NTNU – Trondheim
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Science and Technology

Impact of Climate Change on Hydropower Potential in the Koshi Basin, Nepal

Sajana Marahatta

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Impact of Climate Change on Hydropower Potential in the Koshi Basin, Nepal

Master's Thesis in Hydropower Development

Trondheim, June 2015

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**Science and Technology
Department of Hydraulic and
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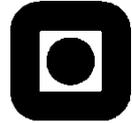
M.Sc. THESIS IN

HYDROPOWER DEVELOPMENT

Candidate: Sajana Marahatta

Title: Impacts of climate change on hydropower potential in the Koshi Basin, Nepal

1. BACKGROUND

Nepal has a large potential for hydropower due to the runoff from the high Himalayas. The projected climate change might influence the potential for producing hydropower in the future, and the purpose of this study is to evaluate how climate change may influence runoff in Nepal and see how these changes will influence the hydropower potential.

2. MAIN QUESTIONS FOR THE THESIS

1. Do a literature review on climate change studies in Nepal and the Himalayas, with a focus on issues related to water resources. Of particular interest will be prediction of future glacier dynamics.

2. Find potential climate scenarios for the area of Nepal. Evaluate if they are useful for the thesis work and select one for the future work. The selected data should be downscaled to a resolution relevant for the study.

3. Select the study area in Nepal and calibrate a rainfall runoff model for this area. This includes the evaluation of input data, finding the catchment boundary and elevation data and other data for the needed for the calibration. This also includes an evaluation of the model to use.

4. Use the caibrated model from task 3) to compute runoff scenarios for the future based on the data from task 2).

5. Run a detailed hydropower simulation for the study area for one or more specific plants. Evaluate changes in inflow and production. Evaluate the potential for adapting to climate change by adjusting the current production system.

6. Run a regional study for the total catchment to try assess the changes in hydropower potential.

3. SUPERVISION, DATA AND INFORMATION INPUT

Professor Knut Alfredsen will be the supervisor of the thesis work.

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

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

4. REPORT FORMAT AND REFERENCE STATEMENT

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

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

The summary shall not contain more than 450 words it shall be prepared for electronic reporting to SIU. The entire thesis may be published on the Internet as full text publishing through SIU.

Reference is made to the full-text-publishing seminar during NORADS winter-seminar. The candidate shall provide a copy of the thesis (as complete as possible) on a CD in addition to the A4 paper report for printing.

The thesis shall be submitted no later than 10th of June 2015.

Trondheim 12th of January 2015

_____

Knut Alfredsen

Professor

FOREWORDS

The thesis entitled 'Impact of Climate Change on Hydropower Potential in the Koshi Basin, Nepal' is submitted to Department of Hydraulic and Environmental Engineering at Norwegian University of Science and Technology, Trondheim in partial fulfilment of the requirements for the degree of Master's in Hydropower Development.

The thesis is an outcome of work done from January to June, 2015 at the department under the supervision of Prof. Knut Alfredsen. Corresponding data collections were made during the field visit in summer 2014. Besides, some parts of the work consist of adoption of codes and models from previous studies with slight modifications. Such inputs have been clearly mentioned wherever necessary.

I hereby declare that the work presented here is my own and all outside contributions have been acknowledged properly.

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Sajana Marahatta

June, 2015

Trondheim, Norway

ACKNOWLEDGEMENTS

ABSTRACT

Water resource has been termed as main source of development, in Nepal. Steep gradients, perennial river system and huge storage as snow in Himalayas makes perfect environment for hydropower production in Nepal. Such favourable environment may not remain same in future due to global climate change. In fact, Himalayas has been identified as the most vulnerable areas to climate change. So, continuous assessment of water resource availability now and in future, is a must to achieve sustainable development. This study aims to identify the possible impacts that climate change brings on hydrology and hydropower potential in Nepal with main focus on Koshi basin of Nepal. Climate change studies on Koshi basin has been done in past but the new thing about this study is that, it attempts to investigate the future projections under latest scenarios i.e. IPCC AR5 scenarios and focuses mainly on possible impacts on hydropower potential.

A good basin scale HBV model setup was done for Koshi basin with proper data quality analysis and selection of best representative stations for the basin. CORDEX data for South Asian domain were selected to make future projections. Analysis were based on two different models, shortly named as MPI and ICHEC and under scenarios RCP 2.6, 4.5 and 8.5 for mid and end century. Results suggested more seasonal impact rather than annual and were different with models used, especially in precipitation projections. MPI suggested usually a decreasing trend of precipitation while ICHEC suggested an increasing trend. Temperature is expected to increase with higher rate in winter and postmonsoon compared to monsoon while precipitation usually showed less rainfall in winter and premonsoon. The results were however different in water availability. Flow simulations under scenarios, showed an increasing trend throughout the year with very few exceptions, which could be a reason of snow melt due to increased temperature. This increased flow under scenarios simulated higher production results with an nMAG model set up made for a run-of-river hydroelectric system and also projected an increased flood spill in future. The extra flood spill could be utilized in upgrading the system in future with necessary planning and studies.

The results support in good hydropower potential in future if done under proper planning and utilization and to some extent, have overcome the fear of too little water available in future in annual basis. However, the seasonal changes are pronounced with higher possibility of warm and dry winters. Besides, the results are based on full basin scale analysis which may not be true on small scales thus sub basin scale analysis are highly recommended. Besides, the

uncertainty in projections could not be neglected, thus different models and study approaches are required for future work.

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ABBREVIATIONS

AR5	IPCC Fifth Assessment Report
CORDEX	Coordinated Regional Climate Downscaling Experiment
DHM	Department of Hydrology and Meteorology
GCM	Global Circulation Model
GHG	Green House Gas
GLOF	Glacial Lake Outburst Flood
GWh/yr	Giga Watt hour per year
HBV	Hydrologiske Byrån Vattenbalans
HEP	Hydro Electric Project
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
Km^2	Square Kilometres
m^3/s	Cubic meter per second
m.a.s.l	Meters above sea level
PP	Precipitation
PROR	Peaking Run-of-River
Q	Discharge
R^2	Nash Sutcliffe Efficiency
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
SMHI	Swedish Meteorological and Hydrological Institute
SRES	Special Report on Emission Scenarios
Stn	Station
SWAT	Soil and Water Assessment Tool
WCRP	World Climate Research Program

1. **INTRODUCTION**

1.1 Background

Climate change has been the topic of discussion these days, worldwide. Warmer days, changes in rain/snow fall pattern, increased sea level, glacier melt, that are being experienced these days, are the indications behind climate change [1]. It has been special matter of concern in the field of water resources availability now and in future. Climate change and hydrology are interrelated but the degree of change that climate brings in hydrology depends on the region of study.

Nepal is a small country in South Asia with an area of 147,181 km^2. Within the small area, it ranges from high Himalayas more than 8,000 m above sea level in north to flat plain area about 100 m on south. The climate system of Nepal is unique, ranging from Tropical to Arctic zones based on altitude. In addition to the steep mountains, abundant water resource is another gift by nature, to Nepal. Most of the rivers are perennial and are usually fed by snow melt. Good water storage as snow and steep gradient makes Nepal rich in hydropower potential. Despite of such huge hydropower potential, the country has not made optimum utilisation of the resources but is on developing stage.

Country's resources are the main backup behind development thus continuous assessment of resource situation is a must. IPCC findings suggest that, Himalayas are the most sensitive areas to climate change. Loss of snow reserve due to high melt rate corresponding to increased temperature and change in runoff patterns are threats to hydropower planning and potential. Sustainable development is achieved only when the current resources are utilised by having careful and parallel study of the future scenarios.

This thesis is thus an approach to see the changes that the future climate will bring on hydrology and simultaneously, on hydropower potential of Nepal. Considering the time limitations, a particular river basin on Eastern side of Nepal known as Koshi River Basin has been selected for studies. The study has been done on basis of IPCC AR5 scenarios which are the latest criteria's possible.

1.2 **Objective**

The main focus of the study would be to see the changes in hydrology in future. The study aims to observe the likely impacts that climate change will bring on water availability in Koshi basin and simulate its consequent effect on power potential.

1.3 **Scope of Study**

The study aims to fulfil the objective through following steps followed in order:

1. Literature review on climate change studies done in Nepal and the Himalayas.
2. Selection of particular study area in Nepal and collection of hydrological and meteorological data required to set a rainfall runoff model.
3. Analyze the quality of data, develop methods to fill missing values, quality control.
4. Choose a rainfall runoff model for study, find other data required to set the model and finally calibrate the model.
5. Find potential climate scenarios for Nepal. Evaluate if they are useful for the thesis work and select suitable ones for future projection. Downscale climate data to relevant resolution.
6. Use the calibrated model from task 4) to compute runoff scenarios for the future based on the data from task 5).
7. Run a detailed hydropower simulation for the study area for specific plant. Evaluate changes in inflow, production and flood spill. Evaluate the potential for adapting to climate change.

1.4 Methodology

Hydrological analysis involves some chronological steps to be followed. Figure 1-1 describes the framework under which this study has been performed. The models used in present study are HBV model and nMAG for hydrological simulations and production planning, respectively.
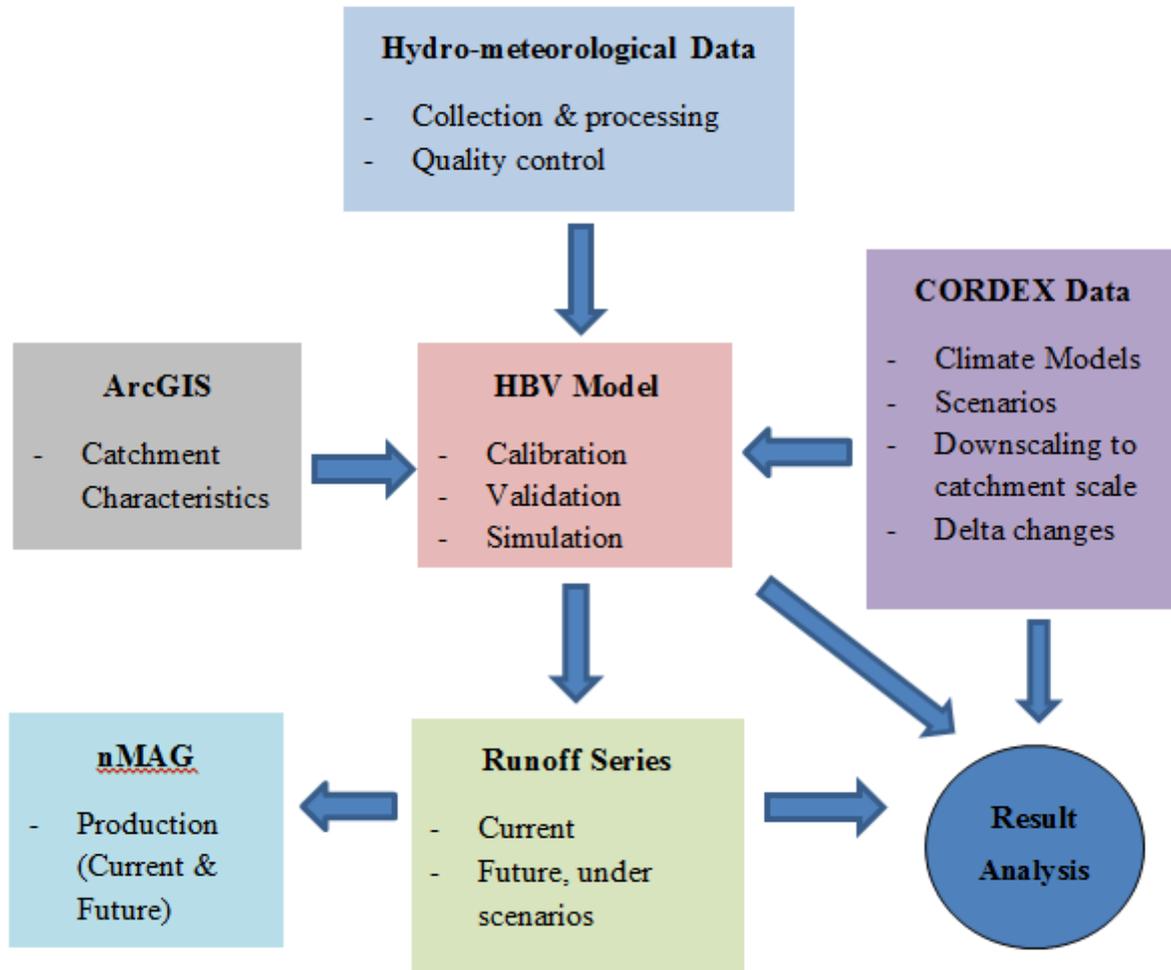
Figure 1-1 Study framework

1.5 Structure

The report has been prepared following the order of tasks performed. The structure of thesis provides an overview of each chapter for easy reference. Every chapters has been well described with introductions, model description if used, tasks performed, result analysis and discussions wherever relevant, with corresponding references.

Chapter 1   Brief introduction to thesis title, objective of study, methodology used and structure of thesis followed with limitations discussed.

Chapter 2   Literature review of studies done on past to have ideas for work, area to be focused on and follow the recommendations to make a better studies wherever possible.

Chapter 3   Introduction to study area, reasons behind its selection, overview of all stations available and data acquisition required for the study.

Chapter 4   Data processing, final selection of stations, filling of missing data and quality control.

Chapter 5   Introduces ArcGIS required for present work and details about catchment delineation.

Chapter 6   Introduces HBV model, reason behind its selection and model setup. Further describes calibration and validation results followed by comparison between different model setups.

Chapter 7   Provides introduction to climate change, downscaling of climate data, calculation of delta changes and their discussions.

Chapter 8   Describes about HBV model simulation under scenarios. Details about input data preparation and subheadings explain model results and discussions.

Chapter 9   Includes introduction to nMAG, description about the hydroelectric project, production simulation under scenarios and result discussion.

Chapter 10   Includes conclusions and recommendations made for further study in related topics.

1.6 Limitations

- Meteorological stations are not available uniformly throughout the selected catchment. Because of this, assumptions were made and, hit and trial methods were adopted, wherever necessary to get results. Such assumptions and steps have been well described with reasons to support them.

- The hydro-meteorological data series available is only from 1994 - 2008. Missing of recent years of data series may limit in incorporating the recent changes that climate change has already brought in hydrology.

- Due to time constraint, model setup has been done for whole catchment rather than on sub catchment scale. Because of this, the study may not be able to capture impacts on local areas due to climate change.

- nMAG setup for production simulations has been done for a smaller system compared to the basin but gives clear picture on purpose of study.

2. LITERATURE REVIEW

There have been some studies on climate change in Himalayas but they are not sufficient. No good snow records, lack of gauging stations in high Himalayas and lack of long term data records even for those established stations might be reasons behind fewer studies.

From analysis of temperature data from 49 stations in Nepal, Shrestha et.al [2] suggested warming temperature trends after 1977. The trends were found higher for Middle Mountains and Himalayas usually between 0.06^0 to 0.12^0C per year while Southern Plains showed trends less than 0.03^0C per year. Such increase in temperature has high impact in snow melting. Thus glaciers retreats have become the main evidences behind climate change and also a threat to society. According to a study made by Bajracharya, Mool [3], in a period of 30 years i.e. between 1970 to 2000, the loss of glacier area was by 5.88% or 0.2% per year in Tamor River basin (a sub catchment of Koshi basin) of Nepal. Such high rate of retreat has increased the number and size of glacial lakes subsequently possessing high threat of GLOF. In more recent studies made in glacier shrinking in Nepal Himalayas by Bajracharya, Shrestha [4], the findings have led to a fear of too much water (GLOFs) and too little water (glacier retreat). They found that, besides the risk of GLOF due to rapid melting, ice reserves as glaciers has declined by a rate of 28 % compared to the record of 2001 which consequently has led to fear of too little water in future.

Recent studies on climate change have focused in observing the precipitation, temperature trends in future based on different climatic models and scenarios described by IPCC. Different rainfall runoff models are then used to simulate the effect of these changes on flow pattern. At such, Bharati, Gurung [1] studied the impact of climate change on water resource development in Koshi River basin, Nepal using SWAT. Results obtained were interesting with time and scale dependency. The projected impacts were found small in annual and total basin scale while more pronounced impacts were observed in seasonal and sub-basin scale. Studies were performed under SRES A2 and B1 scenarios which suggested an increase in temperature by 0.3^0C per decade under both scenarios. Mean annual precipitation was projected to be decreasing by 1-3 % by 2030s but increasing in 2050s by 8-12 % but again these changes were more pronounced at sub-basin scale. Change in flow pattern were more interesting in seasonal basis rather than in annual basis. Their findings suggested wetter monsoon and postmonsoon seasons while flows in winter and premonsoon seasons were supposed to decrease. The future projections are however not similar with every study being made. Results depend on assumptions made for

future projections i.e. the driving forces and models used in analysis. Gosain, Rao [5], in 2011, had similar studies on Koshi basin under A2 and B2 scenarios that resulted in increase of precipitation, snow melt and runoff in future.

More recent studies under latest concentration trajectories (RCPs) were done by Viste and Sorteberg [6]. According to their findings, with the strongest forcing scenario (RCP 8.5), by the end of century (1971-2100), the climate models present reduction in annual snowfall by 50-60 % in Ganges basin while precipitation and temperature are supposed to increase. The Koshi basin is a part of Ganges basin, but it does not mean that the projections will be the same. However, they have mentioned that snowfall in Nepal, Bhutan and Himachal Pradesh were most vulnerable to higher temperatures.

Being specific with hydropower, any change on hydrology will have an impact on potential. Chaulagain [7], suggested that increase in snow melt in recent times though increases hydropower potential but continuous rise in temperature in the same pattern will led to no more ice reserves for future and consequently the potential would decrease. In addition, Chaulagain suggested that Nepal having mostly the runoff projects, they get more vulnerable to stream flow changes.

The present study is thus more about climate change impacts on Koshi basin driven under IPCC latest scenarios i.e. RCP 2.6, 4.5 and 8.5 and for two different time frames; Mid Century (2041 - 2070) and End Century (2071 - 2100).

3. STUDY AREA

3.1 Background

Rivers are well distributed throughout the country. For hydrological studies, Nepal is divided into seven discharge basins. i.e. Kankai Mai river basin, Koshi river basin, Bagmati river basin, Narayani/Gandaki river basin, West Rapti river basin, Karnali river basin and the Mahakali river basin. [8] Figure 3-1 gives an overview of these basins except Kankai Mai river basin which occupies the south - east end of country. It is clear that the three largest ones cover the eastern, central and western part of country and runs from high Himalayas to plain Terai.
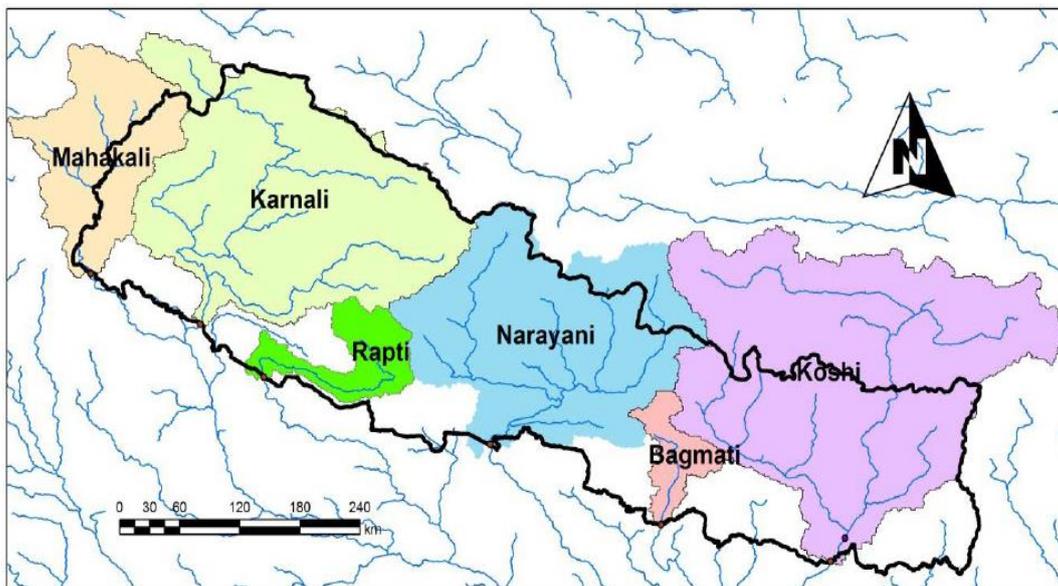
Figure 3-1 Major river basins of Nepal [9]

Among these basins, Koshi basin also known as Saptakoshi has been chosen for further studies. The reasons behind its selection were;

- It is the largest river basin and has huge hydropower potentiality.
- River originates from Tibet and around half of the basin part lies in Tibetan side which makes it an interesting basin for hydrological studies.
- The basin includes many high mountains of country including Mt Everest and includes large number of glaciers, also potentially dangerous glaciers, thus is an important basin for snow and glacier studies.
- As mentioned earlier, Himalayas are the most sensitive areas to climate change, thus impacts due to climate change would be more visible through this basin studies.

3.2   The Koshi Basin

Koshi river basin, also known as Saptakoshi is a network of seven major rivers that flows on eastern part of country i.e. Tamor river, Arun, Dudhkoshi, Likhu, Tamakoshi, Sunkoshi and Indrawati river. Among the tributaries, Sunkoshi, Tamakoshi and Arun originate in Tibet. The basin covers part of Tibet, Nepal and finally drains to India, to meet the Ganges.

