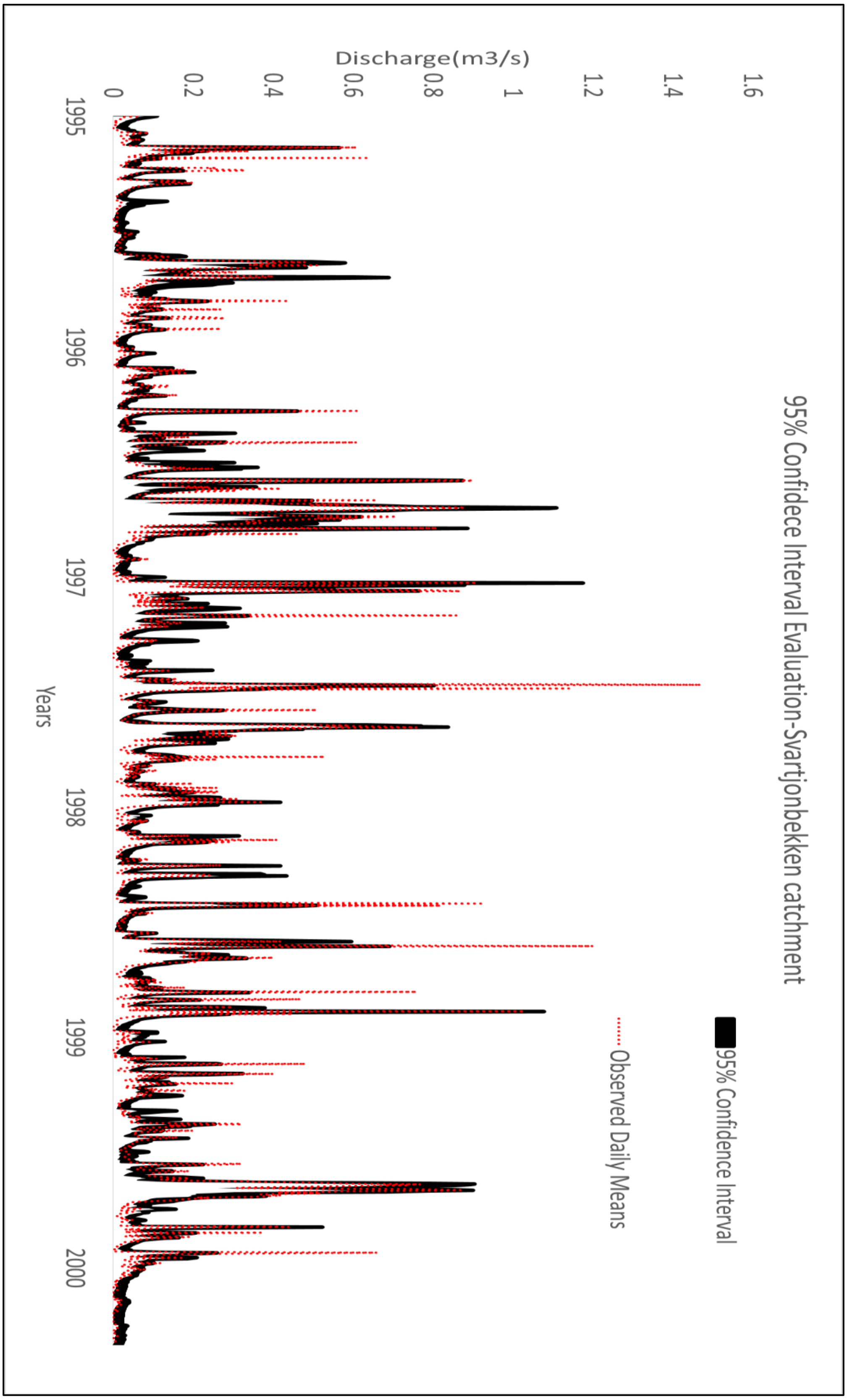


Figure 5.12: 95% Confidence Interval Evaluation-Svartjonbekken catchment

The fundamental reasoning behind the Monte-Carlo analysis is that if multiple parameter sets of comparable model efficiencies are found and simulated over the same time period, variations in model outputs can give significant information regarding the uncertainty inherent with the model outputs and can also act as a caveat for future studies with the models.

A consistent pattern observed with all the study catchments was that the ensemble band width or the spread observed with the ensemble plots were at their highest during the peak snowmelt floods (Between Days 100 and 150). The ensemble band widths were found to be much narrower in other sections of the hydrographs. This strongly suggested that the models ability of accurately simulating the spring melt floods was questionable. This finding further strengthened the arguments made in **Section 5.1** of this study report that the models ability of reproducing the flood frequency analysis was unsatisfactory with best fit model efficiencies. The observed spread with the ensembles during the spring melt floods season might have also been the reason for obtaining parameter sets of much lower model efficiencies which were very much capable of capturing the flood peaks to a great degree of accuracy.

Further, the observed daily mean discharges were juxtaposed with the plots of 95% confidence intervals about the ensemble mean discharges to observe the deviations from the confidence intervals. The deviations observed were minor with most deviations concentrated in the spring flood and the autumn flood seasons which was consistent with the findings of the previously discussed results. The observed deviations were minimal for Hagabru catchment and were significant for Krinsvatn and Svartjonbekken catchments. For Krinsvatn and Svartjonbekken catchments, the models either overestimated or underestimated the spring and autumn flood peaks which led to the observed deviations.

Also, it was an important finding that the 95% confidence interval was found to be lower than the observed daily mean discharges at some sections of the hydrographs and were found to be higher in some sections. This strongly suggested the fact that the model was consistently underestimating or overestimating the spring melt floods and the autumn floods. This was essentially the reasoning behind going for a manual recalibration approach in **Section 5.1** of this study. Although the reasoning behind this flood peak discrepancy trends was unclear, the over parameterized nature of the snow routine within the HBV model could offer an explanation in this regard that the process of calibration can get convoluted leading to higher degree of uncertainties. Hence, it was concluded that the spring melt flood season was particularly sensitive to variation in HBV parameter sets as far as the study catchments were concerned and also the manual calibration approach to obtain good fit for flood frequency analysis was concluded to be the right strategy adopted as the models ability of accurately producing flood peaks was questionable.

Cases presenting the range of uncertainty with the HBV model output were presented in this study. It could be deduced from the discussions that parameter sets with similar model efficiencies could generate disparate simulations. This finding clearly demonstrates the uncertainty range with HBV parameter sets and once again highlights the Equifinality concept. In an earlier discussion it was stated that the approach adopted by the NVE of choosing 25 different parameter sets with comparable model efficiencies would be inappropriate for flood frequency analysis. However, this approach would be very much valid for general runoff generation as it captures a broader uncertainty spectrum. This discussion was intended at elucidating the need for carrying out a Monte-Carlo type of evaluation especially when it comes to general runoff simulations. Looking into the reasoning behind the working of the calibration process would be beyond the scope of this study.

6.0 CLIMATE DATA DOWNSCALING AND EVALUATION

The outline of the process of climate data downscaling has been described in an elaborate manner within the discussions presented in **Chapter 2**. The present discussion aims to present the details of a proposed precipitation climate data downscaling technique and also the evaluation of its performance when employed for practical hydrological applications such as runoff generation and flood frequency analysis.

6.1 QUALITY EVALUATION OF GCM CLIMATE DATA

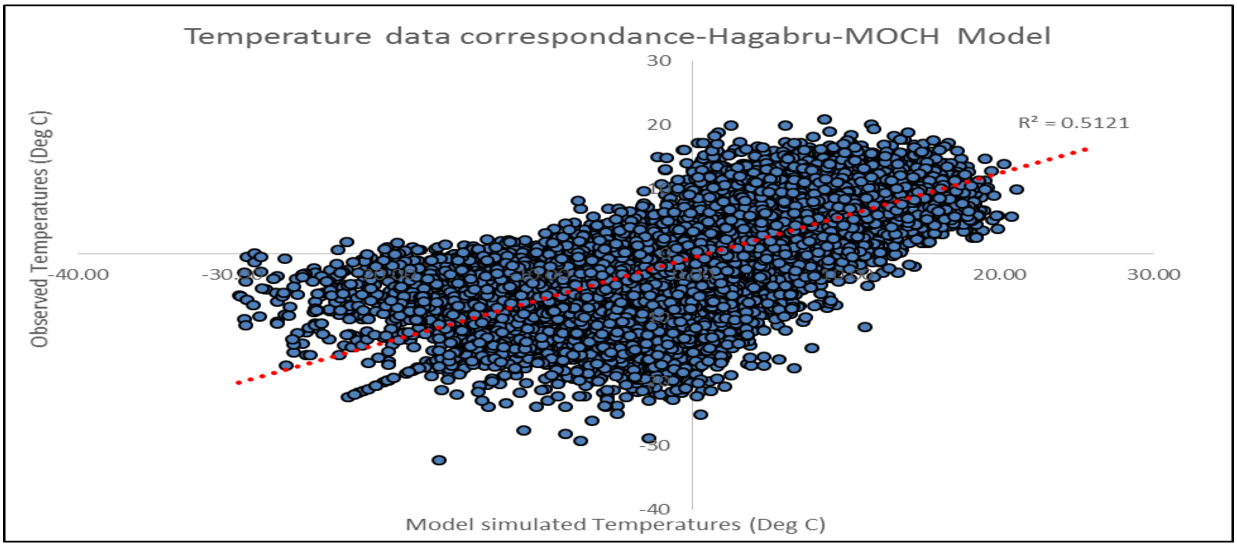
It is a well-known fact that the climate data obtained from a GCM includes systematic biases which hamper the validity of the data for practical applications. **Figures 6.1** represent the correlation between the observed and the GCM simulated climate data for Hagabru catchment. It was apparent that the correlation for temperature time series was much higher when compared to that of precipitation time series. This was due to the fact that GCMs are predominantly designed with the primary objective of simulating temperature changes to a great degree of accuracy by incorporating large number of process computations. Gross assumptions and oversimplifications with respect to simulating precipitation data leads to poor data quality.

A simple linear regression approach would be sufficient for downscaling temperature data whereas implementation of specialized techniques would be necessary in order to obtain downscaled precipitation data of good quality. Since the obtained temperature data was of very good quality, focus has been laid on precipitation data downscaling within this research project.

The quality of input precipitation is generally measured by two different parameters.

1. Monthly Mean Precipitation Values
2. Number of Rainy days in a year

To get an idea about the quality of GCM simulated precipitation data, a comparative study of the previously mentioned parameters was conducted and the results for Hagabru catchment are presented in **Figure 6.2** and **Table 6.1**. From literature review of the well-established methods of precipitation downscaling prevalent at present times, it was apparent that they are primarily designed with the objective of obtaining identical monthly means or rainy day correction. But, the objective of the proposed Antinoise downscaling technique was to obtain similar monthly means, rainy day correction and to go one more step further, to obtain similar daily means with a simple and easily reproducible strategy.



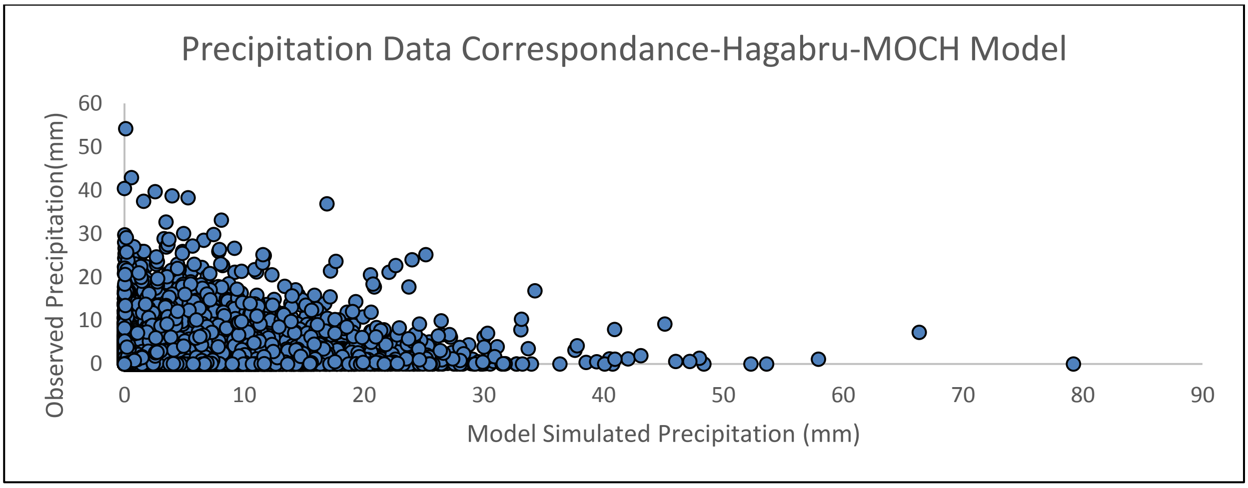


Figure 6.1: Temperature and precipitation data correspondence-Hagabru catchment

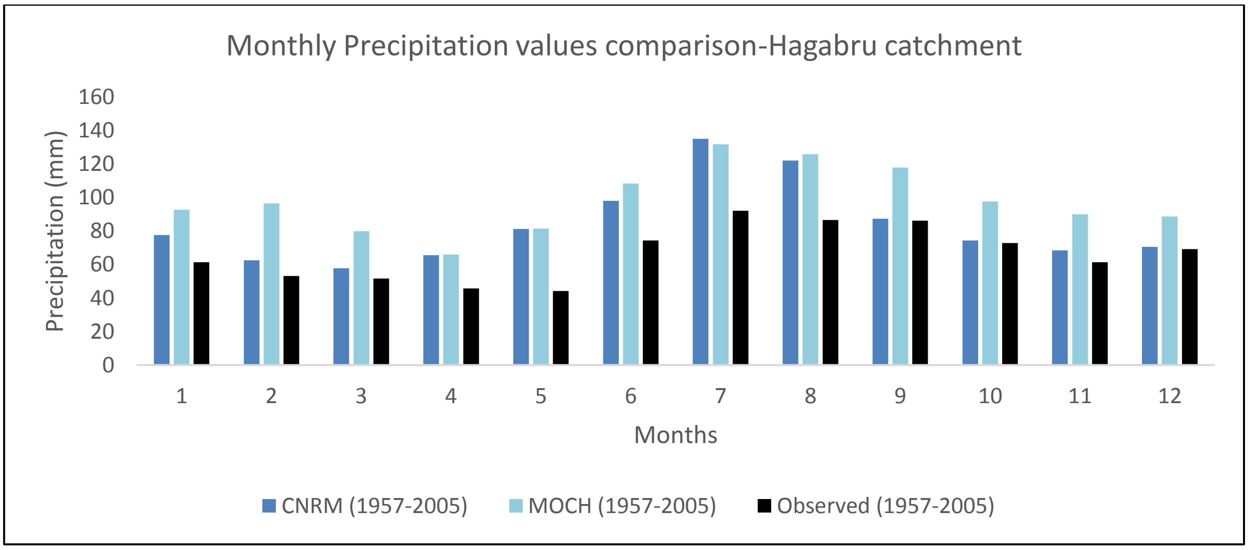


Figure 6.2: Monthly Precipitation data correspondence-Hagabru catchment

Table 6.1: Rainy Days comparison-Hagabru catchment

Model Name	Simulated Average number of rainy days (1957-2005)	Observed average number of rainy days (1957-2005)
CNRM	327	254
MOCH	357	254

As could be observed by the depiction of the monthly mean comparison in **Figure 6.2**, both the models consistently overestimated the precipitation values which led to exorbitant monthly mean values. From **Table 6.1**, it was observed that the models also overestimated the annual rainy days. These overestimations needed to be corrected as these could lead to excess precipitation within the hydrological model and result in invalid calibration. Refining the precipitation data was very essential at this stage of the study.

6.2 ANTINOISE DOWNSCALING-GENESIS

Precipitation downscaling can be quite challenging especially when intended for flood frequency analysis with complex regional topography as the GCM data often renders data of poor correspondence especially for peak flows which necessitates implementation of a specialized precipitation downscaling techniques to correct the GCM data for biases.

Most of the well-established climate data downscaling technique such as linear scaling, Variance scaling and Power transformation are primarily designed with the objective of achieving good agreement for monthly means and not the daily means. Coming up with a strategy for precipitation data downscaling to address this issue was particularly challenging. The Antinoise downscaling method introduced was a preliminary attempt at obtaining precipitation data with similar daily means.

A well-established technique within the discipline of electrical engineering inspired a new downscaling technique termed 'Antinoise Downscaling'. Heavy electrical appliances in close proximity can affect the performance of each other through interactions of the individual electrical field and this phenomenon is known as 'Harmonic Distortion'. This can result in reduces system efficiencies or may even lead to catastrophic explosions. In order to account for this imminent danger, electrical engineers came up with a specialized equipment which detects the pattern of electrical signals from individual equipment's and in turn, generates mirrored electrical signal which cancels out the electrical noise generated by the appliances thereby maintaining system stability. This technique is known as 'Anti-Phase' and is widely implemented in heavy utility structures such as skyscrapers, central internet servers and so on.

A thought experiment gave rise to an idea of implementing this technique for climate data downscaling. If the observed precipitation patterns and the GCM simulated precipitation patterns are assumed as electrical waves, the difference in amplitudes of the wave trends could be termed as 'programing noise'. Correction for this noise by superimposing an 'anti-noise' could result in precipitation data of considerably better quality. The following section presents the implementation and evaluation of this technique for Hagabru catchment.

6.3 ANTINOISE DOWNSCALING TECHNIQUE

Antinoise downscaling works on the assumption that the difference between the observed precipitation patterns and the GCM simulated precipitation patterns follow a consistent trend. This was essentially observed to be the case upon preliminary investigation of the climate data for the study catchments. The pattern difference between the observed precipitation and the GCM simulated precipitation followed a unique trend for a particular GCM. This investigation was carried out only for precipitation data and not for temperature data as it is a well-known fact that temperature data downscaling is a straight forward task as most of the well-established downscaling strategies are capable of correcting the temperature data with great degree of accuracy. Further, the obtained temperature data already had good correspondence with the observed data.

The outline of the general approach adopted in the Antinoise downscaling technique essentially involves 5 steps as discussed below:

STEP 1: Daily average annual precipitation plots were prepared with observed data and GCM simulated historical precipitation data sets.

STEP 2: The difference between the observed and the GCM simulated precipitation plots were computed and were assumed as programing noises for the respective GCMs.

STEP 3: Antinoises which were essentially a mirror image of the delineated noise patterns were prepared for each of the models.

STEP 4: These Antinoise patterns were superimposed on the GCM simulated data on an annual basis with the baseline condition that precipitation can never be less than zero.

STEP 5: Finally, for downscaling future projected precipitation data, an assumption was made. Since the noise patters for the respective GCMs were consistent over an extended period in the past, it was logical to assume that the same noise patterns would persist in the future as the model structure would be unaltered. Hence, the respective Antinoise patterns would be superimposed on the future projected precipitation data for downscaling.

Methodology and performance evaluation of Antinoise downscaling has been presented for Hagabru catchment within this discussion and reference is made to **Appendix 7** and **Appendix 8** for similar evaluations of Krinsvatn and Svartjonbekken catchments. The proposed method could be classified as a statistical downscaling method. Further, it could also be employed as a statistical-dynamic method by implementing the proposed strategy to RCM simulated precipitation data. Hence, the scope for applicability of this approach could be termed broad in nature. The most prominent advantage of the proposed methodology is the user-friendliness and elimination of specialized computing power.

STEP 1: The first step in Antinoise downscaling was to sort the daily observed and GCM simulated precipitation time series on an annual basis (1957-2005). Further, daily average annual precipitation plots were prepared for the sorted data. **Figures 6.3** and **6.4** depict the trends in observed daily average precipitation (P_{OD}), daily average precipitation for CNRM model (P_{G1D}) and MOCH model (P_{G2D}) over the period 1957-2005.

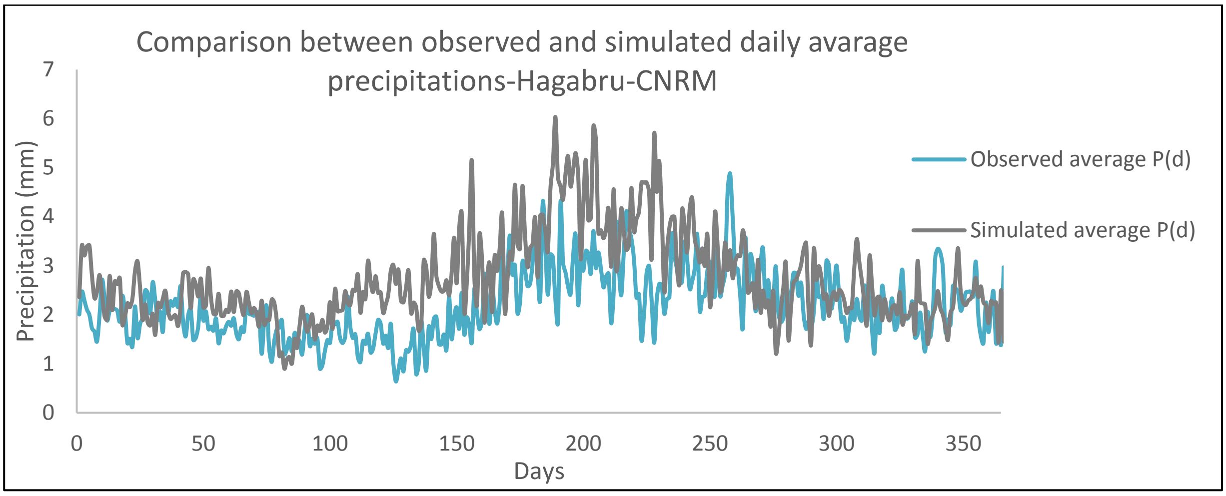


Figure 6.3: Comparison between observed and simulated daily average precipitation-Hagabru catchment-CNRM model

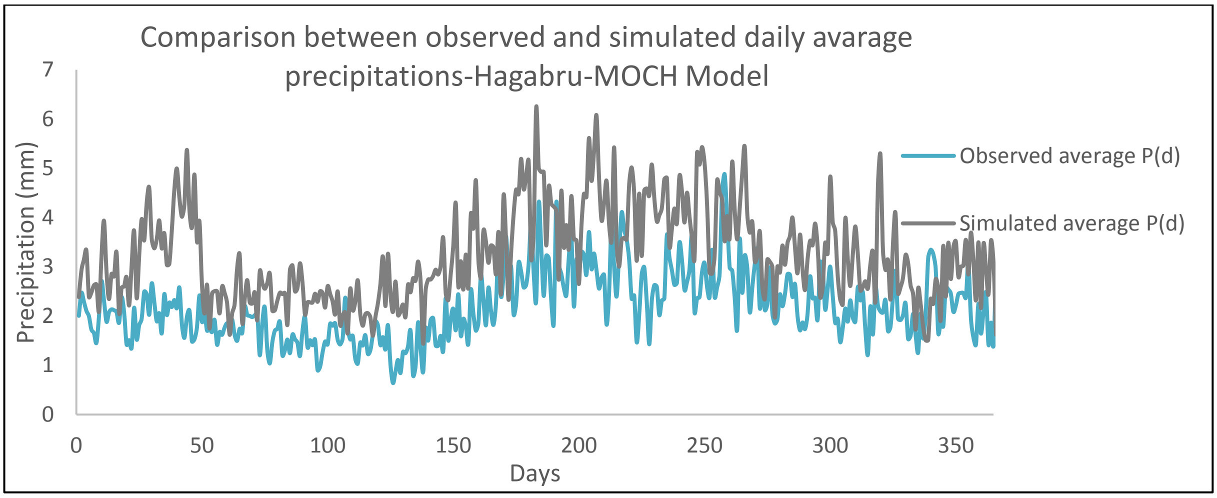


Figure 6.4: Comparison between observed and simulated daily average precipitation-Hagabru catchment-MOCH model

STEP 2: The differences between the annual precipitation plots were computed for each year and analyzed for consistency. It is important to note that the individual differences in precipitation trends were consistent throughout the period of 1957-2005 for both the models with only slight deviations. This suggested that the differences could essentially be termed as 'programing noises'. That is, all of the systematic biases included in the GCM simulated data were assumed to be delineated as part of the noise trends (N_{1D} and N_{2D}). Hence, average trends in differences between the observed and GCM simulated precipitation data over the period of 1957-2005 were computed and were assumed as programming noises for the individual models and have been presented in **Figure 6.5** and **Figure 6.6.**

$$N_{1D}=P_{G1D}-P_{OD} \quad (6)$$

$$N_{2D}=P_{G2D}-P_{OD} \quad (7)$$

Where,

N_{1D}=Average Noise pattern from CNRM model data

N_{2D}=Average Noise pattern from MOCH model data

P_{G1D}=Daily average Precipitation pattern from CNRM model data

P_{G2D}=Daily average Precipitation pattern from CNRM model data

P_{OD}=Daily average Precipitation pattern from observed data

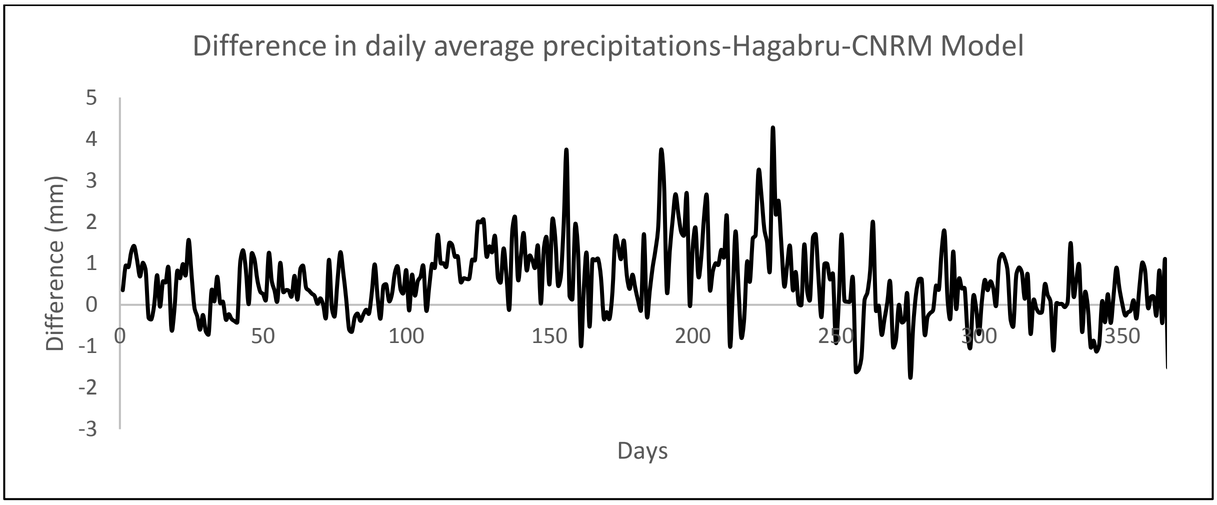


Figure 6.5: Difference in daily average precipitations-Hagabru catchment-CNRM model

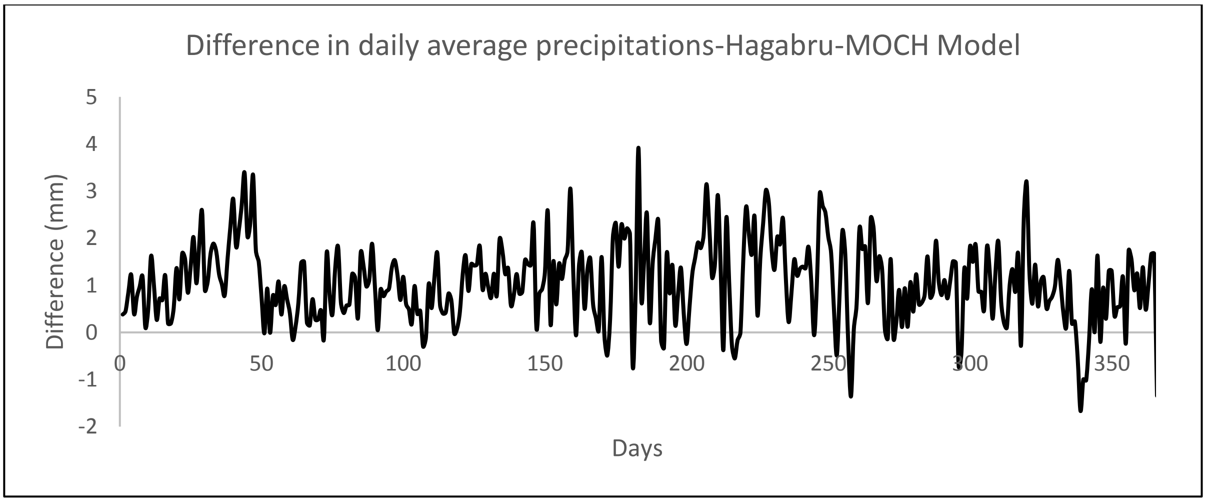


Figure 6.6: Difference in daily average precipitations-Hagabru catchment-MOCH model

STEP 3: Anti-noises were generated to correct for the above depicted programing noises inherent in GCM data. These essentially were mirror images of the noise patterns. The generated anti-noise patterns are presented in **Figure 6.7** and **6.8.**

$$A_{1D} = -N_{1D} \quad (8)$$

$$A_{2D} = -N_{2D} \quad (9)$$

Where,

A_{1D}=Antinoise pattern for CNRM model
A_{2D}=Antinoise pattern for MOCH model

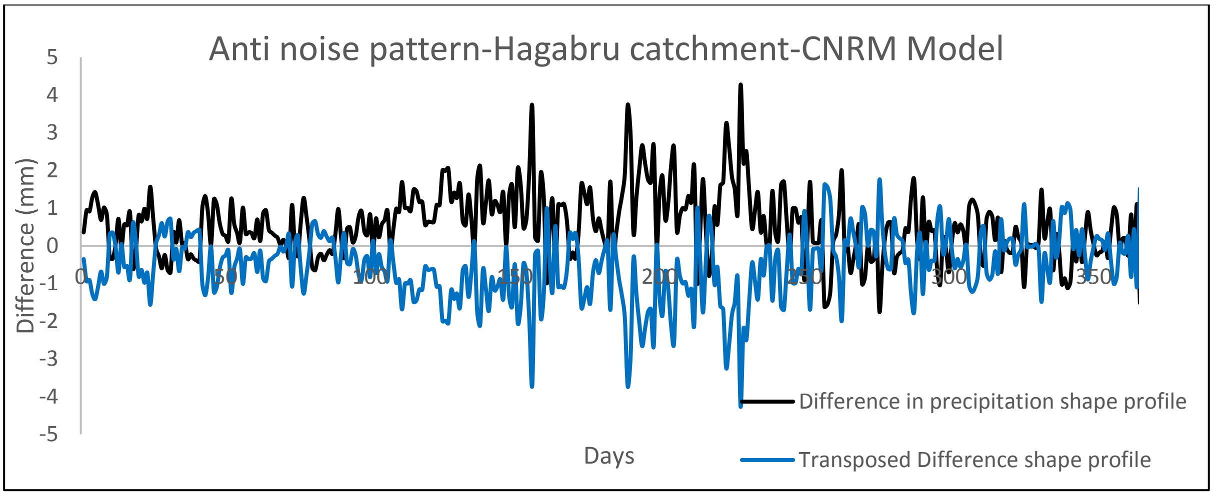


Figure 6.7: Antinoise pattern generation-Hagabru catchment-CNRM model

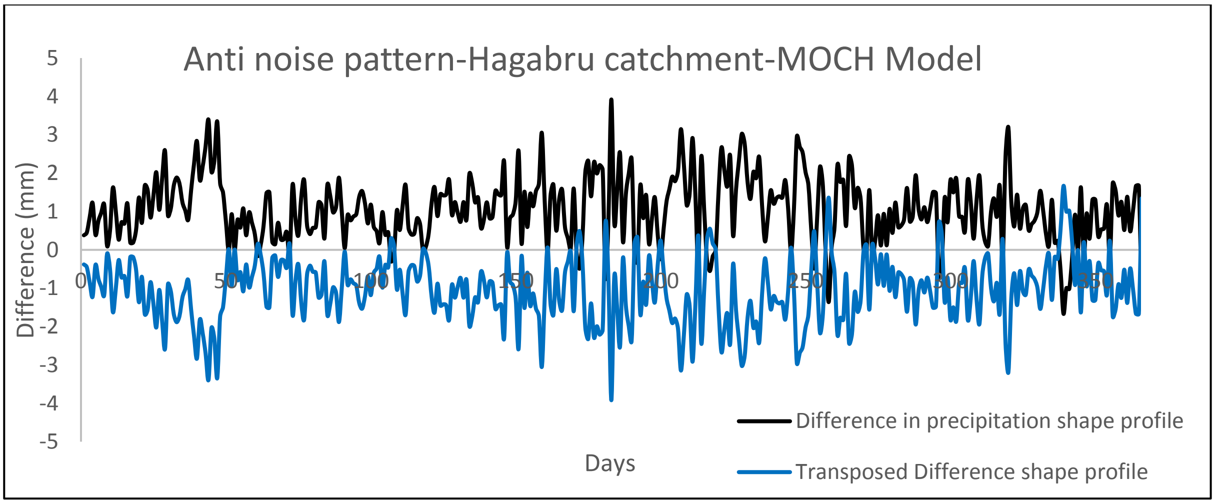


Figure 6.8: Antinoise pattern generation-Hagabru catchment-MOCH model

STEP 4: The generated Antinoise patterns were superimposed on the GCM simulated precipitation time series on an annual basis. That is, the Antinoise pattern were added to the GCM simulated precipitation pattern on an annual basis. The resultant modified precipitation trends are presented in **Figure 6.9** and **6.10.**

$$M_{1D}=IF((P_{G1D}+A_{1D})>=0;(P_{G1D}+A_{1D});0)\text{.....................}(10)$$

$$M_{2D}=IF((P_{G2D}+A_{2D})>=0;(P_{G2D}+A_{2D});0)\text{.....................}(11)$$

Where,
M_{1D}=Modified daily precipitation for CNRM model
M_{1D}=Modified daily precipitation for MOCH model

It is very important to note that **Steps 1** through **3** were carried out using the average annual precipitation patterns over the entire observation period, in this case 1957-2005. But, **Step 4** should be implemented on annual precipitation patterns for each individual year in order to get the corrected daily precipitation series. That is, Antinoise correction should be applied to each individual years.

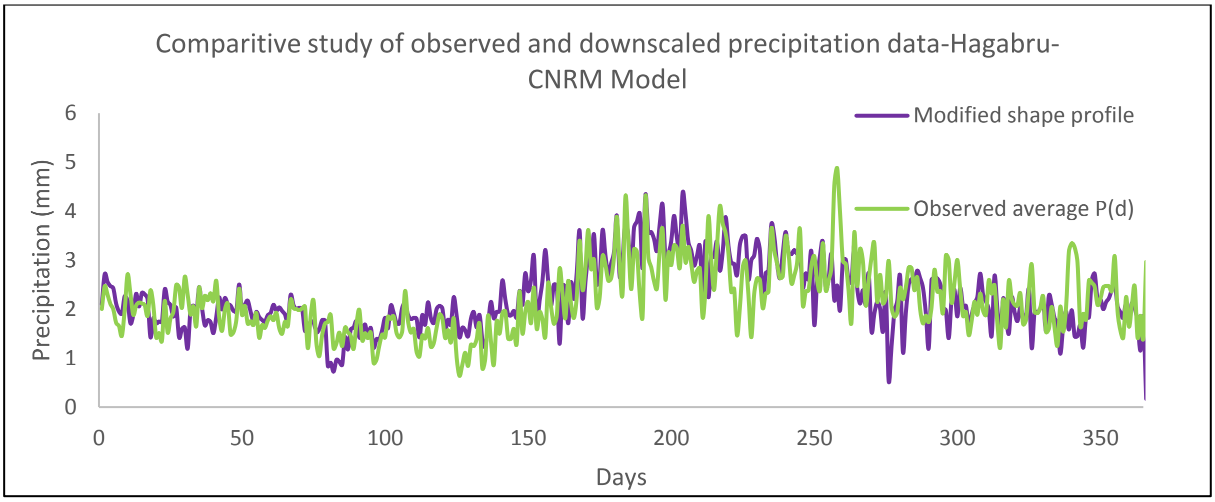


Figure 6.9: Comparison of observed and downscaled precipitation data-Hagabru catchment-CNRM Model

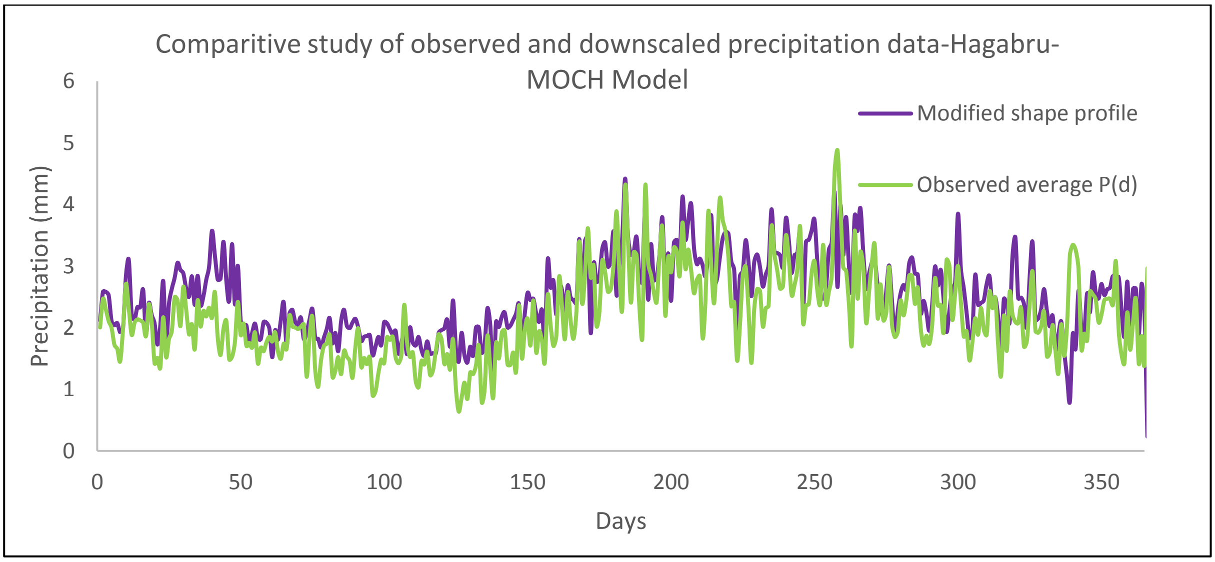


Figure 6.10: Comparison of observed and downscaled precipitation data-Hagabru catchment-MOCH Model

The final modified daily average precipitation should ideally be in resonance with the observed daily average precipitation pattern as depicted above. The proposed methodology corrects the GCM data for daily means. Comparison of average precipitations on a monthly basis are presented in **Figure 6.11**. As can be inferred, the precipitation series corresponded to a reasonable degree even on a monthly basis and this was also a substantial improvement from the initial state. To quantify the improvement in data quality, a comparative study was carried out by computing the correspondence between the observed data and the GCM simulated data. It was found that the correspondence between daily means was improved from R^2=0.20 to 0.82 for CNRM model and from R^2=0.25 to 0.80 for MOCH model. Similar investigations were carried out for Krinsvatn and Svartjonbekken and the proposed methodology greatly enhanced the GCM data quality to obtain good correspondence for daily means and monthly means on every occasion as can be inferred from **Appendix 7** and **8.**

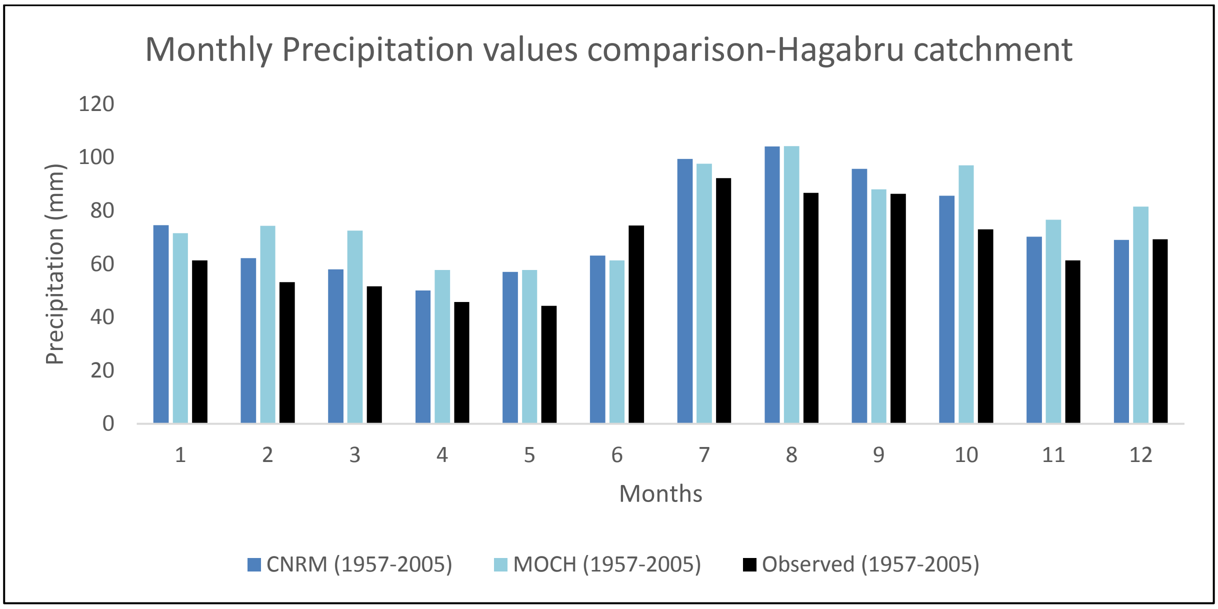


Figure 6.11: Comparison of observed and downscaled monthly average precipitation-Hagabru catchment

Table 6.2: Rainy Days comparison-Hagabru catchment

Model Name	Simulated average number of rainy days (1957-2005)	Observed average number of rainy days (1957-2005)	Downscaled average number of rainy days (1957-2005)
CNRM	327	254	249
MOCH	357	254	216

Also, as can be observed from **Table 6.2,** the rainy day comparisons were substantially improved by Antinoise downscaling technique. Hence, it was safe to conclude that the downscaled precipitation data was of very good quality.