The basin runs from high Himalayas to plain Terai covering an area of 57,811 km^2 (results from chapter Watershed Delineation) upto the outlet point Chatara - Kothu. Having wide geographical coverage and being fed by the snowmelt from Himalayas, the massive water resources of this basin has been the source for several hydropower projects, hectares of irrigation land, fishing and destination for adventurous spots like rafting and canyoning.
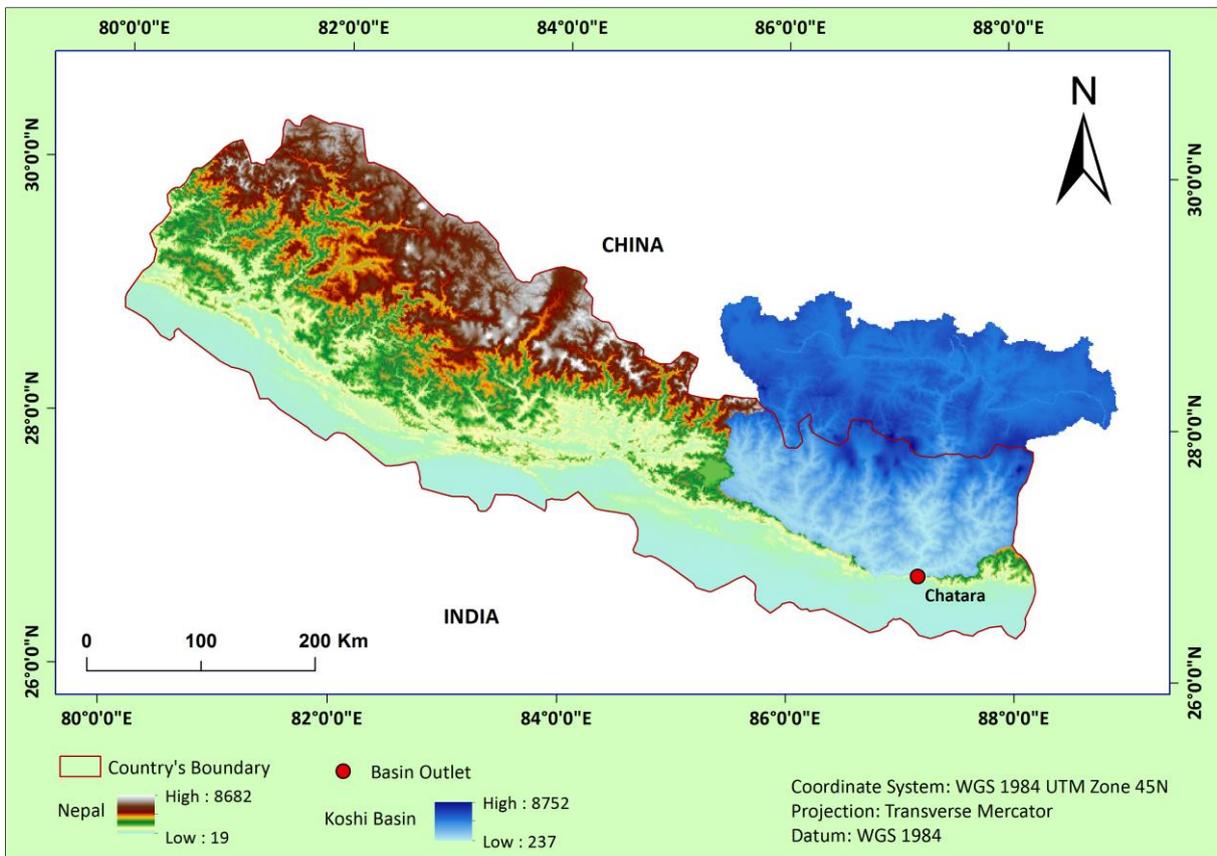
Figure 3-2 Location map of Koshi basin, Nepal

3.3   Hydro - Meteorological Stations

Appendix A is an overview of all hydro - meteorological stations that lie within the catchment boundary, with outlet as gauging station Chatara - Kothu.

3.3.1 Precipitation Stations

According to the data record of Department of Hydrology and Meteorology, there are altogether 282 meteorological stations on operation throughout Nepal out of which 71 lies on Koshi Basin. But, as the outlet point considered here is Chatara - Kothu, there are altogether 54 operating stations that lie within the watershed area considered.
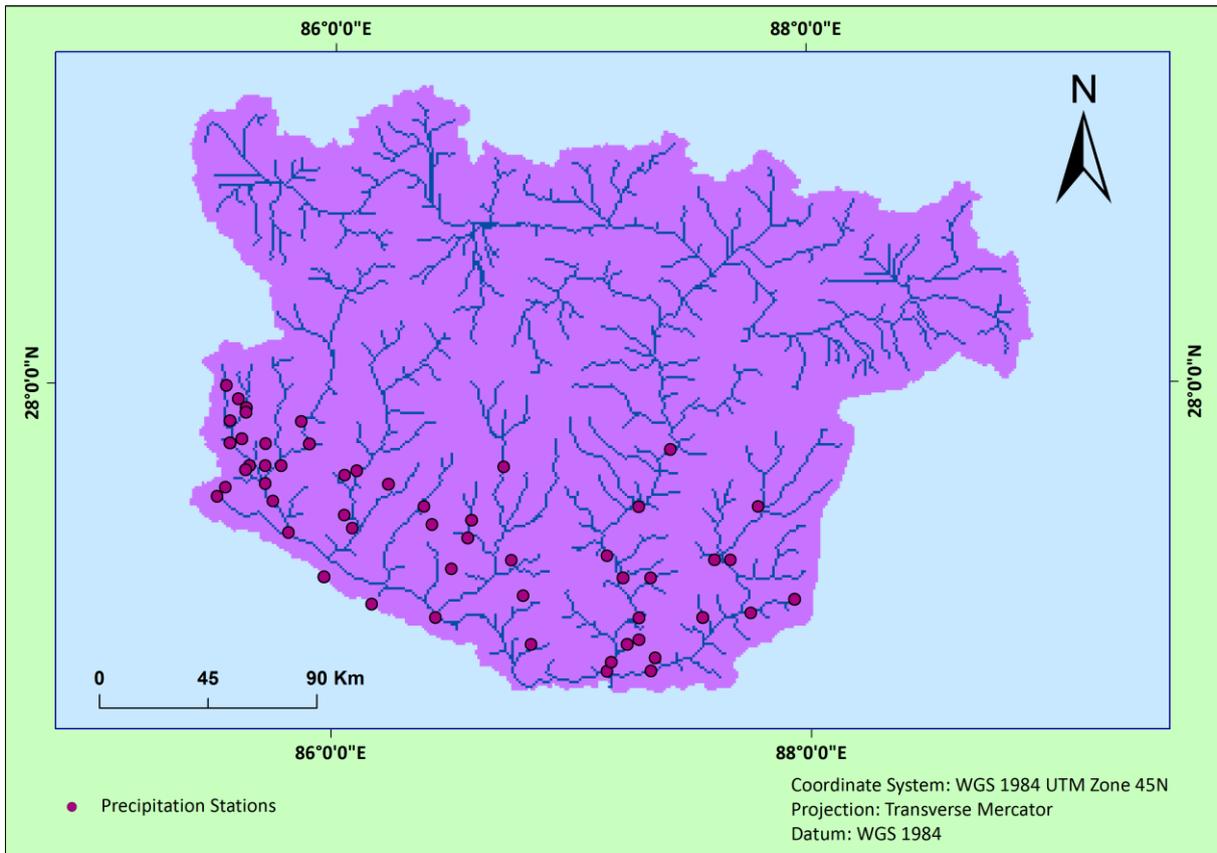
Figure 3-3 Location of precipitation stations in Koshi basin

3.3.2 Hydrological Stations

There are total 51 hydrological stations throughout the country. Altogether 19 hydrological stations are on operation within the Koshi basin according to the record of DHM. But in consideration of outlet point as Chatara-Kothu (Station no. 695) only 17 stations lie within the catchment boundary as shown in Figure 3-4.

3.3.3 Temperature Stations

Altogether 22 temperature stations are recorded on Koshi basin, out of which only 11 stations (as shown in Figure 3-4) that lie within the watershed were considered for further analysis.

3.3.4 Evaporation Stations

There are very few evaporation stations throughout the country and out of which only 3 of them lies on Koshi basin. Further, data collection is made for only 2 stations that lie within the watershed.
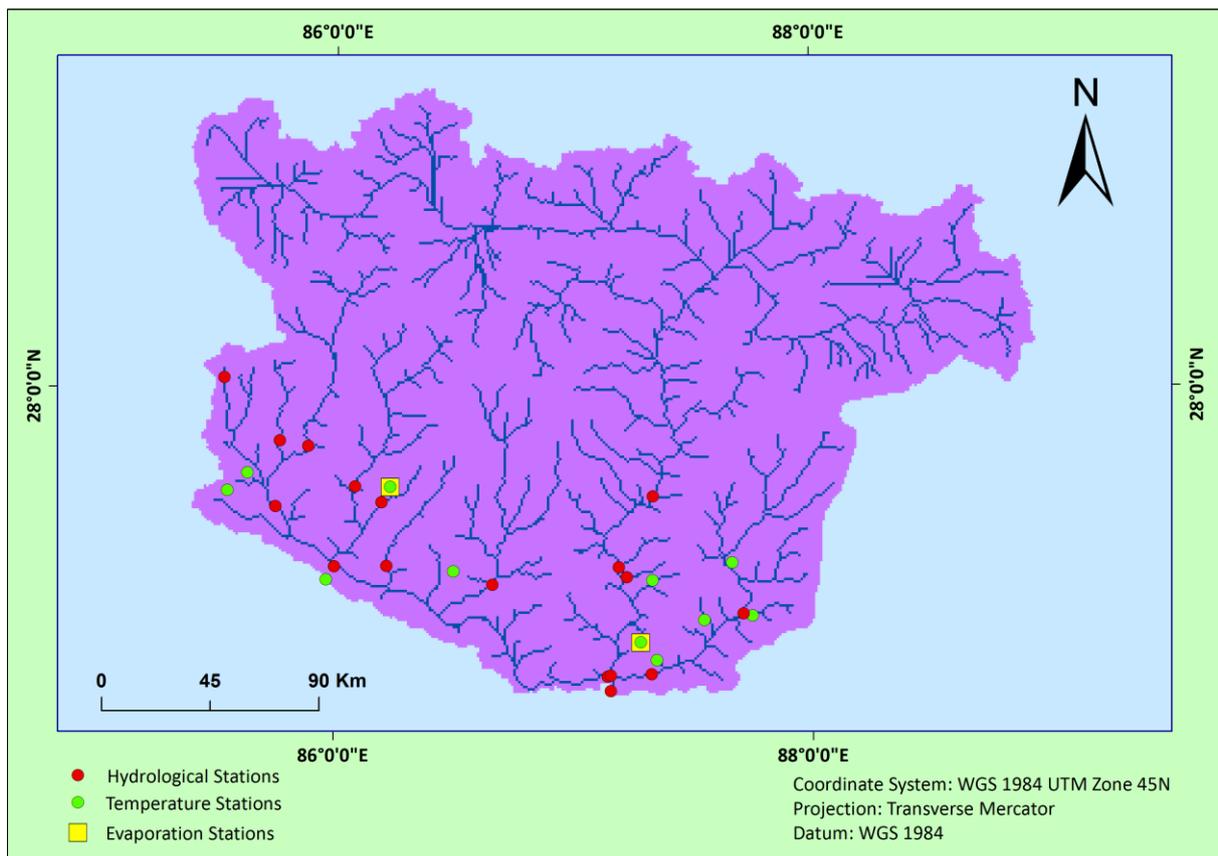
Figure 3-4 Location of temperature, evaporation and gauge stations in Koshi basin

4. DATA PROCESSING AND QUALITY CONTROL

All the hydro - meteorological data used here for analysis were obtained from Department of Hydrology and Meteorology (DHM), Kathmandu, Nepal. Data collection was done for all the station represented by Figure 3-3 and Figure 3-4 in order to avoid limited data availability and have luxury in selection of stations with good quality data. The aim was to have a good range of data available for the study may be for the last 20 years but finally ended up with collection of 15 years of daily data series from 1994 - 2008 for each station. It is always better to have the recent years of data series rather than only up to 2008 and attempt was made in collecting data till 2014 but it remained unsuccessful for most of the stations. Still a good control can be acquired through 15 years of data series available.

4.1 Use of 'R' in Data Analysis

'R' is the statistical programming language and a very handy tool in large data handling and processing. Use of 'R' not only reduces the time and effort needed for large data analysis which would have been a troublesome work if done only in excel but also increases the quality of output. i.e figures and graphs. The version used here is R 3.1.2 and RStudio as a platform for easiness in writing scripts and visualising the changes. The daily data series for precipitation, temperature and discharge available in different and complicated format were converted to two columns of 'Date' and 'Value'. Monthly and yearly averages from the daily series were computed using packages like 'Zoo', 'HydroTSM'. Appendix B includes the scripts used for reading and plotting the data series.

4.1.1 Precipitation Data Analysis

Graphs of daily series, monthly average and annual precipitation for each of the station were plotted using R script and an overview of data quality was obtained. Precipitation data obtained was in a format of 15 text files (representing 15 years) for each station. i.e a total of 15*54 text files with 365 days data in each file, which to compute without 'R' would have been almost hopeless task.

Some interesting graphs and analysis made from those plots were;
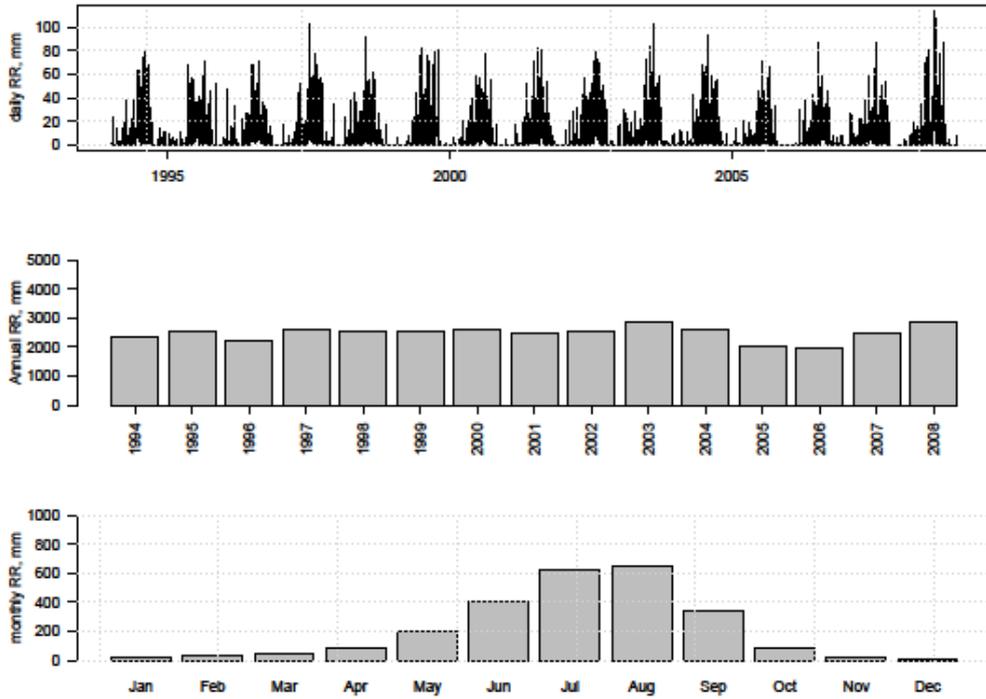
Figure 4-1 Graphs of precipitation data series for station 1103
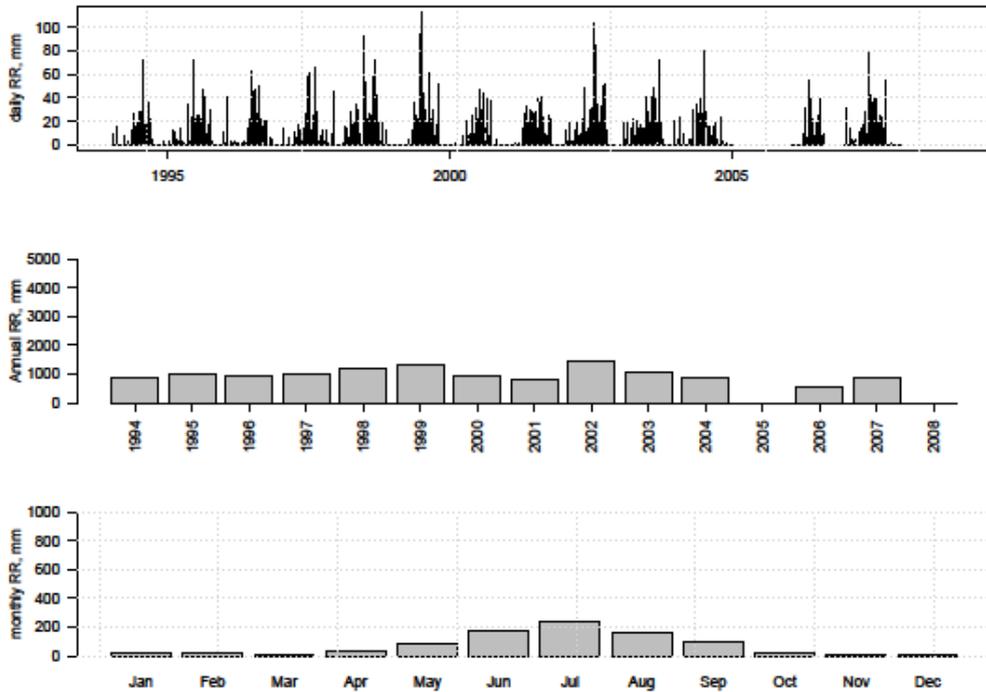
Figure 4-2 Graphs of precipitation data series for station 1028
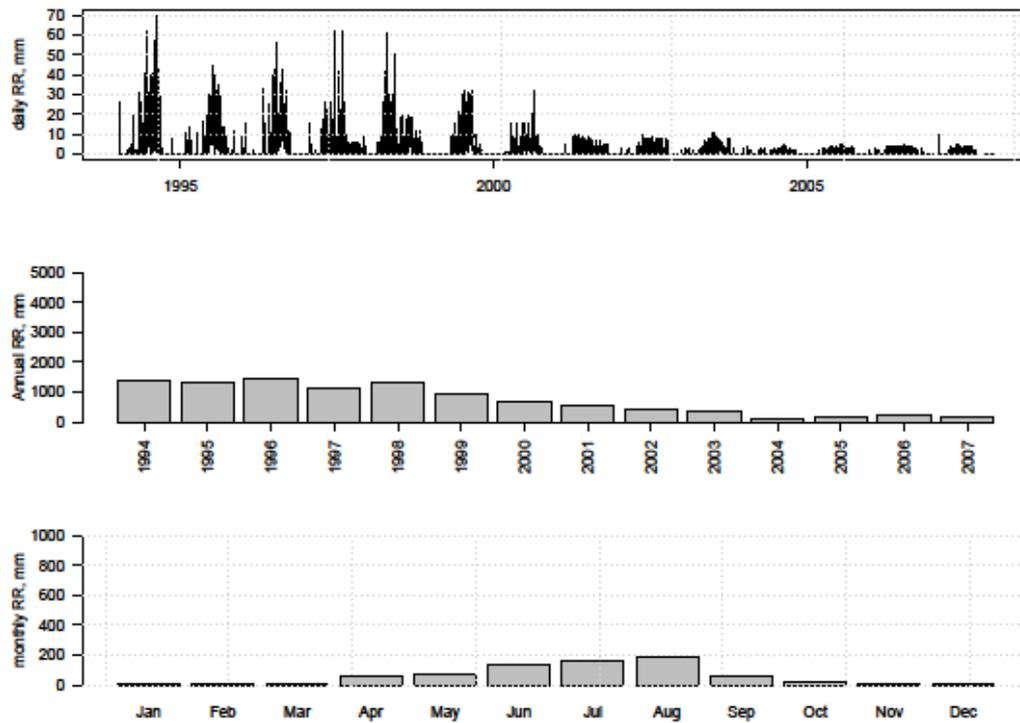
Figure 4-3 Graphs of precipitation data series for station 1104

Figure 4-1 represents good quality of data series with almost no data missing while Figure 4-2, graphs for station number 1028, were with many missing values sometimes a yearlong and more. Filling of such long period of missing data were not possible and using such stations for model setup was of course not the first choice. Similarly, Figure 4-3 represents graph plot for station 1104 with poor quality data. The data for the station seemed suspicious, might be a reason of moved station or bad data records. The data quality of all 54 stations were analysed through similar graphs to see the missing series, unusual trends if any and to have an overview of dry and wet years. Considering those graphs and stations location through GIS analysis (Figure 3-3), an overview was made which resulted in selection of best 9 precipitation stations that were representative for the whole basin.
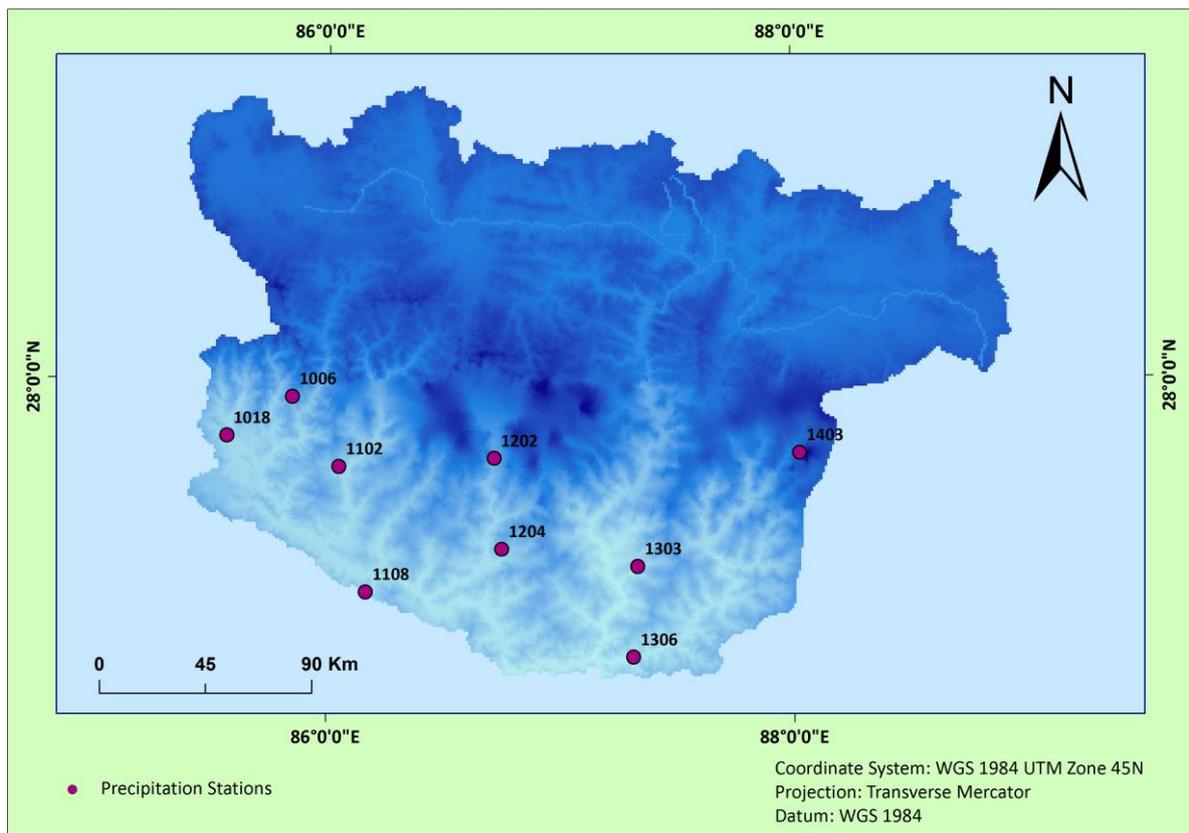
Figure 4-4 Selected precipitation stations for Koshi basin, represented by index number

Table 4-1 Details of selected precipitation stations for Koshi basin

S.N	Index No	Station Name	Elevation	Avg. annual rainfall	Latitude	Longitude
			m.a.s.l	mm		
1	1006	Gumthang	2000	4295	$27^0$52'0"	$85^0$52'0"
2	1018	Baunepati	845	1776	$27^0$47'0"	$85^0$34'0"
3	1102	Charikot	1940	2152	$27^0$40'0"	$86^0$03'0"
4	1108	Bahun Tilpung	1417	2011	$27^0$11'0"	$86^0$10'0"
5	1202	Chaurikhark	2619	2096	$27^0$42'0"	$86^0$43'0"
6	1204	Aiselukhark	2143	2327	$27^0$21'0"	$86^0$45'0"
7	1303	Chainpur	1329	1481	$27^0$17'0"	$87^0$20'0"
8	1306	Munga	1317	1069	$27^0$02'0"	$87^0$14'0"
9	1403	Lungthung	1780	2379	$27^0$33'0"	$87^0$47'0"

4.1.2 Discharge Data Analysis

Similar to precipitation data series, discharge data were obtained in format of one text file for each year/each station. But, the scripts used for reading those data series were different than rainfall, as data were in complicated format of separate columns for each month within each text file (Refer Appendix B). Graphs for daily series were plotted by running those R scripts.

Graphs of daily series for some stations are attached below:
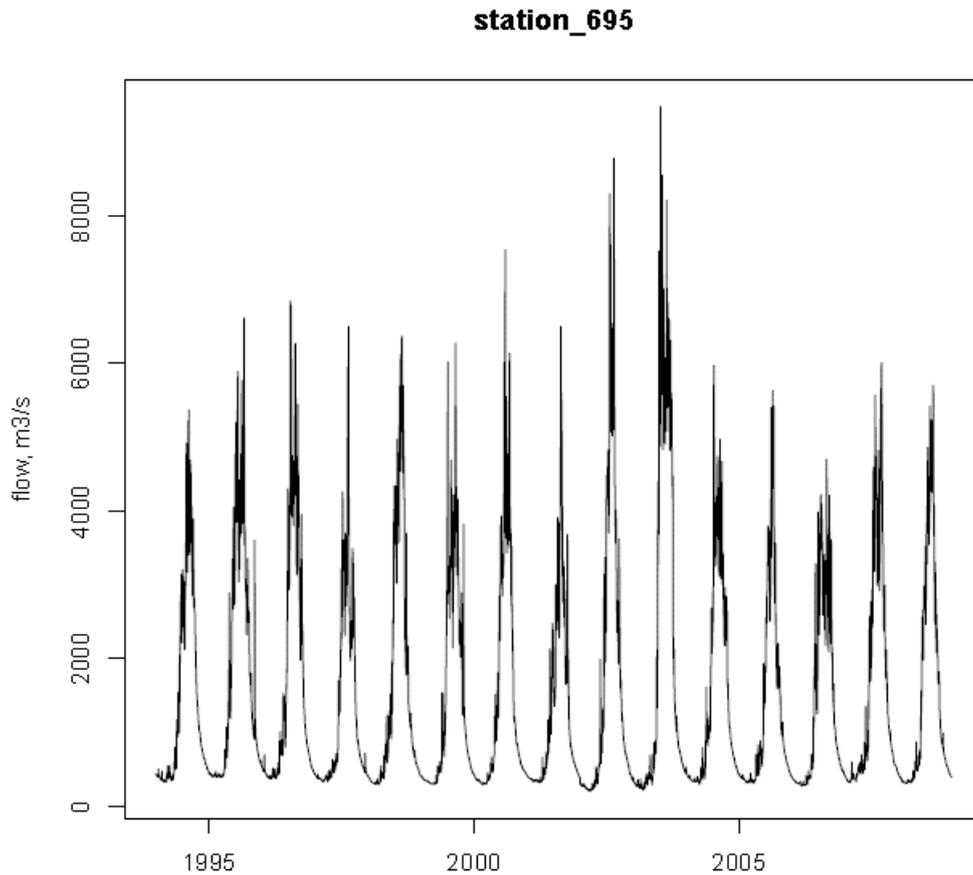
station_695

Figure 4-5 Daily runoff series for the outlet point (Chatara-Kothu)
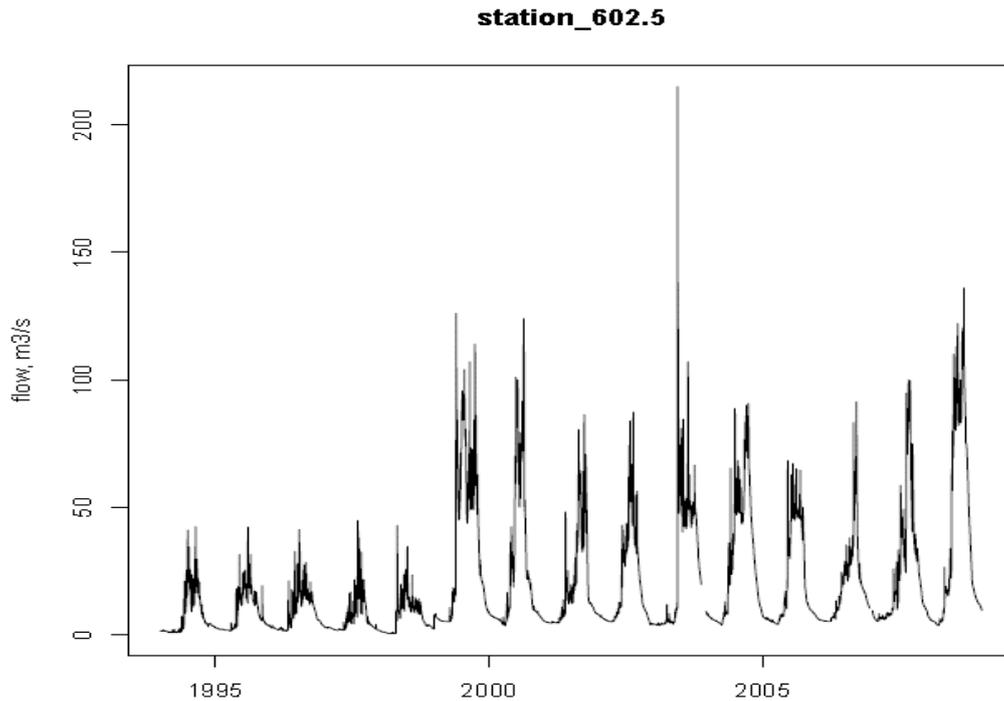
Figure 4-6 Daily runoff series for station 602.5

The 1st graph was of good quality data but the 2nd graph had suspicious data series as it shows poor seasonal variability, which could be a reason of change in gauge location or faulty record. Similar graphs were plotted for 17 discharge stations and quality of data was observed.

Interesting results could have been obtained if these gauge stations could be used and models could be set for sub-catchments, but because of time constraint, the work ended with selection of only one discharge station (Chatara-Kothu), the outlet point within Nepal.

4.1.3 Temperature Data Analysis

There were altogether 11 temperature station data series in similar format to precipitation data. Graphs of daily series, monthly average and yearly average were obtained by running R-scripts similar to that for precipitation data analysis.
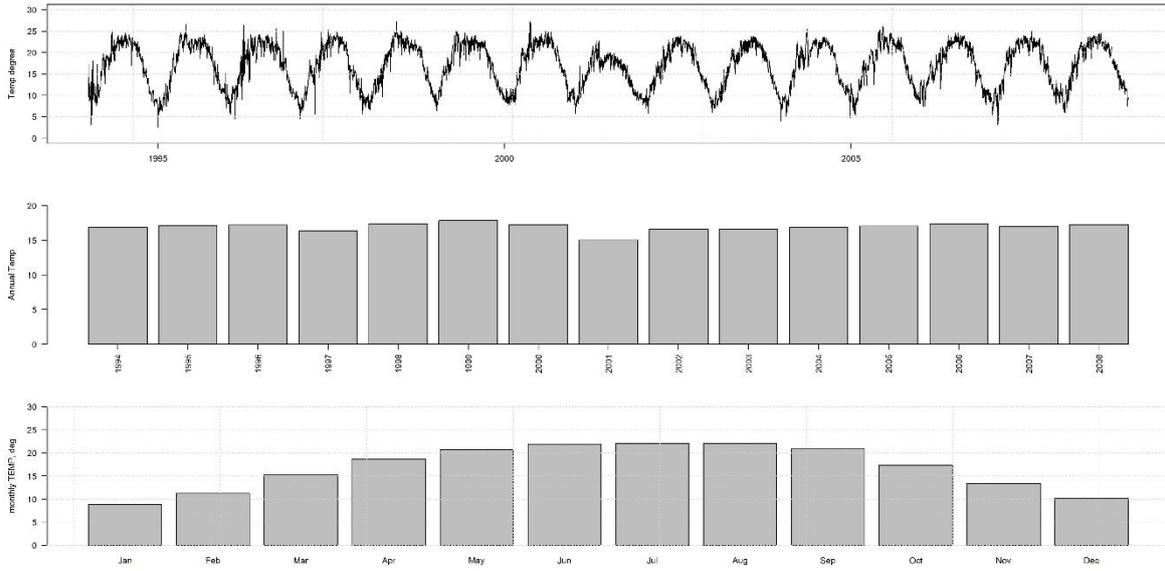
Figure 4-7 Graph of temperature series for station 1024
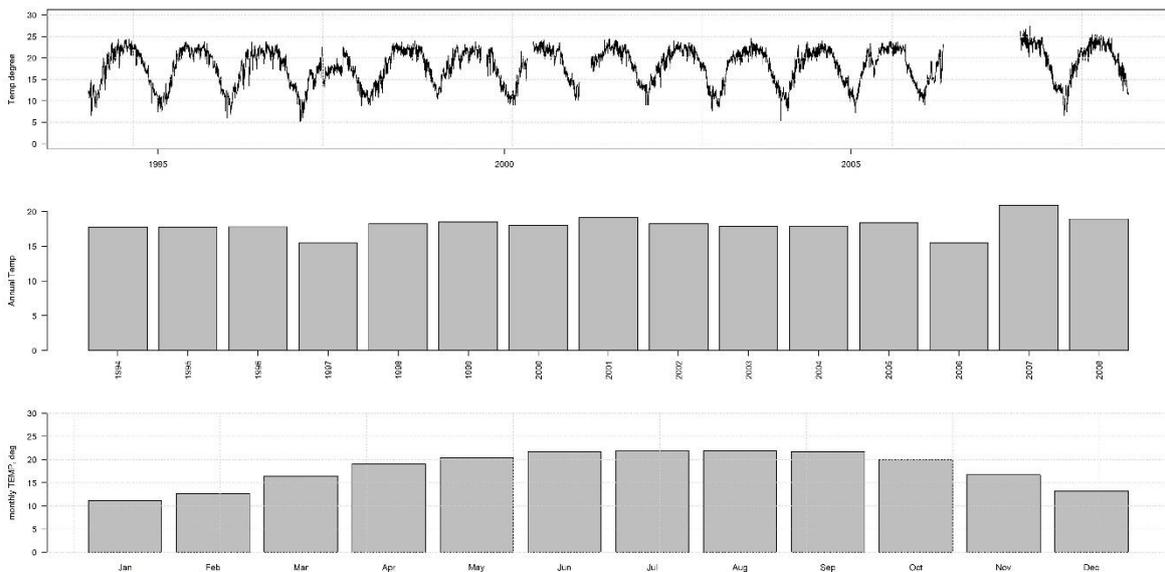
Figure 4-8 Graph of temperature series for station 1314

Figure 4-7 and Figure 4-8 represents good quality of data set and data series with missing values, respectively. Reviewing the graphs, quality of data and the location of temperature stations, best 5 stations that well represent the catchment were selected for further analysis. (Refer Figure 4-10).

4.1.4 Evaporation Data Analysis

Evaporation data from two stations that lie within the watershed were plotted to check the quality of data. Estimation of potential evapotranspiration was also done using Thornthwaite's formula for the corresponding station.

$$PET = 1.6 * \left(\frac{L}{12}\right) * \left(\frac{N}{30}\right) * (\frac{10T_a}{I})^\propto \quad .... \text{ (Thornthwaite's Equation)}$$

Where,

PET = Estimated Potential Evaporation, cm/month

T_a = Average daily temperature, ^{0}C

N = Number of days in the month

L = Average sunshine hours for the month

$$\propto = (6.75 * 10^{-7})I^3 - (7.71 * 10^{-5})I^2 + (1.792 * 10^{-2})I + 0.49239$$

$$I = \sum_{i=1}^{12}(\frac{T_{ai}}{5})^{1.514} \quad ; \text{Is a heat index, depends on monthly mean temperature, } T_{ai}$$

The estimated PET using Thornthwaite's formula was plotted with observed evaporation for the station which gave very different results.
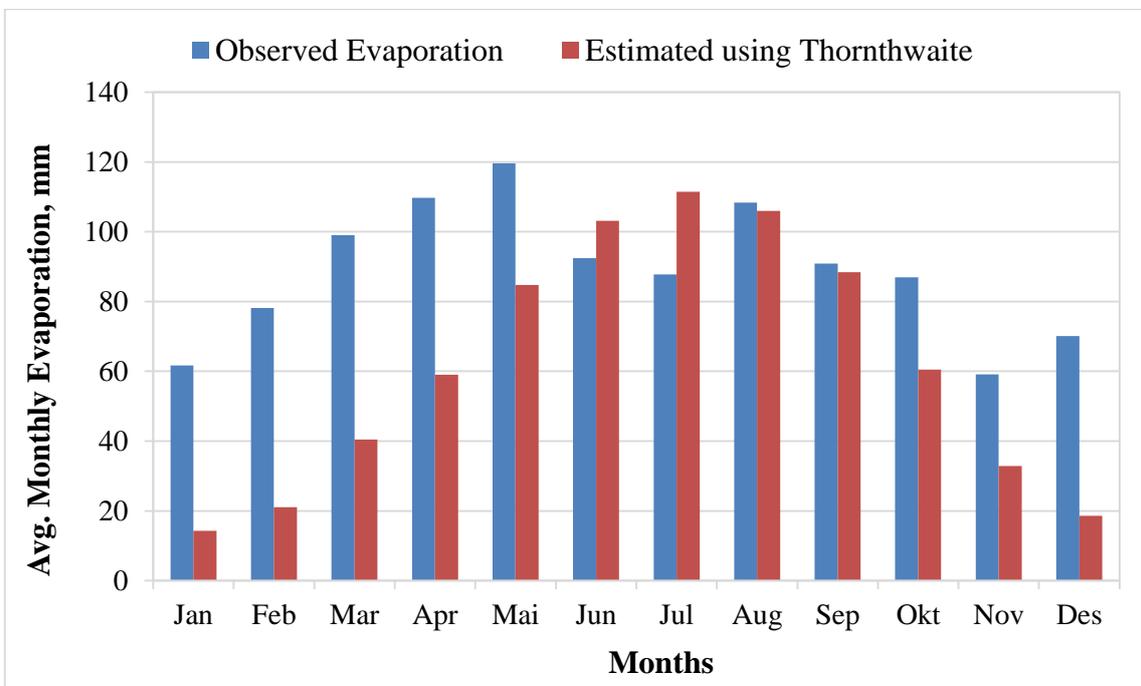
Figure 4-9 Comparison of observed and estimated evaporation for station 1103

This shows that Thornthwaite's equation for PET estimation, in Koshi basin, highly underestimates the evaporation for dry periods and overestimates during monsoon. It is because PET estimation using Thornthwaite is basically based on temperature only which is not true in real world. Besides, actual monthly evaporation trend is different than estimated one. Evaporation during monsoon period was found decreasing which could be an effect of humidity in air during rainy seasons.

This comparison thus led to use of observed evaporation values for further analysis.
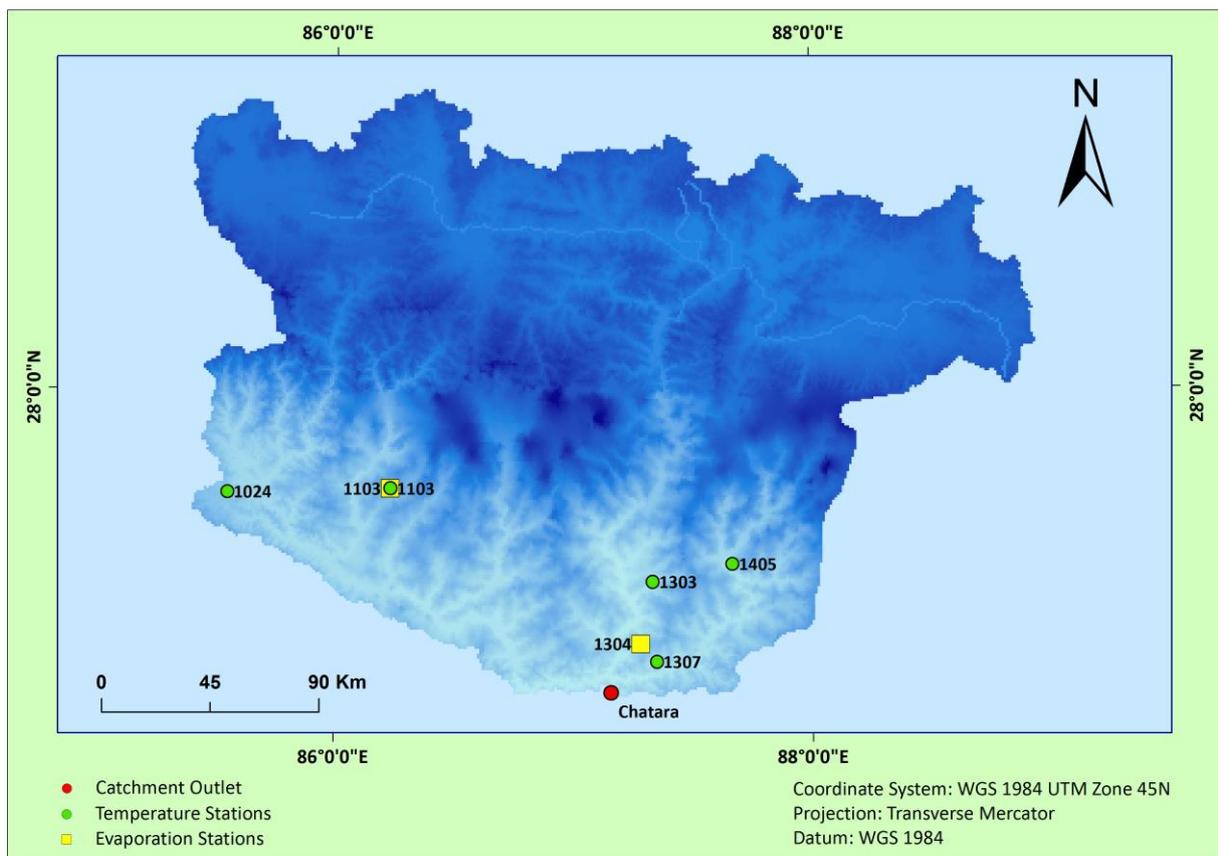
Figure 4-10 Selected stations for Koshi basin, represented by index number

Table 4-2 Details of selected stations of Koshi basin

Index No	Station Name	Station Type	Elevation, m.a.s.l	Latitude	Longitude
695	Chatara - Kothu	Hydrological	140	$26^0 52'00''$	$87^0 09'30''$
1024	Dhulikhel	Temperature	1552	$27^0 37'0''$	$85^0 33'0''$
1103	Jiri	Temperature/ Evaporation	2003	$27^0 38'0''$	$86^0 14'0''$
1303	Chainpur	Temperature	1329	$27^0 17'0''$	$87^0 20'0''$
1304	Pakhribas	Temperature/ Evaporation	1680	$27^0 03'0''$	$87^0 17'0''$
1307	Dhankuta	Temperature	1210	$26^0 59'0''$	$87^0 21'0''$
1405	Taplejung	Temperature	1732	$27^0 21'0''$	$87^0 40'0''$

4.2   Filling of Missing Data

Every data series must be complete before the input to any hydrological model. Data missing can happen due to several reasons like gauge problem, difficulty in reading daily data, personal mistakes in storage, poor storage system and so on. The data series collected from DHM, Nepal had so many missing values and mostly on a long regular series of more than 90 regular days and sometimes a year of missing data. Filling of missing data is itself a challenging part in data analysis and if filling is required for a long series then it leads to uncertainty. Thus to avoid such uncertainty, selection of representative stations were made mostly according to quality of data available as described in Chapter 4.1.