6.4 ANTINOISE DOWNSCALING TECHNIQUE PERFORMANCE EVALUATION

The reasoning behind diverting a lot of effort into climate data downscaling is to preserve the climate change signal from GCM simulated climate data. To understand the meaning of the term climate change signal, let us consider the case of delta change approach. The delta change approach works on the premise that deltas implemented to the observed climate data on a monthly basis provides climate data of a future climatic setting.

The deltas are computed on a monthly basis as the percentage changes for precipitation data and as differences for temperature data. The inner essence of this approach is the transfer of climate change signal from the GCM data to the observed data to eliminate the need for recalibration of the hydrological model with GCM simulated data as this task can usually get extremely complex in obtaining satisfactory hydrological model performance.

To preserve the climate change signal with the GCM simulated climate data, the delta change methodology needs to be avoided and implementation of an alternate downscaling technique and recalibration of the hydrological model would be required. Hence, maximum effort has been diverted in this study for obtaining reasonable model performance with downscaled GCM simulated data and delta change method was considered as a last resort.

The next stage of investigation was evaluation of the performance of downscaled precipitation data when employed as input within the HBV model. The observed precipitation time series were replaced with GCM simulated precipitation time series downscaled with anti-noise downscaling technique within the HBV input files for Hagabru catchment for two different climate models.

GCM simulated historical temperatures were directly employed without any alterations as the data correspondence was very good. The models were further evaluated for practical hydrological applications such as runoff generation and flood frequency analysis. Performance evaluation was carried out for both the GCM models in succession. Since GCM data was available over the period 1956-2005, 1975-1980 was assumed as the standard calibration period.

The calibrations resulted in best fit model efficiencies of 0.60 and 0.58 for MOCH and CNRM models respectively over the period of 1975-1980. The model performance was also satisfactory over the validation periods of 1980-1985 and 1970-1975. To obtain good fit for flood frequency analysis, a manual recalibration was carried out in accordance with the discussions presented in **Chapter** 5 which resulted in reduced model efficiencies of 0.52 and 0.54 for CNRM and MOCH models respectively and this result follows the discussions presented in **Chapter 5** that model efficiencies are reduced when calibrating for flood frequency fit. The resultant simulated outputs for the two GCMs have been presented in **Figure 6.12** and **6.13.**

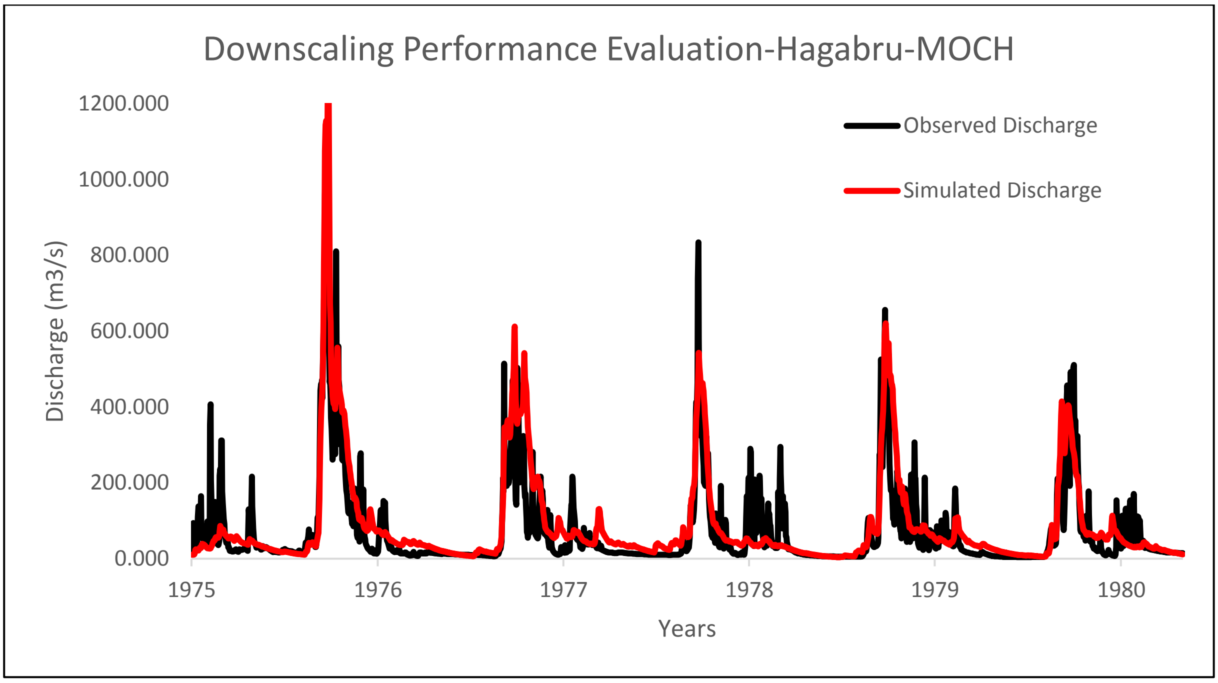


Figure 6.12: Downscaling performance evaluation-Hagabru catchment-MOCH model

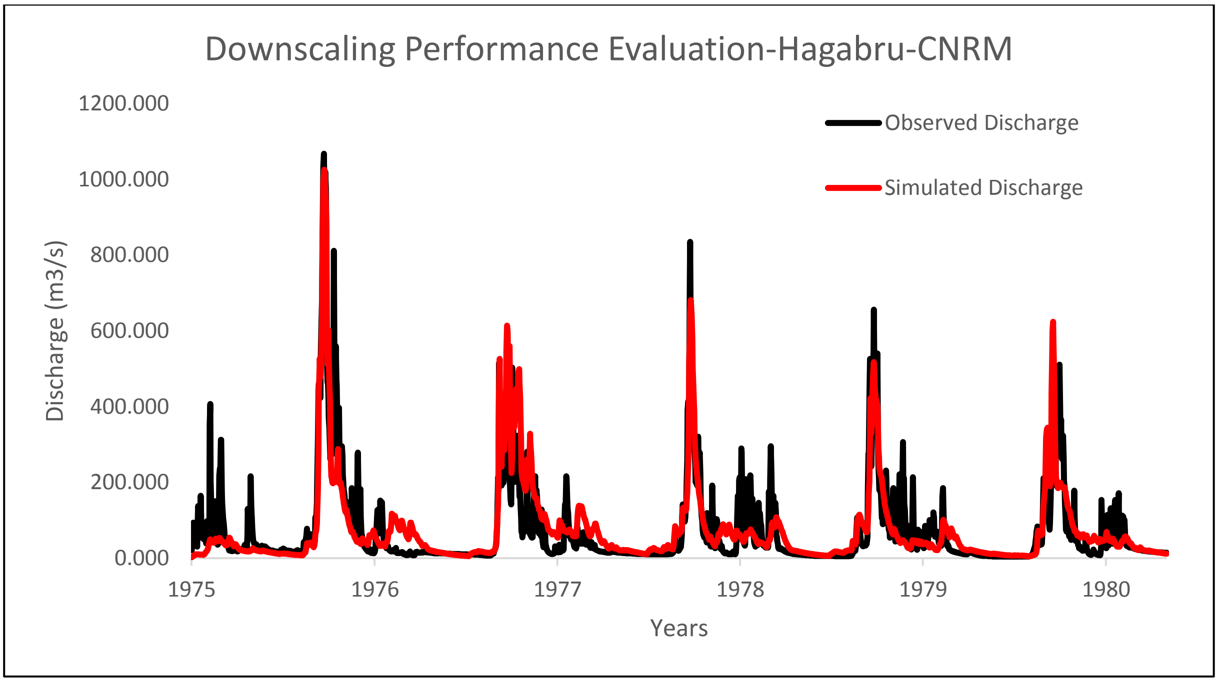


Figure 6.13: Downscaling performance evaluation-Hagabru catchment-CNRM model

It was evident that the model performance was good for spring flood generation process but was severely deficient in the autumn. The models accurately reproduced the rising limbs of the hydrographs and the simulated flood peaks were also in good agreement with the observed flood peaks. Flood frequency analysis was carried out over the period 1957-2005 with HBV simulated runoff records and the results were in very good agreement with the observed flood frequency trends and reference is made to **Appendix 13** for graphical representations of the flood frequency analysis comparisons. But, the recession limbs of the hydrographs were unresponsive as could be inferred from the simulation outputs. The models generated no runoff in the autumn season when significant runoff was observed even though the monthly means were in good agreement. Hence, Investigations were carried out for CNRM model output over the year 1979 to fathom the reason behind the observed discrepancy.

As can be observed from precipitation and runoff scenario comparisons presented in **Figure 6.14**, the downscaled GCM precipitation data was in good agreement with the observed precipitation data during the year 1979. But, it could be noticed that the model simulated almost no runoff variation during days 200 to 300 while there was significant runoff variation observed. Since the input precipitation data seemed to be in good agreement with the observed data, a possible explanation was that the precipitation was being stored in the model as snow. Also, as can be inferred from **Table 6.3**, all the parameters except RCORR, SCORR and the temperature control parameters such as TX, TS and TSN were comparable with the investigations carried out in **Chapter 4** hinting at probable discrepancies with temperature dependent parameters. The parameters TX and TS were set at much lower values within the HBV model for the calibrations with GCM data suggesting that the likelihood of snow precipitation and storage was very high. Also, the fact that SCORR value was consistently set at over 2 suggested that the amount of snow within the model was high. This could also be due to a systematic bias within the GCM simulated temperature employed for the simulations. Hence, the snowpack feature over the year 1979 was studied but surprisingly, the snowpack accumulation and depletion pattern within the HBV model was found to be normal.

Further, tests were carried out with modifications of temperature control parameters but this did not yield any significant improvements to the model output. This could be due to a bias in the proposed downscaling methodology or due to limited data quality of GCM simulated climate data. But the fact that the well-established methodologies such as linear scaling, variance scaling, power transformation and quantile mapping also could not improve model performance suggested that the issue was most probably with the precipitation data quality.

Further versions of the work could look more in depth at investigating this issue. But as far as this study was concerned, it was concluded that the model performance was reliable for spring flood generation and spring flood frequency studies and ineffective for autumn flood generation process. The decision of adopting the obtained calibration for simulating the future runoff scenario was very important. The reasoning behind this was that although the autumn flood generation feature was lost, this was still a worthy bargain for keeping the climate change signal intact with the GCM simulated climate data. Also, since Norwegian hydropower industry is predominantly dependent upon the spring flood generation pattern, investigating this feature with intact climate change signal would be of vital importance.

Table 6.3: HBV parameter set comparison-Hagabru catchment

	Parameter set 1	Parameter Set 2	Parameter Set-CNRM	Parameter Set-MOCH
RCORR	0.995	1.30	0.582	0.646
SCORR	1.312	0.73	2.285	2.013
TX	0.973 Deg C	1.226 Deg C	-1.766 Deg C	0.287 Deg C
TS	0.484 Deg C	2.00 Deg C	-3.00 Deg C	-2.691 Deg C
TSN	-2.92 Deg C	0.08 Deg C	-2.84 Deg C	-2.41 Deg C
CX	3.572 mm/Deg C day	8 mm/Deg C day	5.415 mm/Deg C day	2.091 mm/Deg C day
CXN	1.915 mm/Deg C day	8 mm/Deg C day	1.083 mm/Deg C day	2.045 mm/Deg C day
FC	134.4 mm	53.2 mm	25.9 mm	38.4 mm
FCDEL	0.927	0.1	0.559	0.280
Beta	1.67	0.323	0.100	0.255
KUZ2	2.365 mm/day	7 mm/day	0.612 mm/day	0.649 mm/day
KUZ1	0.558 mm/day	3 mm/day	0.146 mm/day	0.123 mm/day
KUZ	0.050 mm/day	0.5 mm/day	0.014 mm/day	0.014 mm/day
KLZ	0.037 mm/day	0.052 mm/day	0.014 mm/day	0.013 mm/day
UZ1	15.03 mm	17.00 mm	53.11 mm	54.64 mm
UZ2	23.42 mm	50 mm	109.53 mm	101.80 mm
PERC	0.35 mm/day	0.00 mm/day	1.94 mm/day	1.38 mm/day
INFMAX	50 mm/h	50 mm/h	50 mm/h	50 mm/h

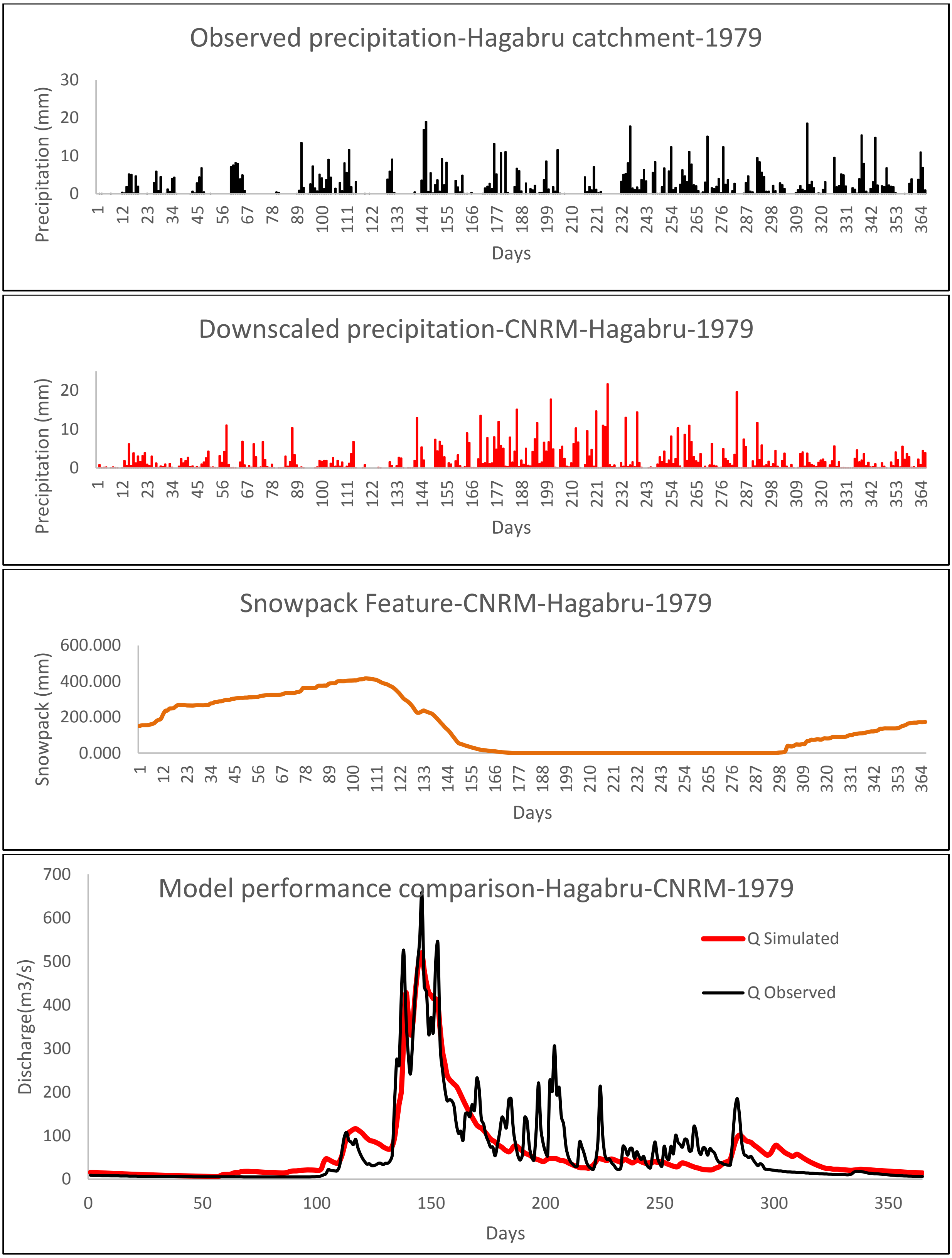


Figure 6.14: HBV output discrepancy evaluation-1979-Hagabru catchment-CNRM model

Similar investigations were carried out for Svartjonbekken catchment and the model output plots and flood frequency plots are presented in **Appendix 9**. It was observed that the model outputs were similar in comparison with Hagabru catchment in that the models were able to simulate the spring flood pattern to a good extent but the autumn period simulations were severely deficient.

The model efficiencies for Svartjonbekken catchment were found to be R^2=0.40 for CNRM and R^2=0.30 for MOCH. These were reasonable model efficiencies considering the fact that Svartjonbekken was a small catchment of 3.7 Km^2 with complex flow response patterns. This could also be attributed to the coarse nature of the available GCM data with a spatial resolution of 144 Km^2. An approximate average of GCM data from the vicinity of Svartjonbekken had to be obtained since Svartjonbekken was a catchment of 3.7 Km^2 area which was much finer than the GCM spatial resolution. But, Hagabru with a catchment area of 3060 Km^2 could obtain more than 20 grid cells. This in turn resulted in higher model efficiencies for Hagabru catchment.

It is essential to understand that the effectiveness of a hydrological model cannot be evaluated solely based on the Nash-Sutcliffe model efficiency criterion. As concluded from the downscaling performance evaluations, the model performances for Hagabru and Svartjonbekken catchment were satisfactory with respect to general hydrograph trends and spring flood frequency trends and the autumn flood generation feature of the models were a consequence of an attempt at preserving the climate change signal.

A surprising finding was that model performance with Krinsvatn catchment was severely deficient with unsatisfactory model efficiencies and severe deficiencies is both the spring and the autumn seasons even though the downscaled precipitation data was in good agreement with observed data with respect to daily mean precipitation and also monthly mean precipitation. This could be attributed to the coastal nature of the catchment where the catchment topography and the weather flux patters can get so complex that the GCMs simulation capabilities are severely hampered and the process of precipitation forecasting renders poor quality data. Multiple downscaling strategies such as quantile mapping, linear scaling, variance scaling and power transformation were implemented but turned out ineffective in improving HBV model performance. Hence, decision was taken to implement delta change method for downscaling future climate data for Krinsvatn catchment as a last resort. This would result in a loss of climate change signal but this was the only remaining option for obtaining reasonable quality simulations for the future.

Prior to the conceptualization of the Antinoise downscaling technique, multiple HBV calibrations were carried out by implementing various downscaling methods such as quantile mapping, linear scaling, variance scaling and power transformation for all the study catchments and yet the model performance was not improved when compared to the results obtained by Antinoise downscaling technique. Hence, Antinoise downscaling technique could still be considered a worthy downscaling alternative but the sample size of three catchments cannot discern the effectiveness of the approach. The sheer volume of effort put in this regard speaks for the complexity and challenging nature of calibration of HBV models with GCM data.

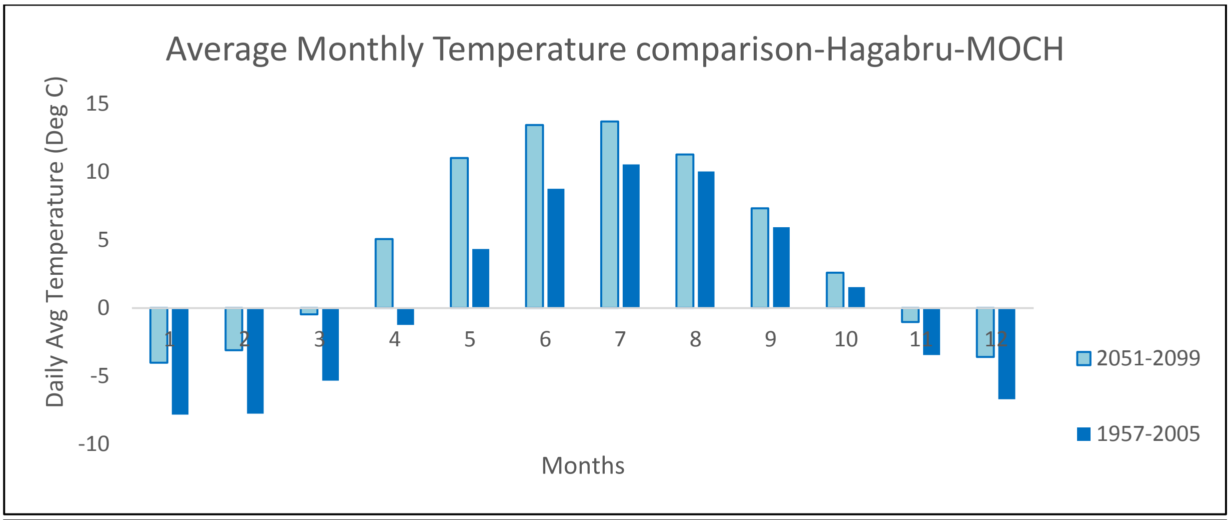
7.0 HYDROLOGICAL FEATURES IN A FUTURE CLIMATE SETTING

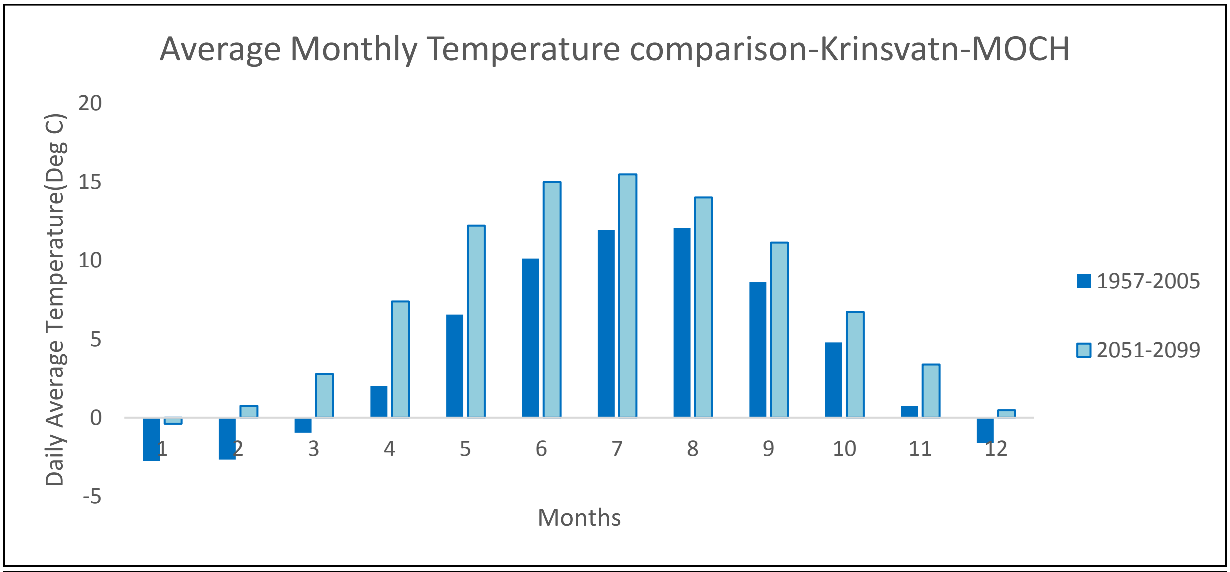
The final leg of the investigation was intended at simulating the runoff patterns in a future climate setting with downscaled climate data as input to comprehend the possible changes imparted to the natural hydrological regimes within the study catchments. The subsequent sections elucidate the details of investigations carried out with respect to climate data downscaling, comparative studies of annual hydrograph trends and also flood frequency analysis. Further, a new graphical technique for the evaluation of hydrograph trends termed ‘Flow Regime Modification Indices’ has been introduced to facilitate the evaluation of changes in hydrograph patterns over an extended period of time. Also, the method has been juxtaposed with the well-established IHA indices to comprehend the fundamental differences with these approaches.

7.1 CLIMATE DATA DOWNSCALING

Antinoise downscaling technique described in previous discussions was implemented for downscaling GCM simulated future precipitation data for Hagabru and Svartjonbekken catchments. Since the noise patterns observed with the respective GCM data were consistently similar over the period 1957-2005 for all the study catchments, it was assumed that the same noise pattern would most probably persist with future GCM patterns on their respective GCM precipitation time series. Hence, the respective Antinoises were superimposed on the simulated GCM precipitation data to obtain downscaled projected precipitation data. Further, GCM simulated temperature data was employed directly within the HBV parameter files without any downscaling being implemented as the data quality was very good as described in the previous sections of the study. For Krinsvatn catchment, delta changes were applied on a monthly basis to downscale the precipitation and temperature data in accordance with standard delta change downscaling procedures.

Projected trends in future temperature and precipitation data have been depicted in **Figure 7.1** and **Figure 7.2** for the study catchments. Much warmer temperature trends were projected by the GCMs in these the catchments especially from January to July. Also, an increased amount of winter precipitation probably in the form of rain due to warmer atmospheric temperatures were predicted. This predicted changes in precipitation pattern was a direct consequence of the added energy to the atmosphere. A warmer atmosphere would have enhanced capacity of storing moisture and this in turn leads to increased amounts of precipitation. Also, this effect would have profound impact on coastal precipitation pattern as can be inferred by the precipitation plot for Krinsvatn catchment. The project changes for Krinsvatn were much drastic in comparison with Svartjonbekken and Hagabru catchments. Also, a key change imparted by a warmer atmosphere would be enhanced evapotranspiration. Hence, the annual evapotranspiration values were scaled accordingly with monthly temperature changes.





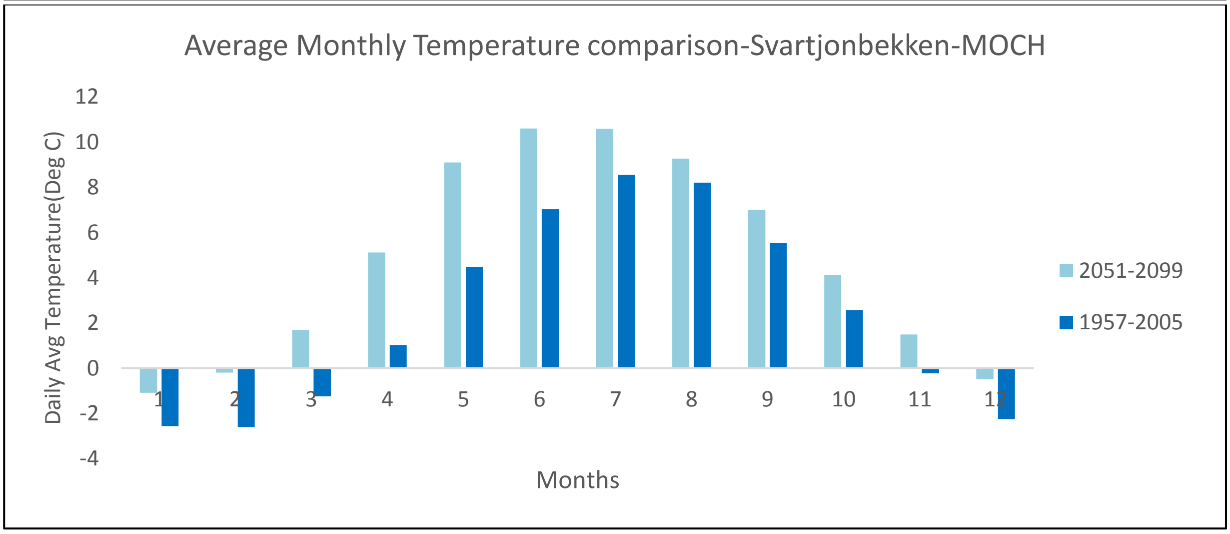


Figure 7.1: Comparative study of downscaled projected temperature with current trend

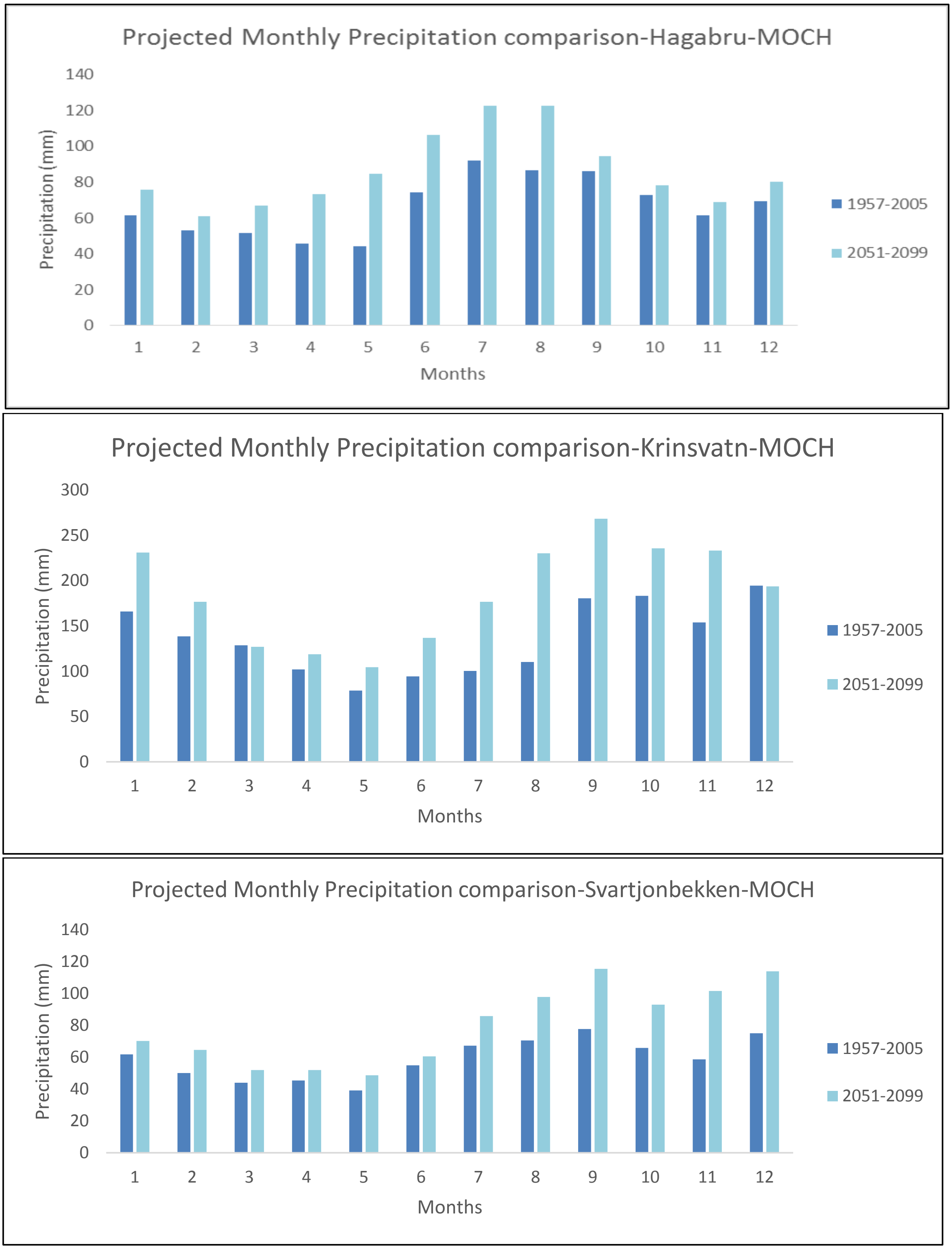


Figure 7.2: Comparative study of downscaled projected precipitation with current trend

7.2 CHANGES IN HYDROLOGICAL REGIMES

Discussions of **chapter 4** clearly demonstrated the fact that stream flow patterns have been undergoing a gradual metamorphosis due to the impacts of a warmer climate as far as the study catchments are concerned. Further, previous research works carried out at the NVE on a much larger scale also have similar findings that the spring flood patterns have been undergoing gradual alterations. These alteration patterns were site specific or in other words, the imparted change patterns were different depending on the location of the study catchments.

The next and perhaps the most vital step in the investigation was simulations of the calibrated HBV models with downscaled GCM climate data as input. Since historical observed precipitation and temperature records were available over a 49 year period over 1957-2005, a future 49 year period 2051-2099 was chosen as the simulation period. Input files were prepared for the respective HBV models with downscaled GCM data as inputs. Simulations were carried out over the period 2051-2099 for all the study catchments with primary emphasis laid on understanding modifications to the general shape of the hydrographs, possible changes imparted to the snow accumulation and depletion characteristics and finally, changes in flood frequency characteristics.

Figure 7.3 and **Figure 7.4** depict the anticipated changes imparted to the natural flow regimes of the selected study catchments in a future climate setting. Annual average hydrographs were prepared for the study catchments over two 25 year periods of 2051-2075 and 2076-2099 employing the generated runoff simulations from the calibrated hydrological models with downscaled climate data as input. Projected snow cover plots were also prepared over the same time periods. The historical average hydrographs were prepared by employing observed discharge data series and the historical average snow cover plots were prepared by employing HBV simulated snow cover data with best fit parameter sets (Parameter Set 1) for the historical observation periods.

A quantitative description of the imparted changes to the flow regimes are discussed in subsequent discussions on the 'Flow Regime Modification Indices'. However, a qualitative overview would be valuable at this stage.

The findings presented in **Figure 7.3** and **Figure 7.4** appeared to be an extrapolation of the trends observed in **chapter 4**. Hagabru catchment had a decreased spring flood magnitude which was progressively shifting towards the left. That is, an earlier and dampened spring flood trend was observed. However, the spring flood patterns seemed to vanish entirely in case of Krinsvatn and Svartjonbekken catchments. This was due to the fact that since Hagabru encompasses catchment hypsographical distribution at much higher altitudes compared to Krinsvatn and Svartjonbekken, the amount of snow accumulation over the winter months would still be considerable as can be observed from the corresponding snow cover plots.

However, Krinsvatn and Svartjonbekken would lose most of their snow pack features due to much warmer temperatures at lower altitudes. Hence, Krinsvatn and Svartjonbekken were poised to lose their snow cover trends entirely in the future and this would in turn lead to a scenario where rain would be the dominating precipitation mechanism which would in turn lead to a more evenly distributed runoff scenario as accurately depicted by the plots.

Also, another noteworthy observation was that for Svartjonbekken and Hagabru catchments, distribution in runoff volumes was observed to be primarily within the spring season while the autumn flow regimes appeared to be undisturbed with minor runoff distributions. However, for Krinsvatn catchment, strong runoff redistributions were observed among both the seasons. This once again pointed at the rapid depletion of snow cover features and also at the dominating influence of rain precipitation in the future at Krinsvatn.

A very important disclaimer would be that interpretations of obtained results in the autumn season of the hydrographs. This section of the simulated hydrographs need to be dealt with caution as it was earlier discussed and concluded that the HBV calibrations for Hagabru and Svartjonbekken catchments were unresponsive for autumn floods or the recession limb of the hydrograph. This could exactly be the reason for the flat nature of the hydrographs in the autumn season for Hagabru and Svartjonbekken. But, for Krinsvatn, the hydrograph is functional in all sections of the hydrograph due to the implementation of the delta change methodology. However, the results obtained for Hagabru and Svartjonbekken were still very valuable as the climate change signals were intact.

A very important finding was that the outputs obtained by employing CNRM model climate data as inputs were consistently lower when compared to the model outputs employing MOCH climate data as inputs. This strongly suggested that an additional uncertainty was imparted to the model outputs due to the internal precipitation generation nature of the GCMs. A dry model such as the CNRM model data resulted in lower magnitude runoffs when compared to the model outputs with MOCH model data. Hence, it was also concluded that an ensemble approach with multiple GCM climate data would be the right for climate impacts on regional hydrology to get an insight into the spectrum of uncertainties.

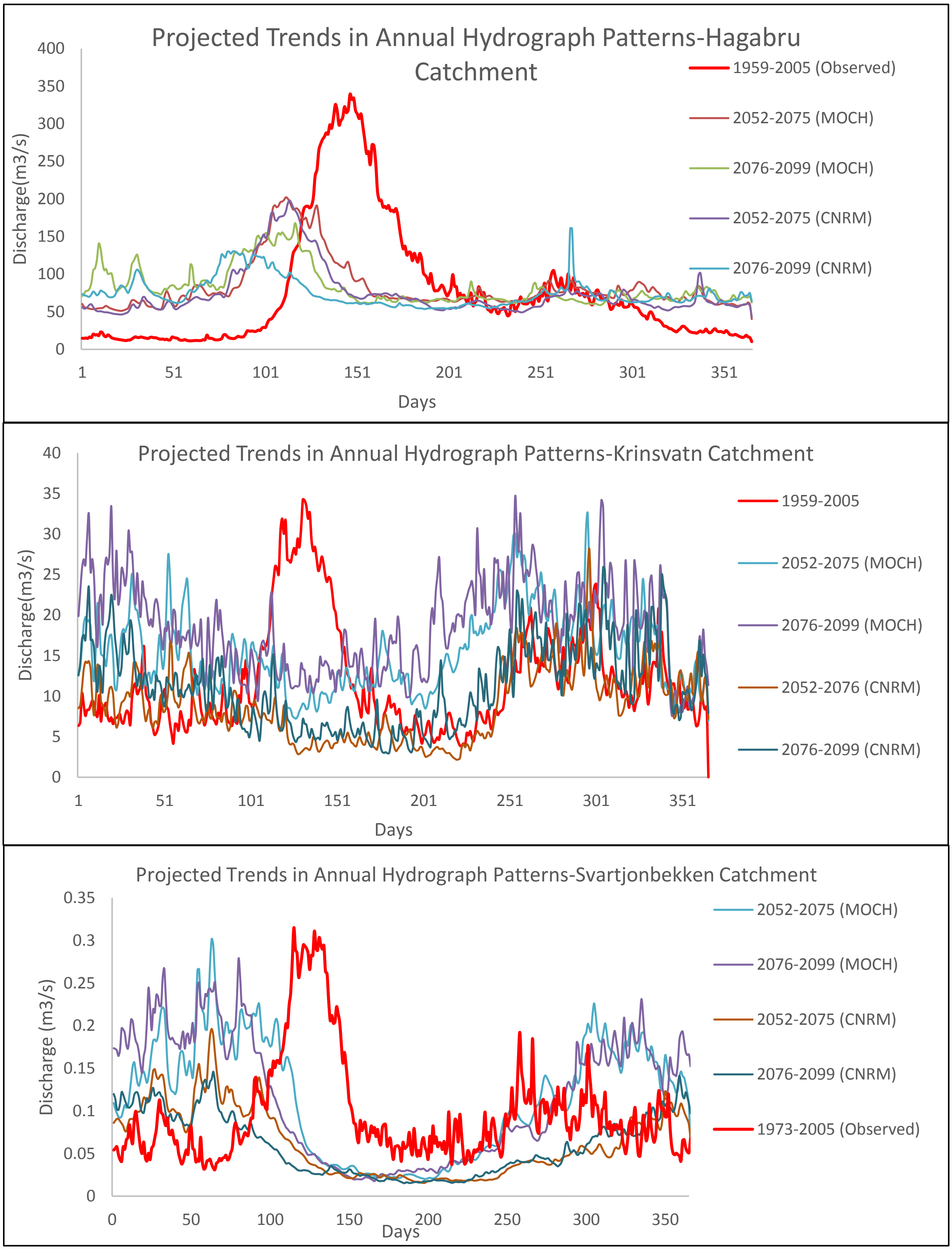


Figure 7.3: Projected Annual Hydrograph trend comparisons

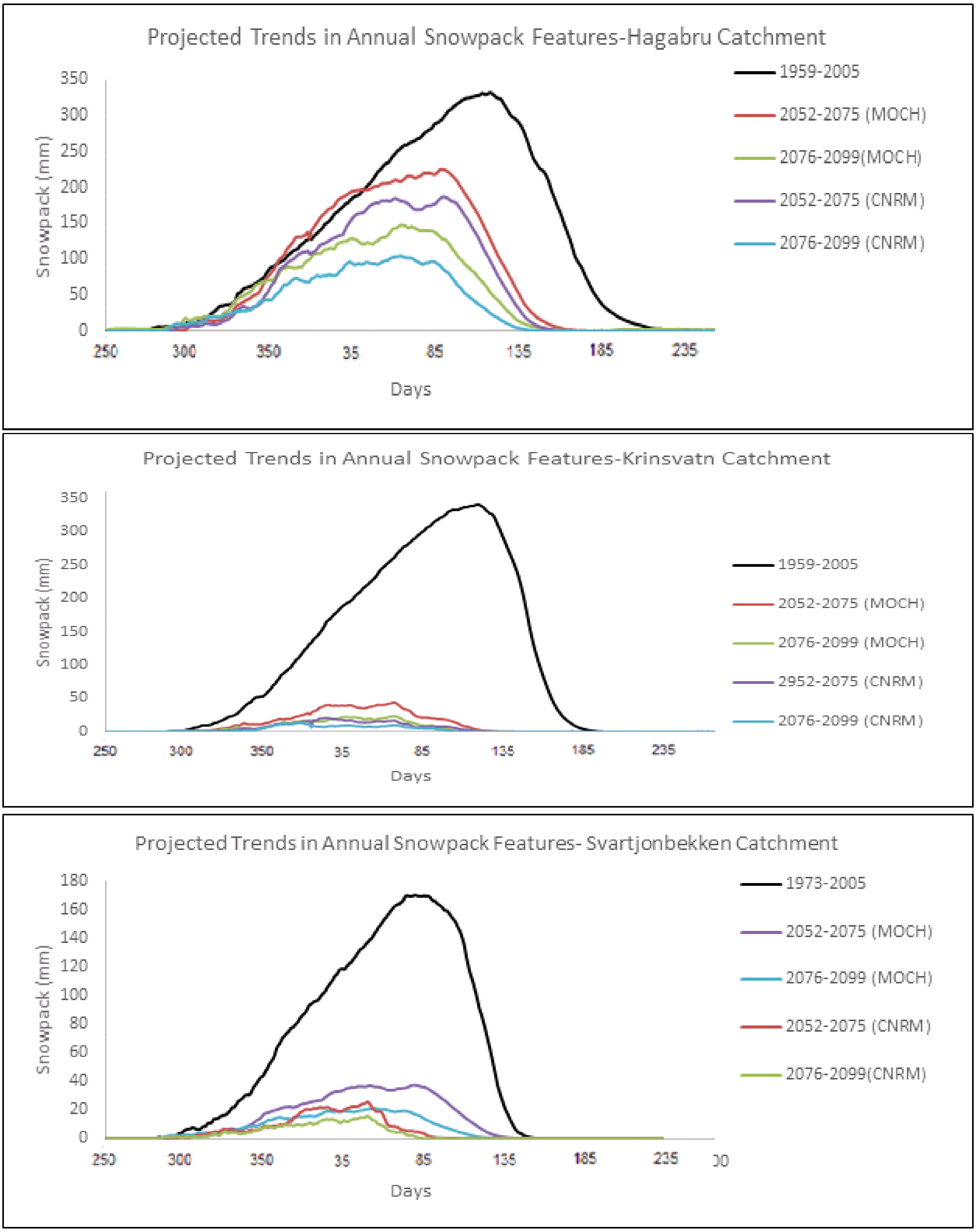


Figure 7.4: Projected Annual Snowpack trend comparisons

7.3 FLOOD FREQUENCY PROJECTIONS

Flood frequency projections for the catchments under consideration over the time period 2051-2099 have been presented in **Appendix 10, Appendix 11** and **Appendix 13** for the two different GCMs employed**.** For convenience of reference, maps depicting average projected changes from the present observed trends for the 100 year and the 1000 year floods on an annual basis and also on a seasonal basis are presented in **Figure 7.5** through **Figure 7.9**. It is important to note that the calibrated HBV models were ineffective in simulating the autumn floods to a satisfactory extent. Hence, autumn floods frequency analysis was excluded from this study.

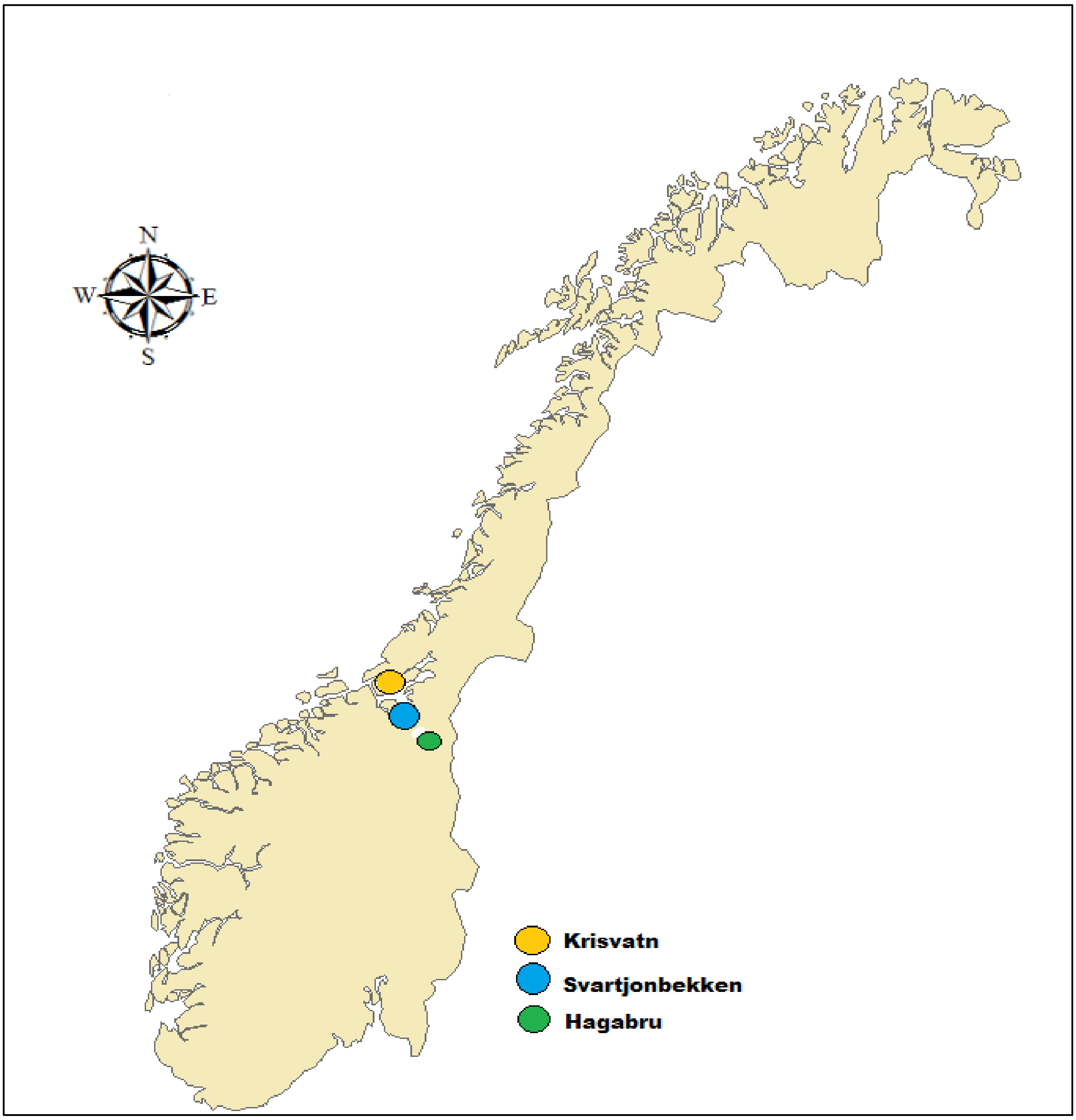


Figure 7.5: Map depicting study catchment locations

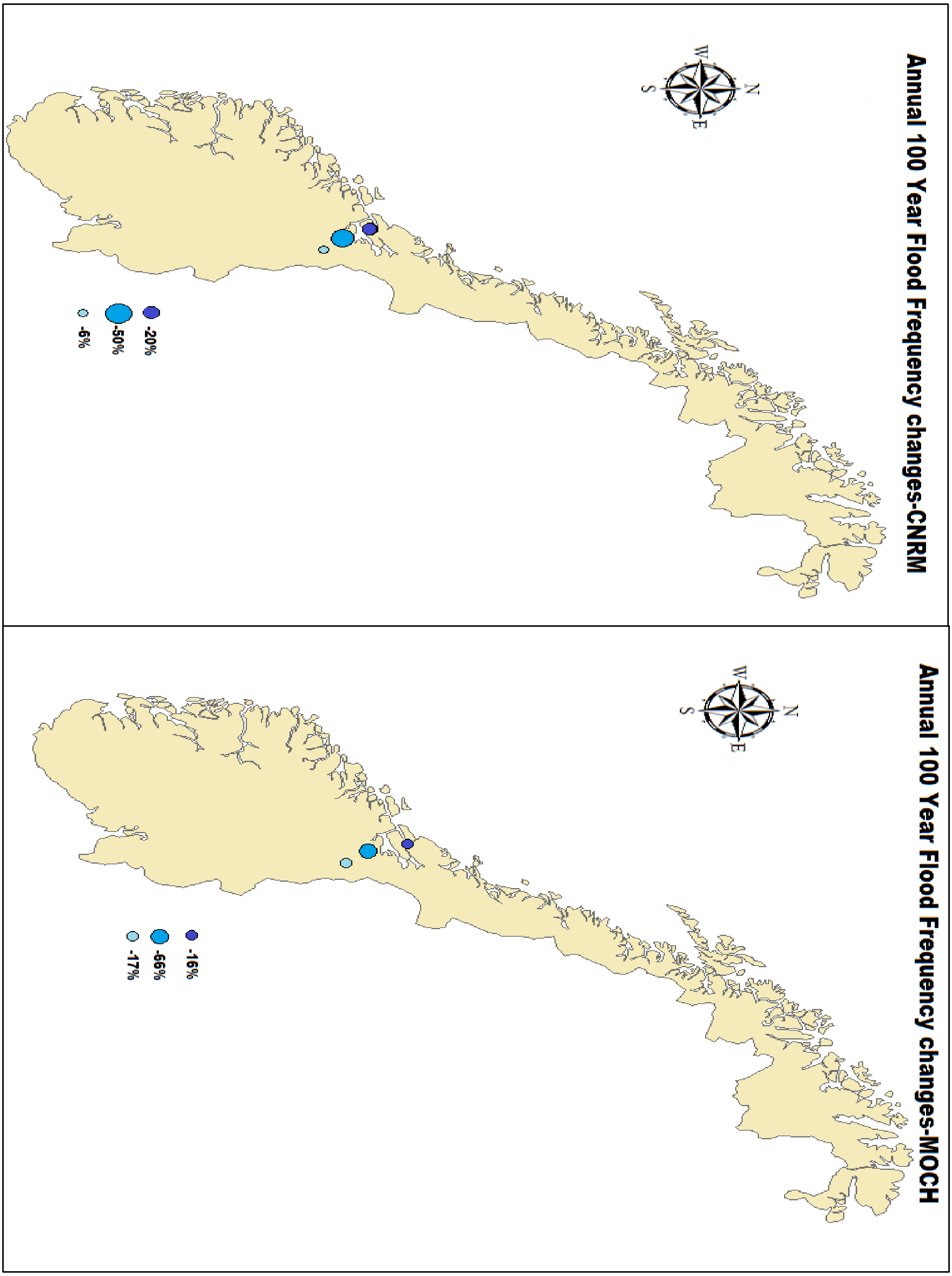


Figure 7.6: Projected Percentage changes in Annual 100 Year Floods

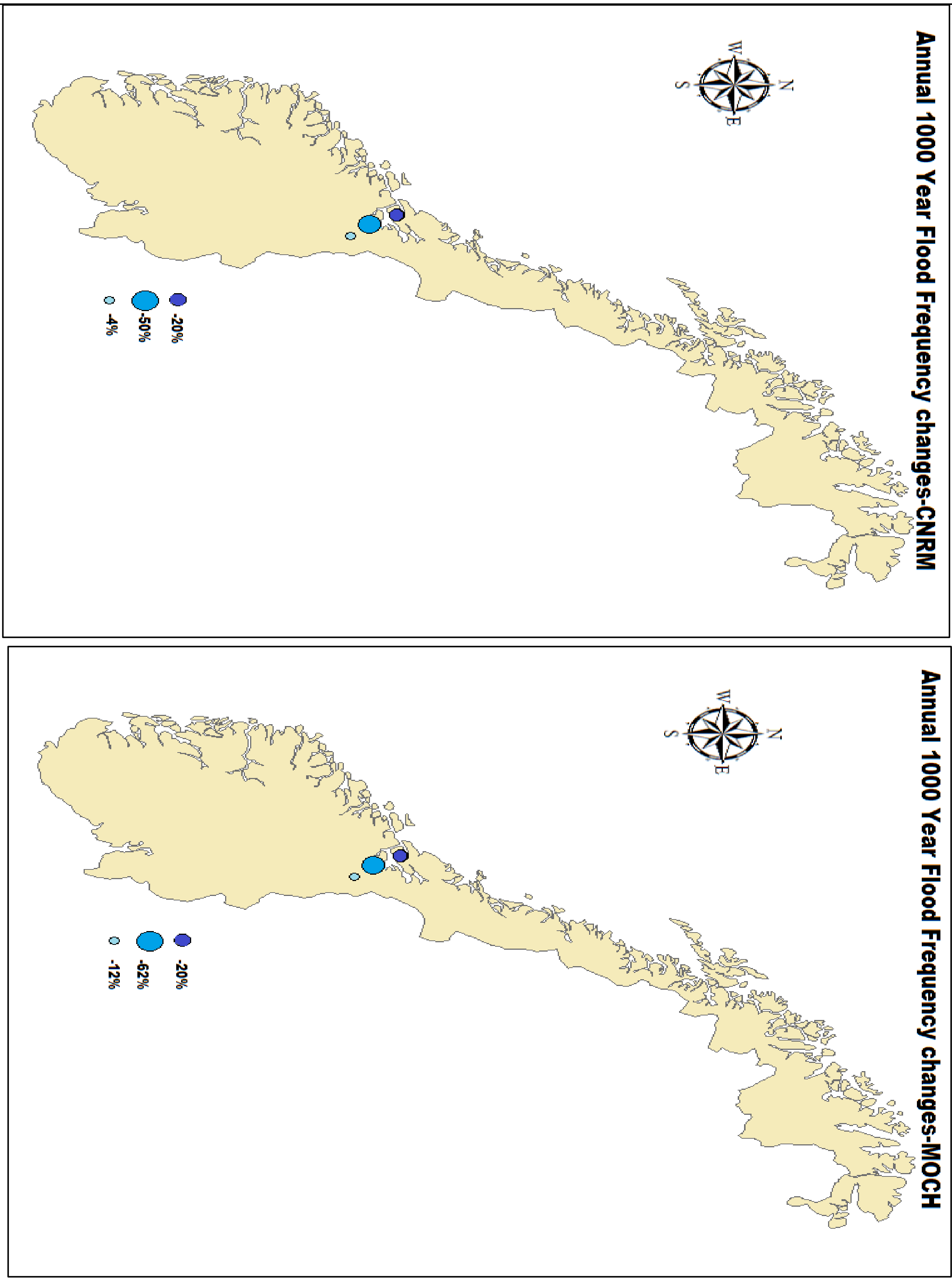


Figure 7.7: Projected Percentage changes in Annual 1000 Year Floods

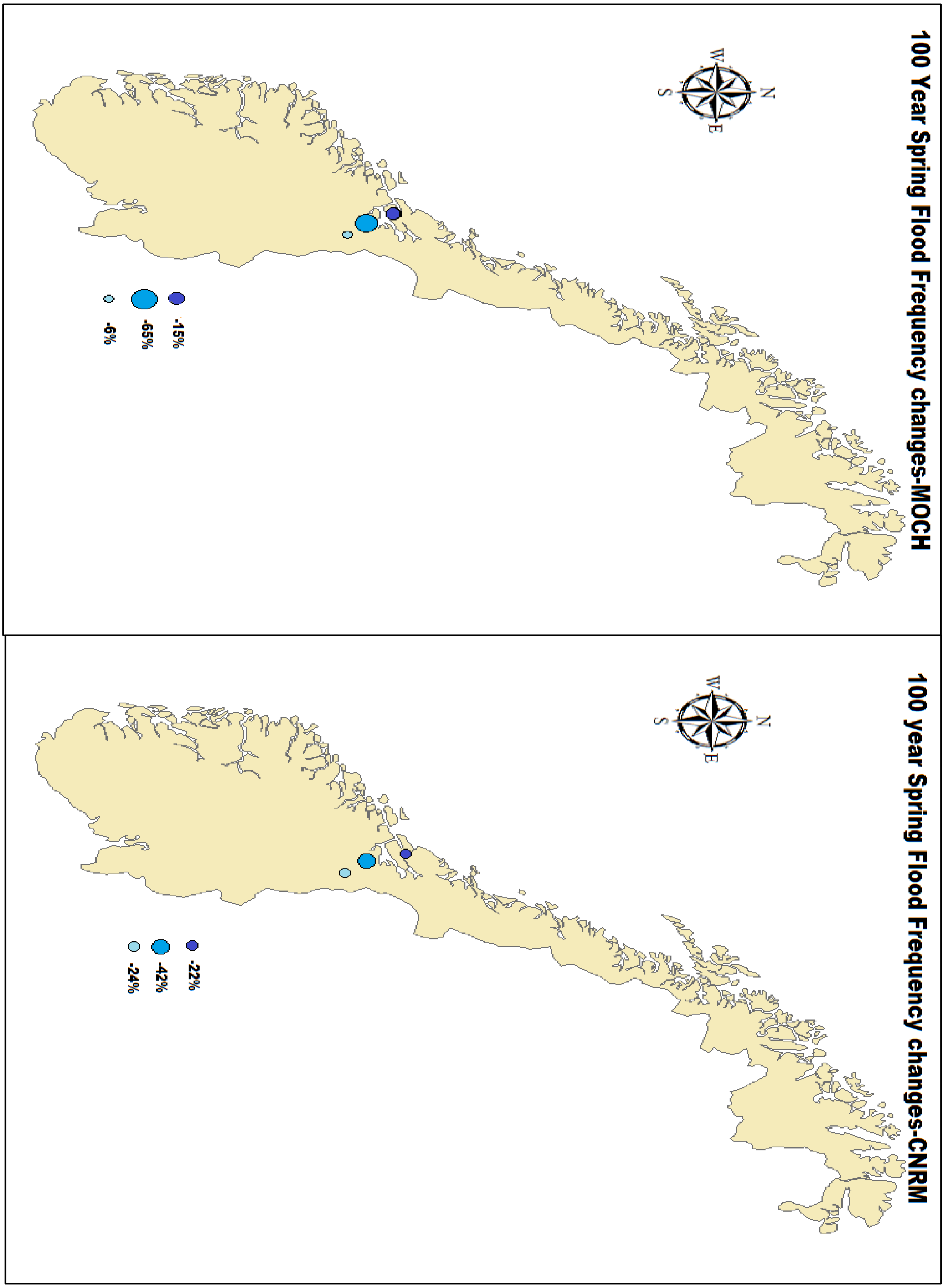
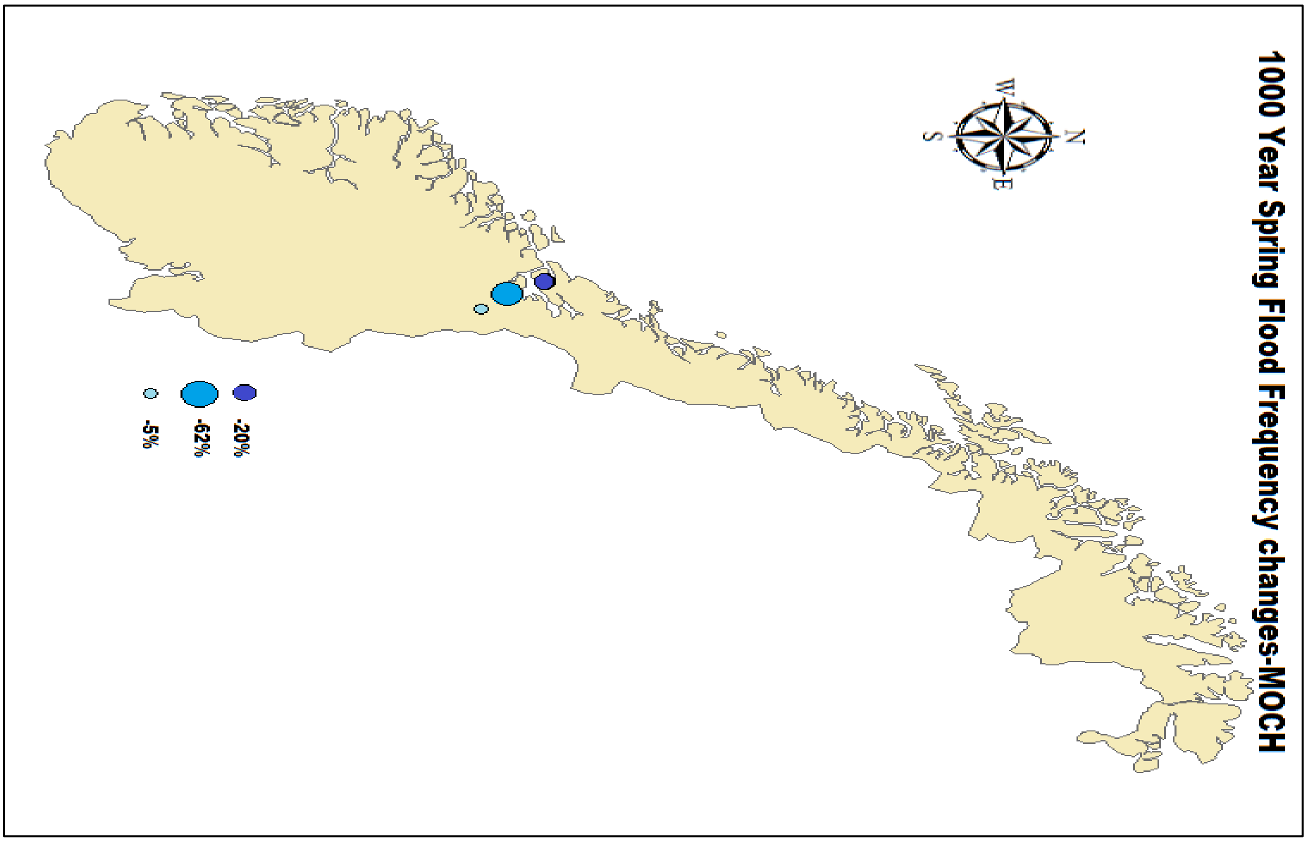


Figure 7.8: Projected Percentage changes in 100 Year Spring Floods



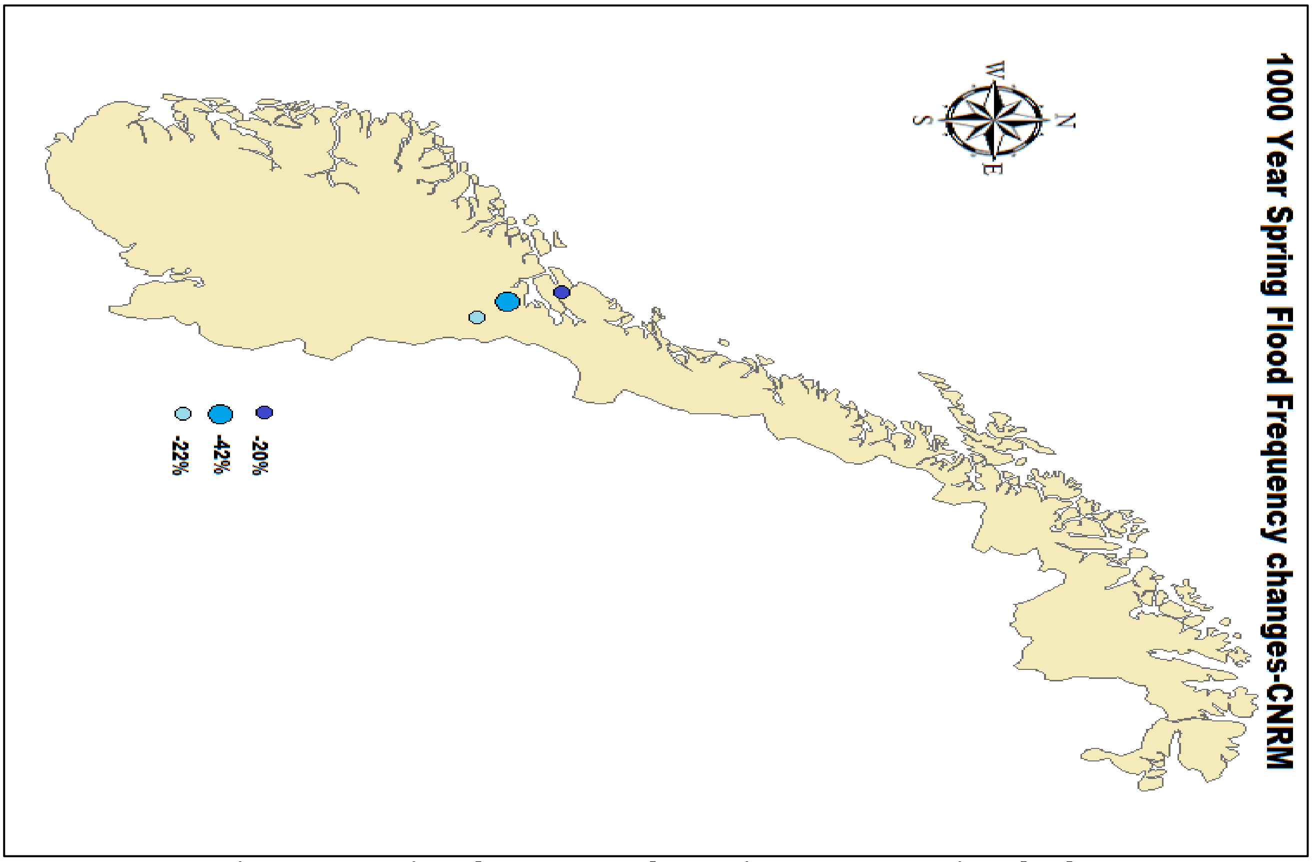


Figure 7.9: Projected Percentage changes in 1000 Year Spring Floods

It was observed that there was a reduction in the magnitudes of floods of the respective return periods in all the study catchments both on an annual basis and as spring floods. That is, the 100 year floods and the 1000 year flood magnitudes were dampened in all the catchments under consideration. Svartjonbekken seems to have been affected the most as large percentage reductions in flood magnitudes were observed for this catchment. This could be due to the fact that Svartjonbekken being a small catchment of 3.7 Km^2 producing rapid flood response patterns would be extremely sensitive to changes in precipitation and also snowmelt patterns in a future climate setting.

Also, reductions were noticed in Hagabru and Krinsvatn catchments. Percentage reductions of flood magnitudes in Krinsvatn catchment were generally higher when compared to Hagabru catchment. This effect could be attributed to the fact that Krinsvatn would face severe reductions in snow accumulation and snowmelt due to a much warmer climate and especially due to its proximity to the ocean. Since the flood frequency trends highly depend on the amount and type of precipitation, Krinsvatn would be undergoing drastic changes in flood patters whereas Hagabru catchment being an inland catchment with most of its snow cover intact would maintain its hydrological regime features to a greater degree.

The findings were also in agreement with the published results of the NVE. "*The projections indicate that the northernmost areas (Finnmark and parts of Troms) and middle and southern inland areas (Hedmark, Oppland and parts of Buskerud, Telemark and Trøndelag) will experience a decrease in the mean annual flood. Catchments located in western and south-western regions (Vestlandet) and coastal regions of southern and south-eastern Norway (Sørlandet and Østlandet) will experience an increase in the mean annual flood* **[34]**". Hence, it was concluded that the current storm water drainage infrastructure would be able to cope with the future changes imparted on to the flood patterns as far as the study catchments of central Norway are concerned. Further, flood projections published in Klima I Norge 2100 report clearly state that drastic reductions in flood magnitudes of 200 year floods are expected in Trøndelag region **[35].**

7.4 FLOW REGIME MODIFICATION INDICES ANALYSIS

The most important issue with handling large scale simulation outputs to obtain quantitative and qualitative description of the possible changes imparted to the natural hydrological regimes is the sheer volume of the generated hydrological data. Analysis of hundreds of generated hydrographs can often be a complex task and implementation of specialized data analysis techniques is generally a prerequisite.

The IHA indices technique has been the generally adopted methodology for evaluating alterations in hydrological regimes. The basic structure and parameterizations involved in the analysis are presented in **Table 7.1**

Table 7.1: Indices of Hydrologic Alterations-Parameterization [33]

<table>
<tr><th>IHA Statistics group</th><th>Regime Characteristics</th><th>Hydrologic Parameters</th></tr>
<tr><td>Group 1: Magnitude of monthly water conditions</td><td>Magnitude
Timing</td><td>Mean value for each calendar month</td></tr>
<tr><td rowspan="10">Group 2: Magnitude and duration of annual extreme water conditions</td><td rowspan="10">Magnitude
Duration</td><td>Annual minima 1-day means</td></tr>
<tr><td>Annual maxima 1-day means</td></tr>
<tr><td>Annual minima 3-day means</td></tr>
<tr><td>Annual maxima 3-day means</td></tr>
<tr><td>Annual minima 7-day means</td></tr>
<tr><td>Annual maxima 7-day means</td></tr>
<tr><td>Annual minima 30-day means</td></tr>
<tr><td>Annual maxima 30-day means</td></tr>
<tr><td>Annual minima 90-day means</td></tr>
<tr><td>Annual maxima 90-day means</td></tr>
<tr><td rowspan="2">Group 3: Timing of annual extreme water conditions</td><td rowspan="2">Timing</td><td>Julian date of each annual 1 day maximum</td></tr>
<tr><td>Julian date of each annual 1 day minimum</td></tr>
<tr><td rowspan="4">Group 4: Frequency and duration of high and low pulses</td><td rowspan="4">Magnitude
Frequency
Duration</td><td>No. of high pulses each year</td></tr>
<tr><td>No. of low pulses each year</td></tr>
<tr><td>Mean duration of high pulses within each year</td></tr>
<tr><td>Mean duration of low pulses within each year</td></tr>
<tr><td rowspan="4">Group 5: Rate and frequency of water condition changes</td><td rowspan="4">Frequency
Rate of Change</td><td>Means of all positive differences between consecutive daily means</td></tr>
<tr><td>Means of all negative differences between consecutive daily values</td></tr>
<tr><td>No. of rises</td></tr>
<tr><td>No. of falls</td></tr>
</table>

Albeit widely used for research applications, a disadvantage with the approach is that the analysis can get convoluted due to the large number of parameters involved. Hence, application based needs generally dictate the choice of parameters for research applications.

But, with regards to the general hydrograph shape analysis, this method was found to be severely under equipped as only a few parameters were even remotely capable of providing information regarding the changes observed in natural shape of the hydrograph in a future climatic setting. When employed for climate change impact studies and especially for evaluating hydrograph shape changes, only few parameters such as mean values for each calendar month, annual 1 day maximum and minimum and Julian date for annual maximum and minimum provide some degree of insight. Even these parameters are not sufficient for understanding all the intricate details of hydrological pattern changes.

To address this issue, a new technique for analyzing changes imparted to the natural flow regime termed 'Flow Regime Modification Indices' has been introduced in this study. The following sections describe the details of the methodology proposed and also compare the obtained results with the IHA indices to discuss possible short comings with the IHA methodology. The depiction incorporating the parameters involved in the technique of flow regime modification indices are represented in **Figure 7.10.**

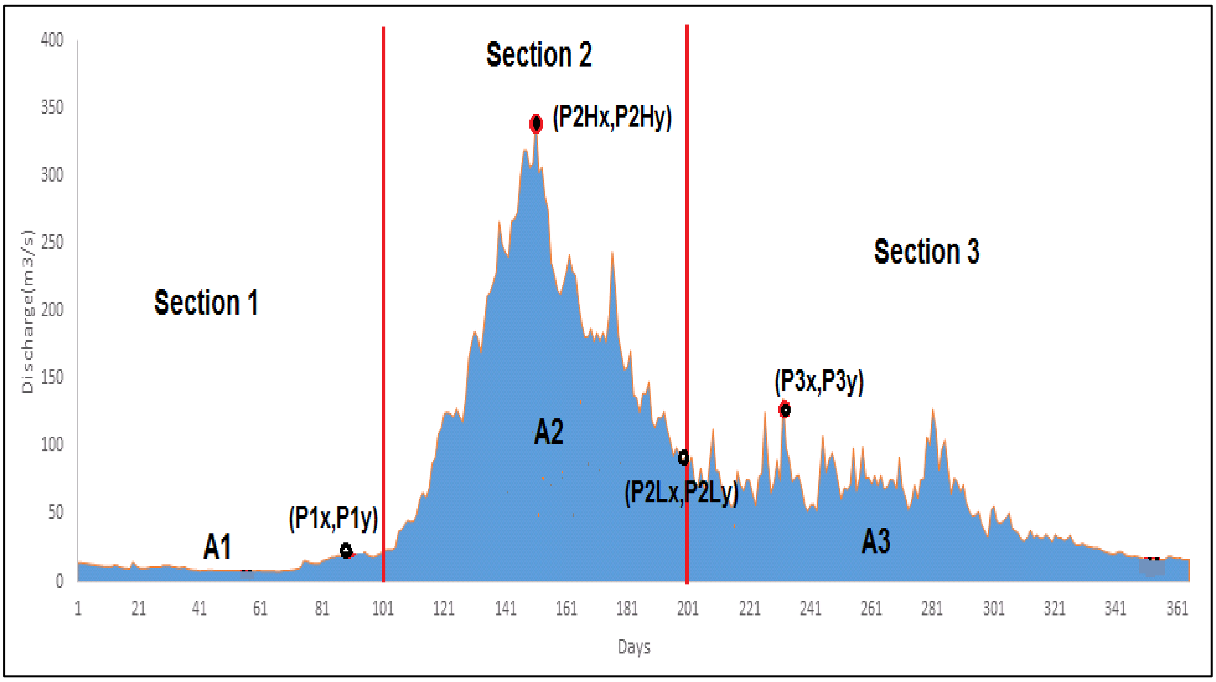


Figure 7.10: Flow Regime Modification Indices-Parameterization Depiction

Where,

A_1=Area coefficient for Section 1=Area under the hydrograph in Section 1

A_2=Area coefficient for Section 2=Area under the hydrograph in Section 2

A_3=Area coefficient for Section 3=Area under the hydrograph in Section 3

P_{1X}=X-coordinate of the highest peak within Section 1

P_{2HX}=X-coordinate of the highest peak within Section 2

P_{2LX}=X-coordinate of the lowest point within Section 2 between Day 150 to 200

P_{3X}=X-coordinate of the highest peak within Section 3

P_{1Y}=Y-coordinate of the highest peak within Section 1

P_{2HY}=Y-coordinate of the highest peak within Section 2

P_{2LY}=Y-coordinate of the lowest point within Section 2 between Day 150 to 200

P_{3Y}=Y-coordinate of the highest peak within Section 3

First of all, the annual hydrograph would be sub-divided into three different sections. Section 1 includes the time period of days 1 to 100, Section 2 includes the time period of days 101 to 200 and Section 3 would include the time period of days 201 to 365. This is to comprehend the changes imparted to the different flow seasons generally observed in cold weather countries such as Norway. However, this method would also be valid for application in different climate settings.

The Area coefficients A_1, A_2 and A_3 represent the volume of water within disparate sections of the hydrograph. They provide valuable insight into the fluctuations of runoff volumes in each section of the hydrograph. This would be especially important when analyzing observed changes in shape of the hydrograph in a future climatic setting. These parameters can be normalized over the mean or can be used in their respective units.

Further, the respective X and Y coordinates of the peaks and the troughs within the sections as depicted in **Figure 7.10** greatly help track the variation in the magnitudes and timings of the different high flow and low flow events. These are particularly important for monitoring the changes imparted to the peak flow and low flow events which are essential indicators of climate change impacts particularly in Norwegian climate settings. (P_{1X},P_{1Y}), (P_{2HX},P_{2HY}) and (P_{3X},P_{3Y}) represent the X and Y locations of the peaks within the respective sections. (P_{2LX},P_{2LY}) represents the low flow value within section 2 between the days 150 and 200 as this period gives good description of the recession trend in the hydrograph.

Flow regime modification indices technique was implemented to comprehend the observed and projected changes in hydrograph trends for the study catchments. Historical observed runoff records used for the analysis until the time period of 2015 and since two different GCMs were employed for runoff projections, average of the runoff simulations were employed over the period 2051-2099 for the flow regime modification indices analysis. Also, the obtained X and Y coordinate plots were normalized with the mean of the respective plots over the period 1957-2099. **Figure 7.11** through **Figure 7.13** represent the flow regime modification indices analysis results for the selected study catchments.

The changes imparted to the hydrograph trends were captured effectively by employing the flow regime modification technique as can be deduced from the presented depictions in **Figure 7.11** through **Figure 7.13**.

The area coefficients help fathom the fluctuations in the amount of runoff generated within each section of the hydrograph and the X and Y coordinate variation plots accurately capture the temporal shifting of the flood peak magnitudes in different sections. These are by far the most important features projected to be influenced by climate change. As it was a new technique, verification of its effectiveness was very important. Hence, the intervals of study were chosen specifically to test the working of the methodology. In **Chapter 4**, the modification to the hydrographs in recent decades was discussed. This could act as a good case study for this methodology to test its effectiveness when implemented for practical applications. Hence, time periods 1958-1970, 1971-1990 and 1991-2015 were chosen as the study periods with historical observed data to check whether the flow regime modification indices could capture the trends observed with the hydrographs. For Svartjonbekken catchment, due to the limitation of available data, 1973-1990 and 1991-2015 were chosen as the study intervals. Since the hydrograph trends were constant until the year 1970, the time period 1958-1970 was chosen to represent the historical average hydrographs as done in **Chapter 5, Figure 5.2**.

From the presented indices plots in **Figure 7.11** to **Figure 7.13**, it could be noticed that the observed historical trends in hydrographs were effectively captured by the flow regime modification indices. As expected, the plots for area coefficient for section 2 (A2) increased in value over the period 1971-1990 and experienced a slump over the period 1991-2015 due to the dampening effect observed with the flood peaks in all the study catchments. For Svartjonbekken catchment, only the slump over the period 1973-2015 could be observed due to limitation in data availability.

Similarly, the Y coordinate for the peak within section 2 (P2HY) behaved as expected with an increase over the period 1971-1990 and a reduction over the period 1991-2015 as discussed in **Chapter 4**. Hence, with these verifications in place, the methodology could be termed reliable in analyzing the future trends in hydrographs. The salient features of the investigation results over the future projected period of 2051-2099 were as follows:

1. **AREA COEFFICIENT FOR SECTION 1 (A1)**

The area coefficient for Section 1 of the hydrographs were projected to undergo sustained increments in the future simulation time period of 2051-2099 as can be observed from the presented A1 plots of **Figure 7.11** to **Figure 7.13**. This suggested redistribution of runoff volume among sections 1 and 2 due to reduced amount of snow and increased rain precipitation.

2. **AREA COEFFICIENT FOR SECTION 2 (A2)**

An interesting observation was made with regards to area coefficient for section 2. The plots of A2 presented in **Figure 7.11** to **Figure 7.13** projected a gradual reduction in runoff volume within section 2 for Hagabru and Svartjonbekken catchments over the time period of 2051-2099 without any fluctuations. But, for Krinsvatn catchment, this parameter experienced a drastic drop over the period 2005-2051 and was seen to be undergoing gradual increments over the period 2051-2099. This observation pointed at snow pack depletion process at Hagabru and Svartjonbekken but Krinsvatn catchment experienced dramatic reductions in snowpack features due to its coastal location and this might have accelerated the uniform distribution of runoff volume resulting in flattening out of the hydrograph in Krinsvatn. This might eventually be the case for Svartjonbekken catchment in the future.

However, this observation comes with a caveat that the period 2015-2051 was an extrapolation period and no simulations were carried out over this period to study the intermediate flow regime behavior.

3. **AREA COEFFICIENT FOR SECTION 3 (A3)**

The area coefficient of Section 3 (A3) for Hagabru and Svartjonbekken was seen to be almost unaltered over the simulation period 2051-2099 with minor increments observed for Hagabru and Svartjonbekken catchments. This strongly suggested a redistribution of runoff volume between section 1 and 2 while section 3 appears to be unaffected suggesting a strong alteration to the spring season runoff pattern while the autumn runoff pattern seemed to be affected to a minor degree for these catchments. But, Krinsvatn catchment was projected to show a strong runoff volume redistribution in both the spring and the autumn seasons. That is, runoff volume from section 2 was redistributed among both section 1 and section 3 and this essentially led to the incremental increase projected for Krinsvatn catchment with the parameter A3.

A noteworthy observation was that the area coefficient plots for all the study catchments exhibited a tendency for intersection at a time period between 2015 and 2051. It should be noted that this was an extrapolated region and hence, the validity of this observation was questionable. However, this observation essentially pointed out the fact that sometime in the future, the runoff volumes in all the sections would be identical or in other words, this equilibrium could essentially be the meaning of the term ‘Uniform Flow’.

4. **THE PEAK WITHIN SECTION 1 (P1X, P1Y)**

The Y coordinate for the peak within section 1 was observed to have been undergoing exponential increments over the future simulation period of 2051-2099. But, the incremental trends were not sustained or in other words, the peak within section 1 was seen to be undergoing fluctuations. Although the reason for this observation was unclear, a rain form of precipitation dominated future climatic setting could offer an explanation in this regard as rain precipitation tends to be much more irregular compared to runoff generated due to snow melt.

The parameter P_{1X} was particularly interesting as it showed a sudden shift in position to day number 100 for Hagabru catchment. This was due to the transition of the spring flood peak within Section 2 towards an earlier point in time. As the spring flood peak was shifting to an earlier point in time, the rising limb of the hydrograph was also undergoing similar shifting resulting in a scenario where the peak within section 1 was consistently at the boundary between section 1 and 2. This was also a consistent trend observed in all the study catchments. For Krinsvatn and Svartjonbekken, a rapid shift of the peak from the middle of Section 2 to the middle of section 1 was observed which led to a reduction in P_{1X}.

5. **THE PEAK WITHIN SECTION 2 (P2HX, P2HY)**

It could be noticed that the Y Coordinates (Flood magnitudes) of the spring floods within section 2 of the hydrographs (P_{2HY}) were found to be consistently declining signaling dampened spring flood magnitude trends in Hagabru and Svartjonbekken catchments. But an interesting observation was made with respect to Krinsvatn catchment. The trend observed with P2HY was similar to the plot of area coefficient for section 2 (A2) for Krinsvatn catchment. The parameter P2HY experienced a drastic reduction over the period 2015-2051 but was seen to be undergoing increments over the period 2051-2099 once again hinting at rapid depletion of snow pack resulting in a uniform flow distribution in a rain dominated future climate setting.

The X coordinate plots (P_{2HX}) showed a shift in the timing of the spring flood hinting at an earlier occurring snowmelt flood for Hagabru and Svartjonbekken catchments while the plot for Krinsvatn catchment was complex with no clear observable trend. This could be due to the fact that gradually shifting peaks were observed for Hagabru catchment while rapid fluctuations were observed at Krinsvatn due to rapidly depleting snow cover features.

6. **THE PEAK WITHIN SECTION 3 (P3X, P3Y)**

The Y coordinates plot within Section 3 (P_{3Y}) suggested that the peaks within section 3 were unaltered in Hagabru catchment but were found to be undergoing increments in Krinsvatn catchment and Svartjonbekken catchments. The X coordinate for the peaks within section 3 were seen to be undergoing rapid fluctuations with no clear observable trend across catchments.

7. **THE LOW FLOW VALUE WITHIN SECTION 2 (P2LX, P2LY)**

The low flow magnitude represented by the coordinates (P_{2LX} and P_{2LY}) showed that the low flow magnitude was unaltered in Hagabru catchment while a dampening effect was observed for the low flow at Svartjonbekken catchments whereas an increasing trend was observed in Krinsvatn catchment. The temporal location of the low flow values were constant at day 200 in all the catchments for an extended period of time but they were projected to shift to an earlier time period in the future due to more uniformly distributed flow regimes.