There were still few missing data in the daily series among the selected 9 precipitation stations. But, data missing were mostly random and if regular, were during dry months like January or in December except for Station 1202 which consists of missing data during start of rainy season.

Table 4-3 Overview of missing data in precipitation stations

Stations	1006	1018	1102	1108	1202	1204	1303	1306	1403
Year/Elevation	2000	845	1940	1417	2619	2143	1329	1317	1780
1994									
1995									
1996									
1997									
1998									
1999									
2000					31 days/Jan				
2001				16 days/Dec					16 days/Dec
2002		29 days/Dec							
2003				16 days/Dec					
2004									
2005									
2006									
2007									
2008					92 days/May				
Total Missing	0	31	35	37	123	5	9	0	75

Random missing data were filled by simple interpolation while the long missing series were estimated using data from nearby stations. Such estimations were done using two different methods [10] :

1. Station - Average Method

   This approach was used when annual precipitation at each station differs by less than 10% from the gauge with missing data.

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

2. Normal - Ratio Method

   If the annual precipitation differs by more than 10% then estimation was done using this approach.

$$\widehat{p_0} = \frac{1}{G} \sum_{g=1}^{G} \frac{P_0}{P_g} p_g$$

Where,

p_0 = Missing data

p_g = Value observed at nearby station for corresponding day

P_0 = Annual average precipitation at missing station

P_g = Annual average precipitation at nearby stations

The precipitation trend for Nepal is such that, it's almost no rainfall during dry seasons so the missing data in dry season usually got zero value.

There were very few random missing data in temperature and evaporation series which were filled by simple interpolation where discharge data had no missing values.

4.3   Data Quality Check

Consistency in data series is equally important to obtain good model results and data quality should be constantly checked through different ways. The various methods used in this thesis to have control on data quality were:

1. Visual Inspection :

   This was the first step in data analysis. Graphs of all station data with missing values were plotted using R and quality of data were inspected and final selections of stations were made as described in chapter 4.1.

2. Accumulation Plot:

   Missing data were estimated for the selected stations and quality of filling was inspected using accumulation plots.
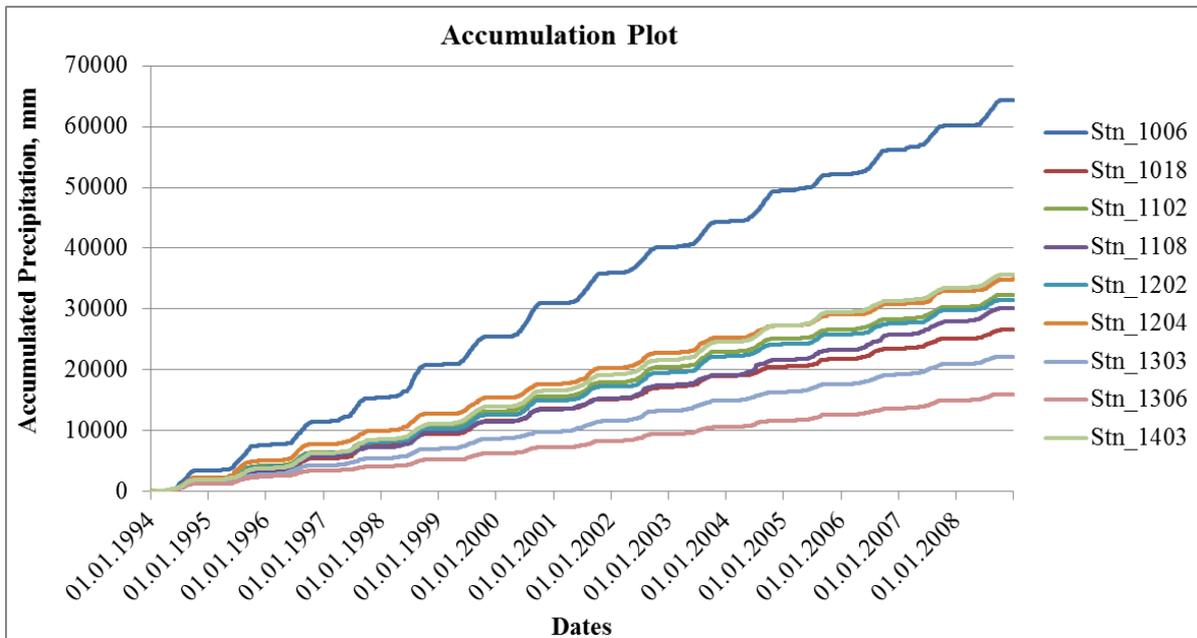
Figure 4-11 Accumulation plot of precipitation time series of all stations

The data quality looks good as the accumulation plot for each station is with equal gradient throughout the study period. It is visual that station 1006 has very high precipitation than any other stations. It must not be a problem with data quality as this is the station with no single missing data and accumulation plot also looks good. Rather this station lies on western part of catchment and usually every station over that area is noted with high precipitation values.

3. Double Mass Curve

This is a very useful method used to check the consistency of data record with other stations. Here, annual precipitation for all stations is calculated and arranged in decreasing order with time. Cumulative annual precipitation for each station is computed and so as the average cumulative annual rainfall for all stations. This average is then plotted against the cumulative annual rainfall for each station to get double mass curve.
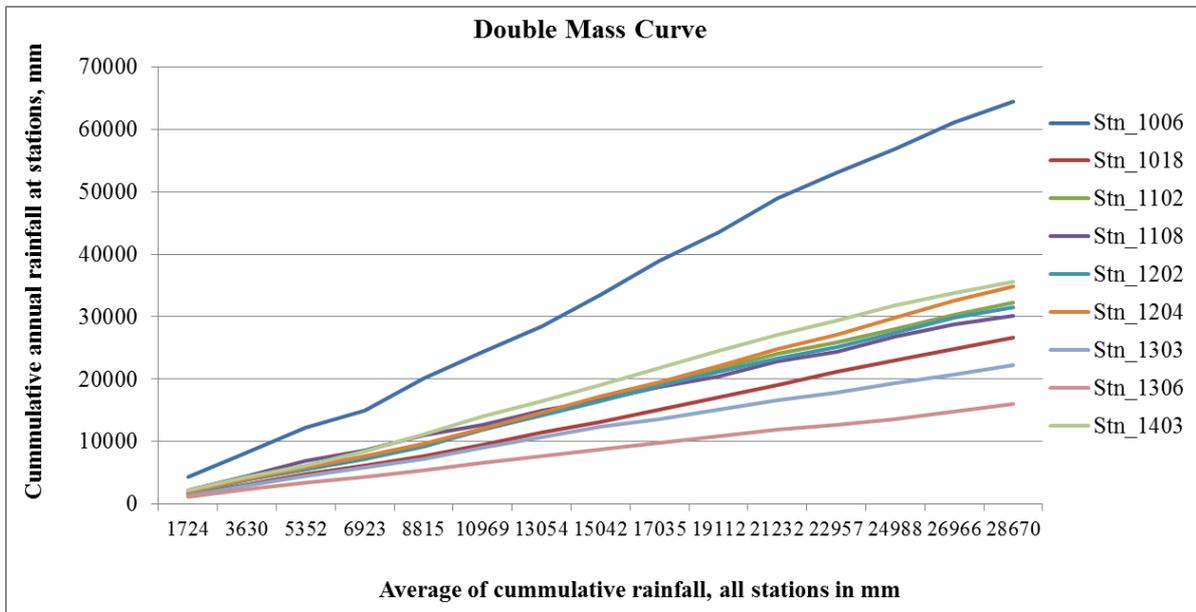
Figure 4-12 Double mass curve

It can be clearly seen that the double mass curve for all the stations looks good. Thus, it can be said that data records were consistent enough and could be used further with good confidence.

5. GEOGRAPHICAL DATA PREPARATION

5.1 Introduction to ArcGIS

ArcGIS is a software program used to create, display and analyse geospatial data, developed by Environmental Systems Research Institute (ESRI). It is an integrated system consisting of three components: Arc Catalog, ArcMap and Arc Toolbox. The version used throughout the study is ArcGIS 10.2.

5.2 Watershed Delineation

Watershed means the area drained by a river or a river system. For any outlet point, the area upstream of it which contributes the flow of water is watershed for that outlet point. It is a main part in any hydrological analysis. Watershed can be delineated using paper maps or by using GIS tools. There is a tool named Archydro which is an extension to ArcGIS, specially used for such delineation work. But it can also be done simply by using Spatial Analyst Tool - Hydrology on ArcGIS.

5.2.1 Requirements for watershed delineation

1. Software package: The one used for this study was ArcGIS 10.2.

2. Digital Elevation Model (DEM): DEM for any study area can be downloaded from Hydro 1K data sets. Hydro 1K consists of DEM in continent basis in a resolution of 1 km*1 km. Resolution requirement depends upon the extent of work and the area of study. For this study, DEM for Asia was downloaded. More information about data extraction can be found on https://lta.cr.usgs.gov/HYDRO1K.

3. Streams Network:

   These are supportive data for analysing and verifying GIS outputs. The stream networks for Asia were downloaded as shape file from http://hydrosheds.cr.usgs.gov/index.php and clipped for the area of interest.

4. Asia Shape File:

   This is an additional data that will be helpful to clip the area of interest. With only DEM, it may be difficult to see exactly the area that needs to be clipped. With the shape file it is always easier to select the region and visualise the exact location of the area of interest. For this thesis, the shape file has been downloaded from http://nils.weidmann.ws/projects/cshapes/shapefile.

5. Outlet point (location of gauging stations): The latitude and longitudes of the stations were converted to decimal degree to enter the coordinates in GIS.

5.2.2 Procedure

Catchment delineation can be done using Arc Hydro or simply by using Hydrology tool from Arc Toolbox. In this thesis simple procedure of using Hydrology tool set gave satisfactory results so the same is adopted. Following procedure has been adopted:

1. Projections and Transformations: In order to have same spatial reference system, all the downloaded data sets were first projected to spatial reference WGS_1984_UTM_ Zone_45N. This can be done using Arc Tolbox - Data Management Tools - Projections and Transformation.

2. Clip: All the downloaded data sets i.e DEM, Stream Networks cover larger area than required, mostly continental basis. Working in such large data set is unnecessary and time consuming. So, the data sets can be clipped to the area of interest prior to delineation. Raster data set can be clipped using Arc Toolbox - Data Management Tools - Raster - Raster Processing - Clip while features can be clipped simply by using Geoprocessing - Clip. A rectangle or a polygon can be made to define the extent of clipping which can be done using following procedure.

   ➢ Open Arc Catalog, right click the working folder and make a new shapefile.
   ➢ Use the editor tool and start new editing.
   ➢ Open create feature tool and select the shape either polygon or rectangle.
   ➢ Construct shape in such a way that it covers the area of interest. Edit the vertices if necessary.
   ➢ Stop and save the edits.

   With the clipping extent and the data sets, clipped DEM was obtained.

3. Catchment delineation:

   Open Arc Toolbox - Spatial Analyst Tool - Hydrology. The following steps were then completed in order to obtain the watershed.

   ➢ Fill: Input - DEM. Removes small imperfections in DEM.
   ➢ Flow Direction: Input - Filled DEM. Provides direction of flow for each cell.

➢ Flow Accumulation: Input - Flow Direction. Makes a link of flow between cells by calculating the number of cells upstream. Outputs are more like stream network. Finer results can be obtained using raster calculator.

➢ Create Watershed Pour Points: Represents the outlet point. An empty shapefile can be made on Arccatalog and defined with the coordinates of outlet point.

➢ Snap Pour Point: To make the pour point lie within the accumulation way. Input feature - Created Pour Point, Input raster - Flow Accumulation and Snap distance - as measured.

➢ Watershed: Input Raster - Flow Direction, Input Feature - Snap Pour Point , Output - Watershed for the outlet point defined.

For area calculations and other use, the catchment raster set is converted to polygon using Arc Toolbox - Conversion Tools - From Raster - Raster to Polygon.

5.3 Results

Catchment area for the study region has been delineated using hydrology toolset from ArcGIS.
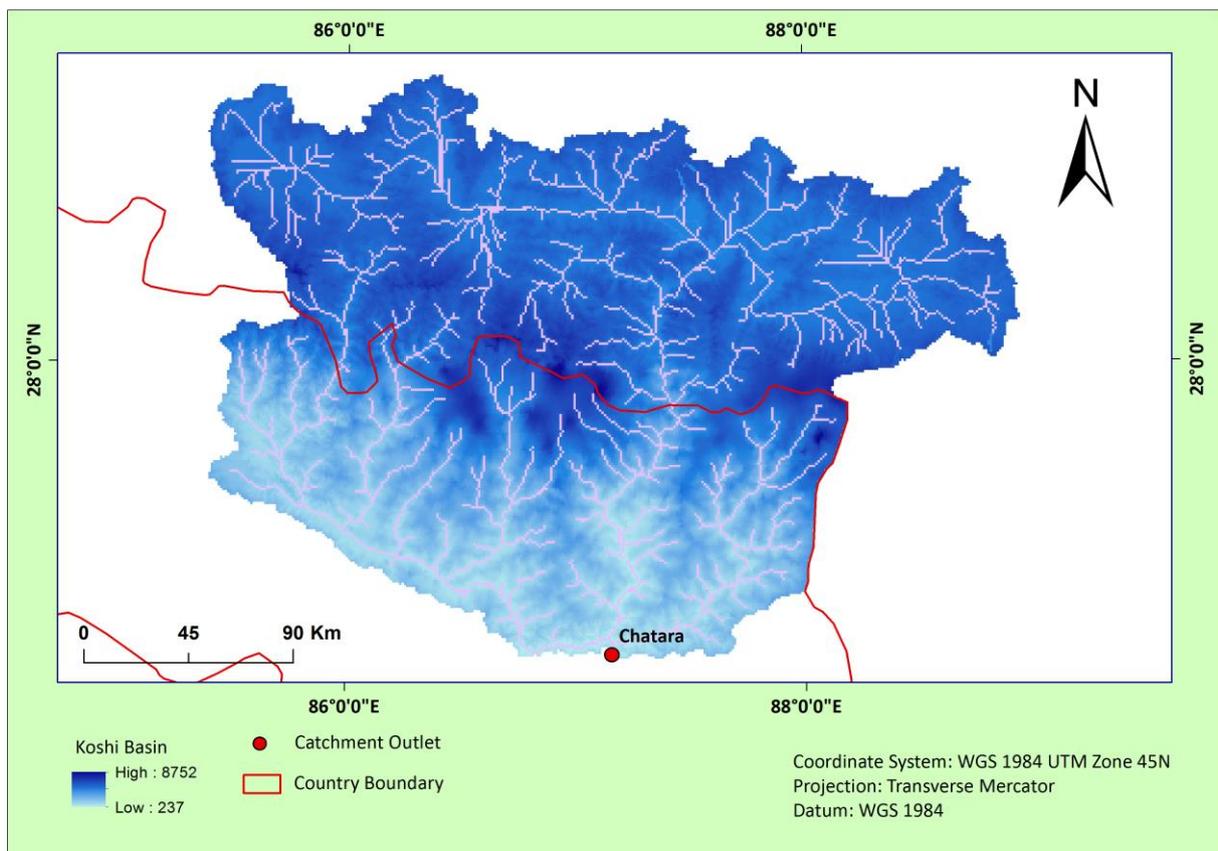
Figure 5-1 Catchment delineation of Koshi using ArcGIS

Considering the outlet point as Chatara - Kothu (gauge station 695), the catchment area obtained was 57,811 km^2. The area is found varying with every studies being made. An area of 57,760 km^2 has been used in a journal [1] while DHM suggests an area of 54,100 km^2. It mostly depends on quality of DEM used. In any case, the differences between areas were not high so the calculations made using GIS has been considered reasonably good and used for further analysis.

5.4   Suggestions on ArcGIS

Use of GIS makes all these hydrological analysis very easy and quick as there's no troublesome work with large paper maps and manual delineation of catchment. But, meanwhile these are software, and complete rely on it can lead to unrealistic results. Cross check on output obtained, should always be done in order to have a good control on the quality of output. Quality check can be done by;

> ➢ Using paper maps and comparing the results.
> ➢ Streams network can be compared with the flow accumulation raster
> ➢ KML is a file format for google earth. Catchment raster can be converted to KML using conversion tools and an overview of terrain can be made using google earth to see suspicious areas if any.

DEM sometimes may have erroneous values in some cells. The same happened with the work and two cell values were higher than neighbouring cells which resulted in different flow direction than expected which consequently delineated incorrect area. Quality check in this case was done by comparing the streams map with the flow accumulation raster to find the erroneous area. For such situation, Raster Editor is a useful tool to perform pixel edits on a raster dataset. The two cell values were edited using this toolbar to obtain the required result. More information about raster editor can be found on ESRI discussion forums.

6. THE HBV MODEL

6.1 Model Introduction

There are different hydrological models available having wide variety of applications. Among them, the excel version of HBV model has been chosen for the study. The main reason behind using this model is its good simulation history in wide variety of environments and particularly in snow fed catchments. Further, it is more users friendly and results are easy to visualise so that good control on quality can be established.

The HBV model is a conceptual model developed by Dr. Sten Bergstrom at Swedish Meteorological and Hydrological Institute (SMHI), at the Hydrologiske Byrån avdeling for Vattenbalans (HBV) during early 1970s. It has then been widely used and revised several times. The model treats catchment as a single unit without consideration of spatial distribution within the catchment thus is also a lumped model though the snow routine is distributed. Inputs for the model are observed precipitation, temperature and potential evapotranspiration. The model has a fixed structure but contains a number of parameters for a catchment which are mostly to be determined through calibration. The model then computes snow accumulation, snow melt, and actual evapotranspiration, storage in soil moisture, groundwater and runoff from the catchment. [11]

6.2 Model Structure

The HBV model represents four main components in land phase of hydrological cycle. i.e. Snow, Soil moisture, Upper zone and Lower zone, represented by Figure 6-1. The model is based on water balance system in those components and also shows dynamic response on water storage to varying meteorological inputs.
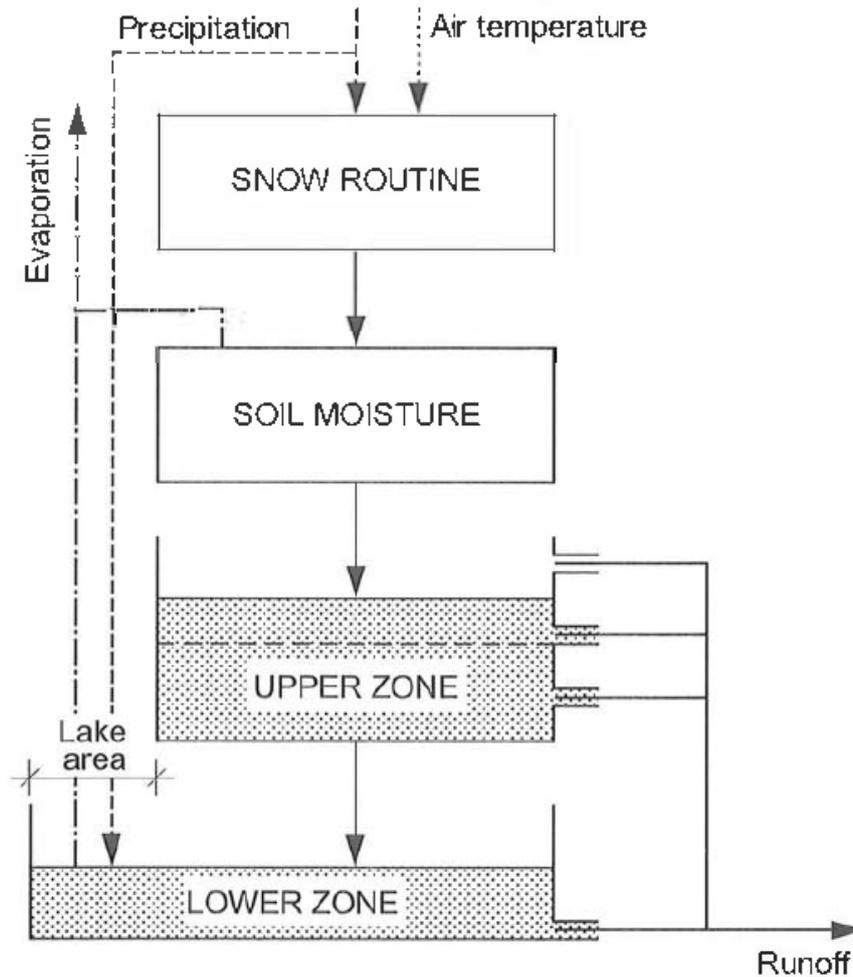
Figure 6-1 Main structure of HBV model [11]