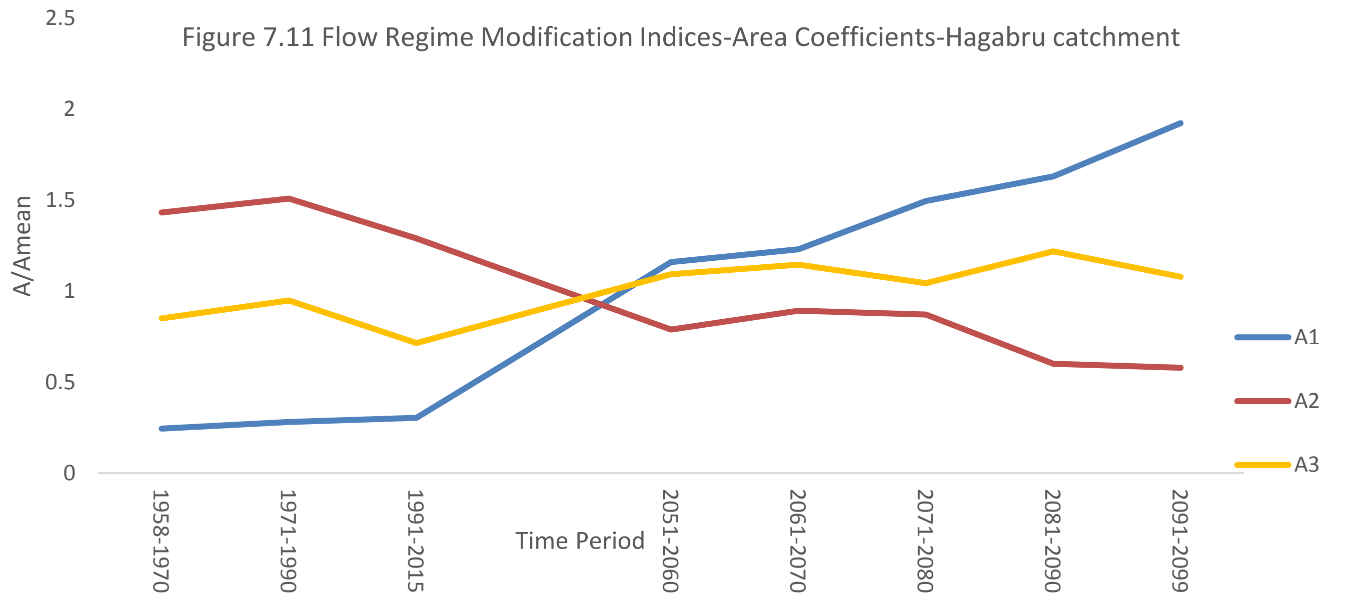


Figure 7.11 Flow Regime Modification Indices-Area Coefficients-Hagabru catchment

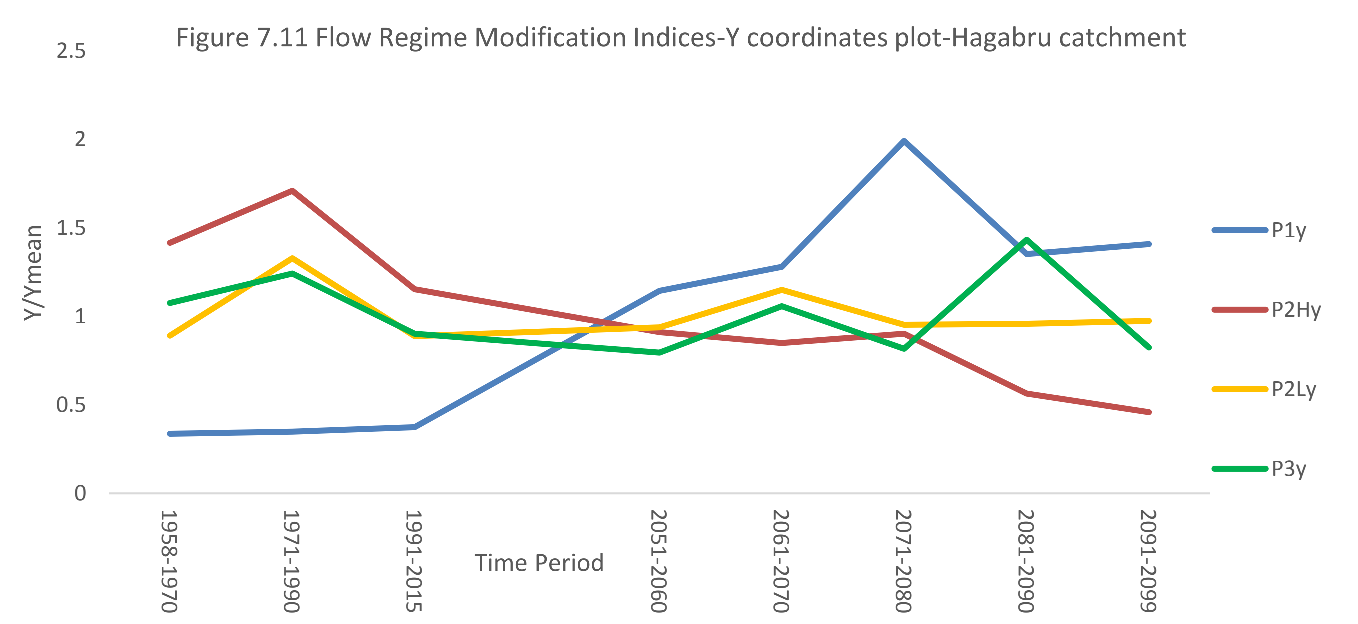


Figure 7.11 Flow Regime Modification Indices-Y coordinates plot-Hagabru catchment

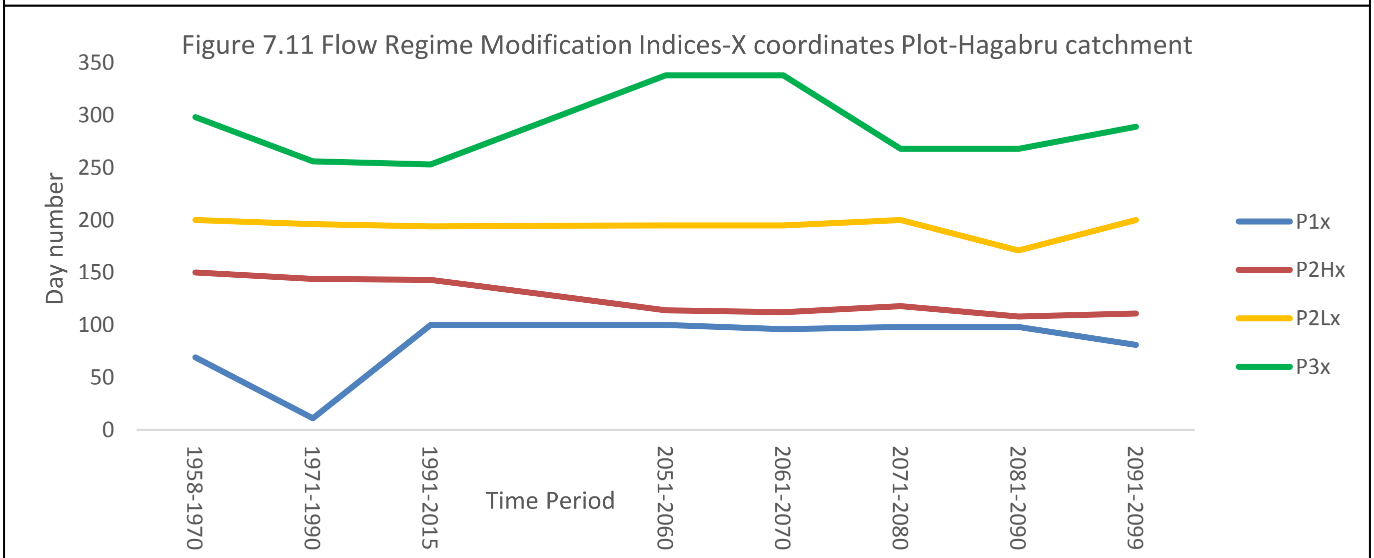


Figure 7.11 Flow Regime Modification Indices-X coordinates Plot-Hagabru catchment

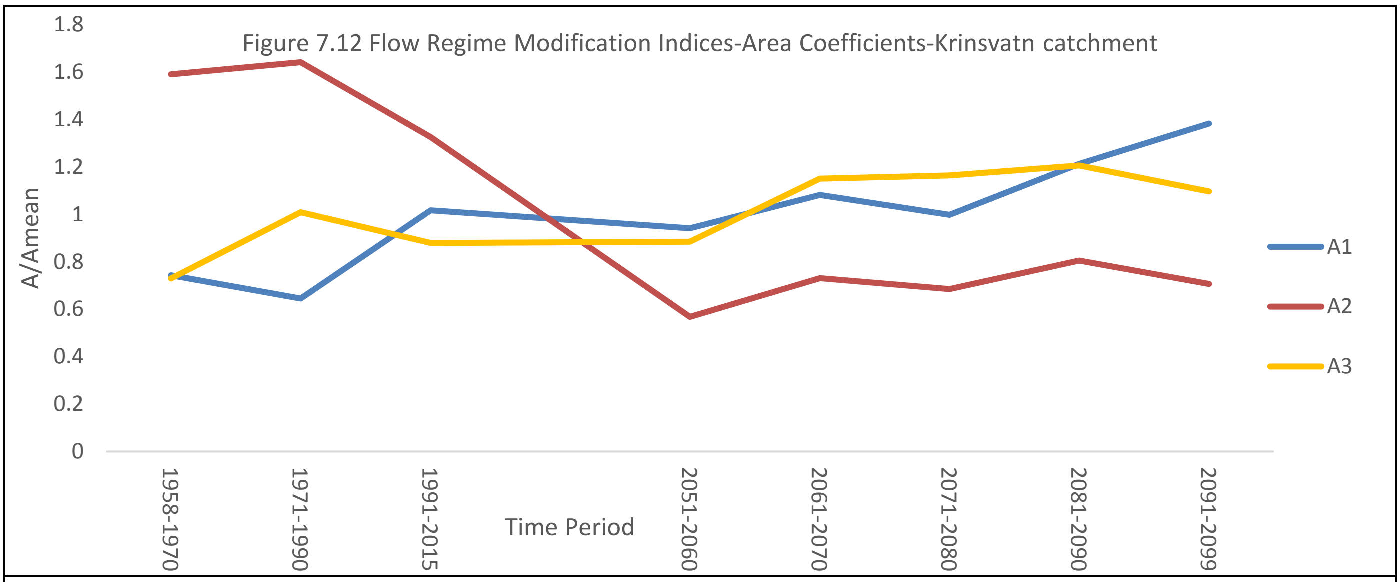


Figure 7.12 Flow Regime Modification Indices-Area Coefficients-Krinsvatn catchment
A/Amean
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1958-1970
1971-1990
1991-2015
2051-2060
2061-2070
2071-2080
2081-2090
2091-2099
Time Period
A1
A2
A3

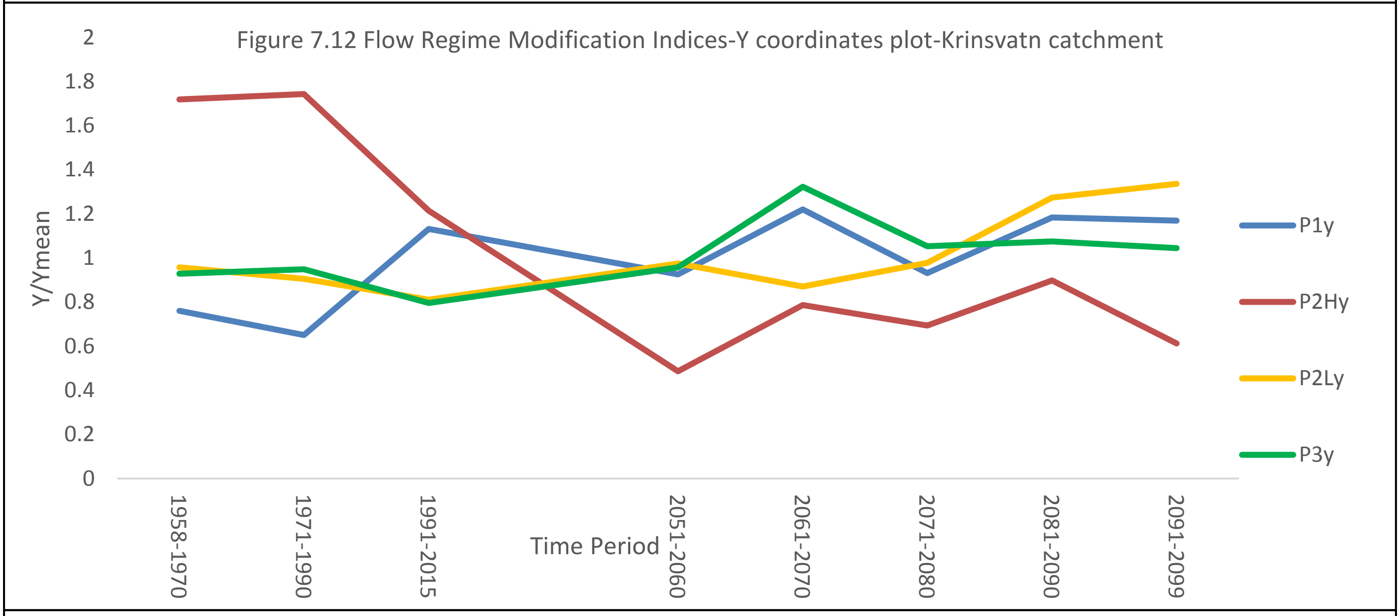


Figure 7.12 Flow Regime Modification Indices-Y coordinates plot-Krinsvatn catchment
Y/Ymean
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1958-1970
1971-1990
1991-2015
2051-2060
2061-2070
2071-2080
2081-2090
2091-2099
Time Period
P1y
P2Hy
P2Ly
P3y

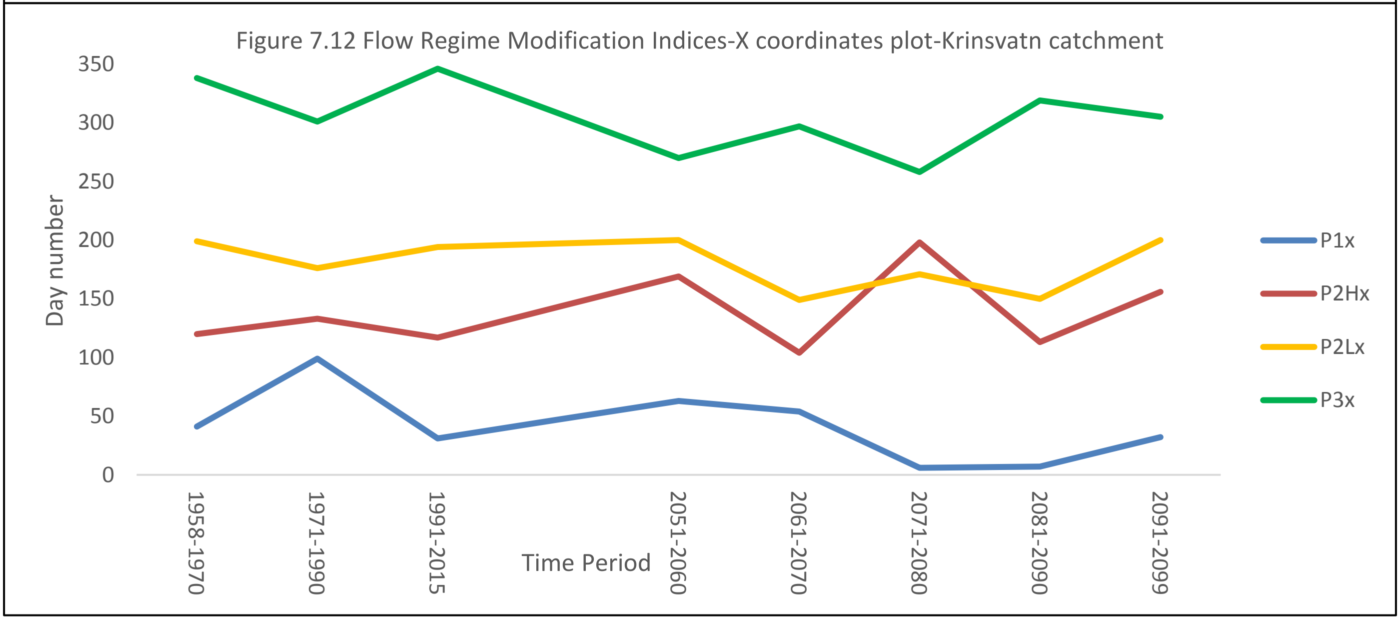


Figure 7.12 Flow Regime Modification Indices-X coordinates plot-Krinsvatn catchment
Day number
350
300
250
200
150
100
50
0
1958-1970
1971-1990
1991-2015
2051-2060
2061-2070
2071-2080
2081-2090
2091-2099
Time Period
P1x
P2Hx
P2Lx
P3x

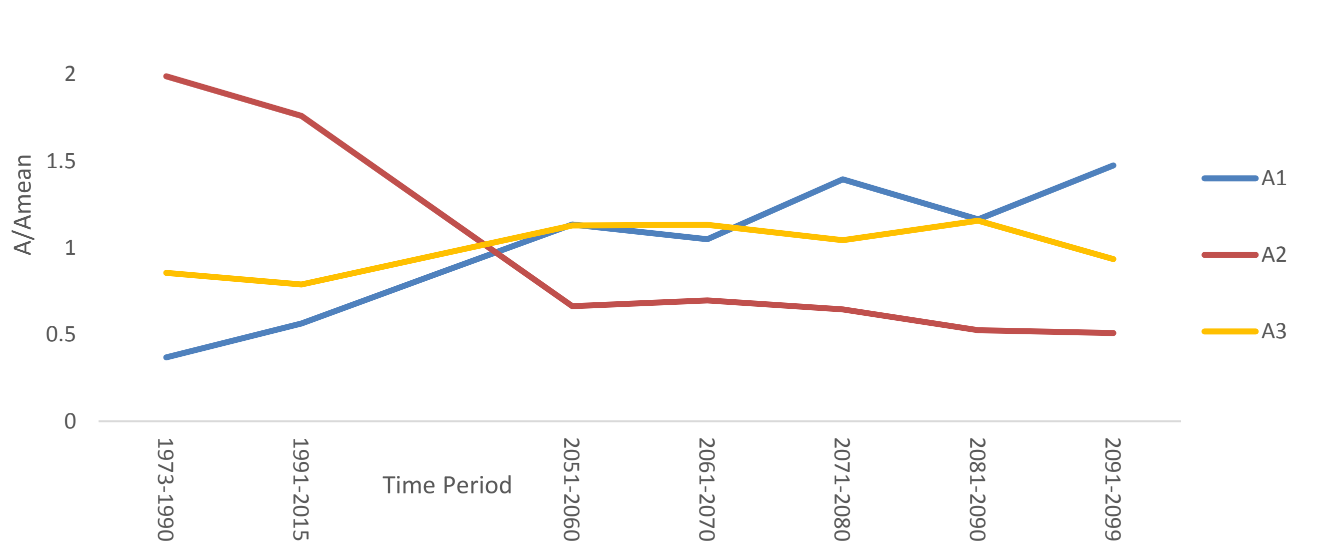


Figure 7.13 Flow Regime Modification Indices-Area Coefficients-Svartjonbekken catchment

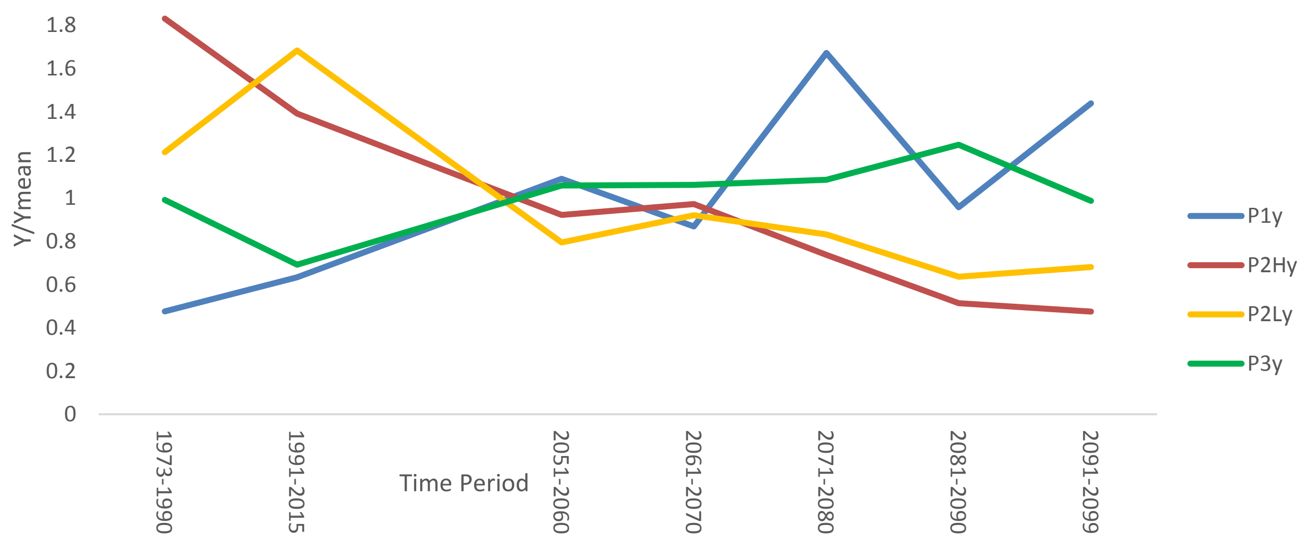


Figure 7.13 Flow Regime Modification Indices-Y coordinates plot-Svartjonbekken catchment

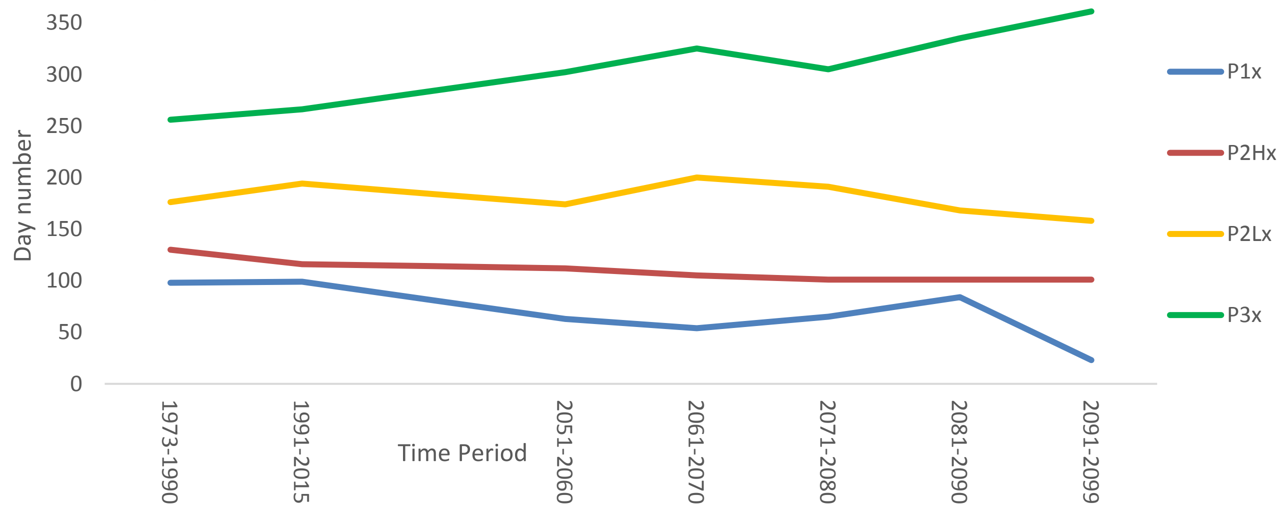


Figure 7.13 Flow Regime Modification Indices-X coordinates plot-Svartjonbekken catchment

Overall, the flow regime modification indices tend to give exhaustive and accurate description of the key changes observed with respect to the general profile of the hydrographs. A comparative study of the analysis with the IHA index method was carried out and the results obtained for the study catchment are presented in **Figure 7.14** through **Figure 7.16**.

The IHA indices which were determined to be applicable in climate change impact analysis were the mean value for each calendar month, Annual minima 1-day means, Annual maxima 1-day means, Julian date of each annual 1 day maximum and Julian date of each annual 1 day minimum. Average values of the chosen IHA indices were computed for the respective time periods as depicted as average for the two climate models.

The major disadvantages observed with the IHA indices approach are listed as follows:

1. The plots with the monthly mean runoffs essentially directly present the shape of the respective hydrographs as can be inferred from the depictions. That is, a poly line connecting the peaks of the IHA monthly mean plots would essentially result in the original hydrographs. Hence, it did not provide any new quantitative or qualitative information which helped to comprehend the changes observed with respect to the seasonal runoff patterns and this issue was addressed by a single plot of area coefficients with the flow regime modification indices method.

2. The Julian day and annual maxima plots present the variation in only one peak in the entire hydrograph. This could either be a spring flood or an autumn flood. Hence, tracking seasonal changes in flood patterns was not possible with the chosen IHA indices. The same applies with the annual minima which could track a single low flow value. For instance, in **Figure 7.15** and **7.16**, the corresponding 1 day maxima and Julian day maxima plots for Hagabru catchment hints at a dampening and earlier occurring spring flood. But, these plots provide no information about the behavior of the adjacent sections of the hydrographs and similar inferences could be made for the 1 day minima and the Julian day minima plots. The X and Y plots within the flow regime modification indices approach clearly indicates the behavior of three different peaks within the hydrograph providing ample amount of information.

3. A very interesting observation was made with respect to the Julian day maximum plot for Krinsvatn catchment. The temporal location of the peak was shifted from Day 110 to Day 260. This essentially was due to the fact that autumn floods were projected to dominate the flow regime in Krinsvatn catchment in the future simulation time periods. Hence, the IHA index Julian Day maximum was essentially tracking the spring flood until the period 2005 and moved on to track the highest autumn flood in the future. This could be extremely confusing for an unfamiliar user and this issue

would be resolved by studying the Y plots for the Flow regime modification indices for different sections of the hydrographs.

4. Not many IHA indices were applicable especially for the purpose of analyzing the general shape of the hydrograph which is a major part of studying the impacts of climate change on regional hydrology.

5. Finally, user friendliness is an important attribute and the numerical and over parameterized nature of the IHA indices approach seemed to be cumbersome.

It was observed that the flow regime modification indices approach was promising due to the informative and user friendly nature of the technique and also due to the graphical nature of the analysis. Further refinement of the technique is highly recommended.

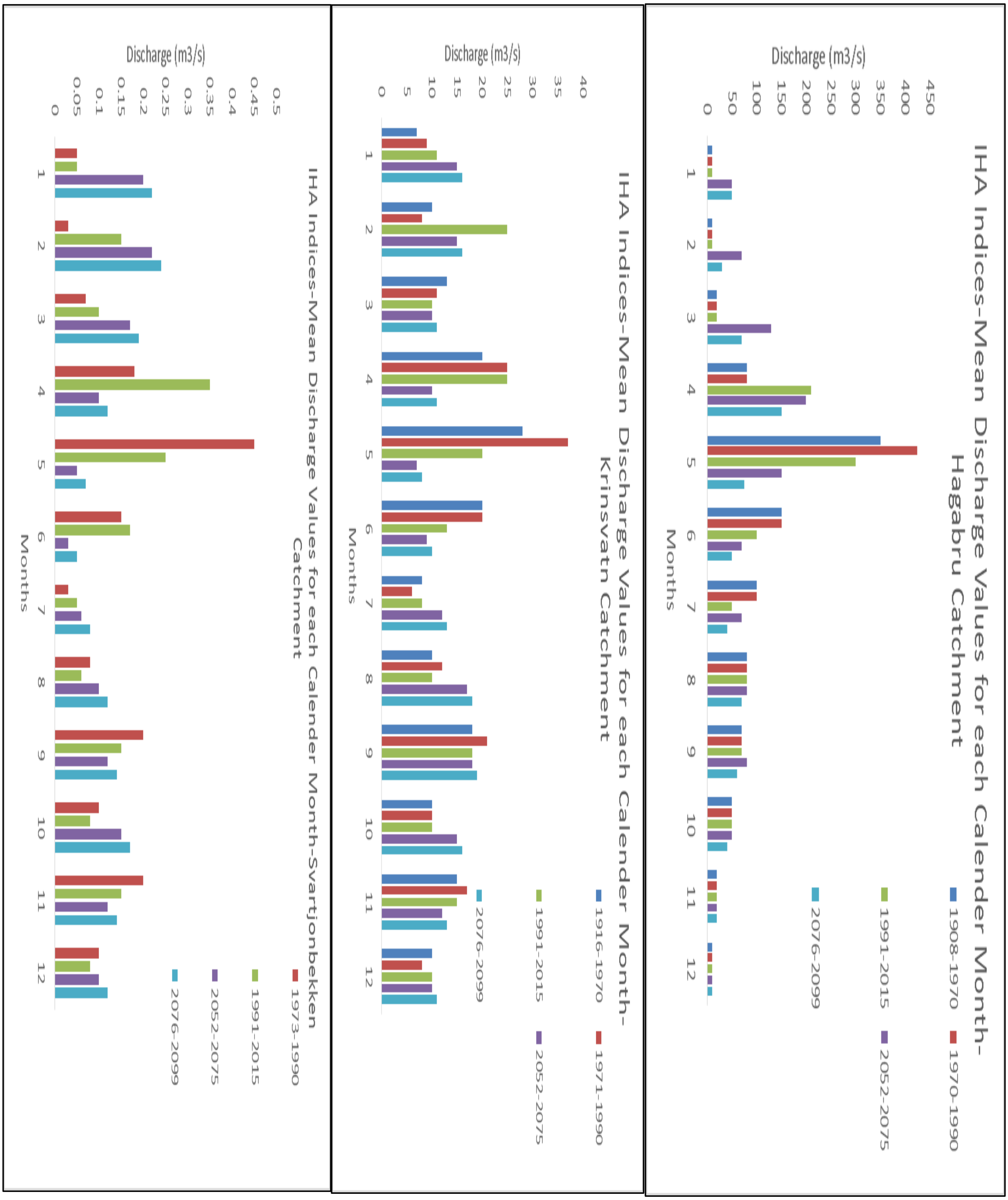


Figure 7.14: IHA Indices-Mean Values for Each Calendar Month

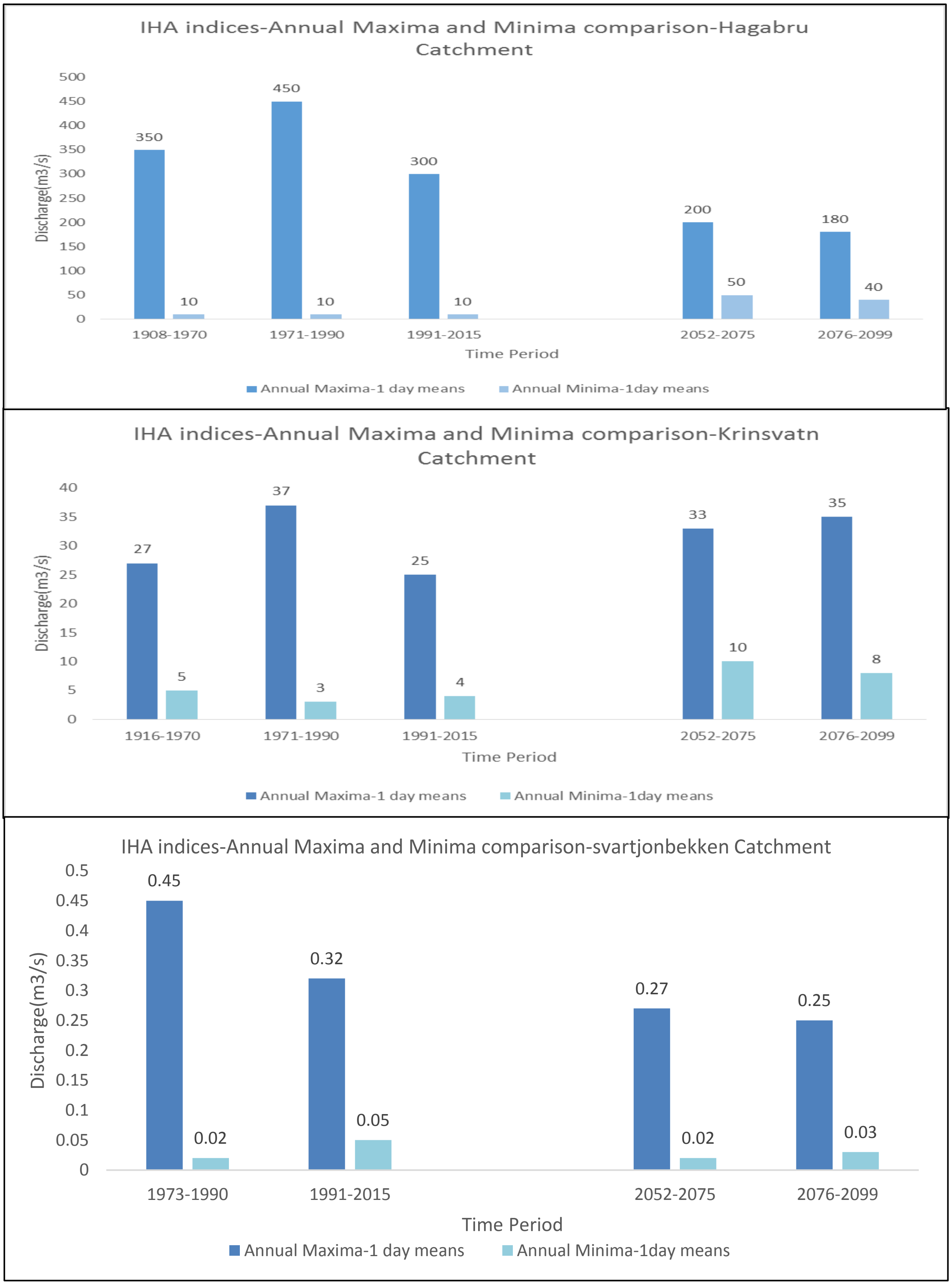


Figure 7.15: IHA Indices-Annual 1 Day Maxima and Minima comparison

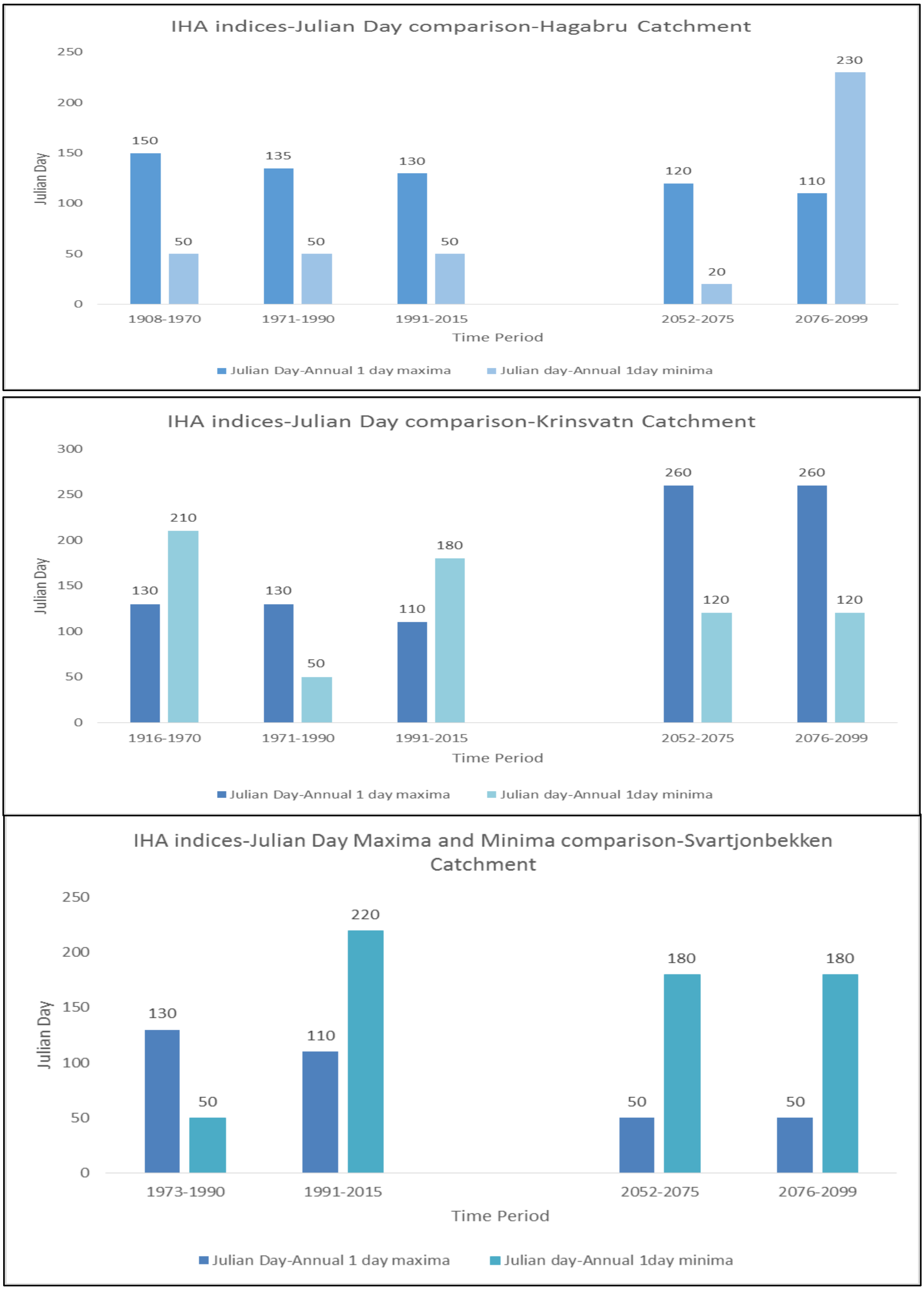


Figure 7.16: IHA Indices-Julian Day Maxima and Minima comparison

8.0 THE 1-YEAR APPROACH

Often, the limiting criteria hindering studies of climate change impacts on hydrology is obtaining good quality observed data which can facilitate the process of climate data downscaling and hydrological modelling. A possible opportunity for addressing this issue might be through the implementation the proposed 1-year approach.

The process of simulating and analysing long runoff records can be time consuming and complex. A simple approach was devised termed the '1-year approach' to address this issue. This discussion is an attempt at demonstrating the fact that a swift and rough estimate of impacts of climate change on flow regimes can be obtained by calibrating and simulating the HBV model for just one year.

The primary objective of the proposed method is to obtain a graphical depiction of the possible impacts of climate change on flow regimes in a single figure through simulations of the HBV model for just 1 year. Instead of analysing hundreds of hydrographs to discern the impacts of climate change on the general flow regime, a single depiction should be able to provide adequate information in this regard.

The HBV models were calibrated for a 1 year period employing GCM simulated historical data as input and simulations were performed by employing GCM simulated climate data over a future time period. The input data for the models were the means of discharge, precipitation and temperature for the respective time periods. The only observed data employed was the runoff time series and apart from that, all the other data used was GCM simulated without any downscaling being implemented. The methodology adopted for the 1 Year approach has been briefly described in the following steps.

STEP 1: Preparation of a 1 year hydrograph computed as daily average over the historical discharge measurement period.

STEP 2: Preparation of daily average precipitation plots with GCM simulated precipitation data for two different time periods. That is over the historical and projected time periods.

STEP 3: Preparation of daily average temperature plots with GCM simulated temperature data for two different time periods. That is over the historical and projected time periods.

STEP 4: Setting up of HBV input parameter file for a 1 year period with the prepared historical discharge, precipitation and temperature plots as inputs with due regard to the snow initialization conditions and calibration of the HBV model over this 1 year period.

STEP 5: Setting up of HBV input parameter file for a 1 year period with the prepared projected precipitation and temperature plots as inputs with due regard to the snow initialization conditions and simulation of the HBV model over this 1 year period.

The proposed methodology was implemented to the case study of Hagabru catchment to verify its efficacy in accurately capturing the changes imparted to the flow regime in a future climatic setting by comparing the obtained results to the investigation results of a complete hydrological modelling approach as previously discussed in this study report. The following steps describe the methodology adopted for the investigation for Hagabru catchment.

STEP 1: A single daily average annual hydrograph was prepared for Hagabru catchment with available historical observed runoff records over the time period of 1957-2005.

STEP 2: Two different daily average precipitation plots were prepared by employing GCM precipitation data over the periods 1957-2005 and 2051-2099 without any downscaling being implemented.

STEP 3: Two different daily average temperature plots were prepared by employing GCM simulated temperature data for two different time periods of 1957-2005 and 2051-2099 without implementing any downscaling on the temperature data.

STEP 4: Two different HBV models were set up with the prepared average discharge, average precipitation and average temperature data over the period of 1957-2005 for just 1 year for two different GCMs. It is very important to note that the HBV model is designed with an initialization condition as no snow on the day 01.09.YYYY. Hence, the data over the period 01.09.YYYY to 31.12.YYYY was repeated within the HBV model setup to address this issue. The models were calibrated for this particular year within the HBV PEST optimization loop and model efficiencies of 0.97 and 0.93 were obtained for MOCH and CNRM models respectively over the 1 year period.

STEP 5: Two new HBV models were setup with prepared average precipitation and average temperature data over the period 2051-2099 once again for a period of just 1 year. Simulations were run with these model setups and the obtained final results are presented in **Figure 8.1.**

It was amazing to see that the results obtained with this simple exercise had a strong resemblance with the results obtained with the long and time consuming approach adopted for climate change impact studies in this report. Although the information available from this depiction was limited, it proved a clear picture regarding the possible modifications to the flow regimes. The major limitation with this method would be the inability to perform flood frequency analysis and the inability of monitoring flow variations over the years on a finer time resolution.

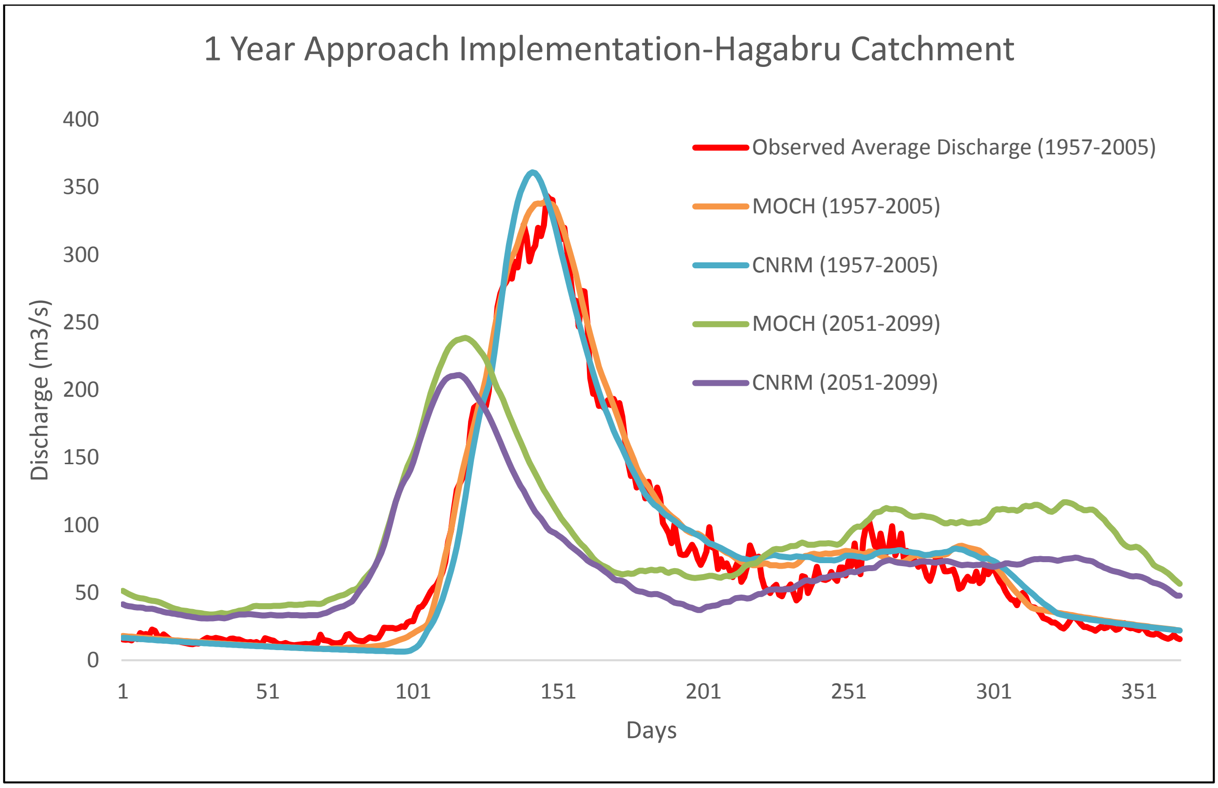


Figure 8.1: 1 Year Approach implementation-Hagabru Catchment

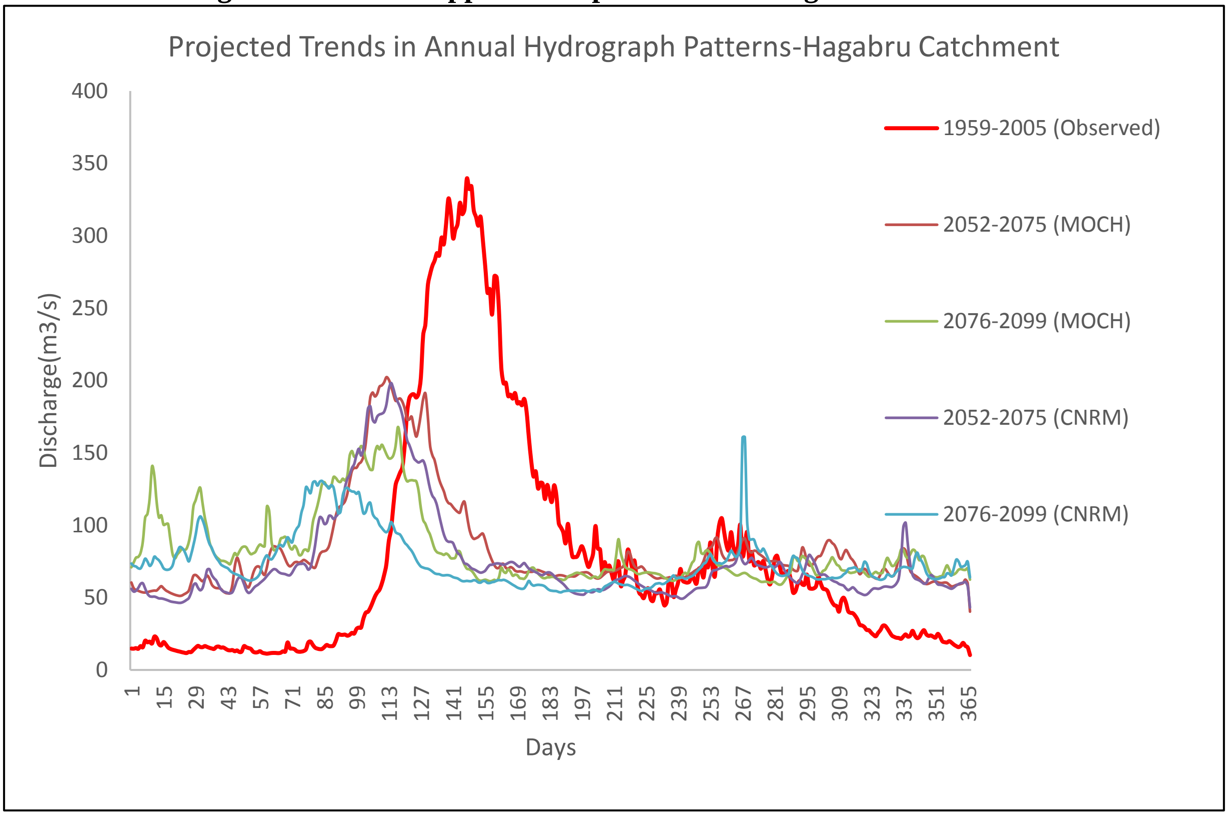


Figure 8.2: Projected trends in annual hydrographs with a complete hydrological modelling approach

This simple exercise clearly demonstrated the fact that similar results could be obtained by simulating the HBV setup for a 365 day periods with daily means as input data over the respective time periods. This method has a great advantage that calibration of the HBV model for a 1 year period is much simpler. Also, this approach could open a doorway for researchers with limited availability of observed data. In this exercise, the only observed data employed was the historical runoff records. All the other inputs were GCM simulated without any downscaling being implemented. Technically, this investigation could be carried out with just a single complete year of observed discharge data with absolutely no requirement for any observed temperature or precipitation data. This exercise also strongly points to the popular belief that GCM simulated climate data is reliable on a monthly or an annual averaged basis and unreliable on a daily time resolution.

9.0 CONCLUSIONS AND RECOMMENDATIONS

The basic premise of this research project has been to analyze possible changes to the natural flow regimes and flood characteristics imparted by the phenomenon of climate change in select catchments of central Norway.

Majority of the prior research works carried out in the region to comprehend the effects of climate change on the hydrograph pattern had focused on simulations of a future time period employing downscaled GCM climate data. These studies had overlooked the trends observable in these catchments at present times. The results obtained from investigations into historical observed runoff data clearly indicated that alterations to the natural flow regimes in the catchments investigated were already evident with dampened spring flood magnitude and an earlier onset of the spring flood peaks. It is recommended that an evaluation of changes to flow regimes be carried out on a much larger scale as the project findings clearly demonstrate prevalent changes to flow regimes. This will facilitate revision of the reclassification of catchments in Norway based on their flow regimes.

Investigations were carried out to discuss the validity of a hydrological model calibrated to obtain a general good fit with the observed data to accurately reproduce flood peaks. The outcome of the investigation reveals that a hydrological model (The HBV model) calibrated to obtain a general good fit (A high R^2 value and a low Accumulated difference value) demonstrated limited ability of reproducing the observed flood peaks and in turn showed a poor correspondence with the observed flood frequency trends. An iterative trial and error procedure was necessary to obtain a parameter set which reproduced the observed flood frequency trends to a high degree of accuracy. It was found that a hydrological model optimized to reproduce flood peaks demonstrated a lower degree of general good fit with the observed runoff trend (A lower R^2 value and a higher accumulated difference value). Hence, it is highly recommended that an ensemble analysis with multiple parameter sets should be carried out to capture the full spectrum of uncertainty from the model output.

A monte-carlo approach which identifies a large number of parameter sets with comparable model efficiencies (High R^2 value) has generally been the adopted methodology to deal with this issue. But, the project findings clearly demonstrates that the model efficiency is generally reduces to a high degree in an attempt to accurately capture the flood peaks. Hence, the monte-carlo approach might have limited capability of addressing the issue of model uncertainty with respect to flood frequency analysis. Hence, a trial and error methodology to identify a single unique parameter set capable of reproducing observed peaks was introduced in this project to get better control over the uncertainty with respect to flood peaks. Further, addition of features within the HBV model which can facilitate the process of identification of this parameter set could be looked into as it would greatly enhance the versatility of the model thereby broadening the horizon of its applicability in research and utility.

But, with regards to comprehending the uncertainties inherent with general runoff generation or the general hydrograph patterns, the monte-carlo approach is highly recommended as minor variations of parameters within the HBV model can result in large scale variation to the hydrograph trends as described in this project.

Climate data downscaling has been the most challenging part of investigations into the impacts of climate change on regional hydrological features. The GCMs and RCMs have come a long way in enhancing their ability to reproduce the precipitation and temperature time series to a reasonable degree of accuracy on a fine resolution. Since the concept of climate change revolves around the phenomenon of changing temperatures, majority of the GCMs and RCMs reproduce the temperature data to a high degree of correspondence with the observed data. But, their ability to reproduce the precipitation data is seriously limited due to the presence of various systematic biases. This effect is magnified when the terrain of the catchments get intricate such as tat observed in Norway.

The previously established downscaling techniques such as scaling, power transformation and quantile mapping are primarily designed to obtain good agreement for monthly means and not daily means. To address this issue, a new precipitation data downscaling technique termed 'Antinoise Downscaling' was introduced as a part of this project. The proposed methodology performed well in correcting the GCM precipitation data for daily means, monthly means and also for the rainy day correction. This method produced satisfactory hydrological model performance as the models were capable of reproducing the observed hydrograph trends and also the spring flood peaks. But, the method still had shortcomings in that the hydrological models had limited ability of reproducing autumn flood peaks. This could be due to a bias in the proposed methodology or due to the limited accuracy of the GCM simulated climate data. But the fact that the well-established methodologies such as linear scaling, variance scaling, power transformation and quantile mapping also could not improve model performance suggested that the issue was most probably with the precipitation data quality. Also, the method performed significantly better in larger catchments when compared to smaller catchments due to the availability of GCM data within a large number of grid cells in the larger catchments. Also, it was found that coastal catchments were particularly hard to calibrate with GCM simulated climate data due to complex weather patterns and topography. The Antinoise downscaling method demonstrates promise in its ability to enhance climate data downscaling accuracy to a daily resolution and it is recommended that further investigations be carried out to sharpen the approach.

Investigations to discern possible changes imparted to the natural hydrological regimes in the selected catchments were carried out. The results revealed that the spring floods in all the catchments studied would be highly influenced with an earlier onset of spring flood peaks and exponential dampening effect of the spring flood peaks in a future climate scenario of 2051-2099. Also, a more uniform distribution of inflow volume was predicted. This was majorly due to the exponential reduction in the snow precipitation, accumulation and melting patterns in a future warmer climatic scenario.

This could have profound impacts on the current established hydro dependent infrastructural setting of Norway from water supply to the all-important hydropower industry. It is highly recommended that hydropower companies commence their preparation to facilitate the transition towards a future climate setting. Especially, new reservoir rule curves and guide curves would need to be designed to recalibrate the reservoir operation routine. Also, hydropower generation routines would have to undergo radical transformation to cope with the changes imparted to inflow scenarios.

The ‘Flow regime modification indices’ method of analysis of hydrograph trends was introduced in this project. Upon scrupulous studies, it was found that these indices provide immense amount of information regarding changes to hydrograph trends over an extended period of time. Further, the graphical nature of the approach adds to its advantages over the previously established techniques such as the IHA indices methodology. Improvements of the proposed methods should be looked into in future works in the area.

Also, a new methodology termed ‘The 1-Year approach’ aimed at obtaining swift graphical estimates of possible changes imparted to the natural flow regimes was introduced in this study. This method gave good results and was capable of accurately reproducing the results obtained by the long procedure generally adapted for climate change impact studies. Although the method had limitations, it could serve as an accessory for climate change studies.

Finally, the flood frequency analysis within a future climatic setting revealed that the flood magnitudes of respective return periods showed a reduction in flood magnitudes in all of the studied catchments on an annual basis and also as spring floods, This entails that the existing storm water drainage infrastructure would be sufficient to cope with the future impacts of climate change in this region.

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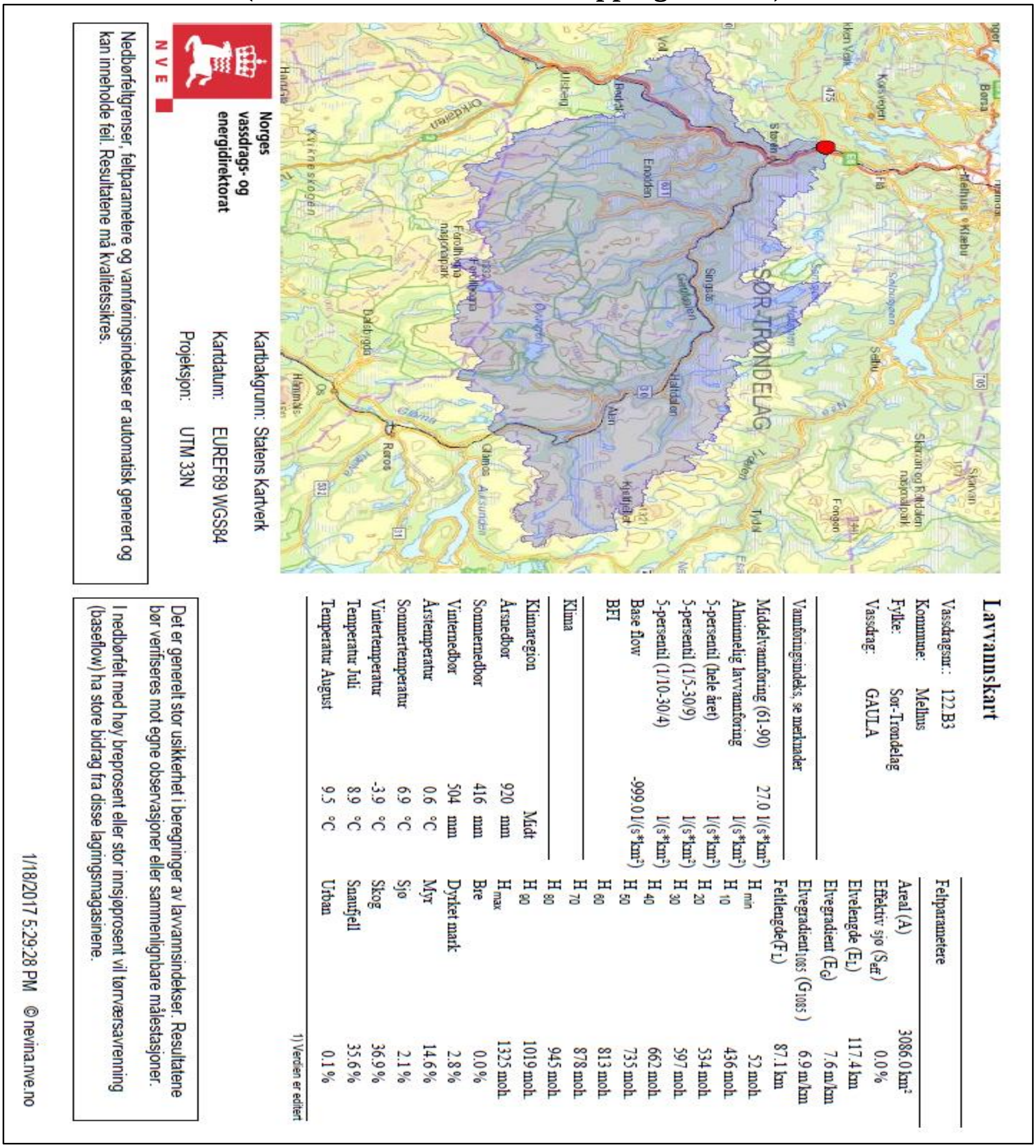
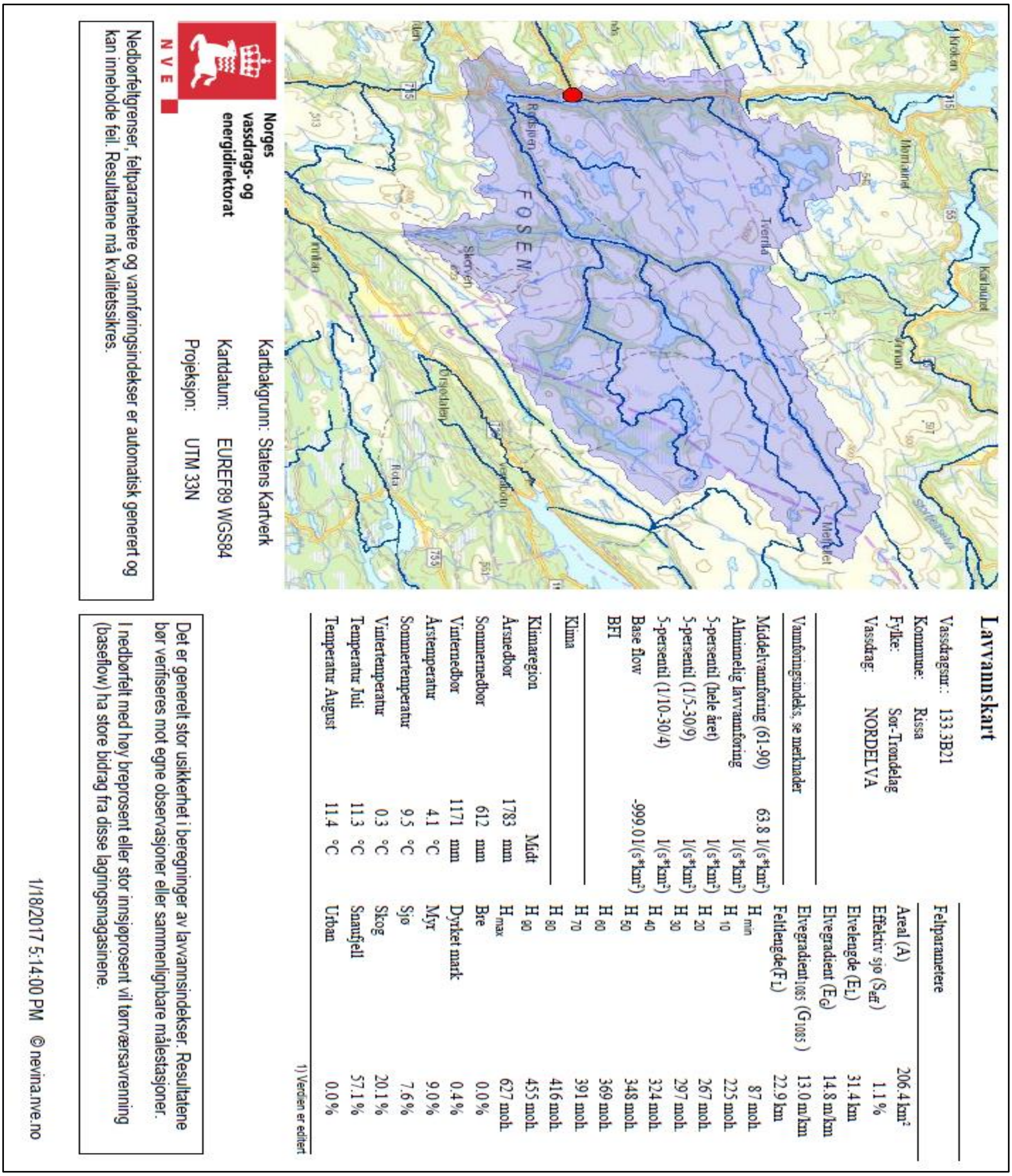
APPENDIX

APPENDIX 1-Salient characteristics of Hagabru catchment (Source: NVE, NEVINA mapping services)



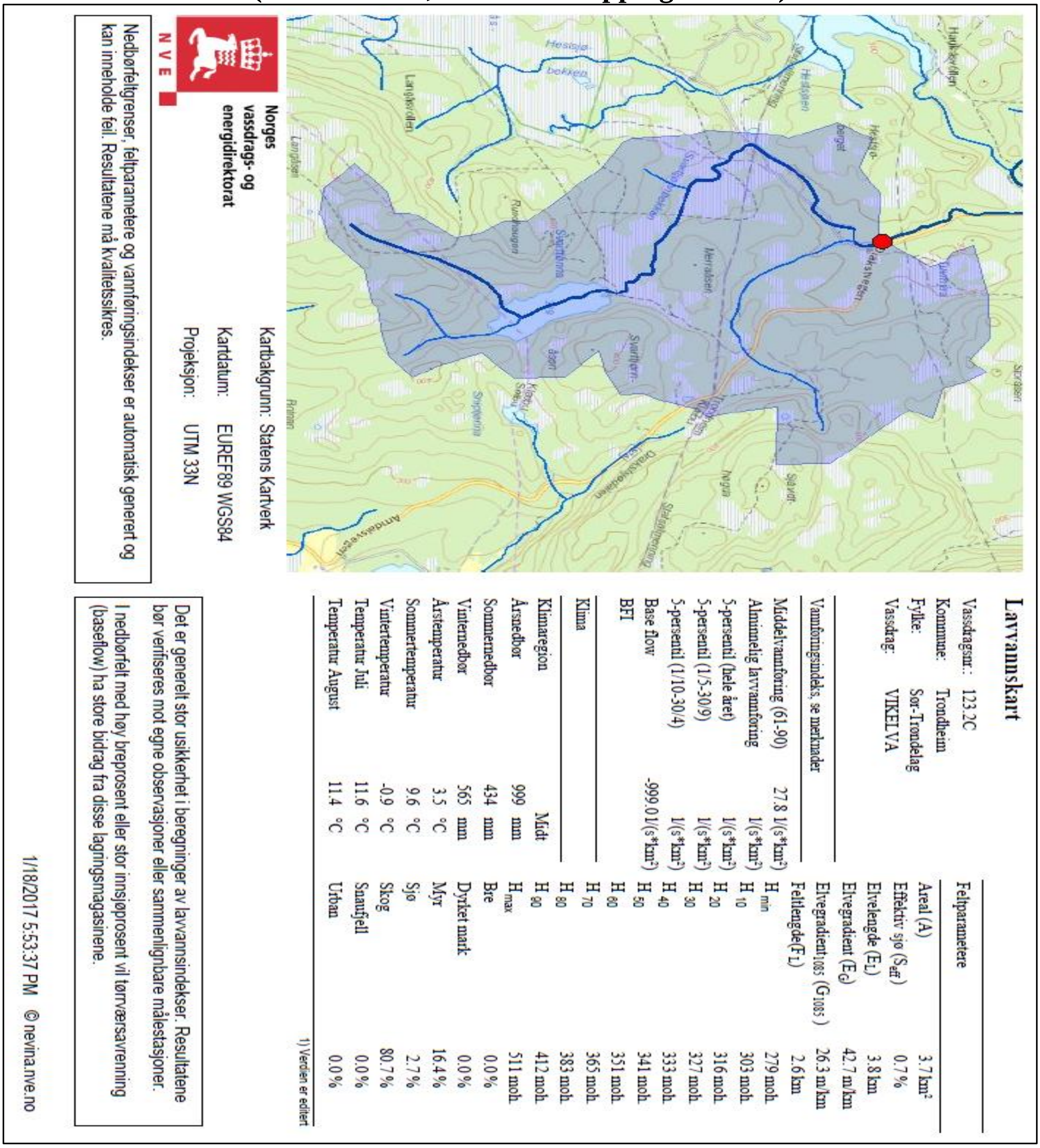
(Figure A1.1: Hagabru Catchment characteristics)

APPENDIX 2-Salient characteristics of Krinsvatn catchment (Source: NVE, NEVINA mapping services)



(Figure A2.1: Krinsvatn Catchment characteristics)

APPENDIX 3-Salient characteristics of Svartjonbekken catchment (Source: NVE, NEVINA mapping services)



Lavvannskart

Vassdragsnr.:	123.2C
Kommune:	Trondheim
Fylke:	Sør-Trøndelag
Vassdrag:	VIKELVA

Vannføringsindeks, se merknader	
Middelvannføring (61-90)	27.8 l/(s*km²)
Alminnelig lavvannføring	l/(s*km²)
5-persentil (hele året)	l/(s*km²)
5-persentil (1/5-30/9)	l/(s*km²)
5-persentil (1/10-30/4)	l/(s*km²)
Base flow	-999.0 l/(s*km²)
BFI	

Klima	
Klimaregion	Midt
Årsnedbør	999 mm
Sommernedbør	434 mm
Vinternedbør	565 mm
Årstemperatur	3.5 °C
Sommertemperatur	9.6 °C
Vintertemperatur	-0.9 °C
Temperatur Juli	11.6 °C
Temperatur August	11.4 °C

Feltparametere	
Areal (A)	3.7 km²
Effektiv sjø (S_{eff})	0.7 %
Elvelengde (E_L)	3.8 km
Elvegradient (E_G)	42.7 m/km
Elvegradient$_{1085}$ (G_{1085})	26.3 m/km
Feltlengde(F_L)	2.6 km
H_{min}	279 moh.
H_{10}	303 moh.
H_{20}	316 moh.
H_{30}	327 moh.
H_{40}	333 moh.
H_{50}	341 moh.
H_{60}	351 moh.
H_{70}	365 moh.
H_{80}	383 moh.
H_{90}	412 moh.
H_{max}	511 moh.
Bre	0.0 %
Dyrket mark	0.0 %
Myr	16.4 %
Sjø	2.7 %
Skog	80.7 %
Snaufjell	0.0 %
Urban	0.0 %

1) Verdien er editert

Norges vassdrags- og energidirektorat

NVE

Kartbakgrunn: Statens Kartverk

Kartdatum: EUREF89 WGS84

Projeksjon: UTM 33N

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

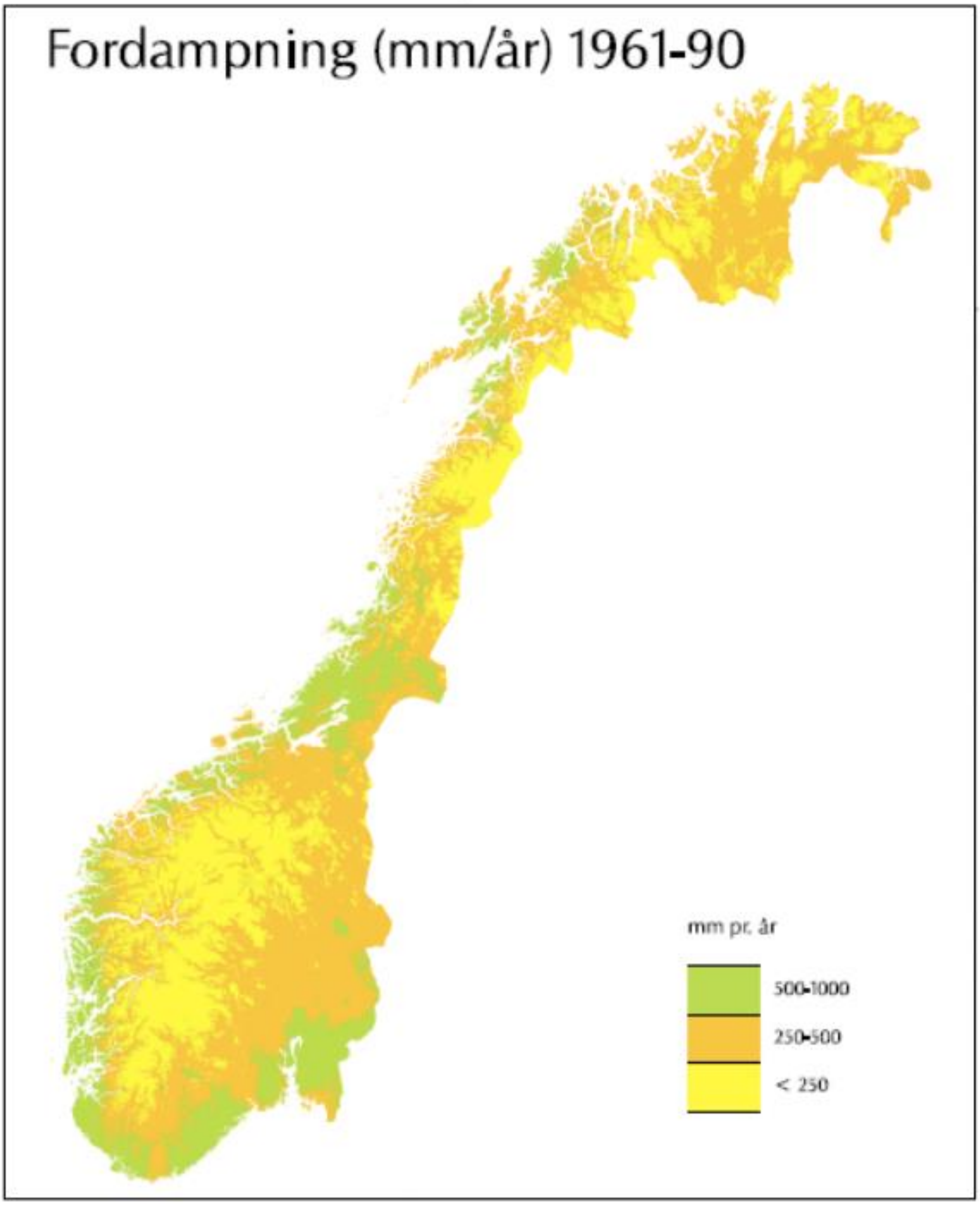
Det er generelt stor usikkerhet i beregninger av lavvannsindekser. Resultatene bør verifiseres mot egne observasjoner eller sammenlignbare målestasjoner.

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

1/18/2017 5:53:37 PM © nevina.nve.no

(Figure A3.1: Svartjonbekken Catchment characteristics)

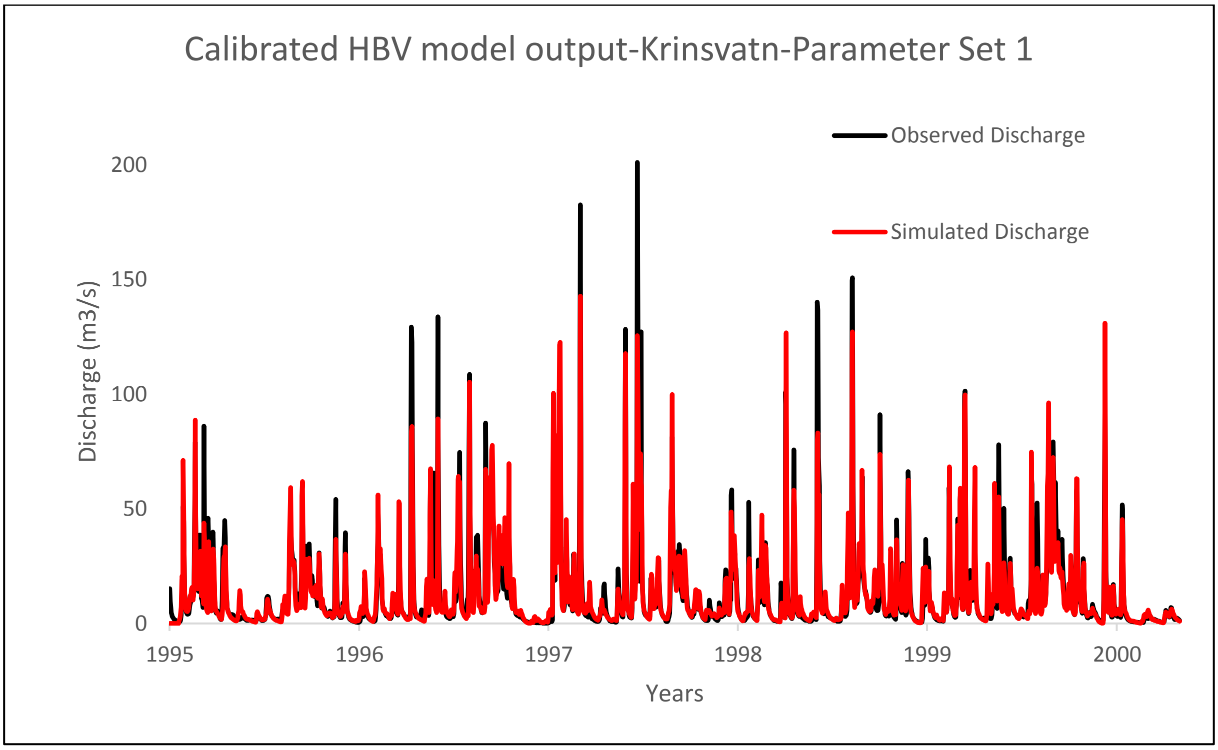
APPENDIX 4- NATIONAL EVAPOTRANSPIRATION MAP, NORWAY (NVE)



(Figure A4.1: NATIONAL EVAPOTRANSPIRATION MAP, NORWAY (NVE)

APPENDIX 5-HBV CALIBRATION COMPARISON-KRINSVATN CATCHMENT

Figure A5.1 depicts the comparison between observed and simulated output for Krinsvatn catchment with best fitting calibration for water balance. The calibration resulted in a Nash-Sutcliffe coefficient of R^2=0.84 and an accumulated difference value of just -41 mm over the calibration period of 1995-2000. The model also performed well over the validation period with an R^2 value of 0.84 over the simulation period 1990-1995 and an R^2 of 0.83 over 2000-2005. The models ability of accurately reproducing the recession curve and the timing of flood peaks was also observed to be of very good quality. Hence, it was concluded that the model calibration with parameter set 1 met the quality requirements for good water balance. But, the resultant flood frequency analysis proved to be unsatisfactory.

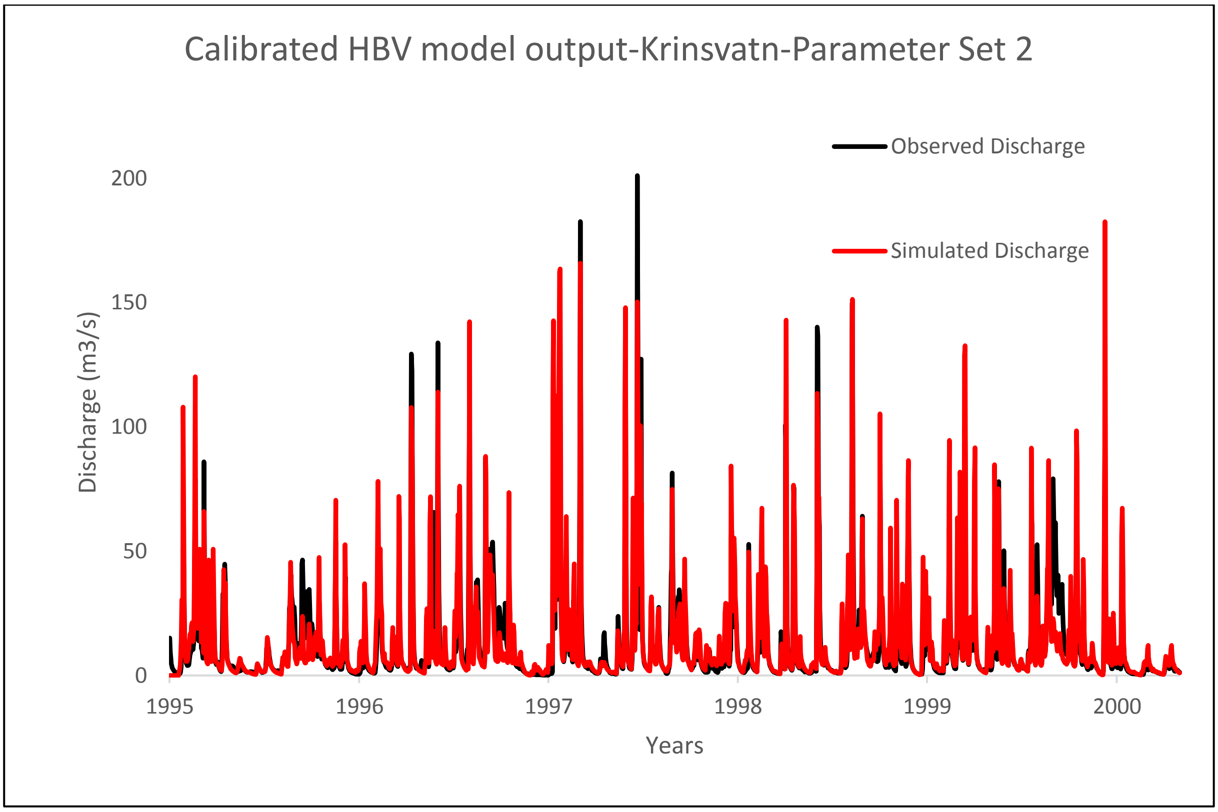


(Figure A5.1: Calibrated HBV model output-Krinsvatn-Parameter set 1)

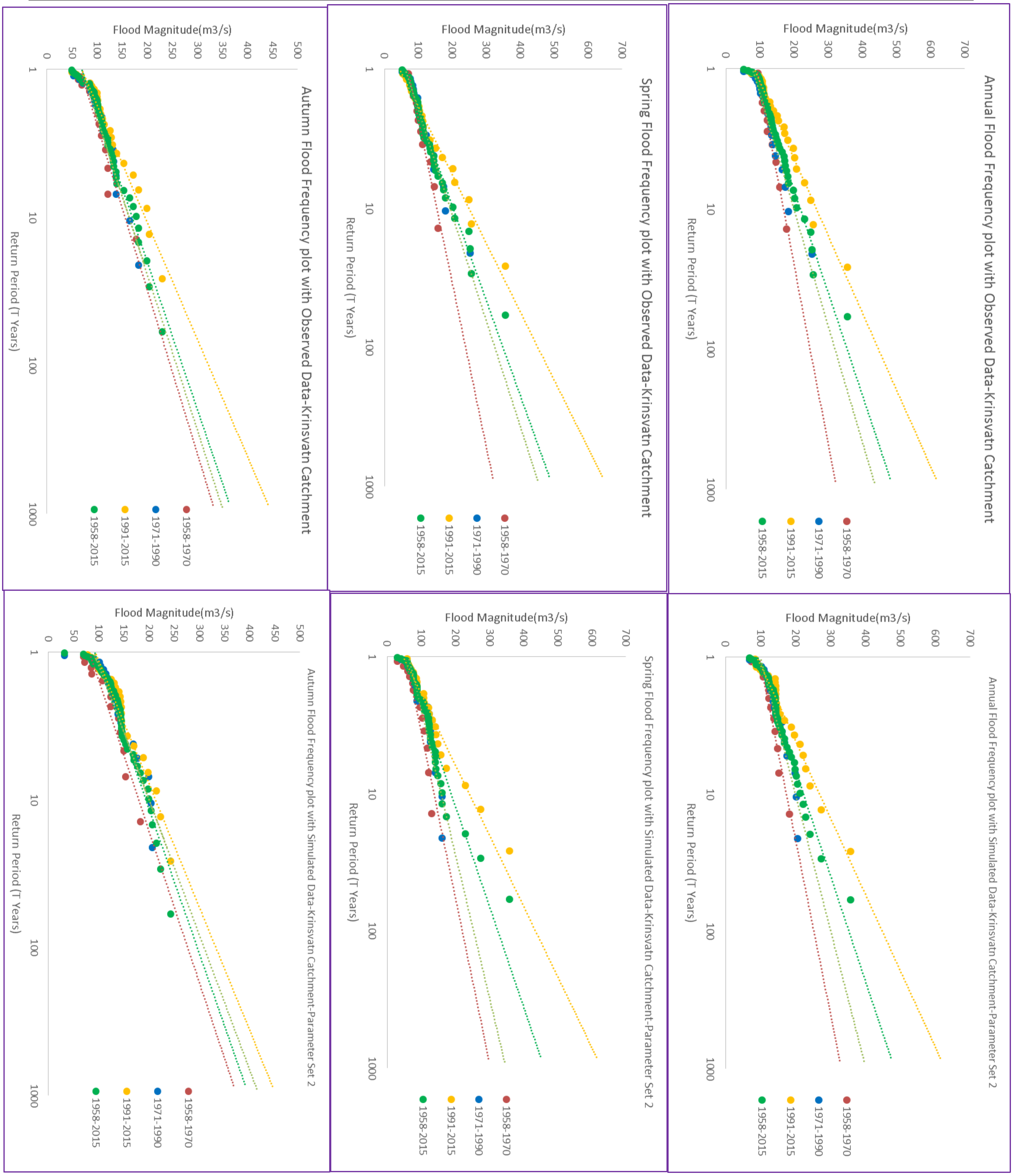
The model underestimated the flood magnitudes to a great extent which inevitably resulted in poor quality flood frequency fit on an annual basis and also on seasonal basis. The model was also unable to reproduce the variation in flood frequency characteristics over the decades. Hence, it could be concluded that the calibration with parameter set 1 was very much suitable for water balance studies but was ineffective for flood frequency analysis.

A recalibration was carried out to address this issue with scrupulous iterative approach with careful modification of parameters to come up with a parameter set capable of reproducing the flood frequency analysis to a good extent. The fundamental methodology adopted for recalibration was manual iterative parameter manipulation to come up with good fit for spring and autumn flood frequency trends. This would automatically result in a good fitting annual flood frequency trend.

It was found that parameter RCORR and the flow response parameters such as KLZ, KUZ and so on were very sensitive with respect to autumn flood frequency trends whereas parameter SCORR and the snow routine parameters were the once in control of the spring floods. It was also found that spring floods were predominantly significant with respect to reproducing the annual flood frequency trends as the annual maximum floods in the study catchments were often spring floods with certain exceptions. The model output comparison with recalibrated parameter set is presented in **Figure A5.2** and the resultant flood frequency trend comparison has been presented in **Figure A5.3**. Recalibration over the period 1995-2000 resulted in an R^2 value of 0.76 and an accumulated difference value of 266.5 mm. Model validation over the periods 2000-2005 and 1990-1995 resulted in R^2 values of 0.72 and 0.70 respectively. It could be observed that the performance coefficients were considerably lower when compared to that obtained from parameter set 1. This was a strong indication that a hydrological model calibrated for obtaining good fit for water balance would be ineffective for flood frequency studies and vice-versa.