6.2.1 The Snow Routine

The structure of snow routine is explained by Figure 6-2. The catchment is divided into elevation zones according to elevation curve. As snow routine is distributed, variables like air temperature, amount of precipitation, precipitation type and snow melt or refreezing is computed for each elevation zone and time step. Snow melt computation is done by degree day model.
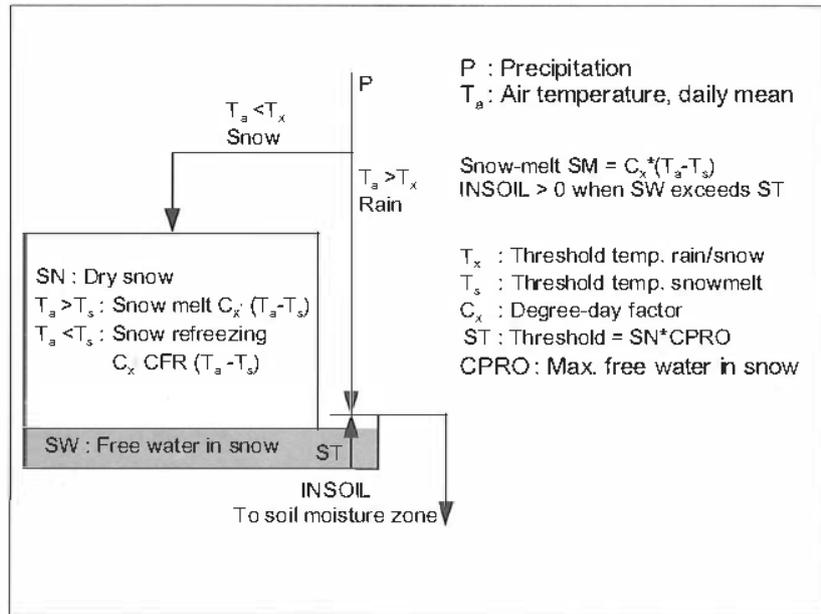
Figure 6-2 The snow routine in HBV model [11]

6.2.2 The Soil Moisture Routine

The soil moisture routine is based on two simple equations and three empirical parameters BETA, FC and LP as shown in Figure 6-3. These parameters are obtained through model calibration. Rainfall or snow melt from snow routine is the input to soil moisture routine which computes water storage in soil, actual evapotranspiration and net runoff generating precipitation as output to the runoff response routine.
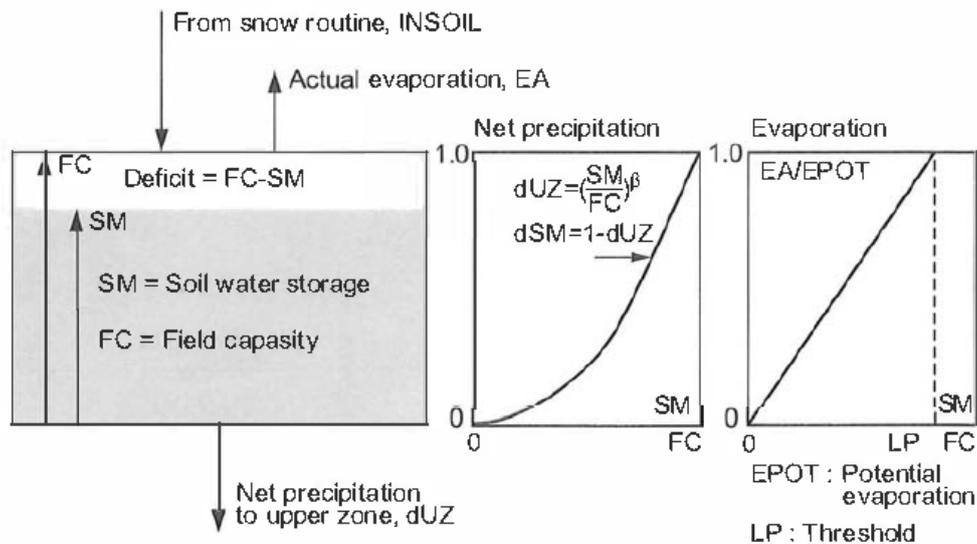
Figure 6-3 The soil moisture routine in HBV model [11]

6.2.3 The Runoff Response Routine

The function of this routine is to convert the input from soil moisture routine into runoff. To do so, this routine is made of two liner tanks known as Upper zone and Lower zone as arranged in Figure 6-4. The upper zone represents quick runoff response as seen in hydrographs while the lower zone represents the groundwater and lake storage that contributes to base flow in the catchment. In addition, this routine also includes the effect of direct precipitation on and evaporation from rivers and lakes in catchment.
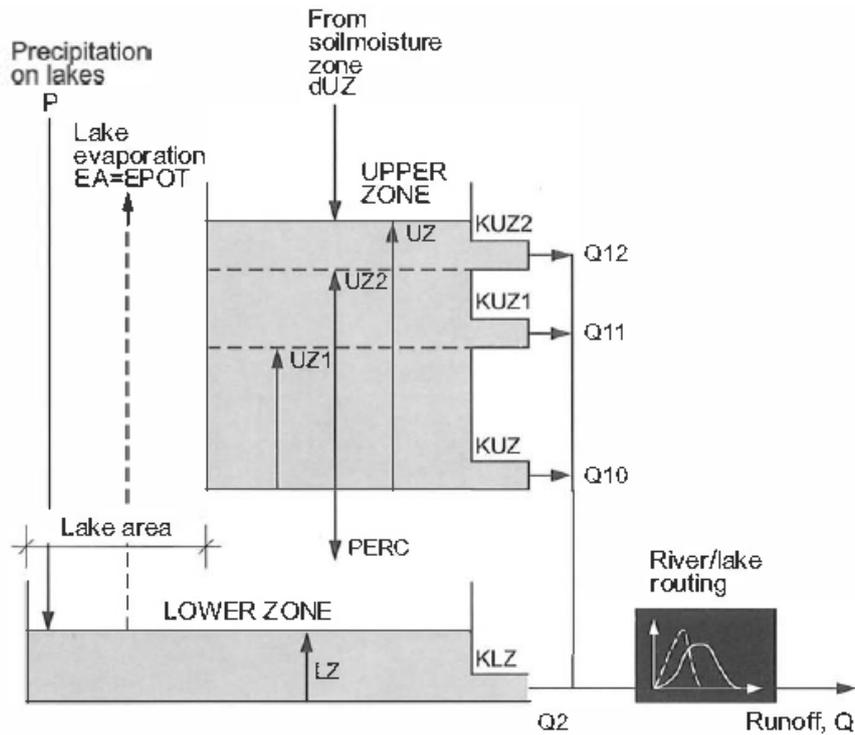
Figure 6-4 The runoff response routine in HBV model [11]

6.3   The Model Setup

The model requires some modification of parameters to make it representative for the study catchment. For this study, two different model setups were done to see the response of each setup, analyse the results and choose one for further study.

Model Setup 1: Model setup including only Nepalese stations available

More than half of the area of catchment lies in Tibetan side and there exist very few stations on that part of catchment. It is itself a challenging part to have data access for any stations out of country, and in addition there are no good records even for those few existing stations in Tibetan part. Attempts were made to have data access for any of the station that would be representative for Tibetan part, but remained unsuccessful. In such situation, to have work progress with available resources, this model setup was done considering only the Nepalese stations available as shown in Figure 4-4.

For this setup, Thiessen polygon could not cover the whole catchment so the challenging part would be to calculate the areal precipitation for the catchment. First the areal precipitation was computed on the basis of best combination of weightage given on basis of hit and trial. Considering the fact that Tibetan part of catchment receives very less rainfall per year, more weightage were given to the stations with less annual rainfall and vice versa. The best combination of weightage found and used in this setup is included in Table 6-1. Further, special attentions were taken in selection of precipitation lapse rate and correction factors for rain/snow to make this areal precipitation representative for the catchment. The detail of precipitation lapse rate is included in chapter 6.4.2.

Table 6-1 Stations and weightage - Model setup 1

Station No	1006	1018	1102	1108	1202	1204	1303	1306	1403	Total
Weightage	0.14	0.08	0.10	0.09	0.12	0.10	0.12	0.09	0.16	1.00

Model Setup 2: Model setup with precipitation station Tingri included

Station Tingri is a precipitation station that lies in Tibetan part of catchment. (Refer details Table 6-2) It was possible to get data from this station during later part of project through http://www.meteomanz.com/, which was out of service for a long period before. But, the data available for the station was from 2007 – 2014 which could not match the data series available

for Nepalese stations (data from 1994 - 2008). The choice was then to observe the calibration results for the overlapping years (2007 and 2008) but again due to susceptible discharge data for year 2008, this calibration also could not happen.

The next step was then to observe the precipitation data for station Tingri to see if it could be best represented by some other stations available in Nepalese part of catchment. Comparisons were done with observed average for all other precipitation stations and with individual station 1306, which has the least rainfall record. Scaling factors were obtained and data series for station Tingri were calculated for different cases. It was then compared with the observed series to see the quality of scaling and if it can be used for further analysis.

Table 6-2 Details of station Tingri

Station	Tingri
Elevation	4,300 m
Latitude	$28^0 38$' N
Longitude	$87^0 05$' E
Average annual rainfall	322.4 mm
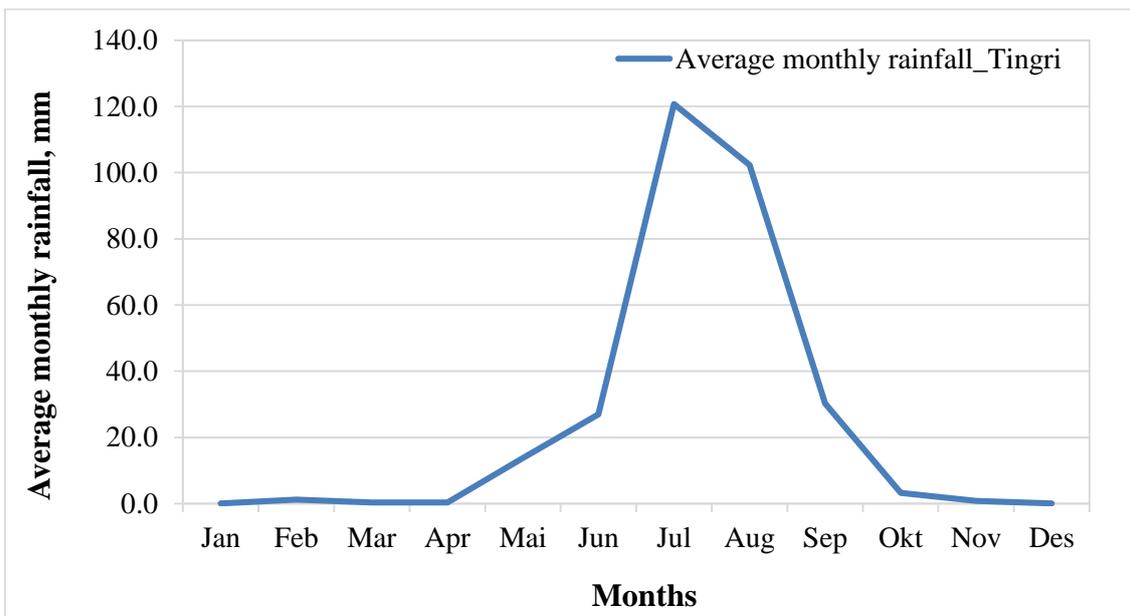
Figure 6-5 Average monthly rainfall at station Tingri
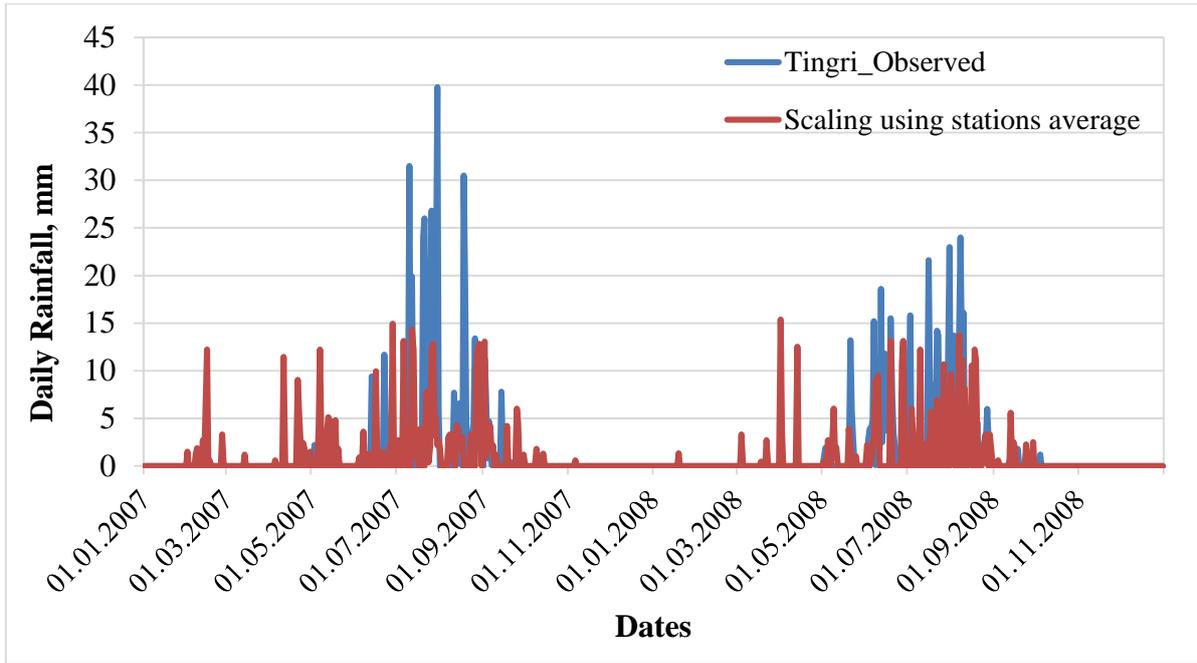
Figure 6-6 Results from scaling average of precipitation data observed at all stations
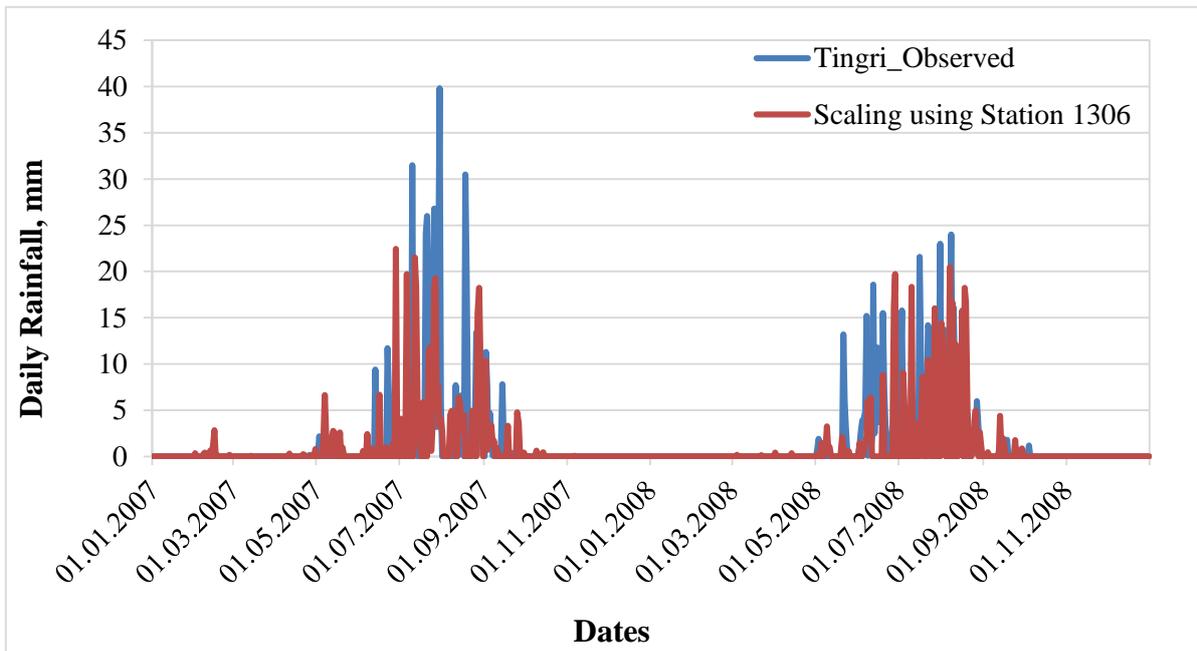
Figure 6-7 Results from scaling precipitation data observed at station 1306

Through the observations, it can be observed that scaled data of station 1306 closely follows the pattern of rainfall observed at station Tingri for the overlapping periods, except some underestimation of peaks. But, still the scaling seems good enough to represent Tingri through station 1306. Thus, this model setup was done by including Tingri with data series obtained by

scaling as above, in addition to all other stations. An overview of the stations used in this setup is shown in Figure 6-8.
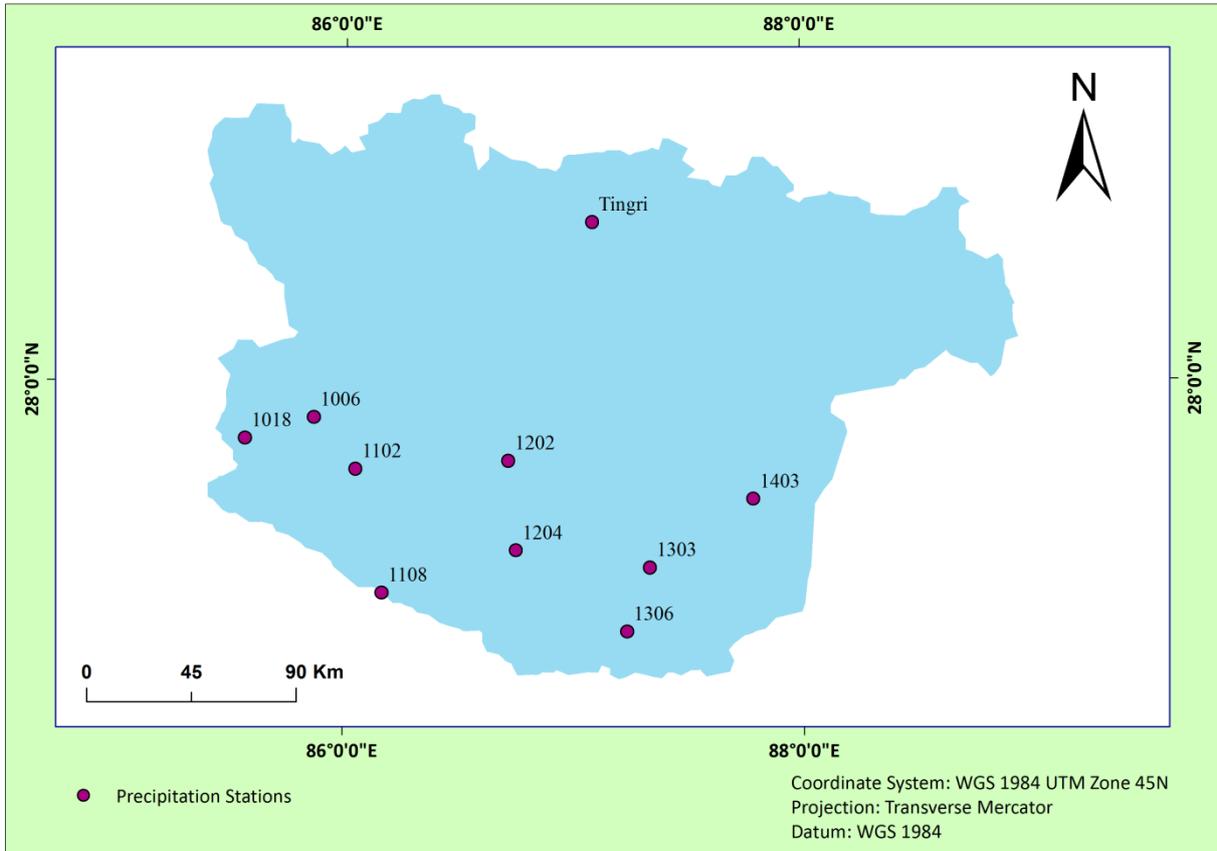
Figure 6-8 Precipitation stations - Model setup 2

In this setup, Thiessen polygon covers almost all area of catchment thus the weightage obtained accordingly with slight modification were;

Table 6-3 Stations and weightage - Model setup 2

Stations	1006	1018	1102	1108	1202	1204	1303	1306	1403	Tingri	Total
Weightage	0.14	0.03	0.05	0.03	0.12	0.06	0.09	0.04	0.16	0.28	1.00

6.4 Model Input

6.4.1 Confined Parameters

Confine parameters includes catchment area, hypsographic curve, area of lakes, glacier elevation and percentage within the catchment. Here, hypsographic curve was obtained through

ArcGIS while lake area and glacier percentage were obtained through land cover analysis and publications made by ICIMOD.
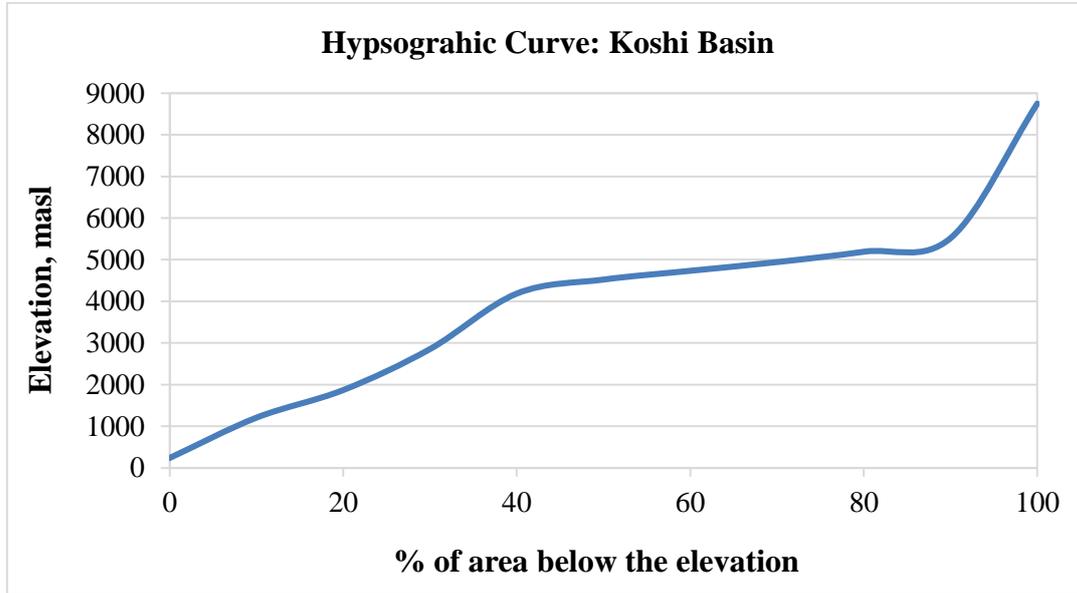
Figure 6-9 Area elevation distribution of Koshi Basin