(Figure A5.2: Calibrated HBV model output-Krinsvatn-Parameter set 2)



(Figure A5.3: Calibrated HBV model flood frequency comparison-Krinsvatn-Parameter set 2)

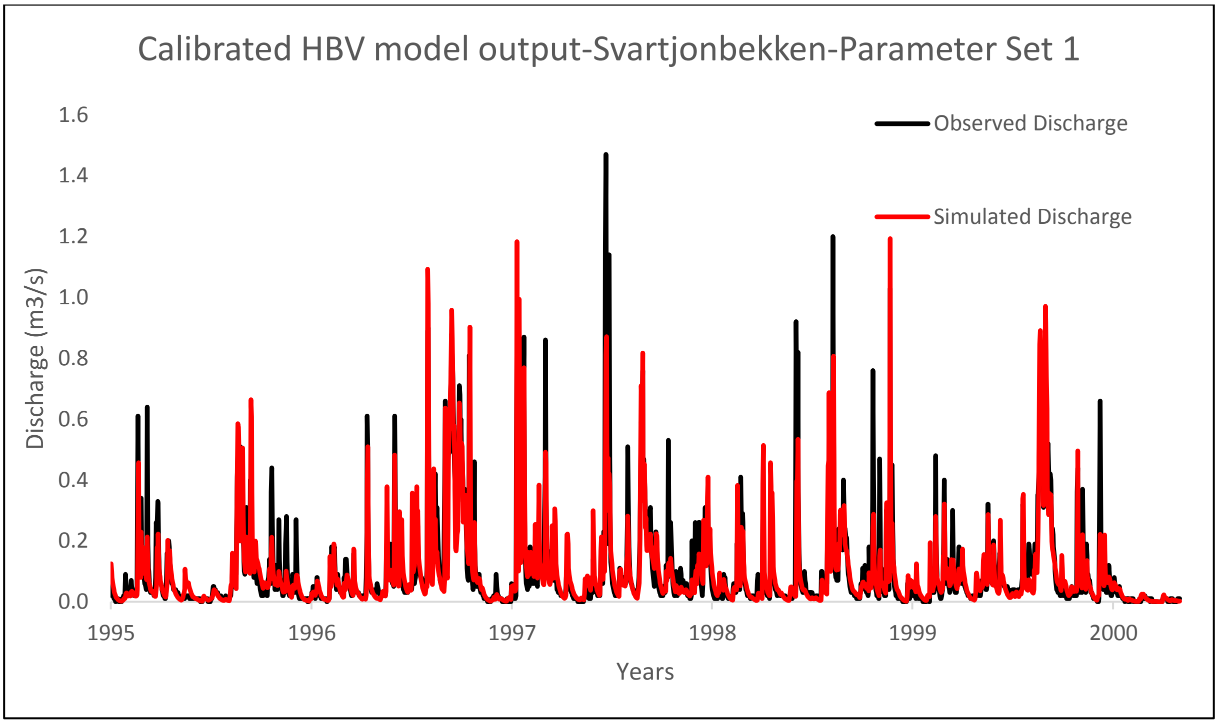
It was clearly observed that the model performance with respect to flood frequency analysis was superior to that obtained from parameter set 1. The model could capture not only the annual flood frequency trend but also the seasonal fluctuations over the decades which suggests that the calibration could be termed reliable for carrying out flood frequency analysis in a future climatic setting. The value of RCORR was changed from 1.28 from parameter set 1 to 1.6 in parameter set 2. Also, the value of SCORR was reduced from 0.86 to 0.3 within parameter set 2.

(Table A5.1: HBV parameter set comparison-Krinsvatn catchment)

	Parameter set 1	**Parameter Set 2**
RCORR	1.288	1.6
SCORR	0.863	0.3
CX	8.527 mm/Deg C day	8 mm/Deg C day
CXN	8.404 mm/Deg C day	8 mm/Deg C day
TX	1.226 Deg C	1.226 Deg C
TS	2.326 Deg C	2.326 Deg C
TSN	0.08 Deg C	0.08 Deg C
KUZ2	3.166 mm/day	3.166 mm/day
KUZ1	0.588 mm/day	0.588 mm/day
KUZ	0.133 mm/day	0.133 mm/day
KLZ	0.092 mm/day	0.092 mm/day

APPENDIX 6-HBV CALIBRATION COMPARISON-SVARTJONBEKKEN CATCHMENT

Figure A6.1 depicts the comparison between observed and simulated output for Svartjonbekken catchment with best fitting calibration for water balance. The calibration resulted in a Nash-Sutcliffe coefficient of R^2=0.72 and an accumulated difference value of -256 mm over the calibration period of 1995-2000. The model also performed well over the validation period with an R^2 value of 0.65 over the simulation period 1990-1995 and an R^2 of 0.73 over 2000-2005. The models ability of accurately reproducing the recession curve and the timing of flood peaks was also observed to be of very good quality. Hence, it was concluded that the model calibration with parameter set 1 met the quality requirements for good water balance. But, the resultant flood frequency analysis proved to be unsatisfactory.

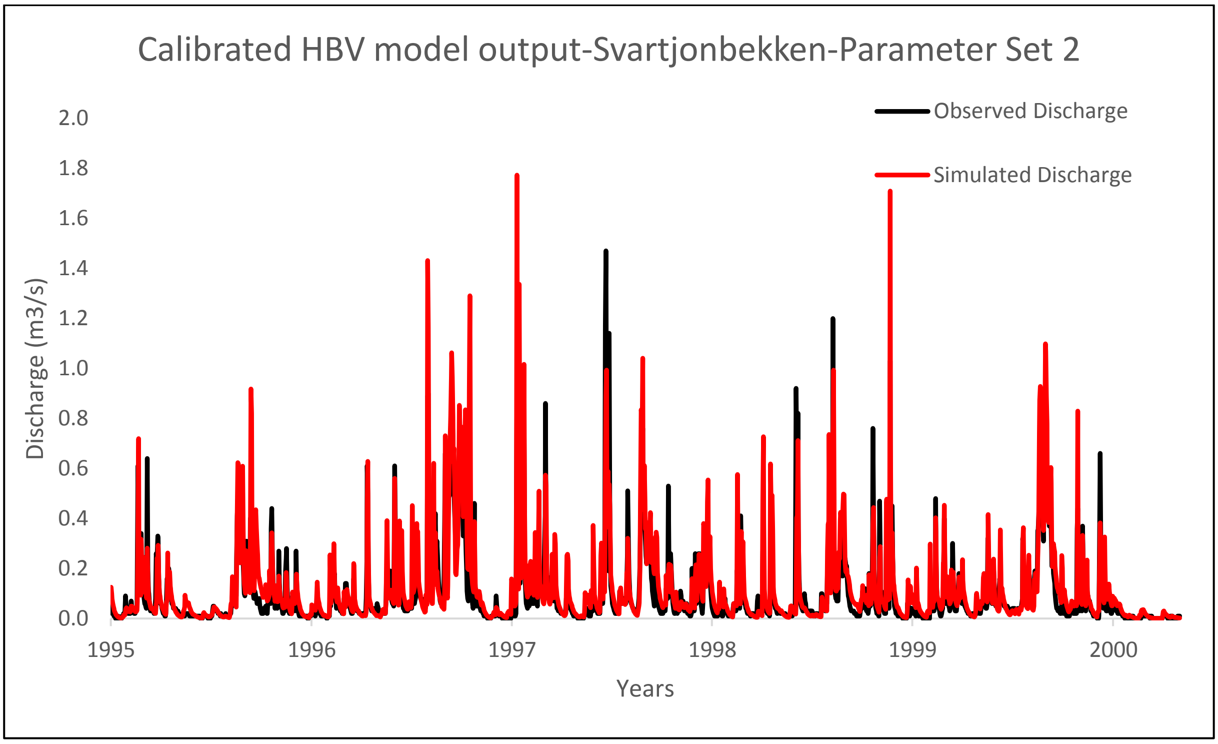


(Figure A6.1: Calibrated HBV model output-Svartjonbekken-Parameter set 1)

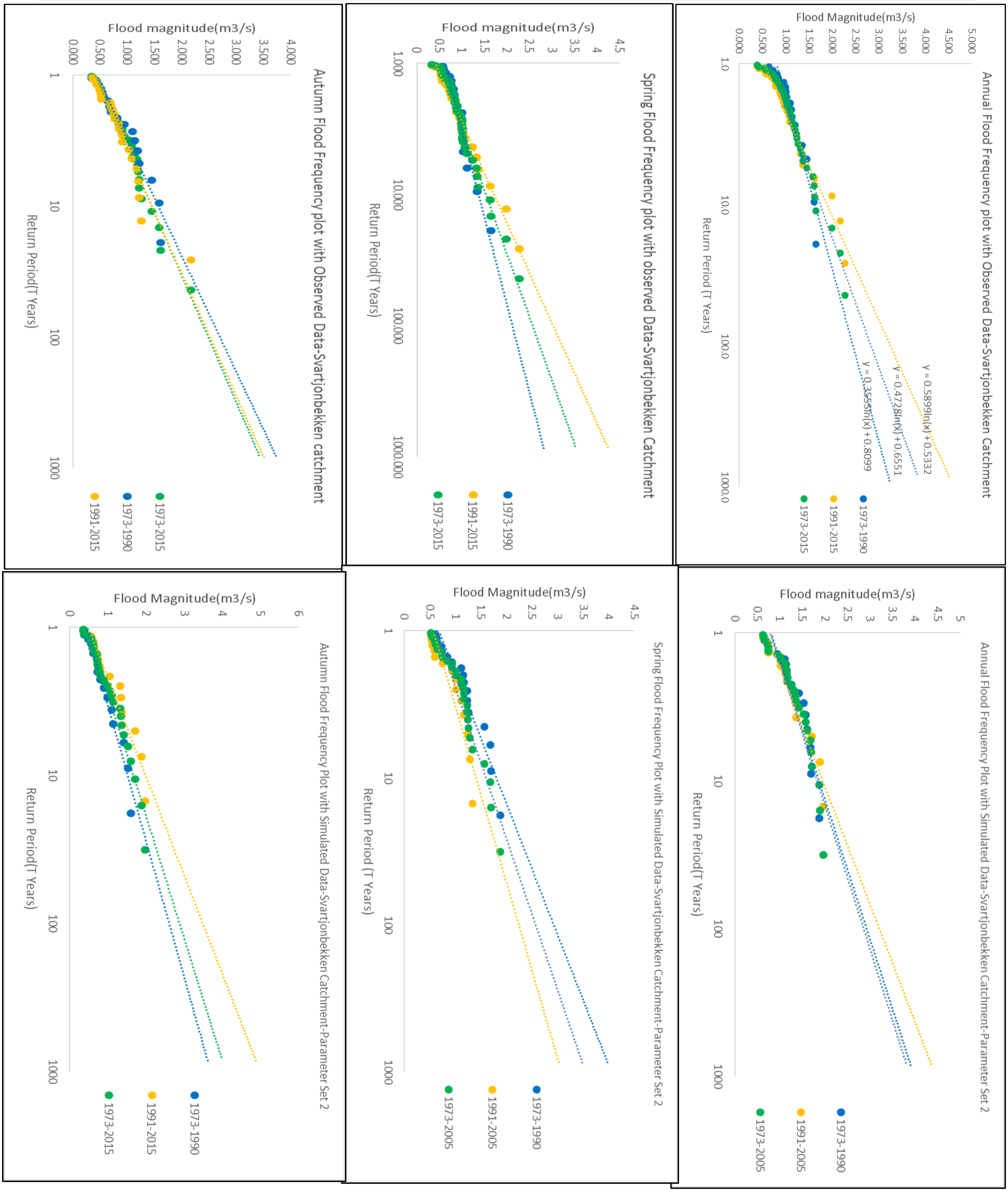
The model underestimated the flood magnitudes to a great extent which inevitably resulted in poor quality flood frequency fit on an annual basis and also on seasonal basis. The model was also unable to reproduce the variation in flood frequency characteristics over the decades. Hence, it could be concluded that the calibration with parameter set 1 was very much suitable for water balance studies but was ineffective for flood frequency analysis.

A recalibration was carried out to address this issue with scrupulous iterative approach with careful modification of parameters to come up with a parameter set capable of reproducing the flood frequency analysis to a good extent. The fundamental methodology adopted for recalibration was manual iterative parameter manipulation to come up with good fit for spring and autumn flood frequency trends. This would automatically result in a good fitting annual flood frequency trend.

It was found that parameter RCORR and the flow response parameters such as KLZ, KUZ and so on were very sensitive with respect to autumn flood frequency trends whereas parameter SCORR and the snow routine parameters were the once in control of the spring floods. It was also found that spring floods were predominantly significant with respect to reproducing the annual flood frequency trends as the annual maximum floods in the study catchments were often spring floods with certain exceptions. The model output comparison with recalibrated parameter set is presented in **Figure A6.2** and the resultant flood frequency trend comparison has been presented in **Figure A6.3**. Recalibration over the period 1995-2000 resulted in an R^2 value of 0.66 and an accumulated difference value of 480 mm. Model validation over the periods 2000-2005 and 1990-1995 resulted in R^2 values of 0.66 and 0.60 respectively. It could be observed that the performance coefficients were considerably lower when compared to that obtained from parameter set 1. This was a strong indication that a hydrological model calibrated for obtaining good fit for water balance would be ineffective for flood frequency studies and vice-versa.



(Figure A6.2: Calibrated HBV model output-Svartjonbekken-Parameter set 2)



(Figure A6.3: Calibrated HBV model flood frequency comparison-Svartjonbekken-Parameter set 2)

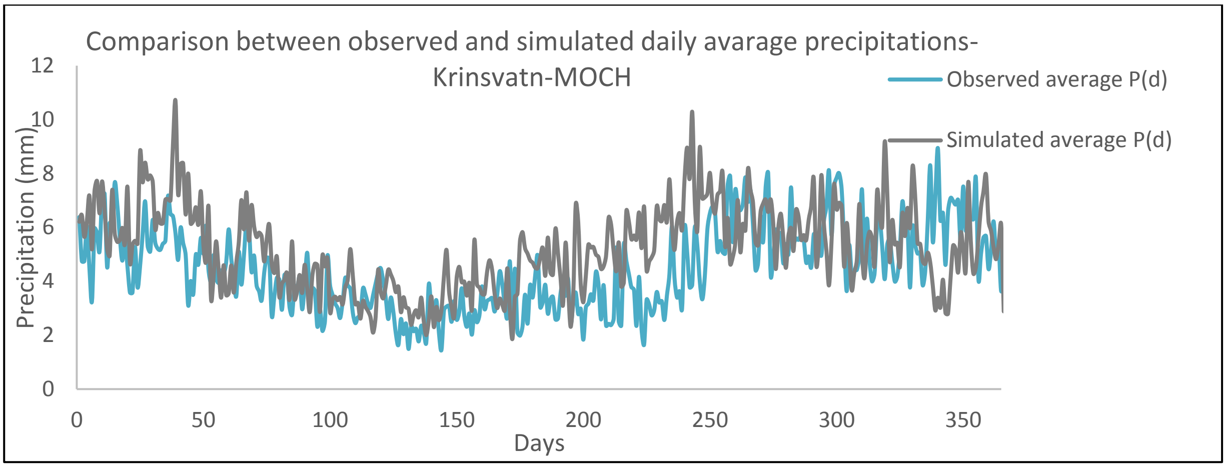
It was clearly observed that the model performance with respect to flood frequency analysis was superior to that obtained from parameter set 1. The model could capture not only the annual flood frequency trend but also the seasonal fluctuations over the decades which suggests that the calibration could be termed reliable for carrying out flood frequency analysis in a future climatic setting. The value of RCORR was changed from 0.96 from parameter set 1 to 1.1 in parameter set 2.

(Table A6.1: HBV parameter set comparison-Svartjonbekken catchment)

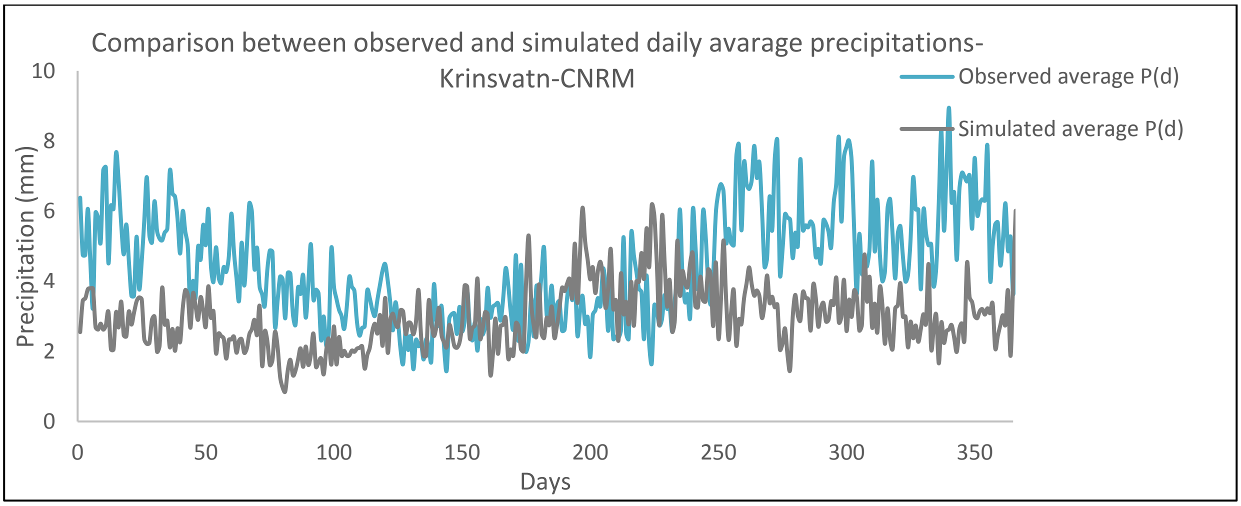
	Parameter set 1	**Parameter Set 2**
RCORR	0.960	1.10
SCORR	0.905	0.905
CX	5.4 mm/Deg C day	5.4 mm/Deg C day
CXN	1.287 mm/Deg C day	1.287 mm/Deg C day
TX	0.786 Deg C	0.786 Deg C
TS	1.795 Deg C	1.795 Deg C
TSN	-2.58 Deg C	-2.58 Deg C
KUZ2	6.032 mm/day	6.032 mm/day
KUZ1	2.217 mm/day	2.217 mm/day
KUZ	1.646 mm/day	1.646 mm/day
KLZ	0.150 mm/day	0.150 mm/day

APPENDIX 7: KRINSVATN CLIMATE DATA DOWNSCALING

STEP 1: The first step in Antinoise downscaling was to sort the daily observed and GCM simulated precipitation time series on an annual basis (1957-2005). Further, daily average annual precipitation plots were prepared for the sorted data. **Figures A7.1** and **A7.2** depict the trends in observed daily average precipitation (P_{OD}), daily average precipitation for CNRM model (P_{G1D}) and MOCH model (P_{G2D}) over the period 1957-2005.



(Figure A7.1: Comparison between observed and simulated daily average precipitation-Krinsvatn-MOCH)



(Figure A7.2: Comparison between observed and simulated daily average precipitation-Krinsvatn-CNRM)

STEP 2: The differences between the annual precipitation plots were computed for each year and analyzed for consistency. It is important to note that the individual differences in precipitation trends were consistent throughout the period of 1957-2005 for both the models with only slight deviations. This suggested that the differences could essentially be termed as 'programing noises'. That is, all of the systematic biases included in the GCM simulated data were assumed to be delineated as part of the noise trends (N_{1D} and N_{2D}). Hence, average trends in differences between the observed and GCM simulated precipitation data over the period of 1957-2005 were computed and were assumed as programming noises for the individual models and have been presented in **Figure A7.3** and **Figure A7.4.**

$$N_{1D}=P_{G1D}-P_{OD}$$

$$N_{2D}=P_{G2D}-P_{OD}$$

Where,

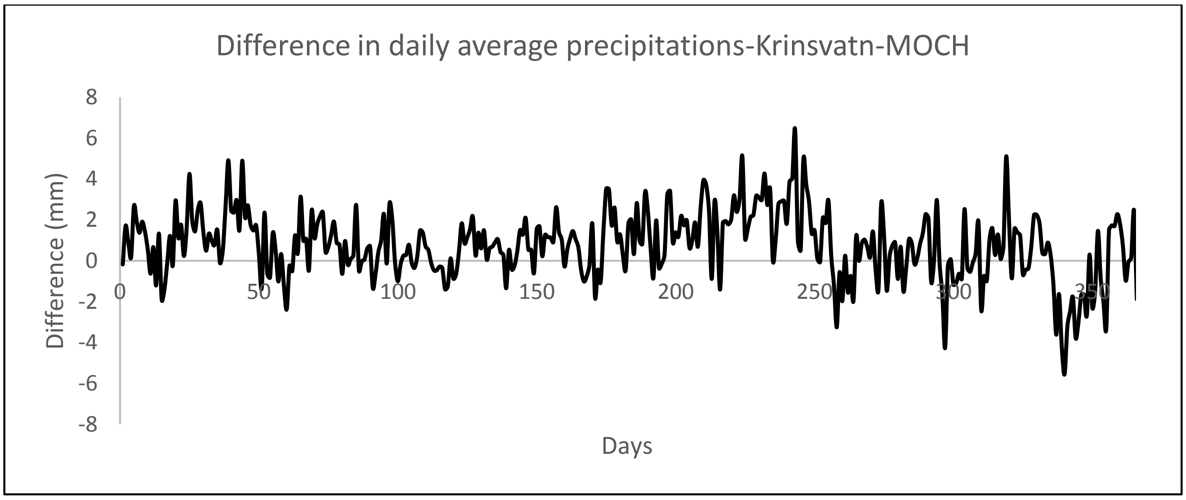
N_{1D}=Average Noise pattern from CNRM model data

N_{2D}=Average Noise pattern from MOCH model data

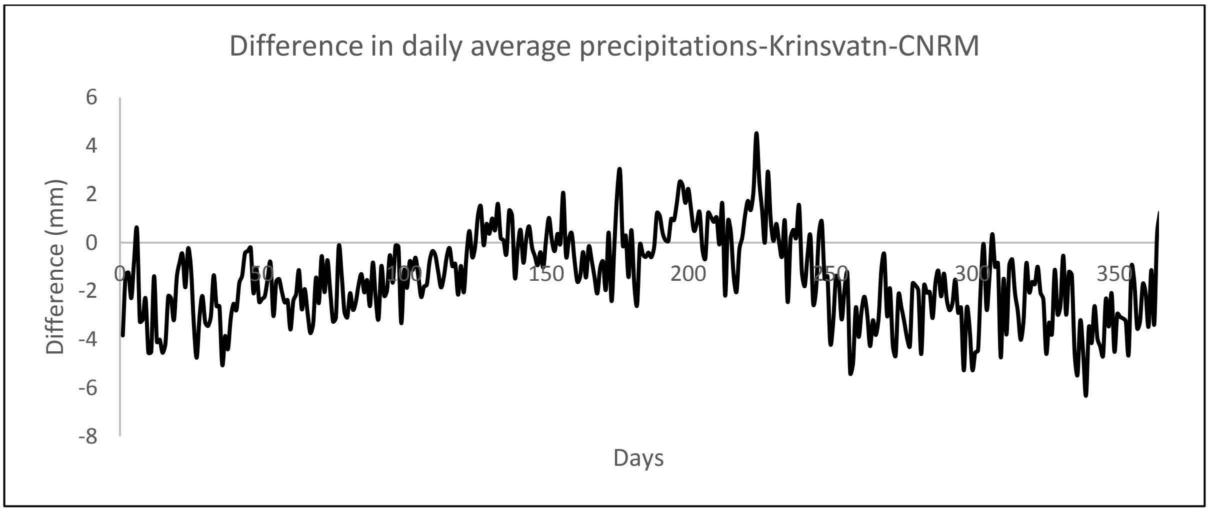
P_{G1D}=Daily average Precipitation pattern from CNRM model data

P_{G2D}=Daily average Precipitation pattern from CNRM model data

P_{OD}=Daily average Precipitation pattern from observed data



(Figure A7.3: Difference in daily average precipitation-Krinsvatn-MOCH)



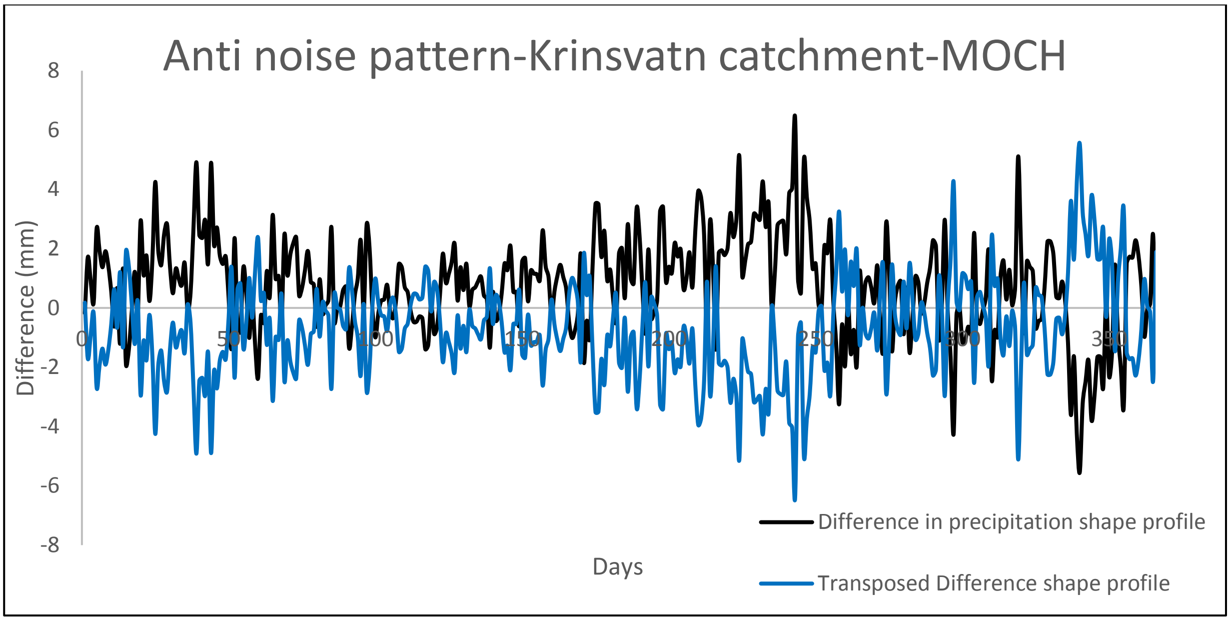
(Figure A7.4: Difference in daily average precipitation-Krinsvatn-CNRM)

STEP 3: Anti-noises are generated to correct for the above depicted programing noises inherent in GCM data. These essentially are the mirror images of the noise patterns. The generated anti-noise patterns are presented in **Figure A7.5** and **A7.6**

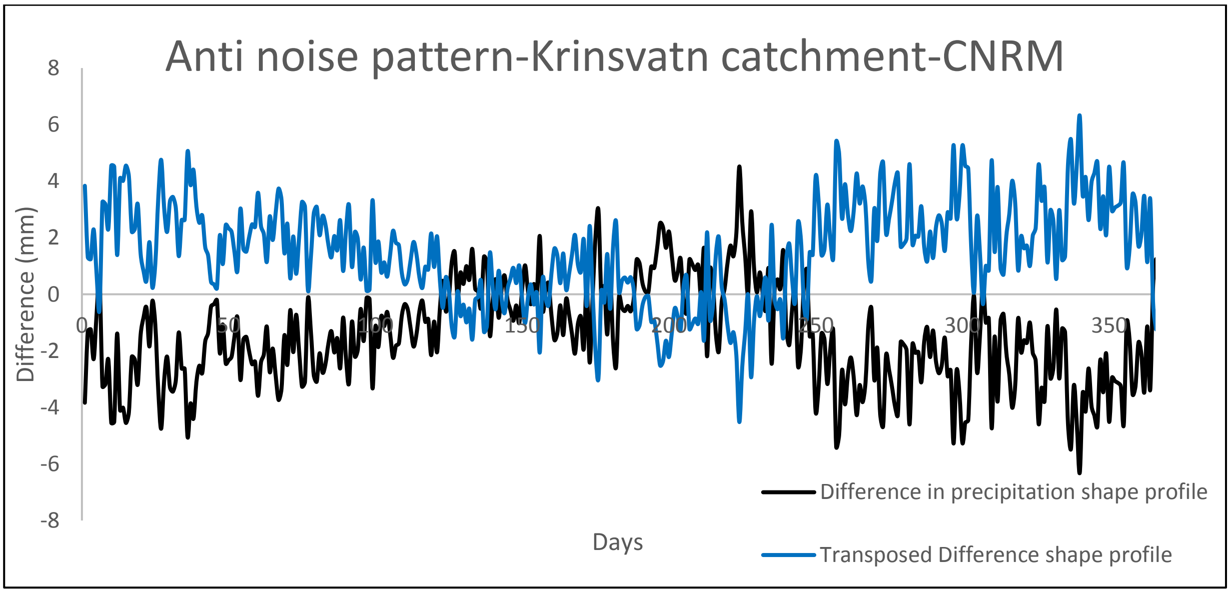
$$A_{1D} = -N_{1D}$$

$$A_{2D} = -N_{2D}$$

Where,
A_{1D}=Antinoise pattern for CNRM model
A_{2D}=Antinoise pattern for MOCH model



(Figure A7.5: Antinoise pattern generation-Krinsvatn-MOCH)

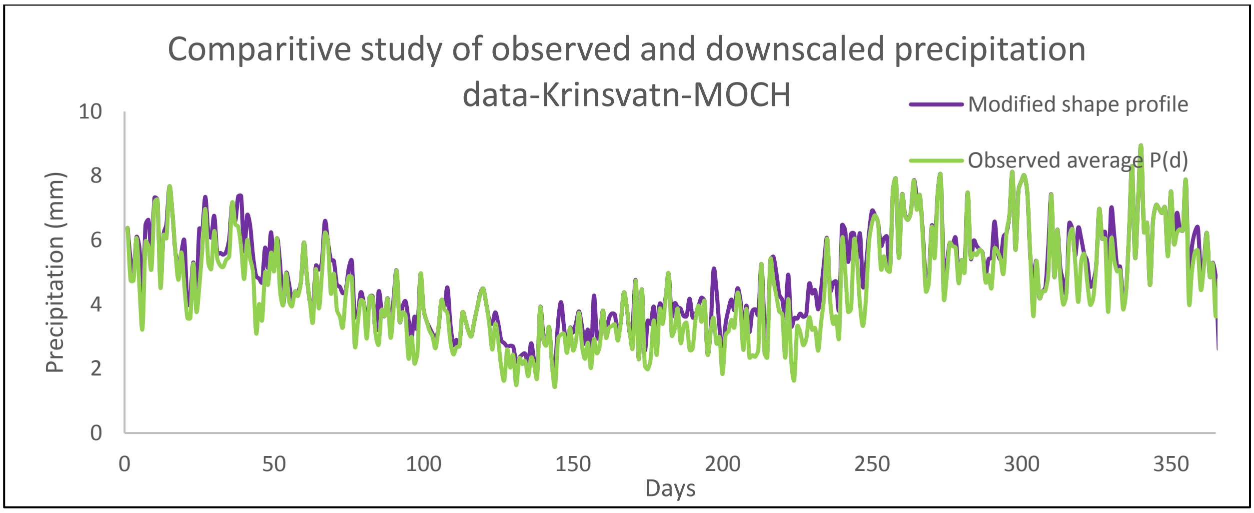


(Figure A7.6: Antinoise pattern generation-Krinsvatn-CNRM)

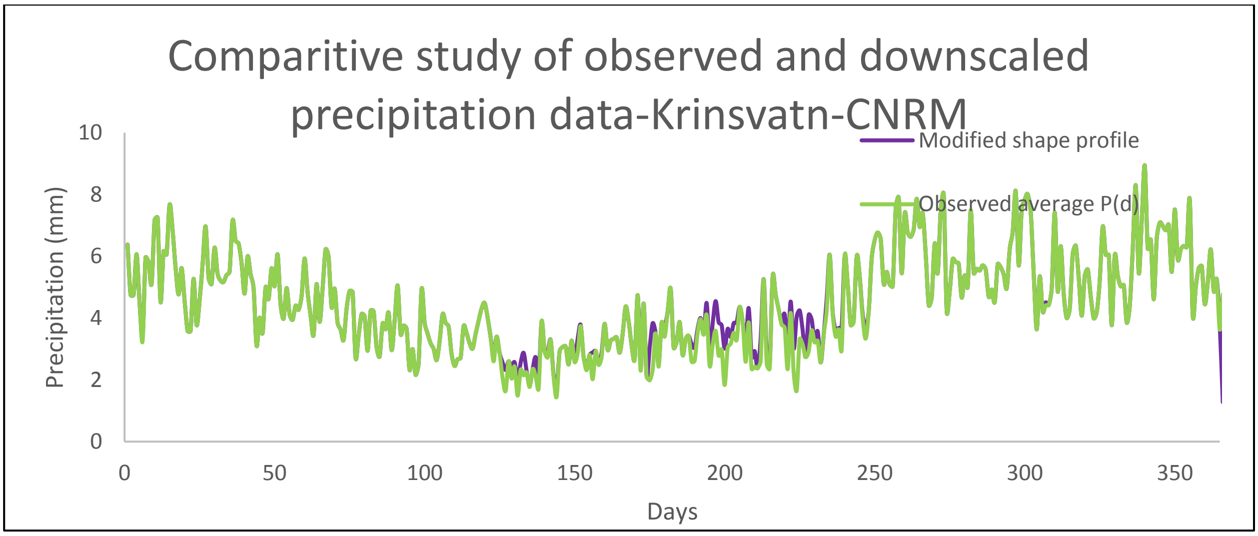
STEP 4: The generated Antinoise patterns were superimposed on the GCM simulated precipitation time series on an annual basis. That is, the Antinoise pattern are to be added to the GCM simulated precipitation pattern on an annual basis. The resultant modified precipitation trends are presented in **Figure A7.7** and **A7.8**.

$$M_{1D}=IF((P_{G1D}+A_{1D})>=0;(P_{G1D}+A_{1D});0)$$
$$M_{2D}=IF((P_{G2D}+A_{2D})>=0;(P_{G2D}+A_{2D});0)$$

Where,
M_{1D}=Modified daily precipitation for CNRM model
M_{1D}=Modified daily precipitation for MOCH model



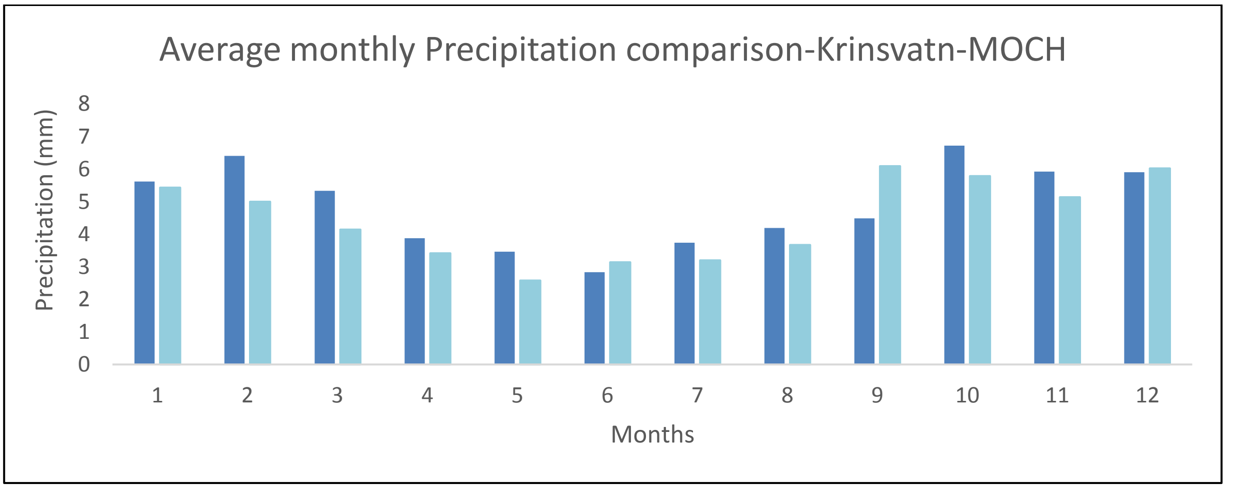
(Figure A7.7: Comparison of observed and downscaled precipitation data-Krinsvatn-MOCH)



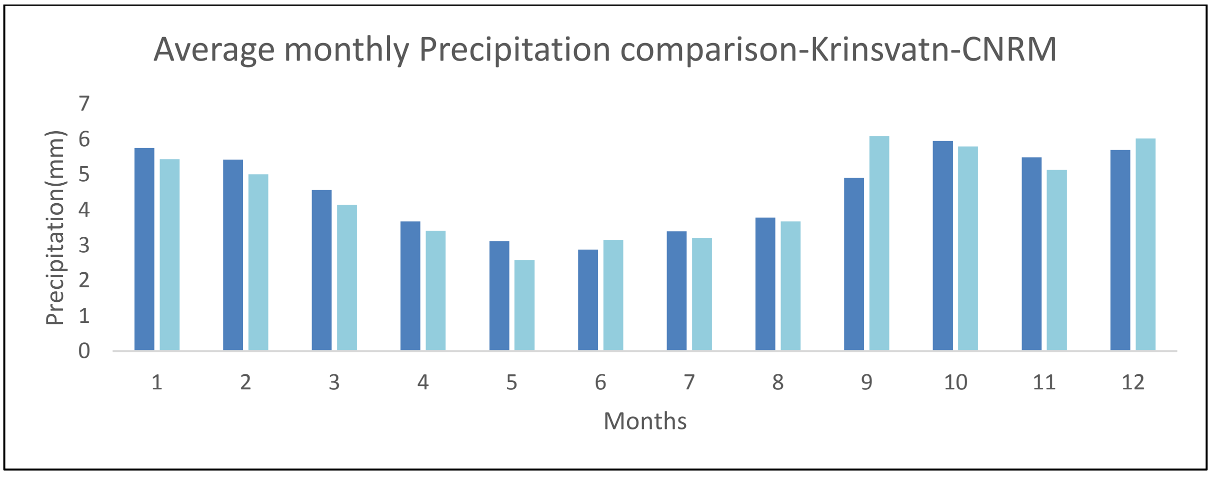
(Figure A7.8: Comparison of observed and downscaled precipitation data-Krinsvatn-CNRM)

It is very important to note that Steps 1 through 3 are carried out using the average annual precipitation patterns over the entire observation period, in this case 1957-2005. But, Steps 4 should be implemented on annual precipitation patterns for each individual year in order to get the corrected daily precipitation series. That is, Antinoise correction should be applied to each individual years.

The final modified daily average precipitation should ideally be in resonance with the observed daily average precipitation pattern as depicted above. The proposed methodology corrects the GCM data for daily mean and also monthly means. Comparison of daily average precipitations on a monthly basis are presented in **Figure A7.9** and **A7.10**. As can be inferred, the precipitation series correspond to an excellent degree even on a monthly basis.



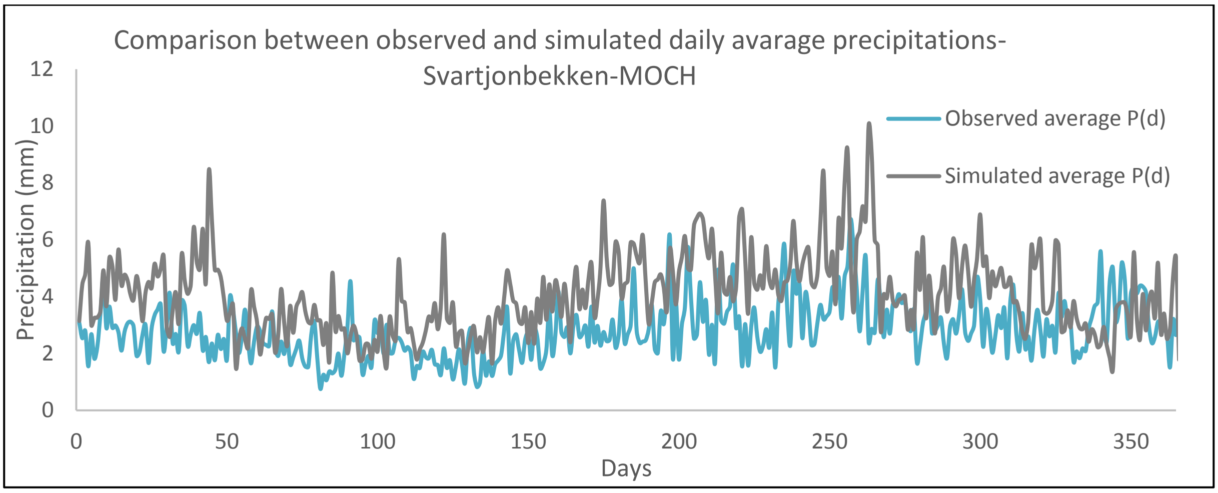
(Figure A7.9: Comparison of observed and downscaled monthly average precipitation-Krinsvatn-MOCH)



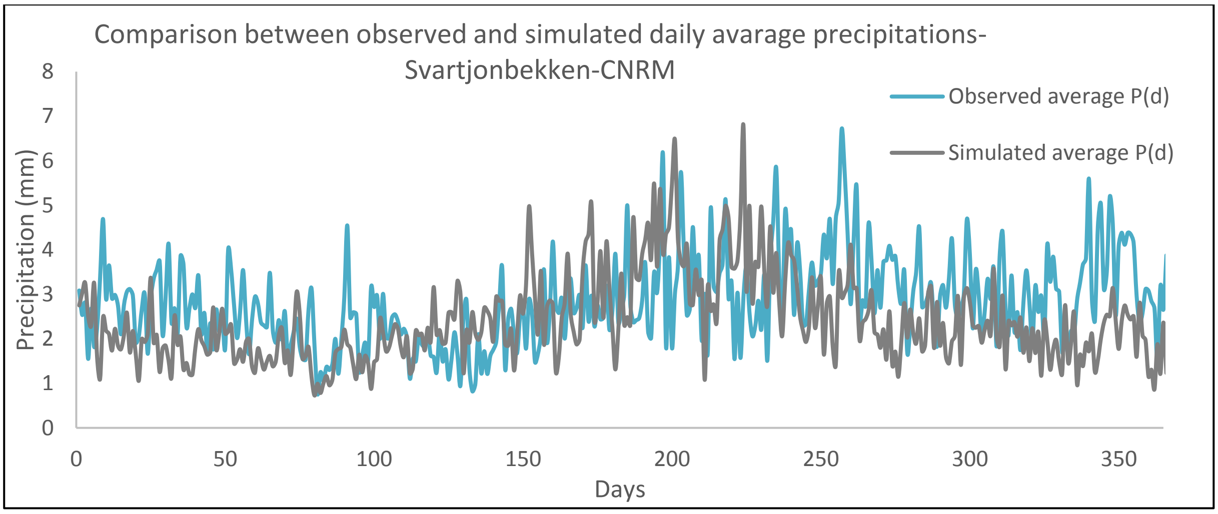
(Figure A7.10: Comparison of observed and downscaled monthly average precipitation-Krinsvatn-CNRM)

APPENDIX 8- SVARTJONBEKKEN CLIMATE DATA DOWNSCALING

STEP 1: The first step in Antinoise downscaling was to sort the daily observed and GCM simulated precipitation time series on an annual basis (1973-2005). Further, daily average annual precipitation plots were prepared for the sorted data. **Figures A8.1** and **A8.2** depict the trends in observed daily average precipitation (P_{OD}), daily average precipitation for CNRM model (P_{G1D}) and MOCH model (P_{G2D}) over the period 1973-2005.



(Figure A8.1: Comparison of observed and simulated daily average precipitation-Svartjonbekken-MOCH)



(Figure A8.2: Comparison of observed and simulated daily average precipitation-Svartjonbekken-CNRM)

STEP 2: The differences between the annual precipitation plots were computed for each year and analyzed for consistency. It is important to note that the individual differences in precipitation trends were consistent throughout the period of 1973-2005 for both the models with only slight deviations. This suggested that the differences could essentially be termed as 'programing noises'. That is, all of the systematic biases included in the GCM simulated data were assumed to be delineated as part of the noise trends (N_{1D} and N_{2D}). Hence, average trends in differences between the observed and GCM simulated precipitation data over the period of 1973-2005 were computed and were assumed as programming noises for the individual models and have been presented in **Figure A8.3** and **Figure A8.4.**

$$\mathbf{N_{1D}=P_{G1D}-P_{OD}}$$

$$\mathbf{N_{2D}=P_{G2D}-P_{OD}}$$

Where,

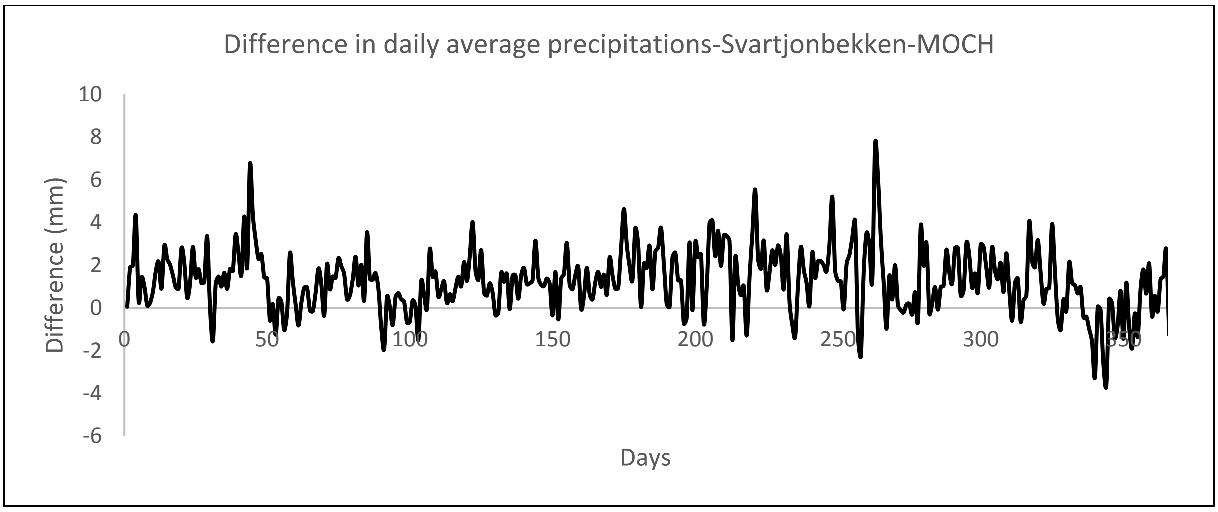
N_{1D}=Average Noise pattern from CNRM model data

N_{2D}=Average Noise pattern from MOCH model data

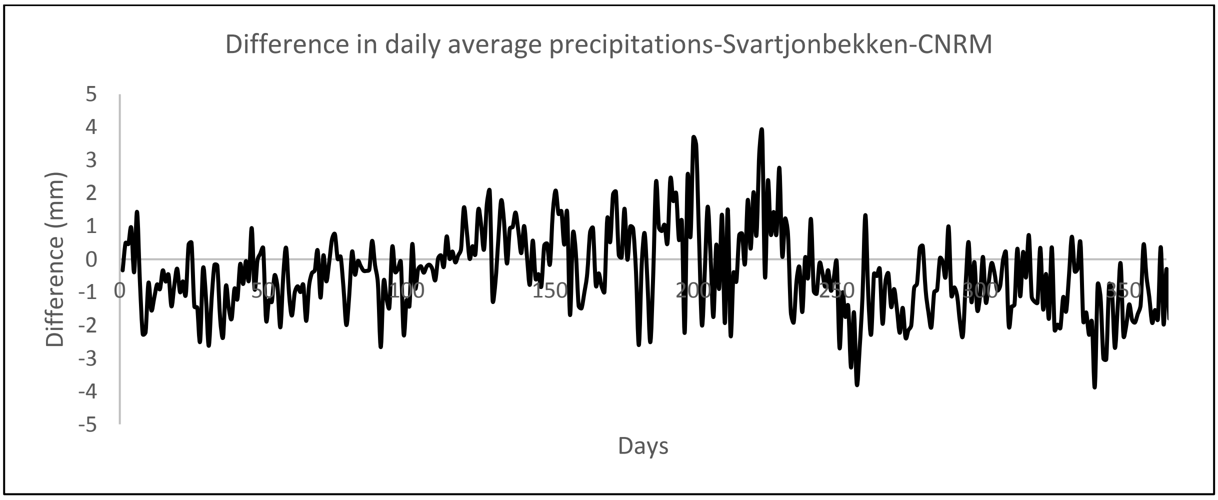
P_{G1D}=Daily average Precipitation pattern from CNRM model data

P_{G2D}=Daily average Precipitation pattern from CNRM model data

P_{OD}=Daily average Precipitation pattern from observed data



(Figure A8.3: Difference in daily average precipitation-Svartjonbekken-MOCH)



(Figure A8.4: Difference in daily average precipitation-Svartjonbekken-CNRM)

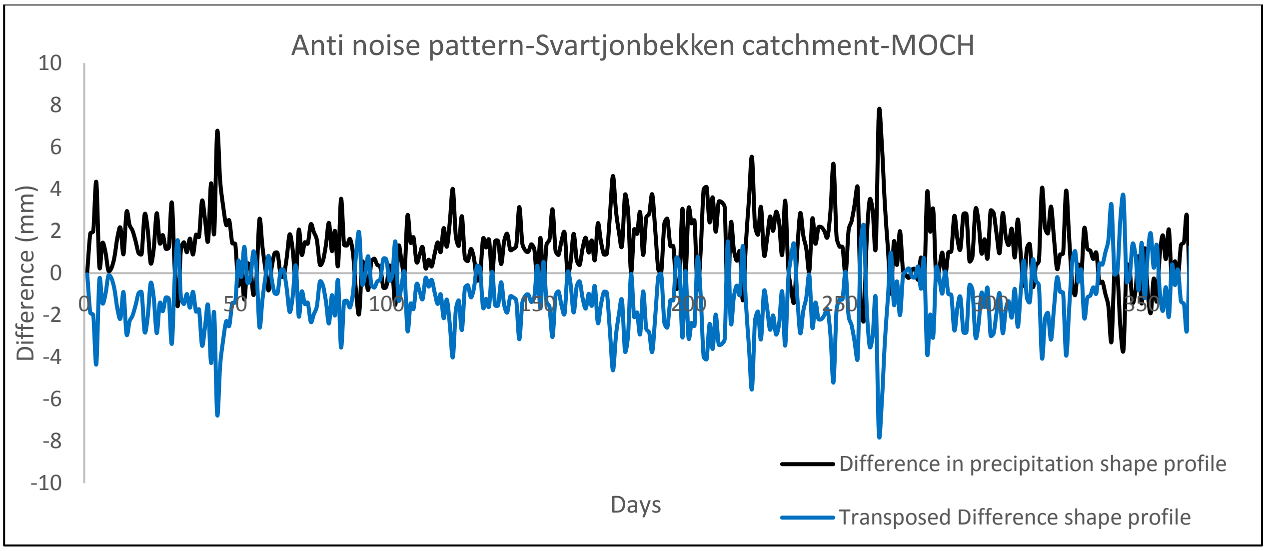
STEP 3: Anti-noises are generated to correct for the above depicted programing noises inherent in GCM data. These essentially were mirror images of the noise patterns. The generated anti-noise patterns are presented in **Figure A8.5** and **A8.6**

$$\mathbf{A_{1D} = -N_{1D}}$$

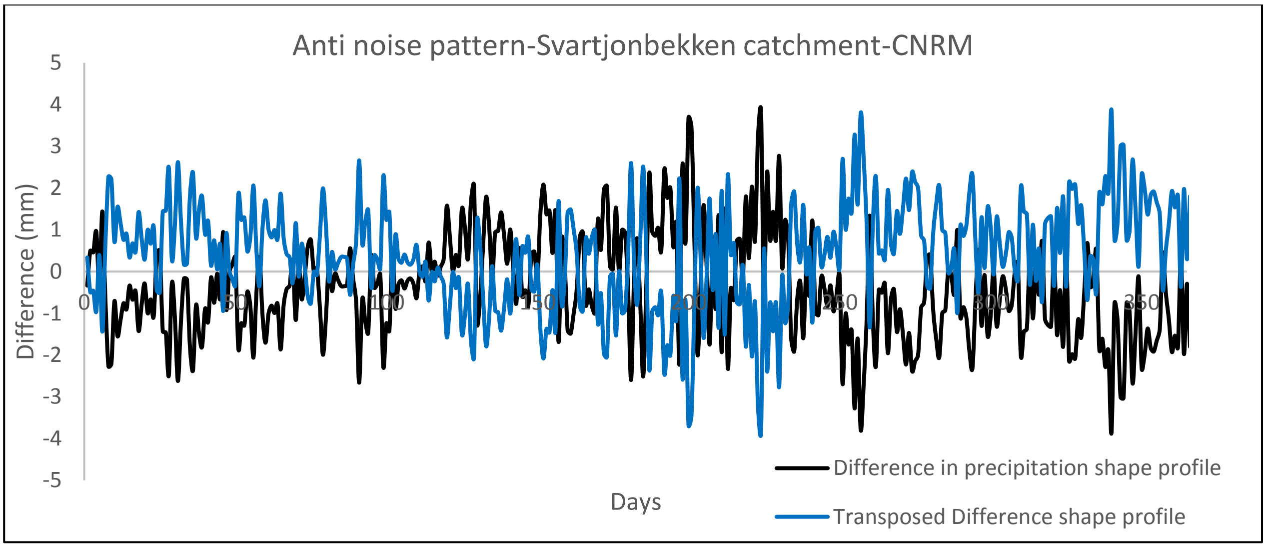
$$\mathbf{A_{2D} = -N_{2D}}$$

Where,

A_{1D}=Antinoise pattern for CNRM model
A_{2D}=Antinoise pattern for MOCH model



(Figure A8.5: Antinoise pattern generation-Svartjonbekken-MOCH)



(Figure A8.6: Antinoise pattern generation-Svartjonbekken-CNRM)

STEP 4: The generated Antinoise patterns were superimposed on the GCM simulated precipitation time series on an annual basis. That is, the Antinoise pattern are to be added to the GCM simulated precipitation pattern on an annual basis. The resultant modified precipitation trends are presented in **Figure A8.7** and **A8.8**.

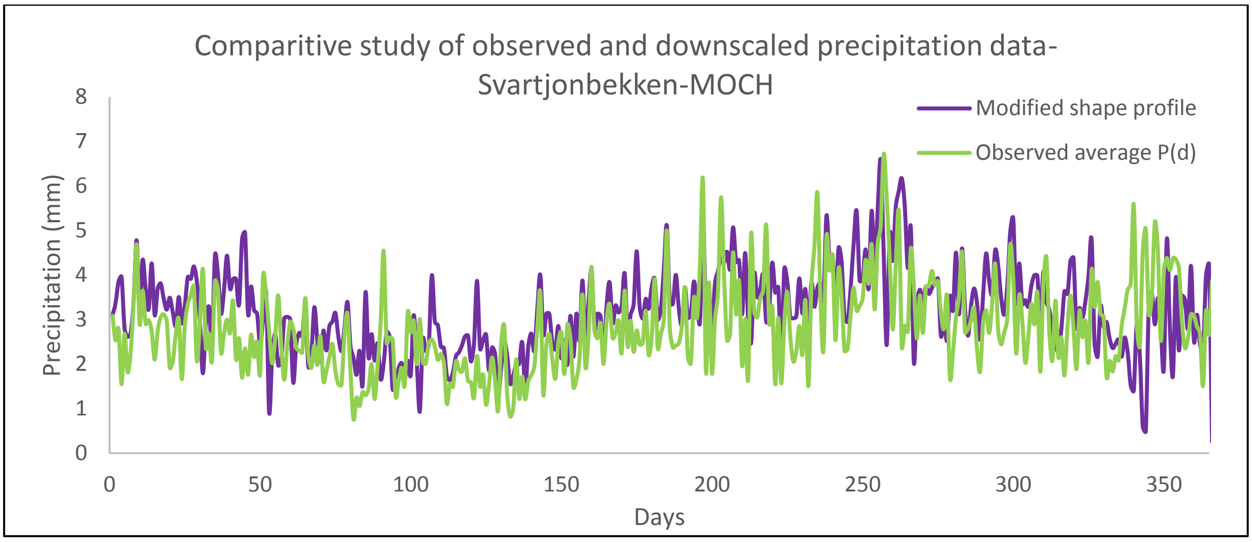
$$\mathbf{M_{1D}=IF((P_{G1D}+A_{1D})>=0;(P_{G1D}+A_{1D});0)}$$

$$\mathbf{M_{2D}=IF((P_{G2D}+A_{2D})>=0;(P_{G2D}+A_{2D});0)}$$

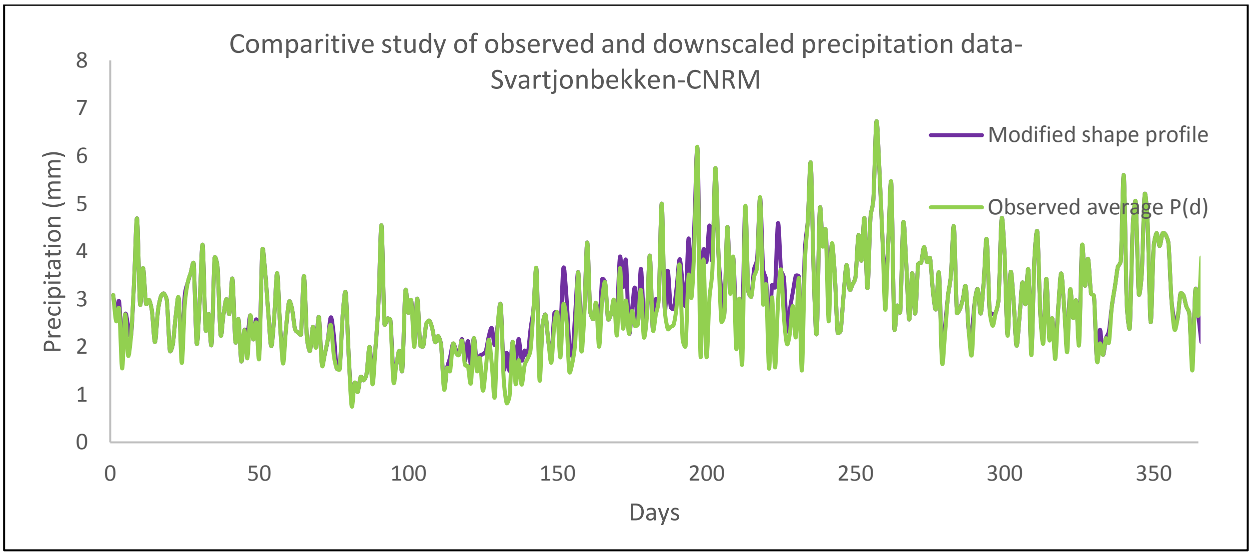
Where,

M_{1D}=Modified daily precipitation for CNRM model

M_{1D}=Modified daily precipitation for MOCH model



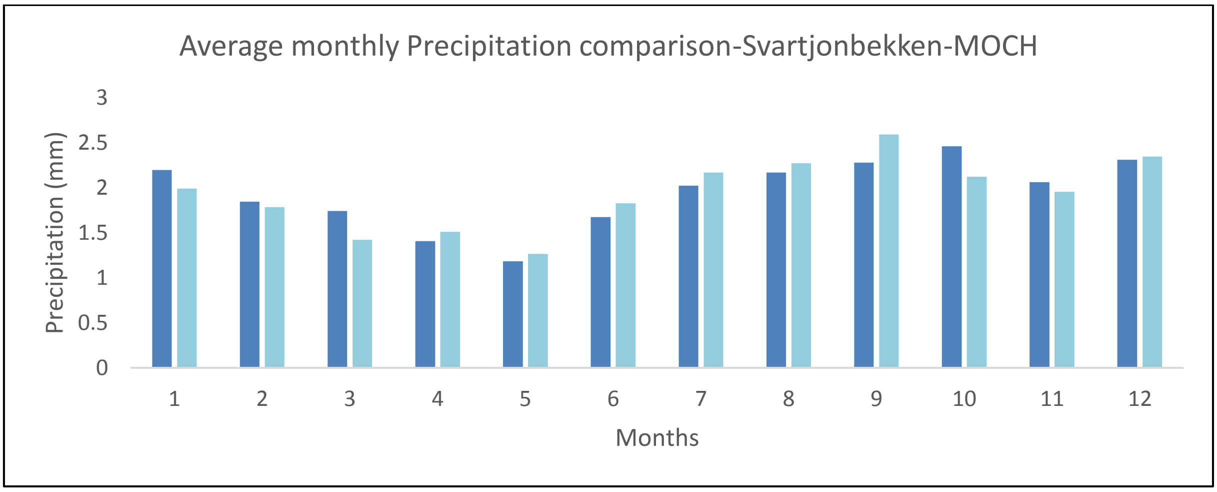
(Figure A8.7: Comparison between observed and downscaled precipitation data-Svartjonbekken-MOCH)



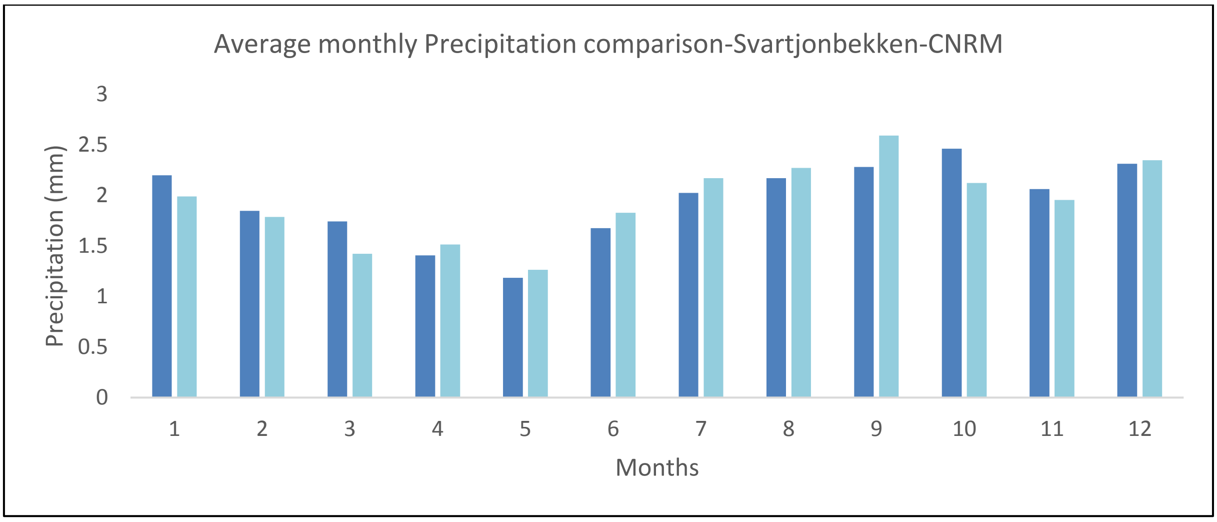
(Figure A8.8: Comparison between observed and downscaled precipitation data-Svartjonbekken-CNRM)

It is very important to note that Steps 1 through 3 are carried out using the average annual precipitation patterns over the entire observation period, in this case 1973-2005. But, Steps 4 should be implemented on annual precipitation patterns for each individual year in order to get the corrected daily precipitation series. That is, Antinoise correction should be applied to each individual years.

The final modified daily average precipitation should ideally be in resonance with the observed daily average precipitation pattern as depicted above. The proposed methodology corrects the GCM data for daily mean and also monthly means. Comparison of daily average precipitations on a monthly basis are presented in **Figure A8.9** and **A8.10**. As can be inferred, the precipitation series correspond to an excellent degree even on a monthly basis.

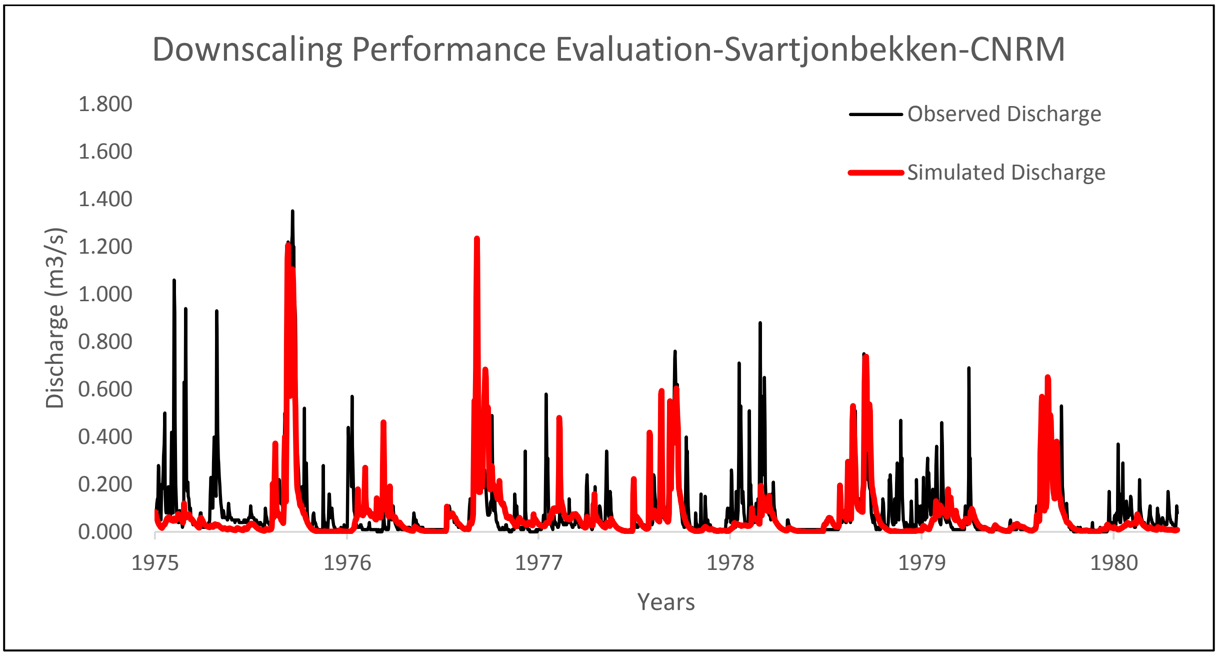


(Figure A8.9: Comparison between observed and downscaled monthly average precipitation-Svartjonbekken-MOCH)

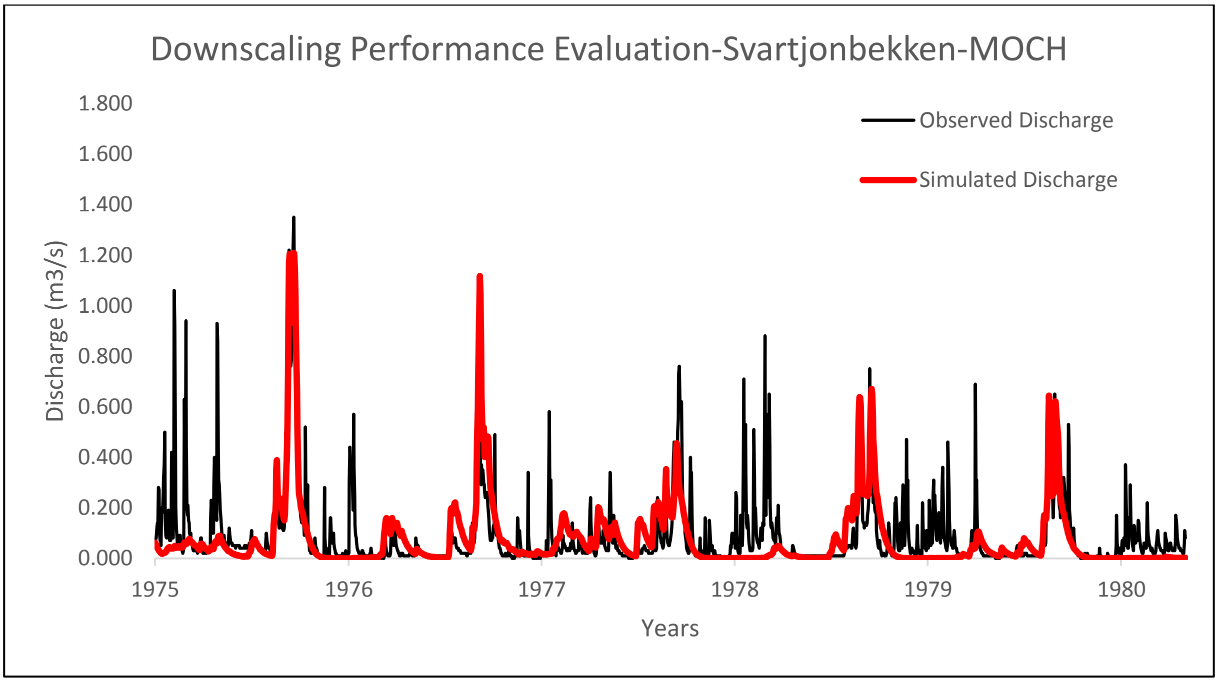


(Figure A8.10: Comparison between observed and downscaled monthly average precipitation-Svartjonbekken-CNRM)

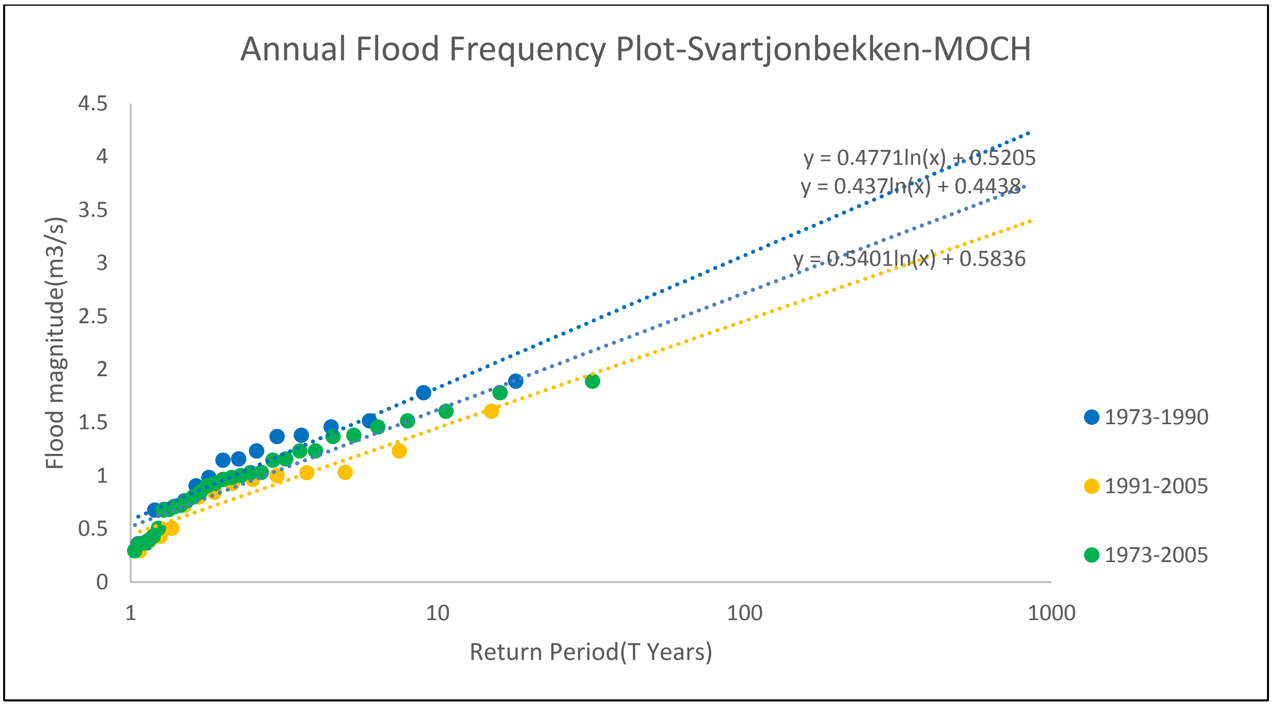
APPENDIX 9-DOWNSCALING PERFORMANCE EVALUATION-SVARTJONBEKKEN CATCHMENT



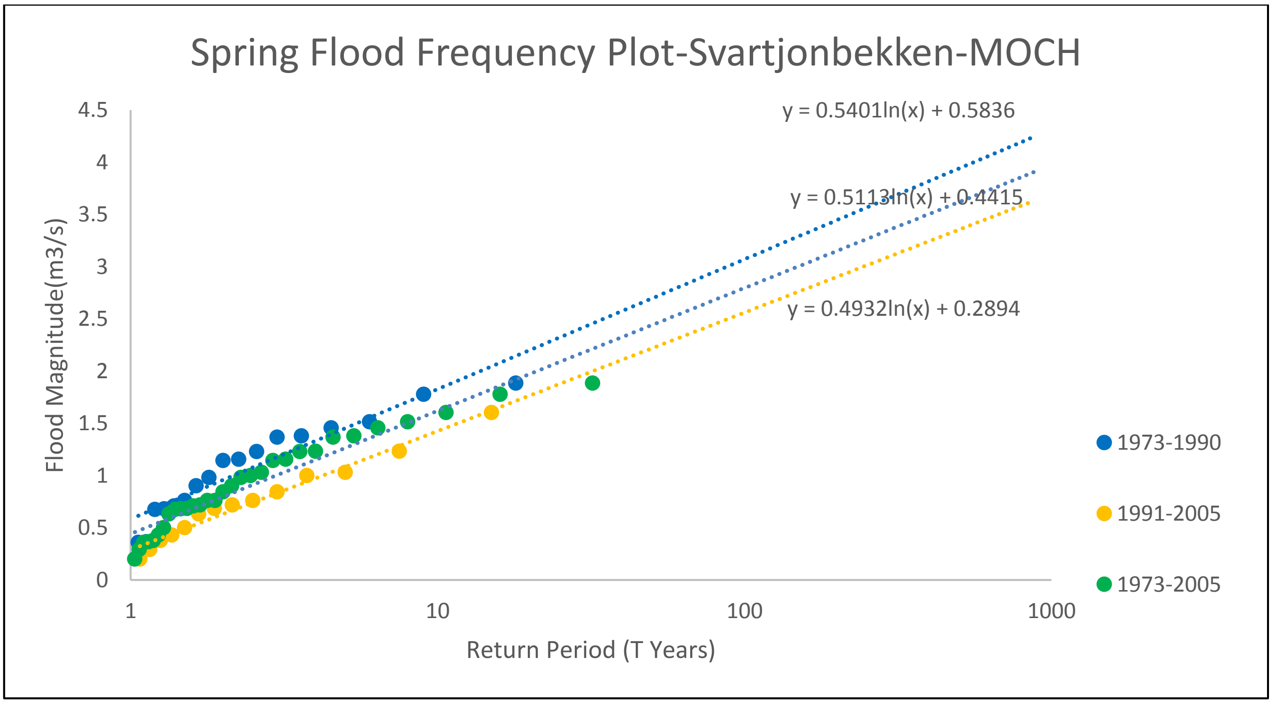
(Figure A9.1: Comparison between observed and simulated runoff-Svartjonbekken-CNRM Model)



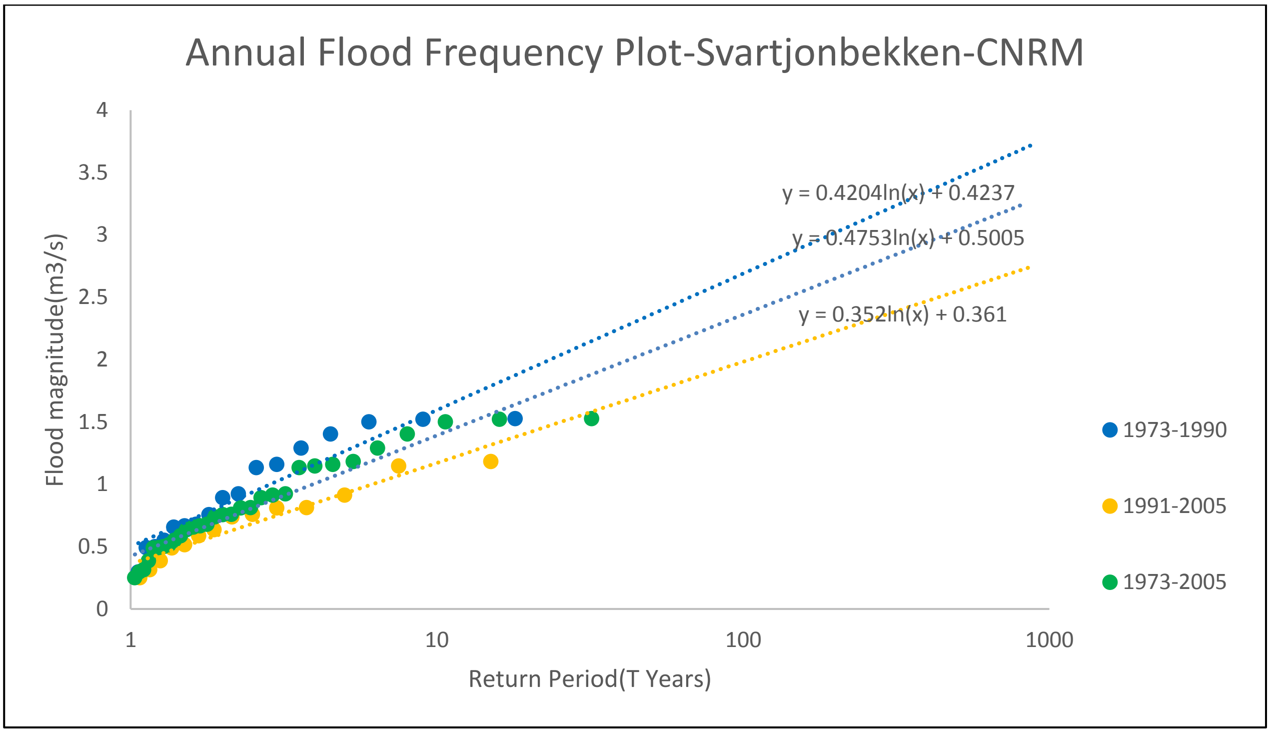
(Figure A9.2: Comparison between observed and simulated runoff-Svartjonbekken-MOCH Model)



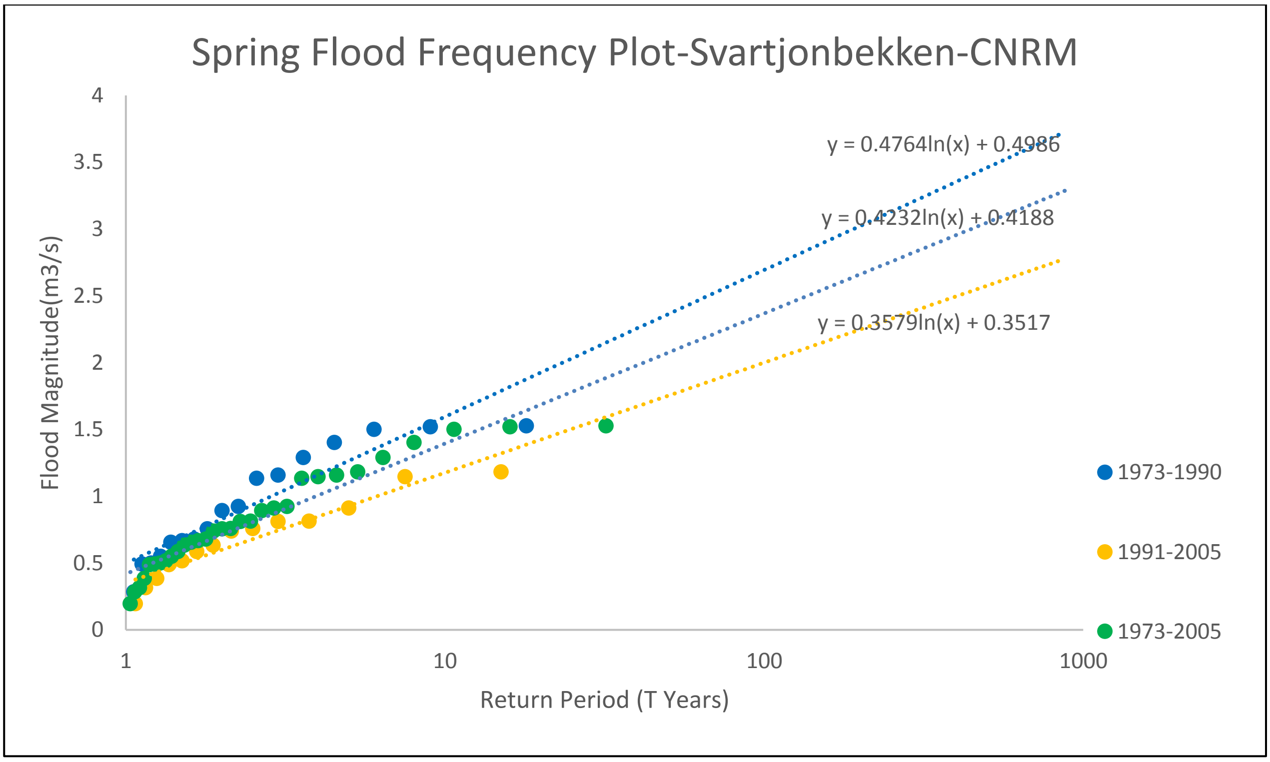
(Figure A9.3: Annual Flood Frequency plot with simulated data-Svartjonbekken-MOCH)



(Figure A9.4: Spring Flood Frequency plot with simulated data-Svartjonbekken-MOCH)



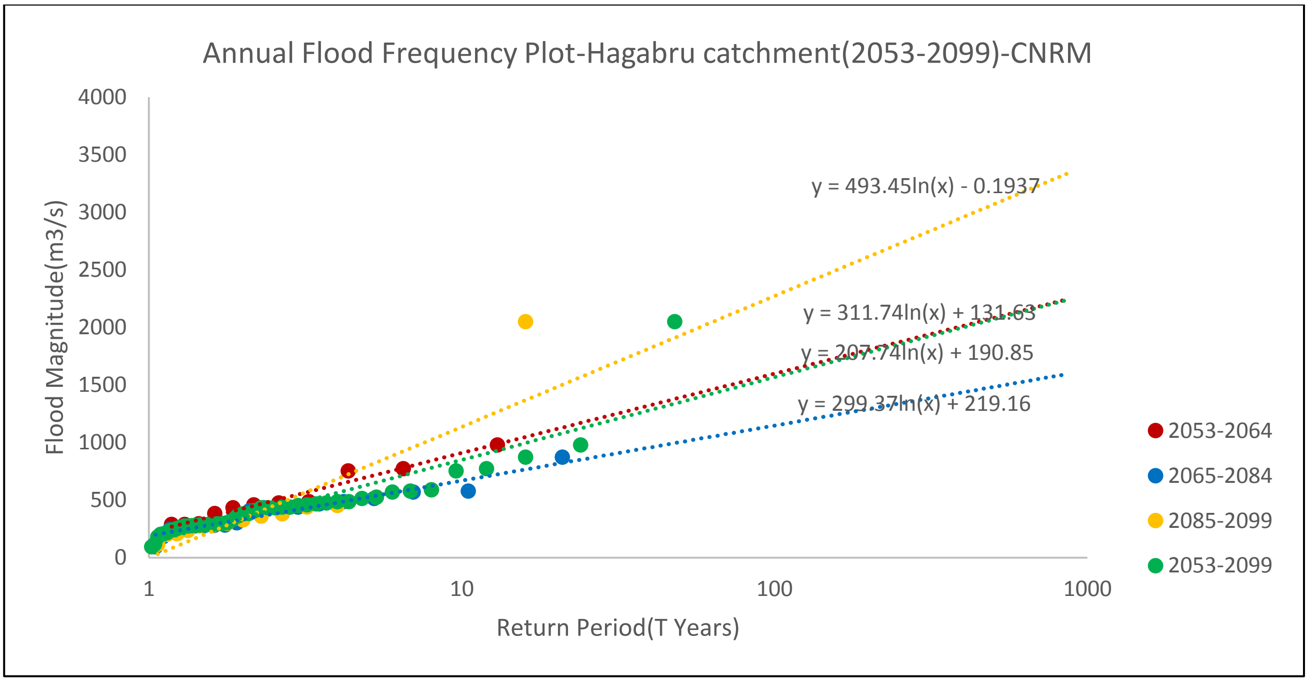
(Figure A9.5: Annual Flood Frequency plot with simulated data-Svartjonbekken-CNRM)