Table 6-4 Confined Parameters for the Catchment

Catchment Area			57811		km²		
Glacial Lake Percentage			0.04		%		
Glaciers Percentage			1.91		%		
Basin			Koshi				
Area-elevation distribution			Catchment Type		Glacier Model Parameters		
Zone	% of total area	Elevation		Forest	Mountain	Zone	Area Covered	% Coverage
1	10% <	1206	m.a.s.l	1	0	861	0	0
2	20% <	1870	m.a.s.l	1	0	1524	0	0
3	30% <	2855	m.a.s.l	1	0	2323	0	0
4	40% <	4188	m.a.s.l	1	0	3594	0	0
5	50% <	4524	m.a.s.l	1	0	4386	8.4	0.01
6	60% <	4735	m.a.s.l	0	1	4638	92	0.16
7	70% <	4945	m.a.s.l	0	1	4839	379	0.66
8	80% <	5194	m.a.s.l	0	1	5067	384.6	0.67
9	90% <	5526	m.a.s.l	0	1	5348	154	0.27
10	100% <	8752	m.a.s.l	0	1	5993	84.5	0.15
						Sum	1102.5	1.91

6.4.2 Regional Parameters

Precipitation Lapse Rate:

Lapse rates are important in order to calculate the areal precipitation over the whole catchment. Precipitation increases with elevation up to certain limit. But, in case of Nepal, the elevation zones are very high; effect of windward/Leeward sides are more pronounced and some local effects makes precipitation patterns so irregular to define. Furthermore, the stations available in Nepalese side of catchment are only up to around 3000 m which makes it difficult to define precipitation pattern in high Himalayas.
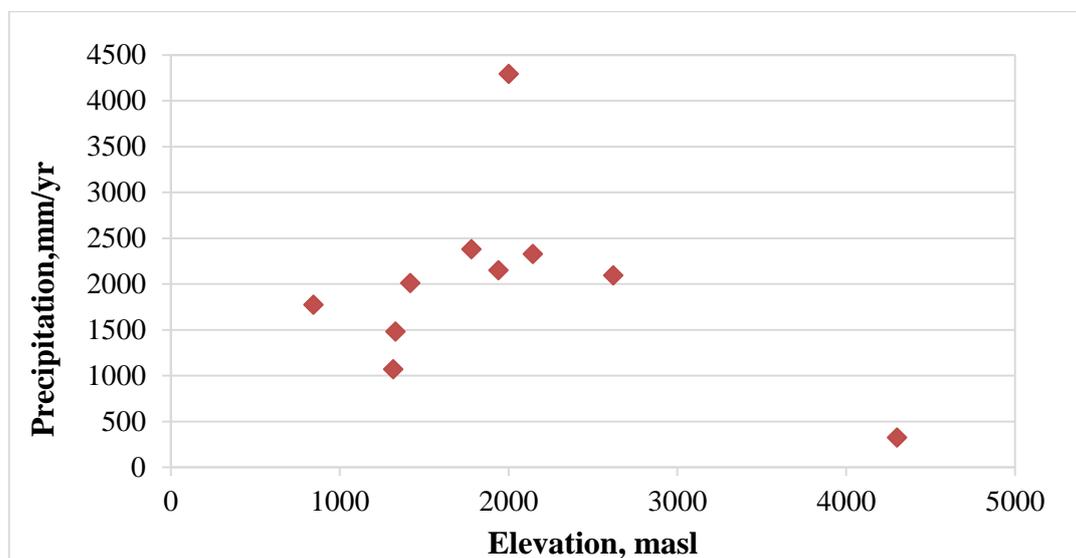
Figure 6-10 Elevation vs average annual precipitation for stations

From graph, it is clear that the rainfall pattern is very difficult to define due to which determining the precipitation lapse rate is a challenging task. At such, lapse rate was found through hit and trial with gradual increase up to certain elevation (i.e. up to 4000 m) and then through manual input with decreasing trend for higher elevation. The lapse rate adopted for both the setups were;

Table 6-5 Precipitation lapse rates for different model setups

	Model Setup 1	Model Setup 2	
Elevation, m	By + 3% per 100 m	By +2 % per 100 m	Choice of parameter
1206	0.83	0.73	Increasing trend- by defined percentage
1870	1.03	0.86	
2855	1.33	1.06	
4188	0.65	0.65	Decreasing trend - by manual input
4524	0.60	0.60	
4735	0.55	0.55	
4945	0.50	0.50	
5194	0.45	0.45	
5526	0.40	0.40	
8752	0.30	0.30	

Temperature Lapse Rate

This was also found through hit and trial and different values were adopted for days with precipitation and clear days. The values adopted were;

1. At Precipitation, Tlp = - 0.50 ^{0}C/100 m
2. No Precipitation, Tlo = - 0.80 ^{0}C/100 m

Using these values, areal temperature series for the catchment was established.

6.4.3 Hydrological and Meteorological Data

Daily precipitation data for all stations were converted to single series with consideration of station weightage as mentioned earlier. Precipitation lapse rate and corrections factors as discussed were then applied to obtain areal precipitation.

For temperature series, the two station data available were given equal weightage and areal temperature series were calculated using corresponding temperature lapse rates.

Table 6-6 Elevation of Hydro - meteorological stations

Areal Elevation, masl	Model Setup 1	Model Setup 2
Precipitation Station	1760	2549
Temperature Station	1565	1565

Good quality of runoff data is necessary for model calibration. Thus, recorded daily data at basin outlet i.e Chatara-Kothu was used both for calibration and validation of model. Out of 15 years of data series from 1994 - 2008, the runoff series for year 2008 seems suspicious, thus was discarded.

Having observed evaporation series, the same was used as model input. Average of two stations data record was done to make evaporation representative for the catchment.

6.5   Model Calibration

HBV model calibration refers to the process of determining the set of free parameters that gives best possible correspondence between observed and simulated runoff from a catchment. (Refer Figure 6-11)
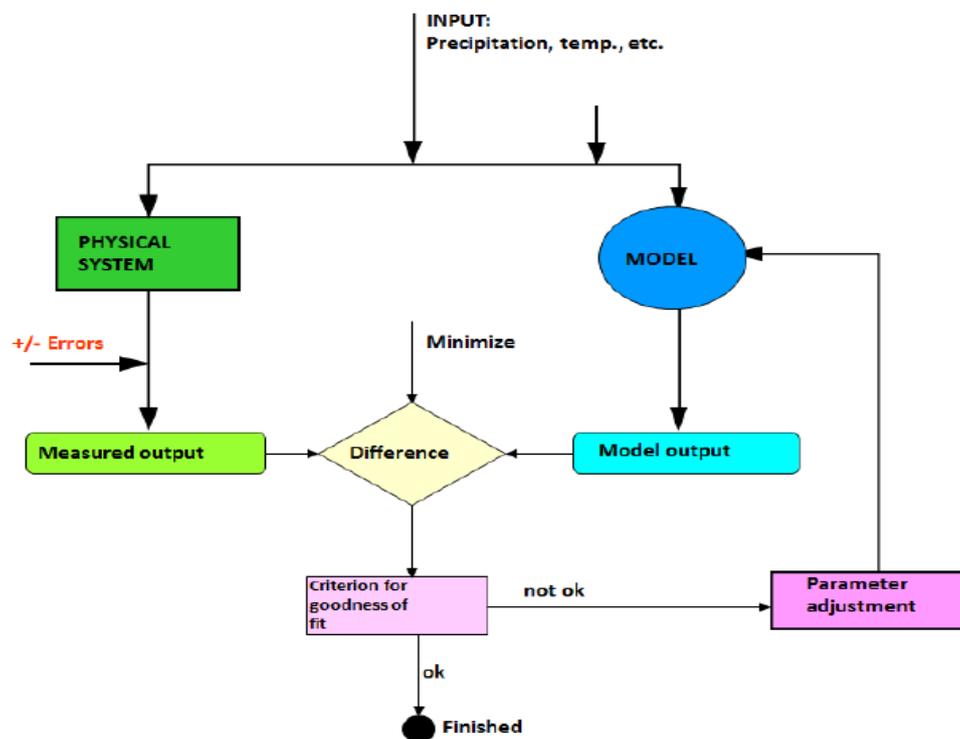
Figure 6-11 Calibration Process [11]

There are two ways of calibration:

1. Manual Calibration
2. Automatic Calibration

The model used is the latest excel version with possibility of running optimizer. Automatic calibration was the first choice made but the results obtained were strange and unrealistic one.

Thus, calibration was done manually for both the setups. The data series were divided into three parts and calibration was done for middle period of 5 years from 1999 - 2003, with simulation results of year 1998 as the initial start for the calibration purpose. Rest of the years were then used for model validation. Manual calibration of the model resulted following values as set of free parameters.

Table 6-7 HBV free parameters for Koshi Basin

Description	Symbol	Range	Adopted Values		Units	Within Limit
			Setup 1	Setup 2		
Rain Correction	PKORR	1.05 - 1.2	0.75	0.8		No
Snow Correction	SKORR	1.15 - 1.5	0.60	0.6		No
Elevation Corr	HPKORR	1.0 - 1.10	3.0	2.0	% pr. 100 m	No
Degree-day factor	CX	3.0 - 6.0	1.00	1.0	mm/0C/day	Yes
Threshold snow-melt	TS	-1.0 - 2.0	0.81	0.81	Degree C.	Yes
Threshold Rain/Snow	TX	-1.0 - 2.0	-1.0	-1.0	Degree C.	Yes
Liquid water	CPRO		10.0	10.0	% of dry snow	
Field_capacity	FC	75 - 300	180.0	180.0	mm	Yes
BETA	BETA	1.0 - 4.0	1.70	1.70		Yes
Threshold evaporation	LP%	70 - 100 %	70	70	%	Yes
Fast drainage Coff	KUZ2	0.1 - 0.5	0.5	0.5	1/day	Yes
Slow drainage Coff	KUZ1	0.05 - 0.15	0.12	0.12	1/day	Yes
Threshold	UZ1	10 - 40	40.0	40.0	mm	Yes
Percolation	PERC	0.5 - 1.0	1.0	1.0	mm/day	Yes
Drainage Coff	KLZ	0.005 - 0.002	0.005	0.005	1/day	Yes
	PRO		10.0	10.0	% of normal melt rate	

It can be observed that some of the parameters do not lie within the range of recommended values. It should be noted that the recommended values are the results of various tests made with data series from catchments of Norway which do not necessarily need to fit for every cases.

Selections of these parameters were made through different ways:

1. Subjective Method:

    Observed and simulated hydrographs were plotted and quality of fit was observed with a target of obtaining best fit possible. The snow curves were also observed to note any unusual trends.
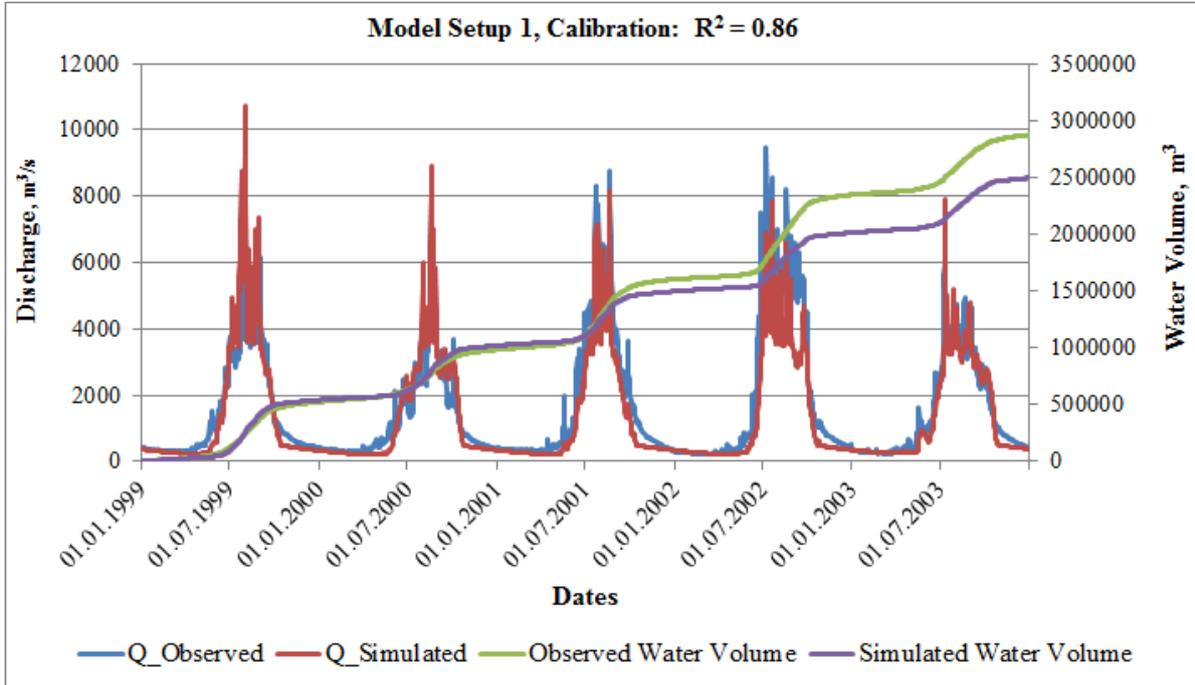
Figure 6-12 Calibration results for Koshi basin, Model setup 1 (Year 1999 - 2003)
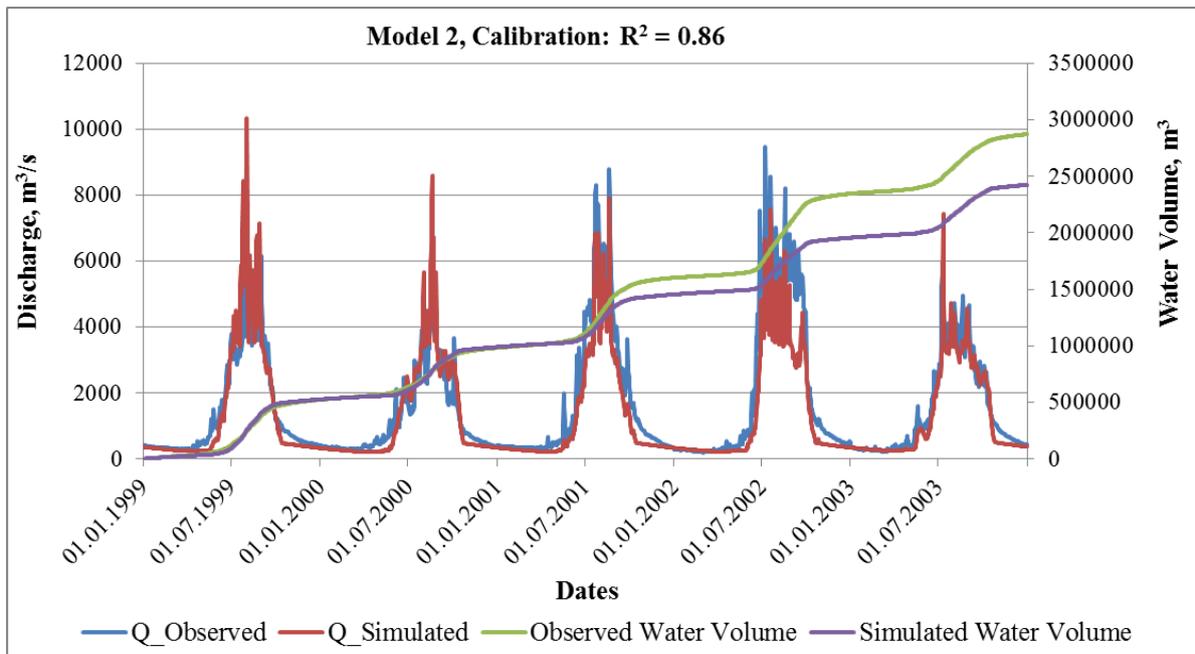
Figure 6-13 Calibration results for Koshi basin, Model setup 2 (Year 1999 - 2003)

2. Objective Method:

The goodness of fit is also obtained by Nash efficiency criterion (R^2). Higher the value better the model fit.

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

Where, $Q_0 = Observed\ runoff,\ \bar{Q}_0 = Average\ runoff,\ Q_s = Simulated\ runoff$

3. Choice of parameter has been done considering their logic, i.e. (KLZ < KUZ1 < KUZ2) has always been maintained. [13]

Table 6-8 Summary of Koshi basin HBV model calibration

Years		1999	2000	2001	2002	2003	Average
Model setup 1	R^2	0.81	0.82	0.91	0.81	0.93	0.86
Model setup 2	R^2	0.85	0.85	0.90	0.79	0.93	0.86

The calibration results for both the model setup were satisfactory with an average R^2 of 0.86 except not being able to catch peak during 2001 and 2002. Because of underestimation of peak in those two years, the water volume seems to have accumulated deviation from observation.

6.6 Model Validation

After having model optimally calibrated, validation was done to check whether goodness of fit has been maintained on data set outside the period of calibration. Validation of model is done for rest of the years before and after the calibration period.

Table 6-9 Results of model validation

Years	Model Setup 1	Model Setup 2	Remarks
1994	0.82	0.79	
1995	0.89	0.89	
1996	0.78	0.79	
1997	0.80	0.83	
1998	0.86	0.89	
2004	0.84	0.83	
2005	0.83	0.82	
2006	0.87	0.85	
2007	0.93	0.92	
2008	-38.79	-38.69	Omitted
Average	0.85	0.84	

Year 2008 has been excluded from validation period due to suspicious observed runoff data. The yearly average for this year was found much low than the averages for rest of the years which must be a reason behind bad simulation for this year. Besides, validation results look good as calibration in terms of R^2 and so as in figures with better results for model setup 1. The figures for model validation are presented in Appendix C.

6.7   Result Analysis

The model was calibrated and validated fairly well if compared only with R^2 value for both the setups. But, it should be noted that R^2 is only a mathematical term and complete rely on this value to decide the goodness of fit cannot be made. Furthermore, R^2 value and quality of fit cannot be directly linked. Calibration result for year 2001 is a good example behind this fact. R^2 value for this year was obtained more than 0.9 which is theoretically very good calibration, but it didn't show the same quality with graphs plotted between observed and simulated runoff. Thus, to make a good analysis of results, graphs of simulated and observed runoff were plotted together with the water balance observed in the model. Referring the graphs, it can be clearly seen that the initial years of calibration had good fit graphs with well-maintained water balance, until calibration reach to the end of year 2001. After this point, high discrepancies were observed, even higher in year 2002 and then well maintained by the end of calibration period.

Same trend has been observed in both setups. It can also be noticed that the year 2002 might be a flood year as it has higher runoff compared to rest of the years, and model may have failed to catch flood peaks because of average precipitation data storage system, which can also be a reason behind observed discrepancy.

The total number of precipitation stations used in analysis was 9 for the first case and 10 in the second case. It should be noticed that the catchment area is relatively large to be expected to be covered uniformly by the number of stations used. Furthermore, the elevation range of the catchment is so wide that the precipitation stations do not cover all those ranges of elevation especially the Himalayas. Because of this, there exists uncertainty in describing the trend of precipitation in higher elevation which might have impact in areal precipitation and consequently on model calibration. In addition, the fact that the catchment consist of both windward and leeward sides of high Himalayas cannot be ignored. The two regions have so different precipitation trend that, it is a challenging task to include correctly, the impact of this on model. Nevertheless, attempt has been made to address all these challenges through careful provision of station weightage and adjusting the parameters like PGRAD, TGRAD, PKORR, SKORR to the finest level during model calibration. Due to large elevation range, PGRAD could not be just a single value increasing or decreasing with elevation. Adjustments in model have been made in such a way that precipitation increases up to certain level and then decreases for higher elevation as described earlier. But still, there always exists some areas which could be improved through model handling experience. The results from automatic optimisation did not work, might be because the parameter ranges recommended were based on experience on Norwegian catchments which may not be the same for other areas. Thus, the parameter values obtained in both the cases were the result of manual calibration which again, has some areas always available for improvement.

Model validation has been done for rest of the data series outside the period of calibration. The validation results seems good enough with an average R^2 value of 0.85 and 0.84 for two setups, respectively with better results for first setup. The graphs on observed and simulated discharge also show good fit but failing to catch peak in some years. Besides, the early period of rising and falling limbs has been slightly underestimated in almost all years which could have been better with model experiences. Overall, model setup has been considered good enough to proceed further.

In conclusion, the HBV model has been calibrated for 5 years i.e 1999 - 2003, which is the middle period of the data series available and has been validated for rest of the years. Manual calibration has been done for both setups described and quality of calibration and validation were good in terms of graph plot and R^2. Water balance was also found to be within reasonable limit. Nevertheless, there exist good possibilities for improvements in model by having more and evenly distributed stations, particularly stations in Tibetan part and also good experience in manual calibration.

6.8   Comparison of Model Setups

The two different model setup as explained above has its own importance. Theoretical procedures on hydrological analysis may not work sometime depending on the project, which can be easily experienced with first setup. Thiessen polygon could not cover whole catchment with available stations only, thus left a challenge in assigning station weightage. It is always an important issue with Nepalese catchments as meteorological stations are not uniformly distributed compared to elevation. Thus working with such setup was necessary to have ideas to deal on such situations and in most cases the only choice left.

The second setup would have been better if the data series used for Tingri were the actual observed. But still with the setup as explained, it can be observed how model reacts when highest weightage is given to the station with very less annual rainfall. It also helps to understand the influence of Tibetan part, which is actually the leeward side, on catchment hydrology.

The calibration results for both the cases were almost same (Refer Figure 6-12 and Figure 6-13) under slightly different parameter values (Table 6-7). But still water balance within the model was found better maintained with the first setup and so as the validation results. From the results it can be said that, a good HBV model can be set up with only available resources as in case first, if taken care in assigning the model parameters. It could also be a reason that Tibetan part has less influence on hydrology of catchment which can be counterbalanced by wise selection of model parameters. This may not be true if analysis were done on small scale like in sub catchment level. Large catchment area, high discharge at outlet, snow melt from Himalayas and high rainfall in Nepalese side may have shadowed the effect of Tibetan part that receives very less annual rainfall. Further, the second setup was also based on assumptions which may have several shortcomings. Thus, results from first setup have been chosen for further analysis.

7. CLIMATE MODELS

7.1   Background

Global Circulation Model (GCM) can provide reliable information about projection of climate of earth in future. GCMs represents climate usually in a resolution of between 250 and 600 km, horizontal and sometimes even up to 1000 km. The resolution is more like global representation which would be quite coarse for regional impact assessment. [14]

On other side, Regional Climate Models (RCMs) are driven by GCMs over limited area and can provide much smaller scale of information compared to GCM. RCMs are thus widely used in detail impact assessment and planning. Further, the finer resolution of climatic data sets represented by RCMs helps in detail and more accurate representation of localised extreme events. [15]

Thus to do regional climate analysis, the first step would be to downscale data from GCM for the area of interest. There are different ways of extracting climate data for a region. It can be direct use of RCM and adapting it to the catchment scale or downscaling data directly from GCM through statistical downscaling methods.
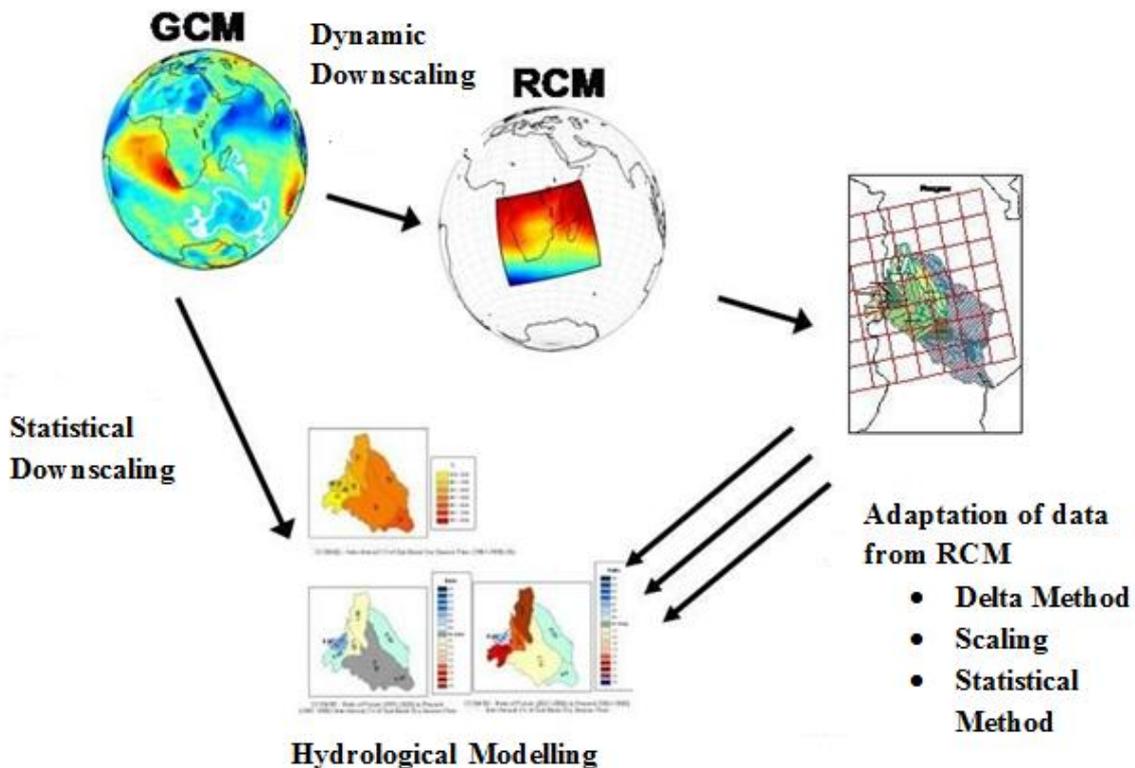
Figure 7-1 Schematic representation of different ways of downscaling climate data [16]

7.2   RCPs - An Introduction

The representative concentration pathways, commonly known as RCPs, are the representation to concentration of GHG emission by 2100. They are named on emission of GHG from all sources expressed in Watts per square meter i.e. RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5.(Refer Table 7-1) These are the scenarios adopted by IPCC for its fifth assessment report (AR5) in 2013 which supersede SRES projections. RCP 8.5 is the strongest forcing scenario while RCP 2.6 is the weakest one.

Table 7-1 Description of RCPs [17]

RCPs	Description
RCP 2.6	Peak in radiative forcing at ~ 3 W/m^2 before 2100 and decline
RCP 4.5	Pathway without overshoot to 4.5 W/m^2, at stabilization after 2100.
RCP 6	Pathway without overshoot to 6 W/m^2, at stabilization after 2100.
RCP 8.5	Rising pathway leading to 8.5 W/m^2 in 2100.
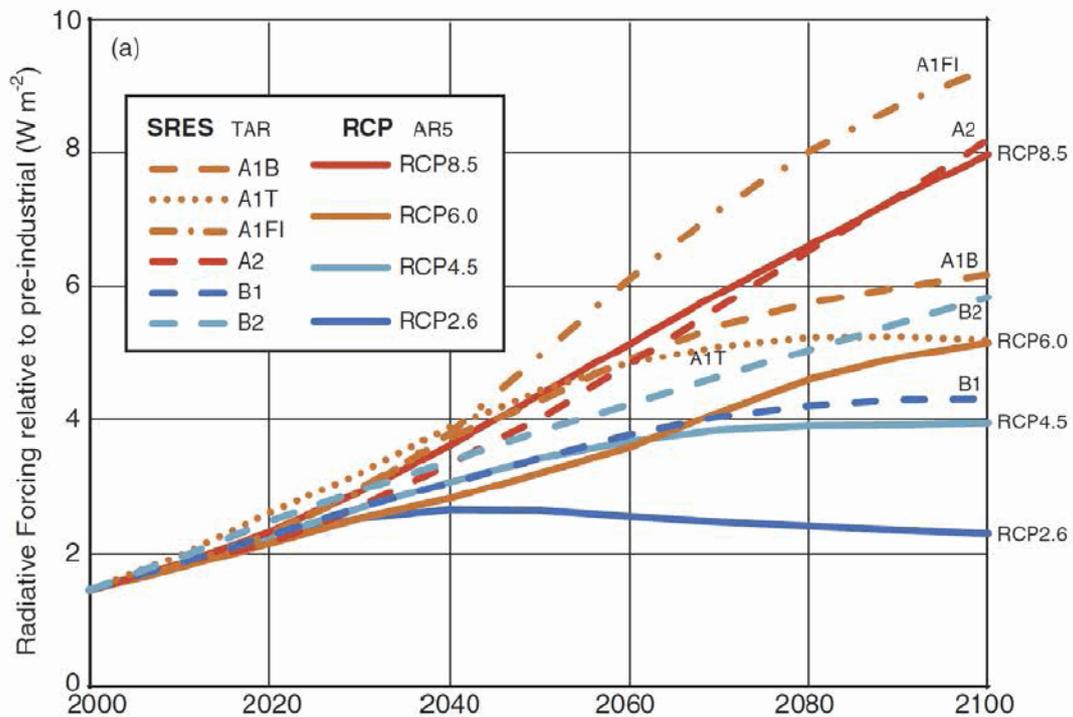
Figure 7-2 Comparison between SRES and RCPs [18]

From Figure 7-2 it can be observed that, the forcing scenarios A2 and RCP 8.5 are of similar nature and so as B1 and RCP 4.5. Thus, results from these set of scenarios may be comparable.

7.3 CORDEX Data

CORDEX is a project formed under World Climate Research Program (WCRP) during the timeline of Fifth Assessment Report of IPCC and works on preparing improved regional climate projections worldwide. [19] [20] CORDEX works on several domains and Nepal lies on South Asian domain. Different RCMs available for South Asian domain have been used to get climatic datasets corresponding for the catchment. There are altogether 6 climate models in operation for South Asia but unfortunately all of them do not have corresponding data series required for this analysis. Some have missing precipitation data set while some have data set only upto 2030. Thus, choice of model has been made corresponding to data availability and scope of work. For South Asia, data were available in resolution of 0.44^0 (approximately 50 km). All scenarios available within a model have been used to reduce uncertainty of analysis.

Details of climate models used to analyse future conditions in Koshi basin are listed below:

Table 7-2 Summary of climate data used (Details from CORDEX: South Asia)

Experiment Name		REMO_2009	RCA4(ICHEC)
Driving GCM		MPI-ESM-LR (Giorgetta et al 2013)	Irish Centre for High-End Computing (ICHEC), European Consortium ESM (EC-EARTH; Hazeleger et al. 2012)
Resolution, degrees		0.44	0.44
Historical Series		1971 - 2000	
RCP Scenarios	RCP_2.6	Yes	No
	RCP_4.5	Yes	Yes
	RCP_8.5	Yes	Yes
Future Period	Mid Century	2041 - 2070	
	End Century	2071 - 2100	
Contributing Institute		Climate Service Center, Hamburg, Germany	Rosssy Centre, Swedish Meteorological and Hydrological Institute (SMHI), Sweden
Legends Used		MPI	ICHEC

Time slice of 30 years were selected both for control period and future period to calculate delta change for analysis. Future period was further divided into two time frames: 2041 - 2070 and 2071 - 2100 represented as Mid Century and End Century, respectively.

7.3.1 Data Download

These models consist of data sets in daily, monthly and seasonal format. Because of some undergoing maintenance in CORDEX for South Asia, data required has been downloaded from ftp://cccr.tropmet.res.in/ with user name and password obtained on request. All data used in this analysis were daily data sets available in .NC format. Data were noted as 'pr' for Precipitation and 'tas' for Temperature. There were thus 6 NC files under each category and each file consisting of daily data for 5 years.

7.3.2 Data Processing

A series of R scripts used in a Doctoral Theses [20] at NTNU for climate change analysis with CORDEX data set has been used with some modifications, for data processing. It was beyond the scope of work to develop new scripts thus the same has been used with slight modification. Data storing and scripts running were carried out in steps with separate folder for each step, in order to have ease in processing and avoid confusion and mishandling of data.

Table 7-3 Summary of climate change data processing

Steps	1	2	3
Objective	• To extract grid points that lie within the boundary of catchment	• Extraction of daily data from .nc files corresponding to those grid points • Store results as text and Rdata files.	• Convert daily data to monthly average • Calculate delta change for those grid points • Average the delta change computed to represent the catchment
Inputs	• Any temp .nc file • Catchment area shape file	• Output from Step 1 • Folders having .nc files (Historical and Scenarios)	Rdata from Step 2
R Script	Refer Appendix D: R Scripts used for Climate Data Processing		
Output	Information of those grid points within catchment as Rdata and text file	Text file and Rdata of data series corresponding to the grid points	Average monthly delta change for each scenario

As an output from Step 1, there were altogether 24 grid points within the catchment for data set with resolution 0.44^0.
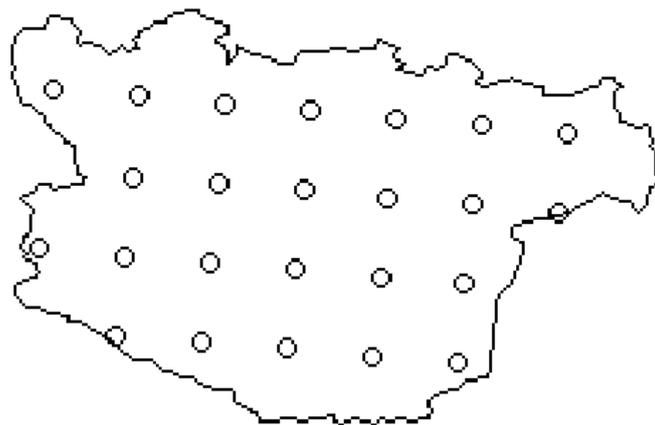
Figure 7-3 Grid points for climate data within the catchment

7.4 Delta Change Analysis

The delta change computed running the scripts were the average of monthly change calculated for those 24 grid points. It might have been interesting to choose only those grid points that lie near the meteorological stations used in analysis and compute the delta change for catchment in accordance with station weightage. But, the delta change computed for each grid points do not differ much in values so simple average was done to make it representative for the catchment.

7.4.1 Temperature Delta Change

Temperature is expected to rise worldwide and the results were found same for Koshi basin also. Table 7-4 is an overview of average annual temperature change in future under two different models where it can be found that the annual changes are almost consistent with both the models. Results suggests that, on average, temperature is expected to increase by 2.56^0 and 3.58^0 than the current situation, by mid and end century, respectively. (Average of results from two models, refer table below) though the changes under scenario RCP 8.5 is more pronounced.

Table 7-4 Average annual temperature change in future

Average annual temperature change, ^0C				
Models	MPI		ICHEC	
Scenarios/Period	Mid Century	End Century	Mid Century	End Century
RCP_2.6	1.7	1.4	-	-
RCP_4.5	2.5	3	2	2.5
RCP_8.5	3.6	5.9	3	5.1
Average	2.6	3.4	2.5	3.8

However, the monthly distribution of this change is not uniform throughout the year. (Refer Figure 7-4, Figure 7-5). High increase in temperature is expected in winter compared to monsoon under almost all scenarios. It can also be observed that, mid-century temperature rise are expected to be higher than end century when driven by RCP 2.6 while high influence in temperature are expected in both centuries under RCP 8.5.
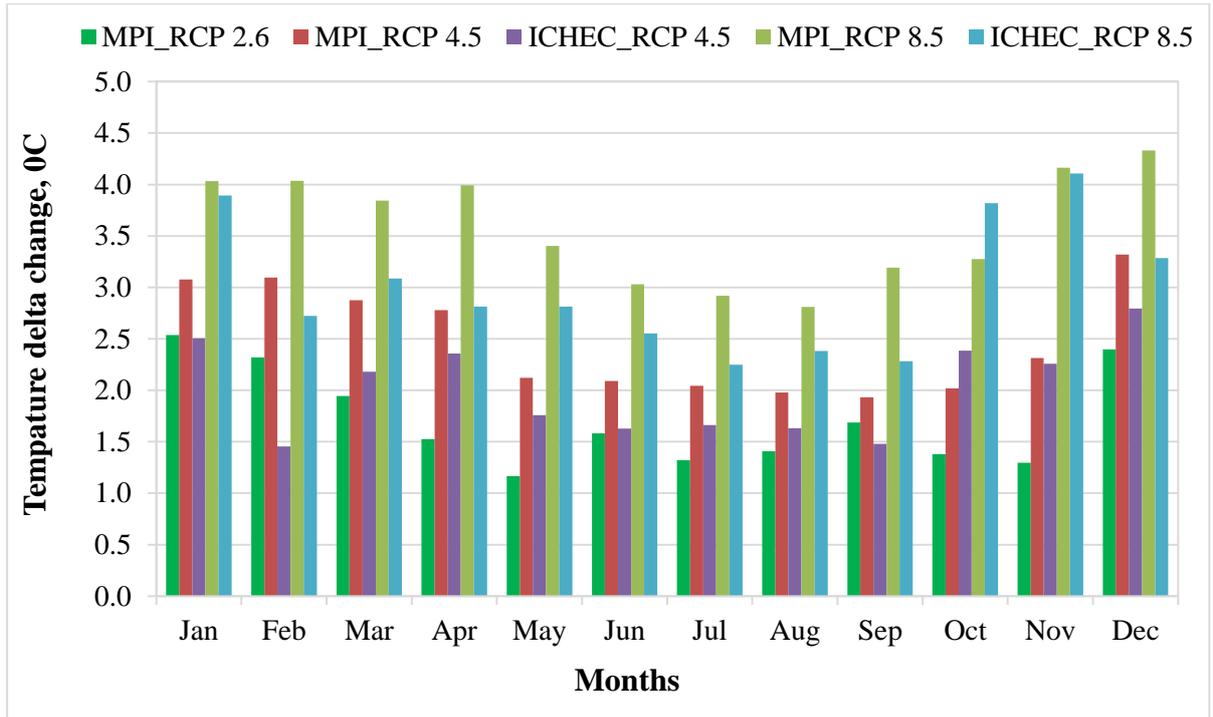
Figure 7-4 Temperature delta change by mid century
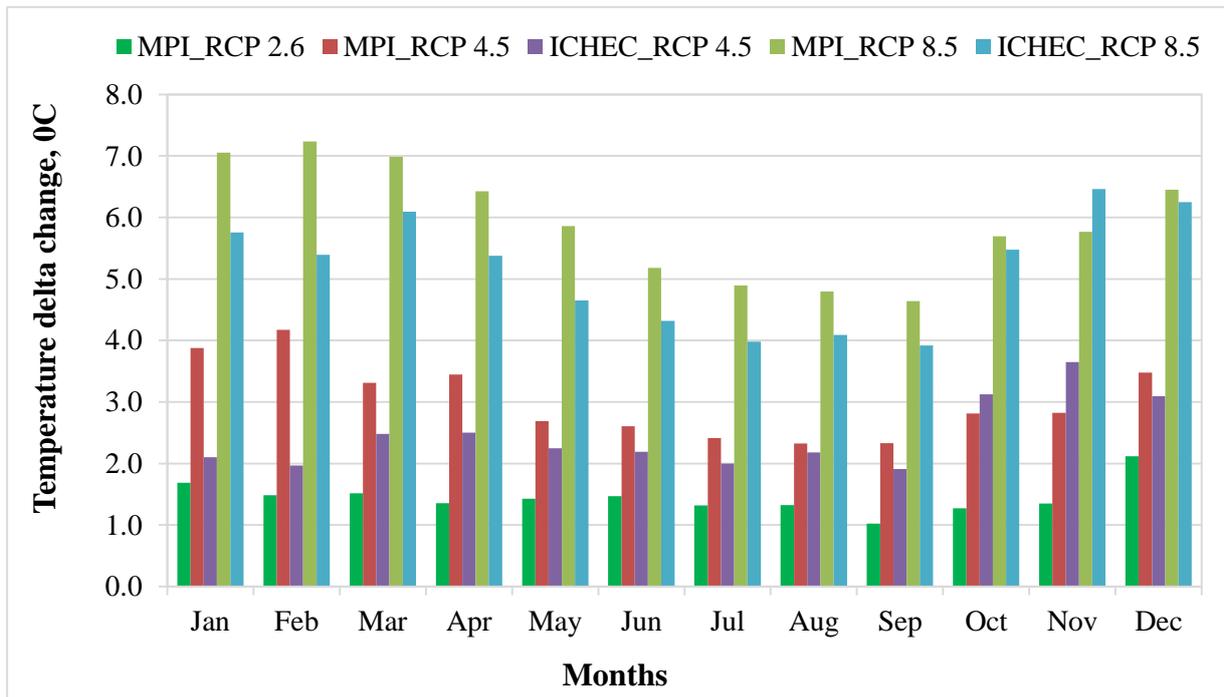
Figure 7-5 Temperature delta change by end century

In Nepal, the seasonal changes are more important as water availability is very seasonal. Thus, the observations were averaged to make it representative for seasons, i.e. Winter (December - February), Premonsoon (March - May), Monsoon (June - September) and Postmonsoon (October - November).