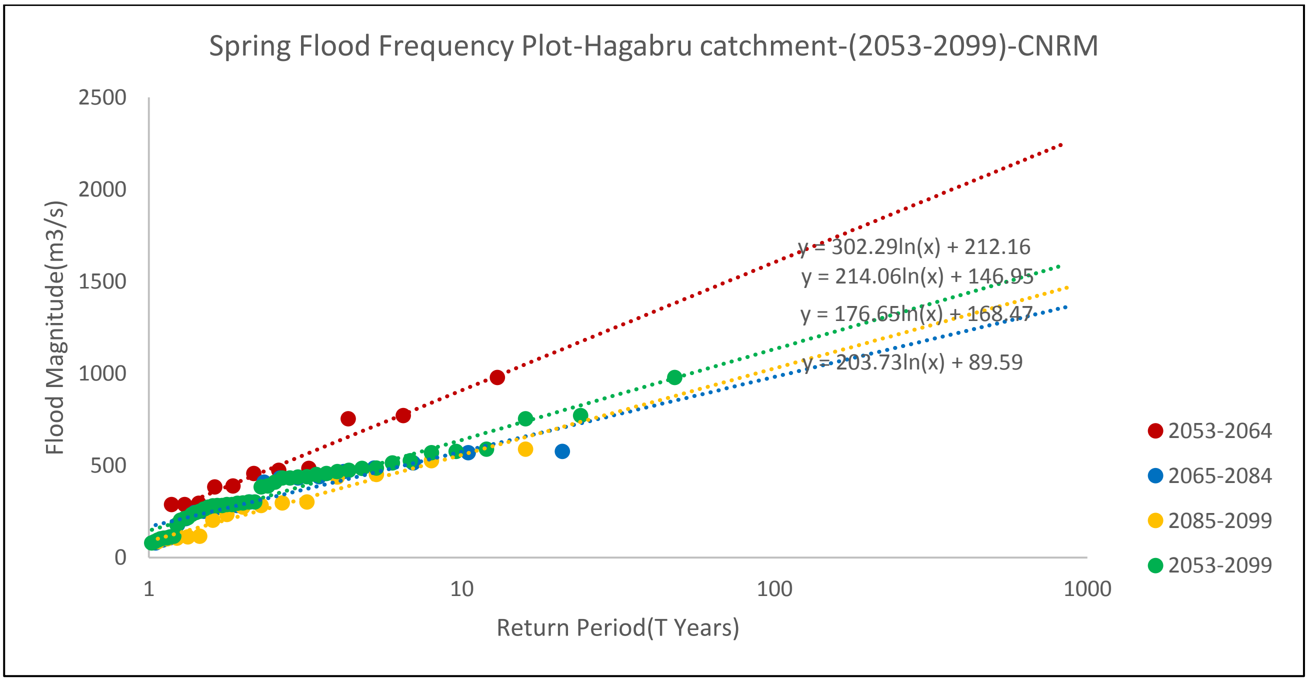
(Figure A9.6: Spring Flood Frequency plot with simulated data-Svartjonbekken-CNRM)

APPENDIX 10-FLOOD FREQUENCY ANALYSIS IN A FUTURE CLIMATE SETTING-HAGABRU CATCHMENT

CNRM MODEL OUTPUTS

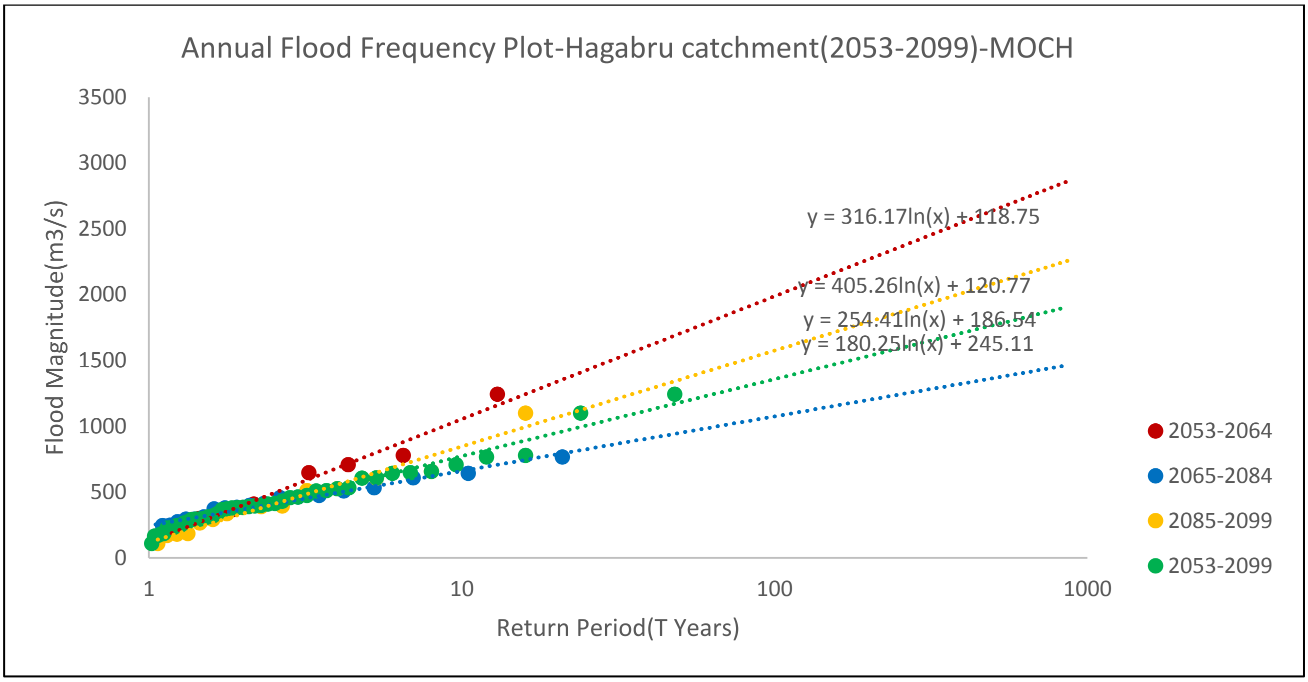


(Figure A10.1: Annual Flood Frequency Plot (2053-2099)-Hagabru catchment-CNRM)

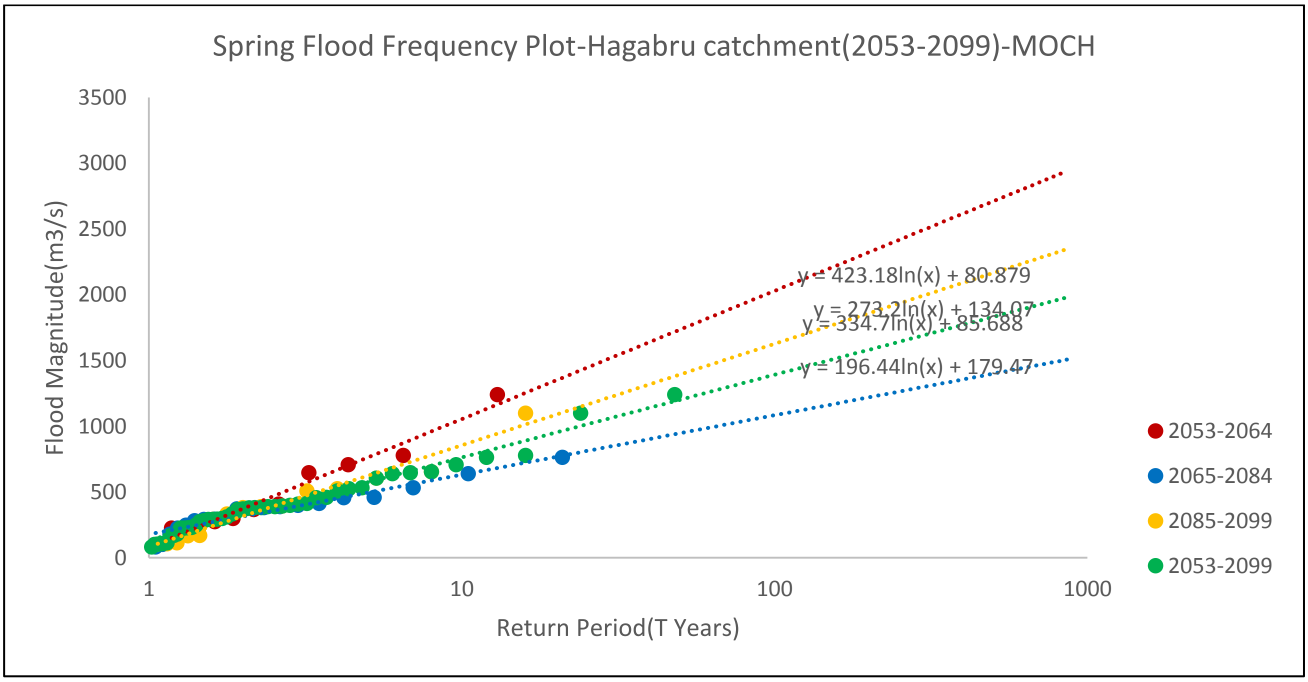


(Figure A10.2: Spring Flood Frequency Plot (2053-2099)-Hagabru catchment-CNRM)

MOCH MODEL OUTPUTS



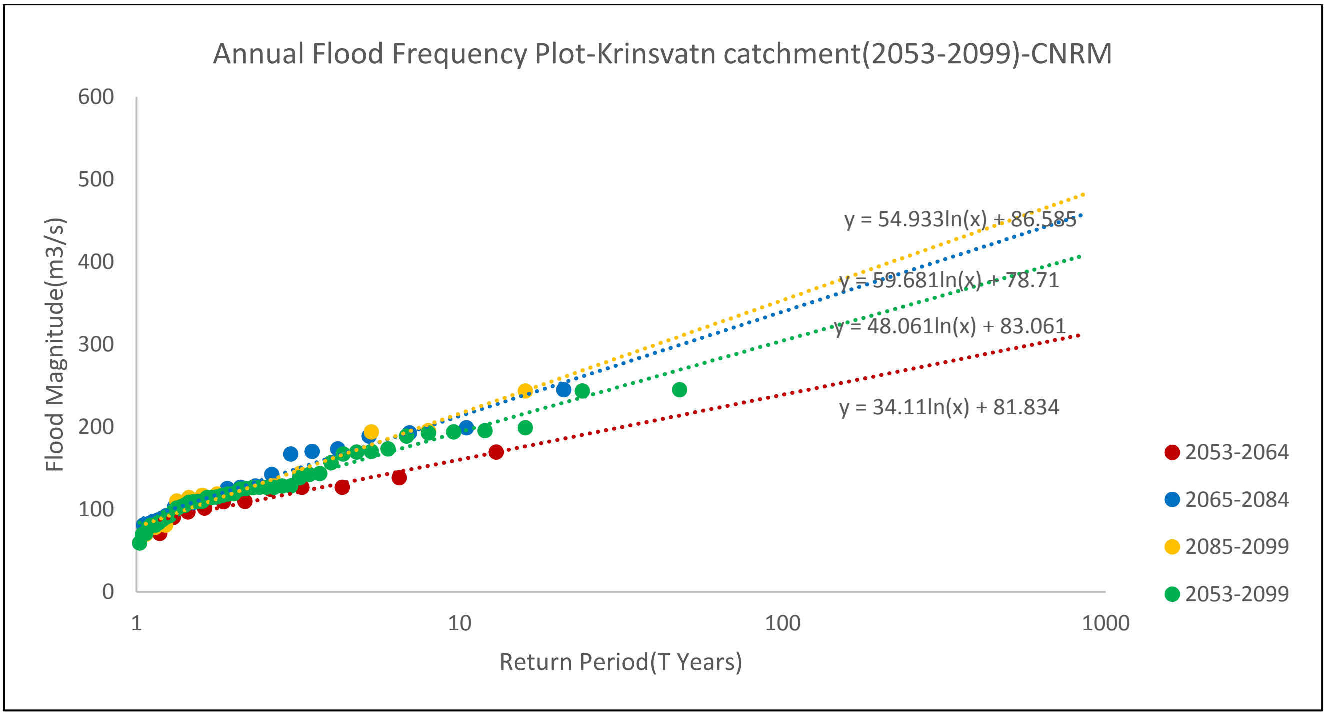
(Figure A10.3: Annual Flood Frequency Plot (2053-2099)-Hagabru catchment-MOCH)



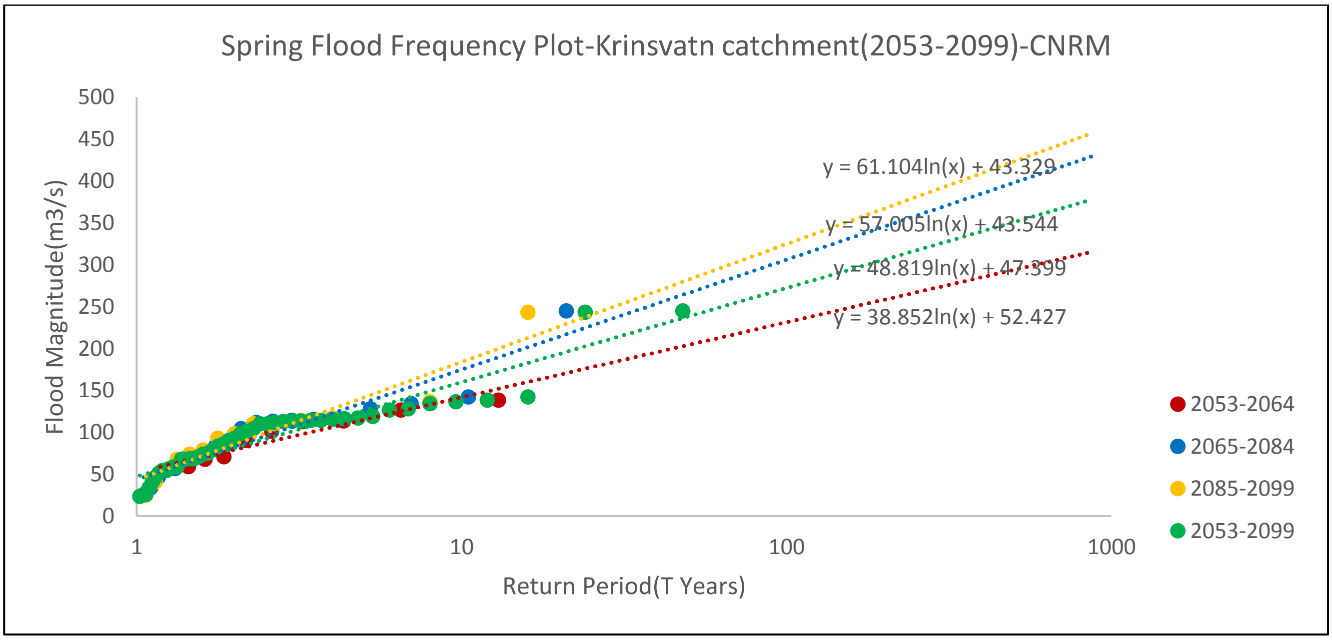
(Figure A10.4: Spring Flood Frequency Plot (2053-2099)-Hagabru catchment-MOCH)

APPENDIX 11-FLOOD FREQUENCY ANALYSIS IN A FUTURE CLIMATE SETTING-KRINSVATN CATCHMENT

CNRM MODEL OUTPUTS

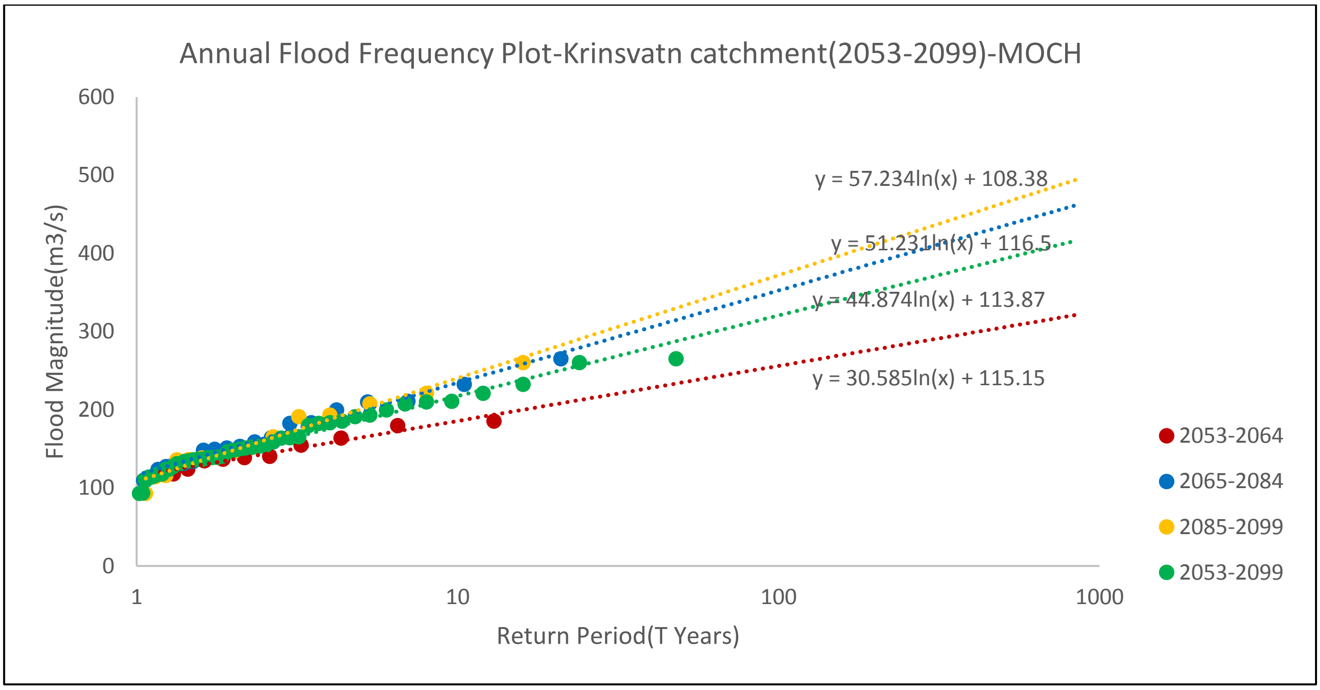


(Figure A11.1: Annual Flood Frequency Plot (2053-2099)-Krinsvatn catchment-CNRM)

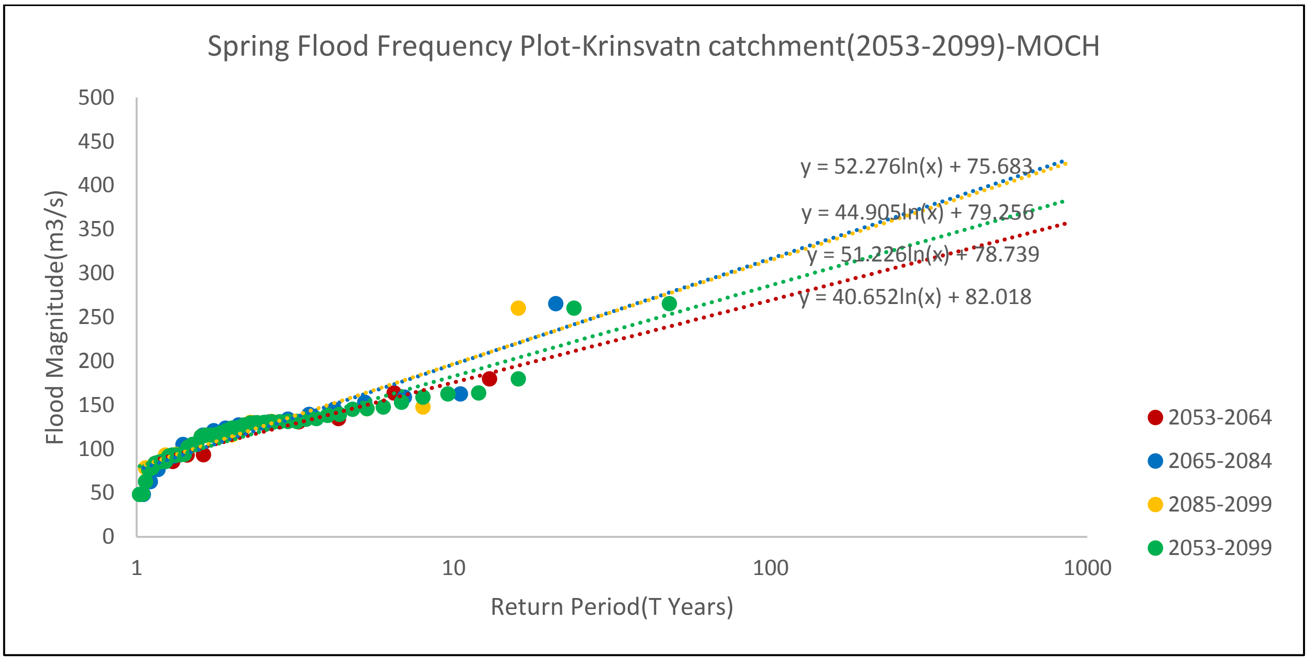


(Figure A11.2: Spring Flood Frequency Plot (2053-2099)-Krinsvatn catchment-CNRM)

MOCH MODEL OUTPUTS



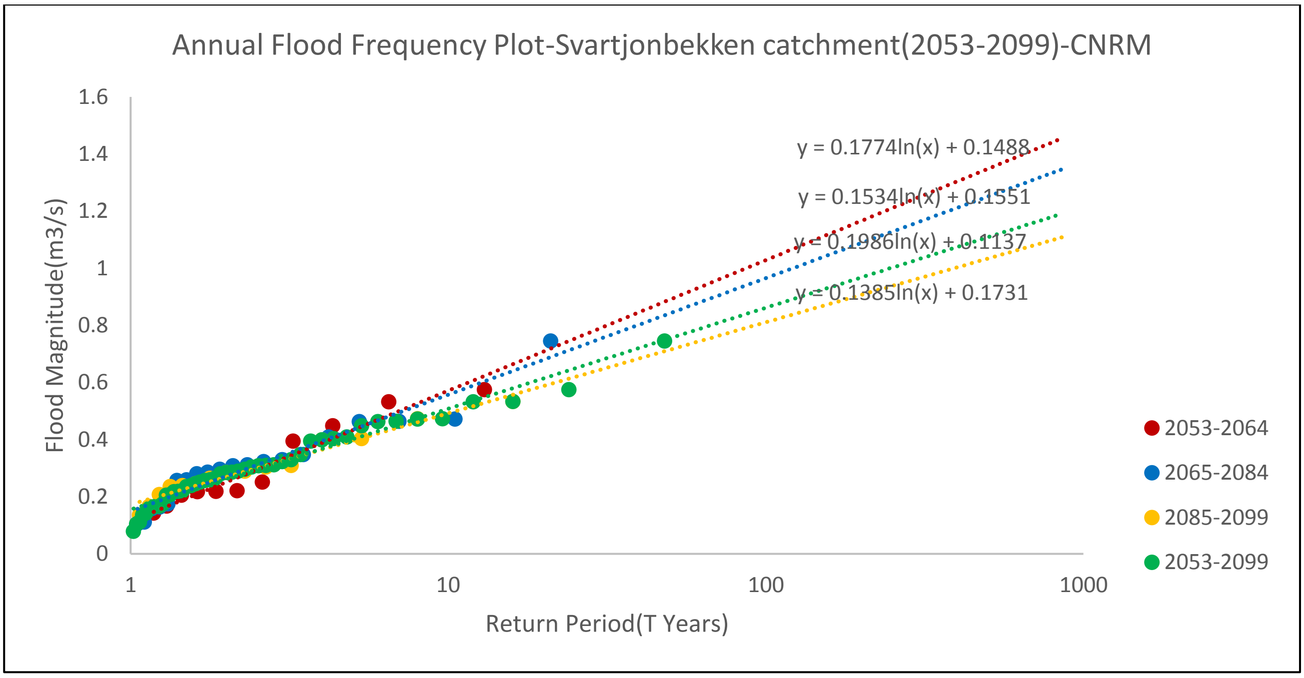
(Figure A11.3: Annual Flood Frequency Plot (2053-2099)-Krinsvatn catchment-MOCH)



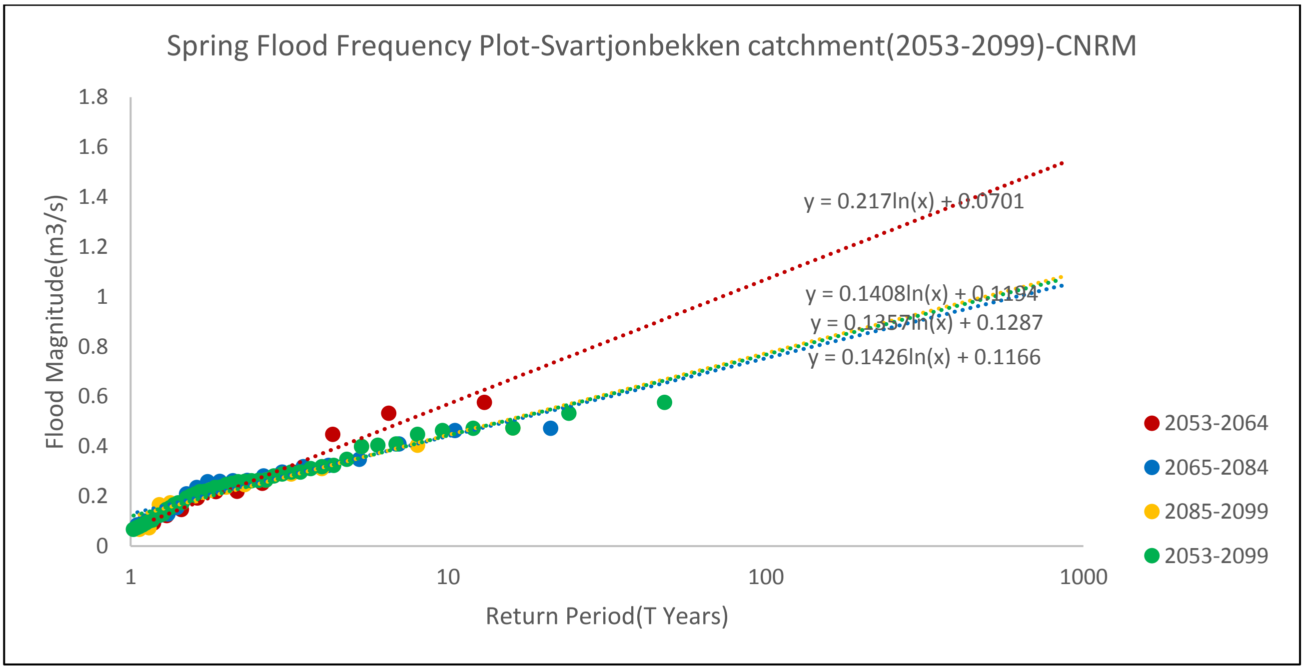
(Figure A11.4: Spring Flood Frequency Plot (2053-2099)-Krinsvatn catchment-MOCH)

APPENDIX 12-FLOOD FREQUENCY ANALYSIS IN A FUTURE CLIMATE SETTING-SVARTJONBEKKEN CATCHMENT

CNRM MODEL OUTPUTS

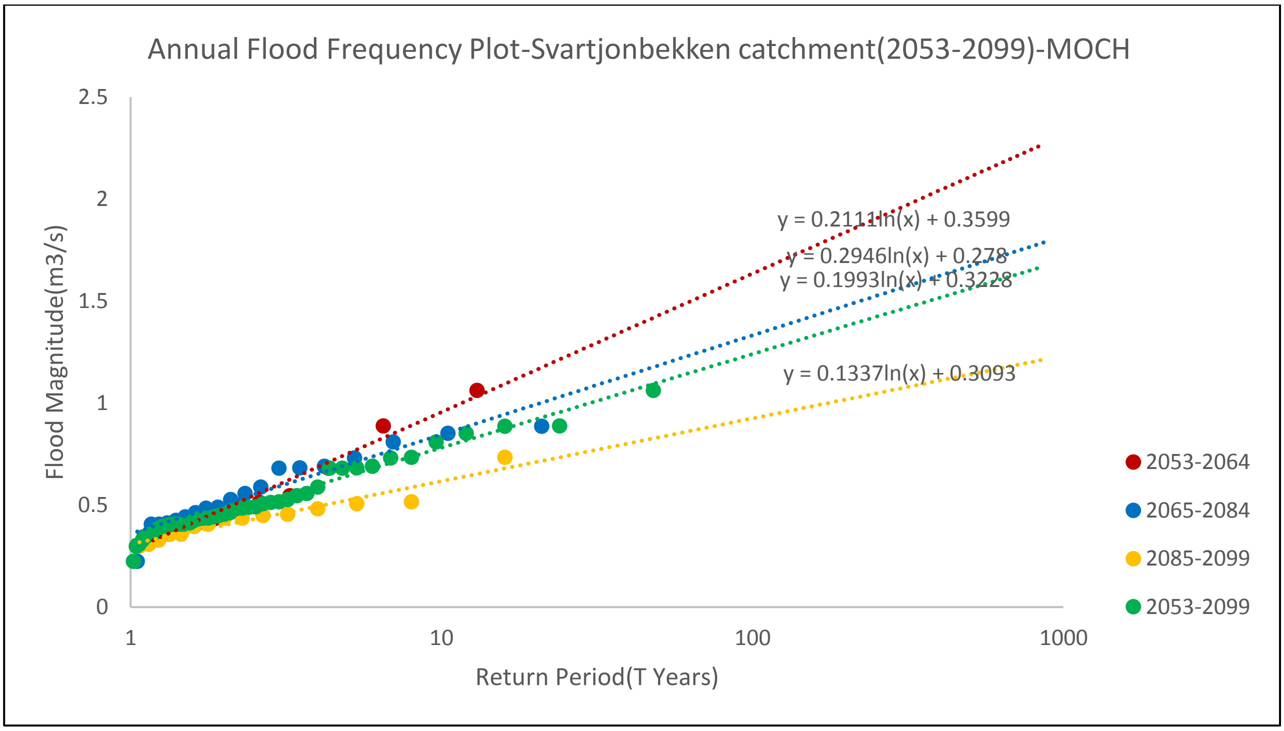


(Figure A12.1: Annual Flood Frequency Plot (2053-2099)-Svartjonbekken catchment-CNRM)

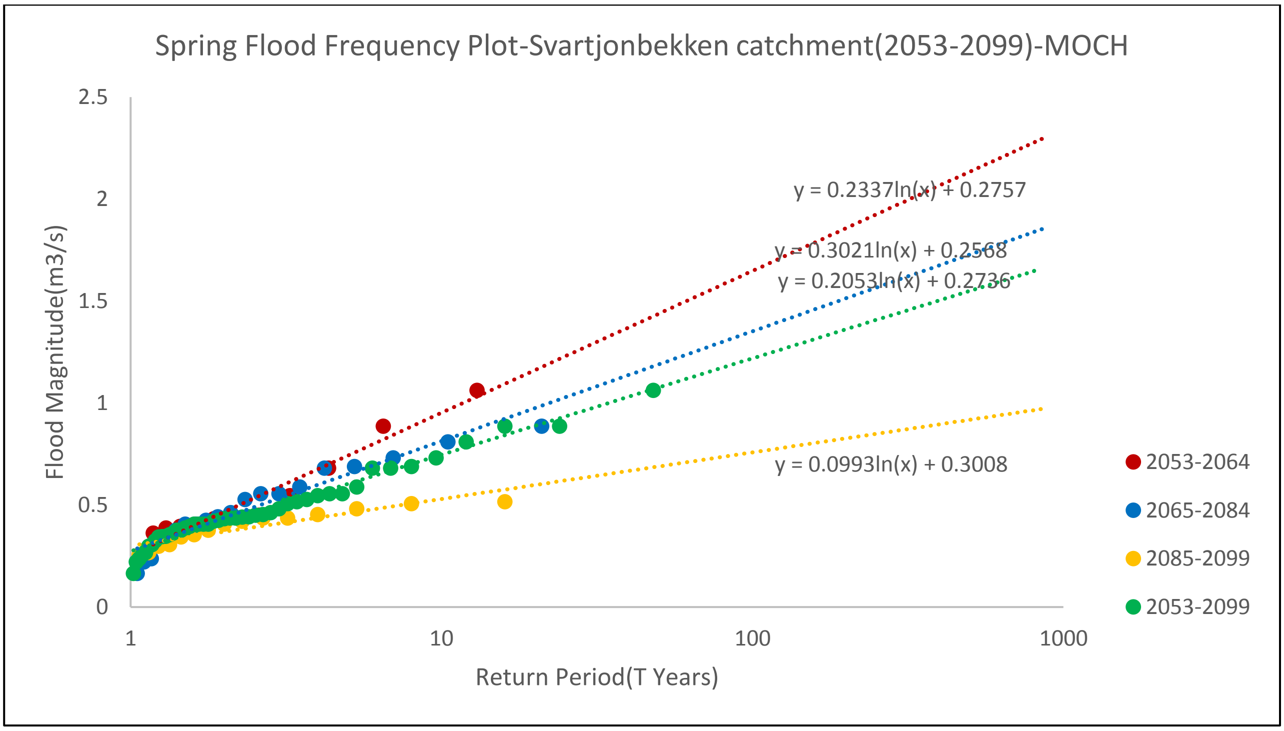


(Figure A12.2: Spring Flood Frequency Plot (2053-2099)-Svartjonbekken catchment-CNRM)

MOCH MODEL OUTPUTS



(Figure A12.3: Annual Flood Frequency Plot (2053-2099)-Svartjonbekken catchment-MOCH)



(Figure A12.4: Spring Flood Frequency Plot (2053-2099)-Svartjonbekken catchment-MOCH)

APPENDIX 13-FLOOD FREQUENCY ANALYSIS WITH SIMULATED RUNOFF-HAGABRU CATCHMENT

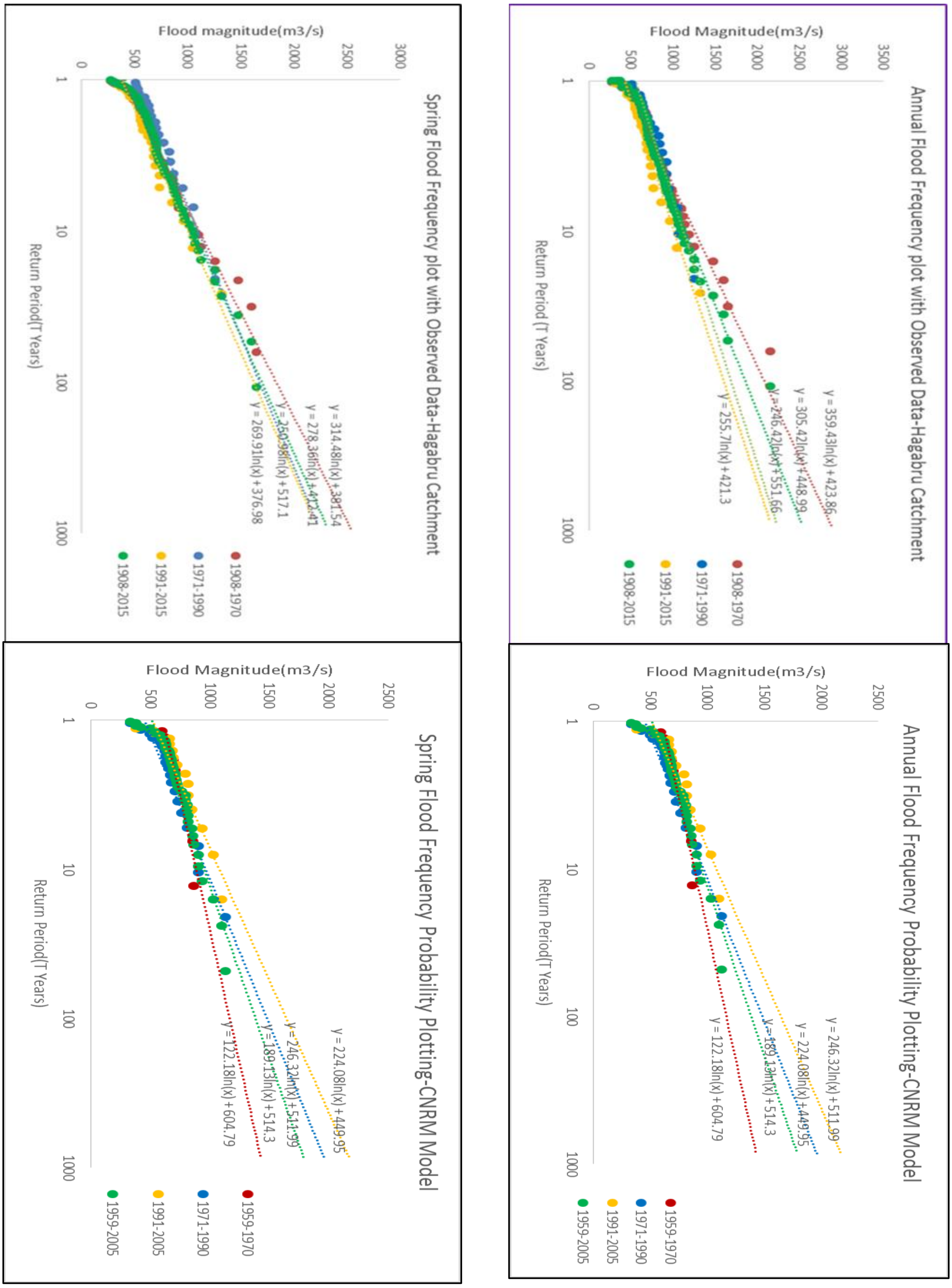


Figure A13.1: Flood frequency analysis with simulated output-Hagabru catchment-CNRM Model

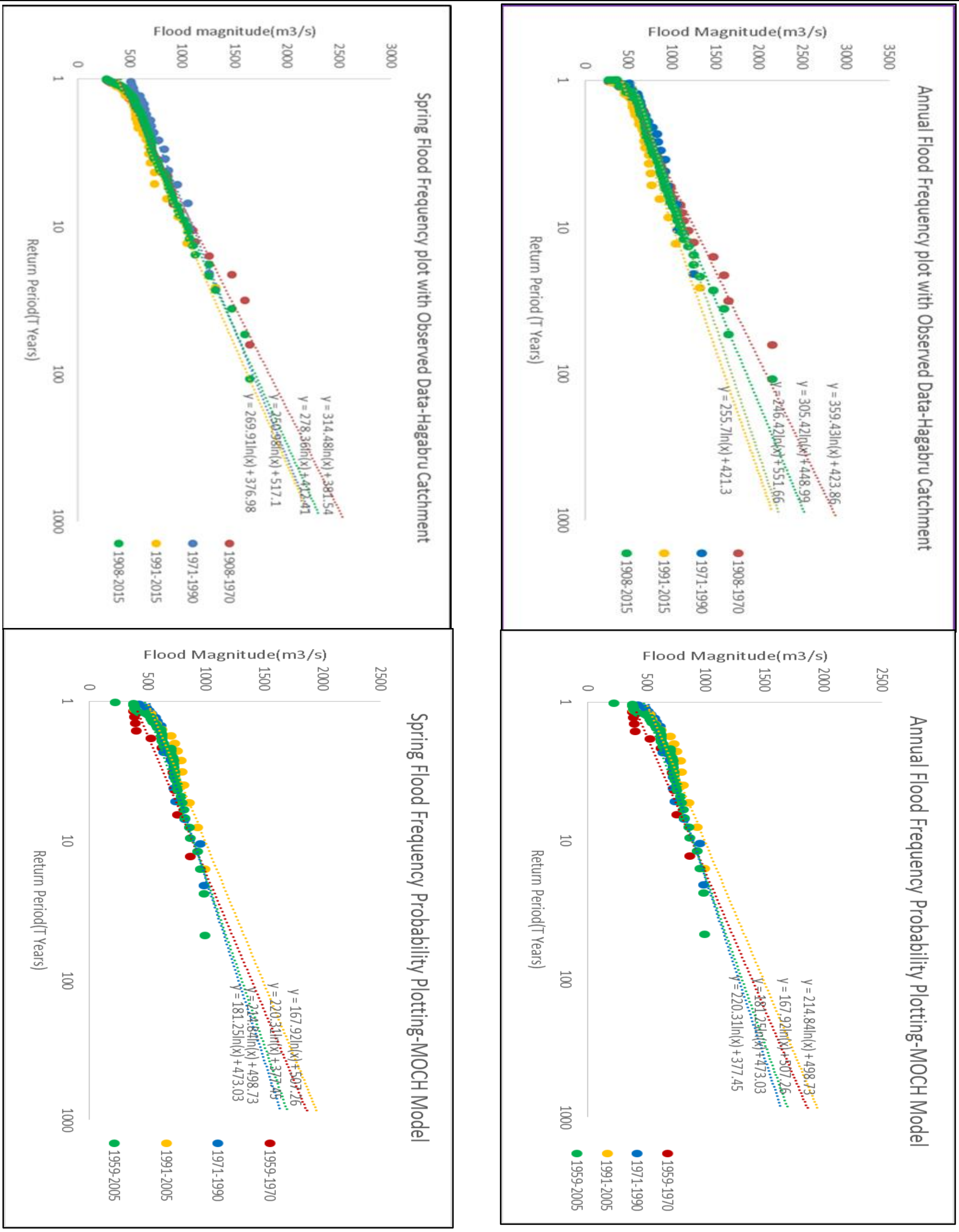


Figure A13.2: Flood frequency analysis with simulated output-Hagabru catchment-MOCH Model

NOTES