Table 7-5 Seasonal temperature change in future, expressed in ^{0}C

Time Period	Models	Scenarios	Winter	Premonsoon	Monsoon	Postmonsoon
Mid Century	MPI	RCP 2.6	2.4	1.5	1.5	1.3
		RCP 4.5	3.2	2.6	2.0	2.2
		RCP 8.5	4.1	3.7	3.0	3.7
	ICHEC	RCP 4.5	2.3	2.1	1.6	2.3
		RCP 8.5	3.3	2.9	2.4	4.0
End Century	MPI	RCP 2.6	1.8	1.4	1.3	1.3
		RCP 4.5	3.8	3.1	2.4	2.8
		RCP 8.5	6.9	6.4	4.9	5.7
	ICHEC	RCP 4.5	2.4	2.4	2.1	3.4
		RCP 8.5	5.8	5.4	4.1	6.0
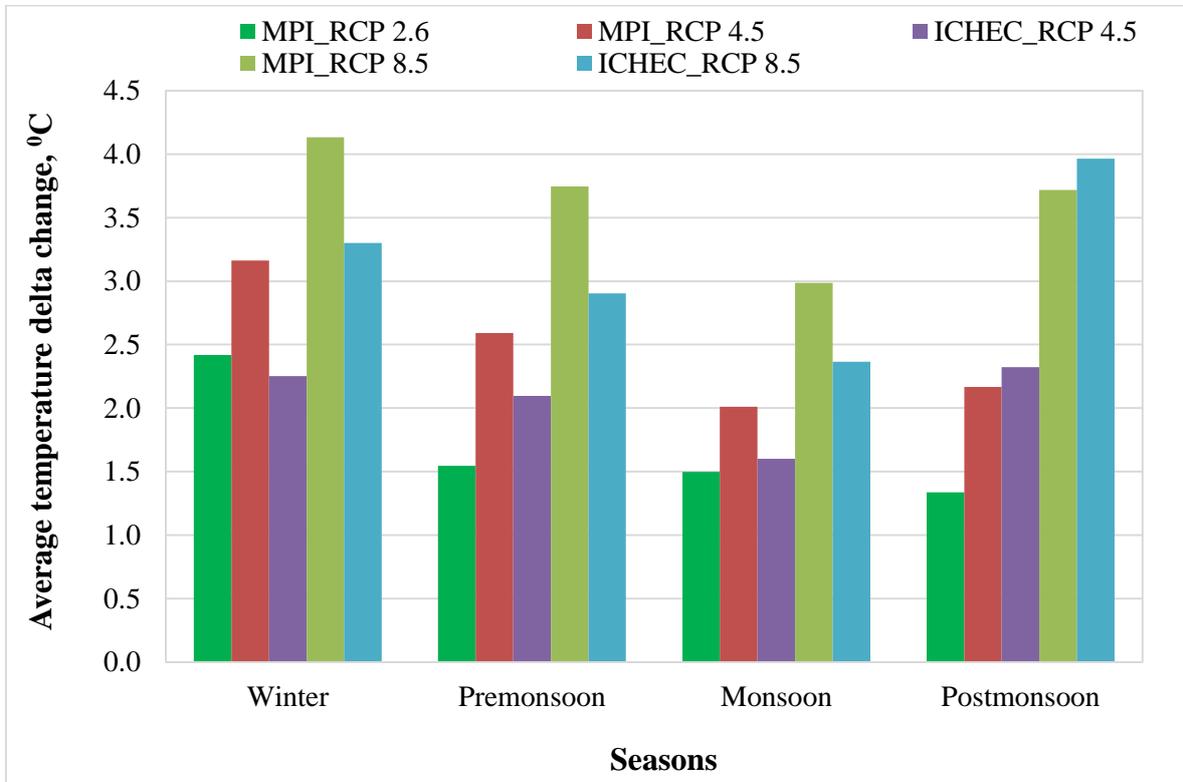
Figure 7-6 Seasonal distribution of temperature change by mid century
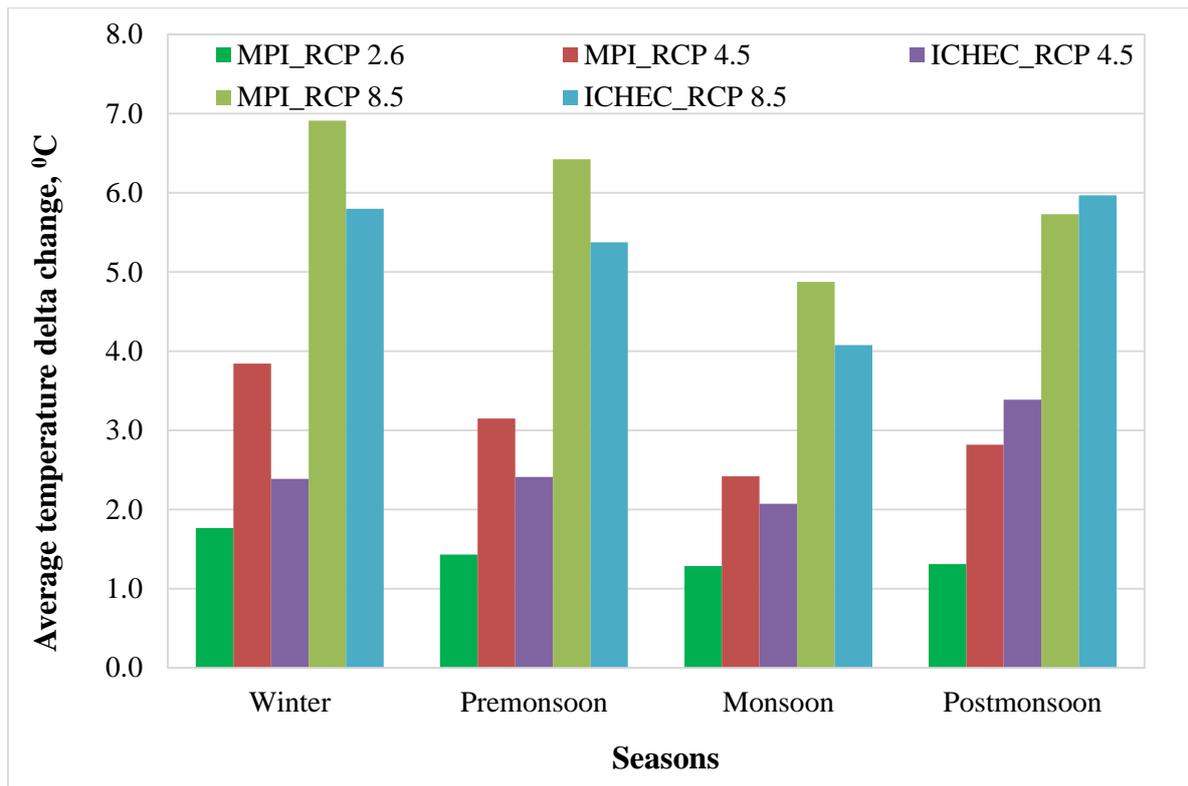
Figure 7-7 Seasonal distribution of temperature change by end century

It shows that higher rate of temperature rise is expected in winter and post monsoon compared to premonsoon while monsoon temperature rise is expected to be in smaller extent under every scenarios and time frames. This type of change has considerable impact on snow melting time and quantity of melt. In addition, except post monsoon, MPI suggested higher rate of temperature rise compared to ICHEC for both the time frames.

7.4.2 Precipitation Delta Change

Precipitation trends obtained were more complex compared to temperature. The results were different for each model and with each scenario. On average, model MPI suggests that precipitation possess decreasing trend in future while it's increasing with model ICHEC.

Table 7-6 Average annual precipitation delta change in future

Average annual precipitation delta change, %				
Models	MPI		ICHEC	
Scenarios/Period	Mid Century	End Century	Mid Century	End Century
RCP 2.6	-3.4	7.3	-	-
RCP 4.5	-11	-5.8	12.9	15.6
RCP 8.5	-4	-13.3	5.4	11.1
Average	-6.1	-3.9	9.2	13.4

Further, monthly distribution of precipitation delta change was found even more complex. Referring Figure 7-8(A) & Figure 7-9(C), model MPI suggests that precipitation is mostly supposed to decrease usually during dry periods (with few exceptions) and increase in wet periods. But, referring Figure 7-8(B) & Figure 7-9(D), model ICHEC suggests completely different precipitation pattern. Precipitation seems mostly increasing throughout the year (with few exceptions).

It should also be noticed that the percentage change are found very large for dry periods compared to wet seasons which is because of relative calculation of change. Small increment in smaller value can give higher percentage change compared to the opposite case.
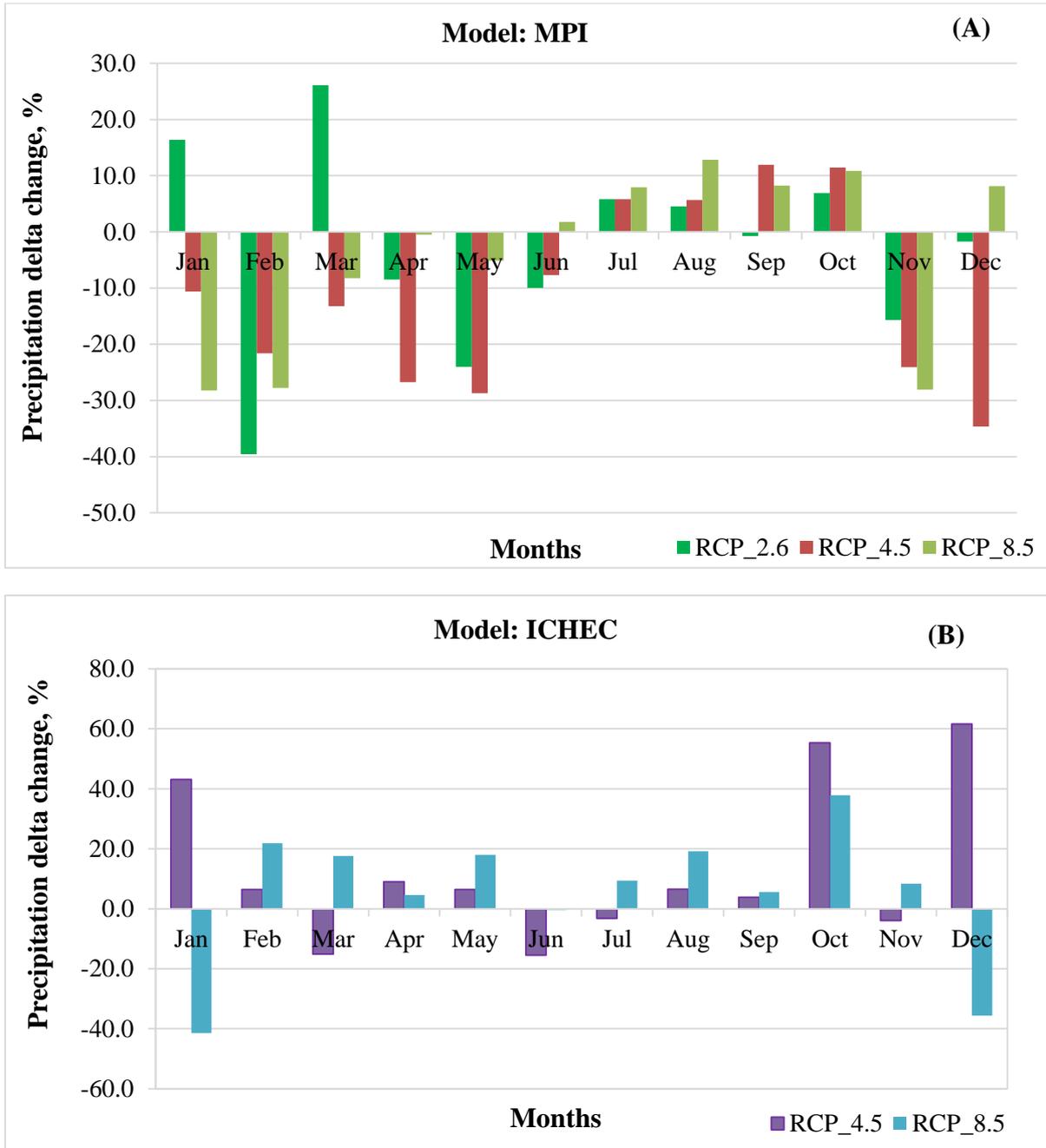
Figure 7-8 (A, B) Precipitation delta change under models and scenarios, by mid century
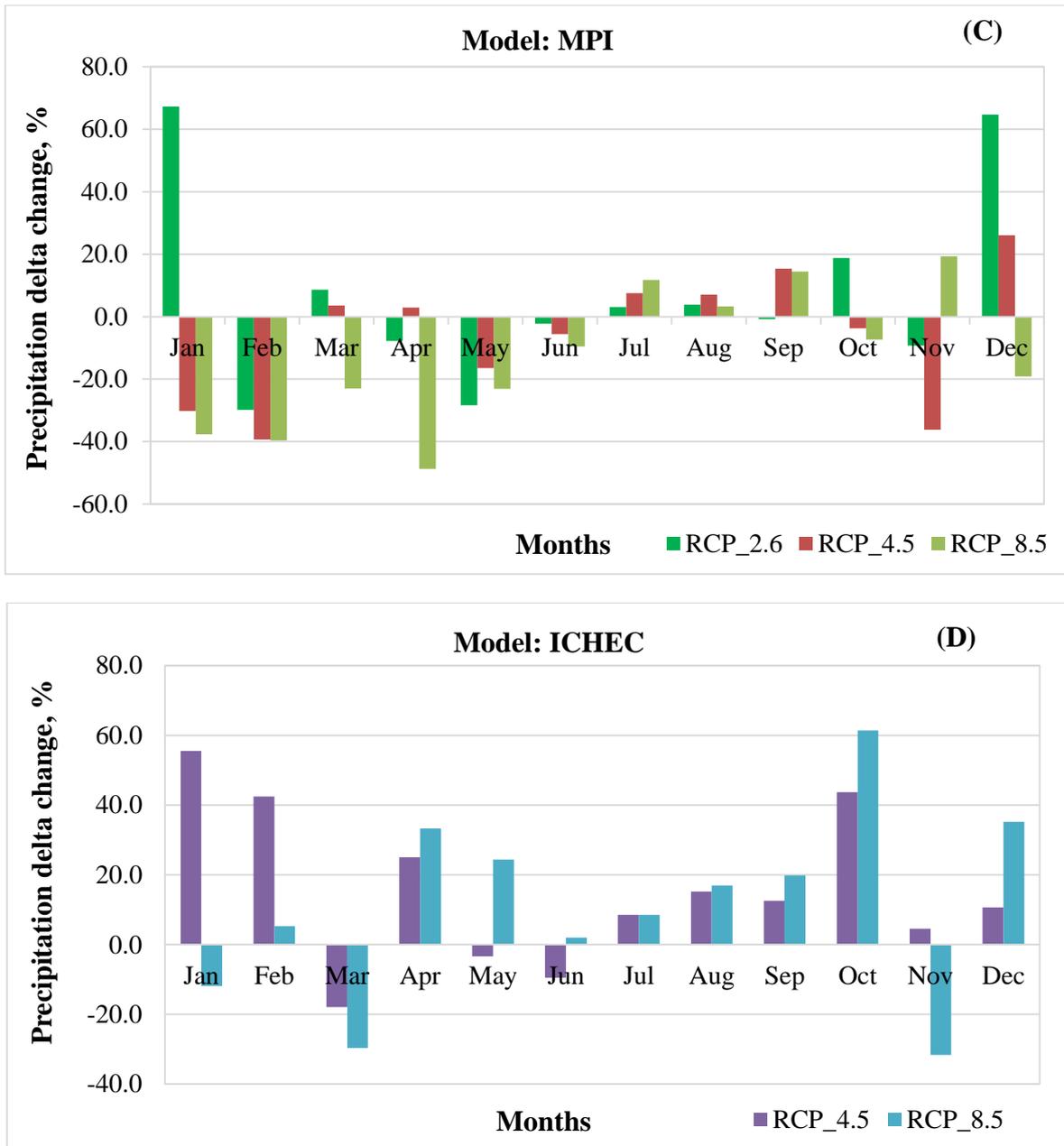
Figure 7-9 (C, D) Precipitation delta change under models and scenarios by end century

The observations were further categorised to seasonal distribution to have a clear picture of future conditions:

Table 7-7 Seasonal precipitation change in future, expressed in %

Time Period	Models	Scenarios	Winter (Dec-Feb)	Premonsoon (Mar-May)	Monsoon (Jun-Sep)	Postmonsoon (Oct-Nov)
Mid Century	MPI	RCP 2.6	-8.3	-2.1	-0.1	-4.4
		RCP 4.5	-22.3	-22.9	3.9	-6.3
		RCP 8.5	-15.9	-4.6	7.7	-8.6
	ICHEC	RCP 4.5	37.0	0.1	-2.1	25.7
		RCP 8.5	-18.4	13.4	8.4	23.1
End Century	MPI	RCP 2.6	34.1	-9.2	1.0	4.8
		RCP 4.5	-14.5	-3.3	6.1	-20.0
		RCP 8.5	-32.1	-31.6	5.0	6.0
	ICHEC	RCP 4.5	36.2	1.3	6.7	24.1
		RCP 8.5	9.5	9.3	11.8	14.9
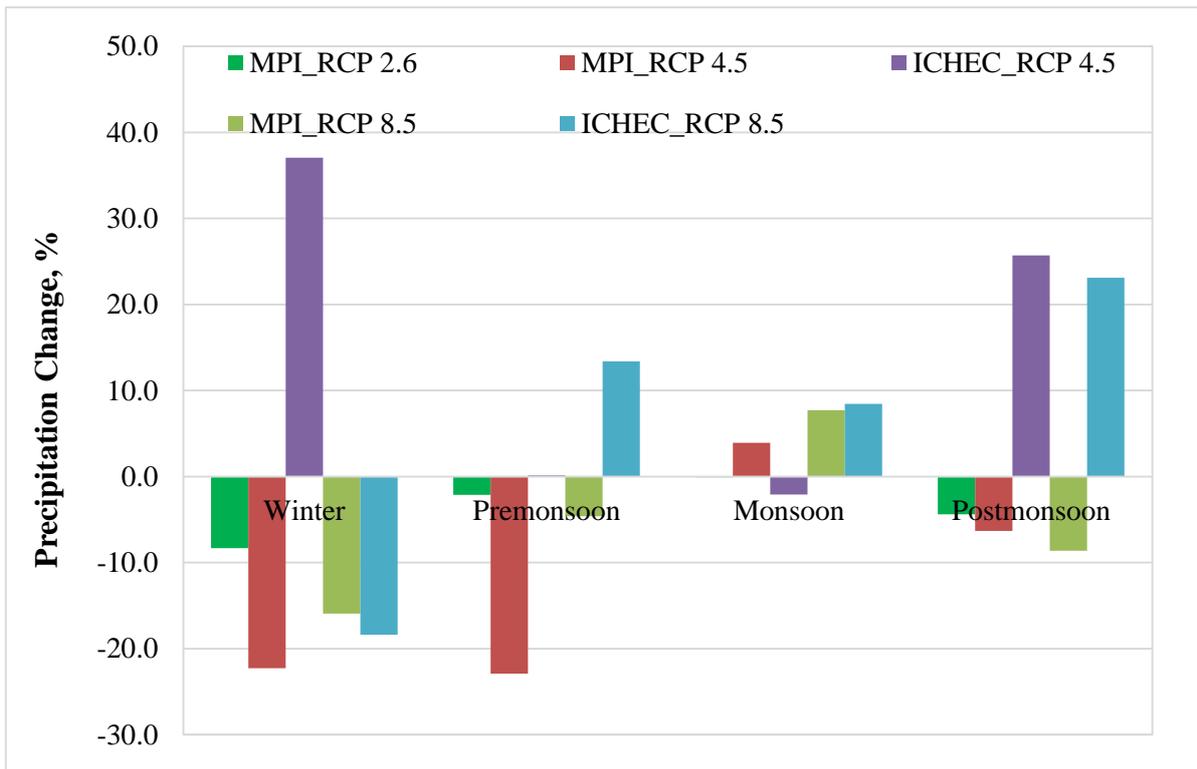
Figure 7-10 Seasonal precipitation change by mid century
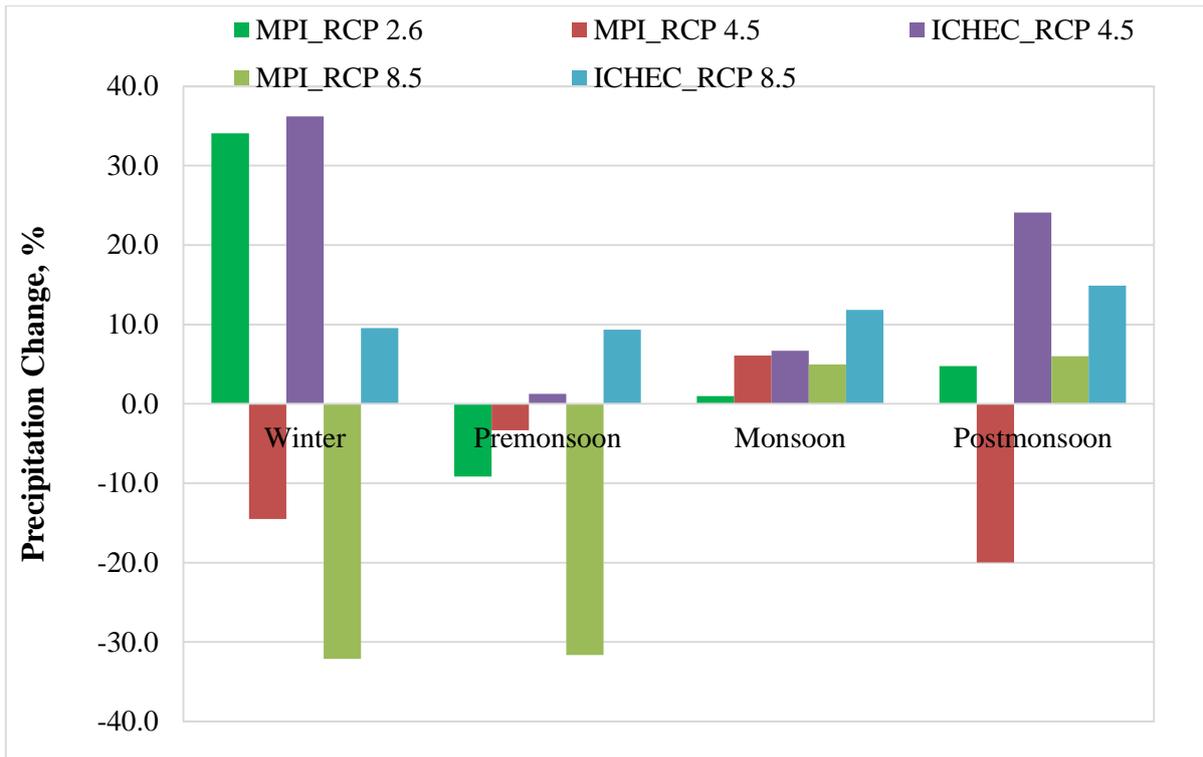
Figure 7-11 Seasonal precipitation change by end century

In general, the dry winter period and premonsoon are supposed to get highly affected due to decrease in precipitation. Further, the seasonal distribution clearly shows that the precipitation scenarios by mid-century are supposed to be more critical compared to end century due to drier winter periods under most of the scenarios. The monsoon and postmonsoon are supposed to be wetter in future. The decreasing trends were mostly under model MPI while projections under ICHEC were found increasing (with very few exceptions during mid-century).

7.5   Historical Precipitation - Trend Analysis

The precipitation delta change being completely different for two models, made the requirement of further analysis on data available from CORDEX. At such, historical precipitation data series were compared with the station observed data. Among the 24 grid points from climate data, grid point V2 lies close to one of the precipitation station 1204. Thus, overlapping period (1994 - 2000) of data series for this grid point was compared with observed precipitation data for station 1204.
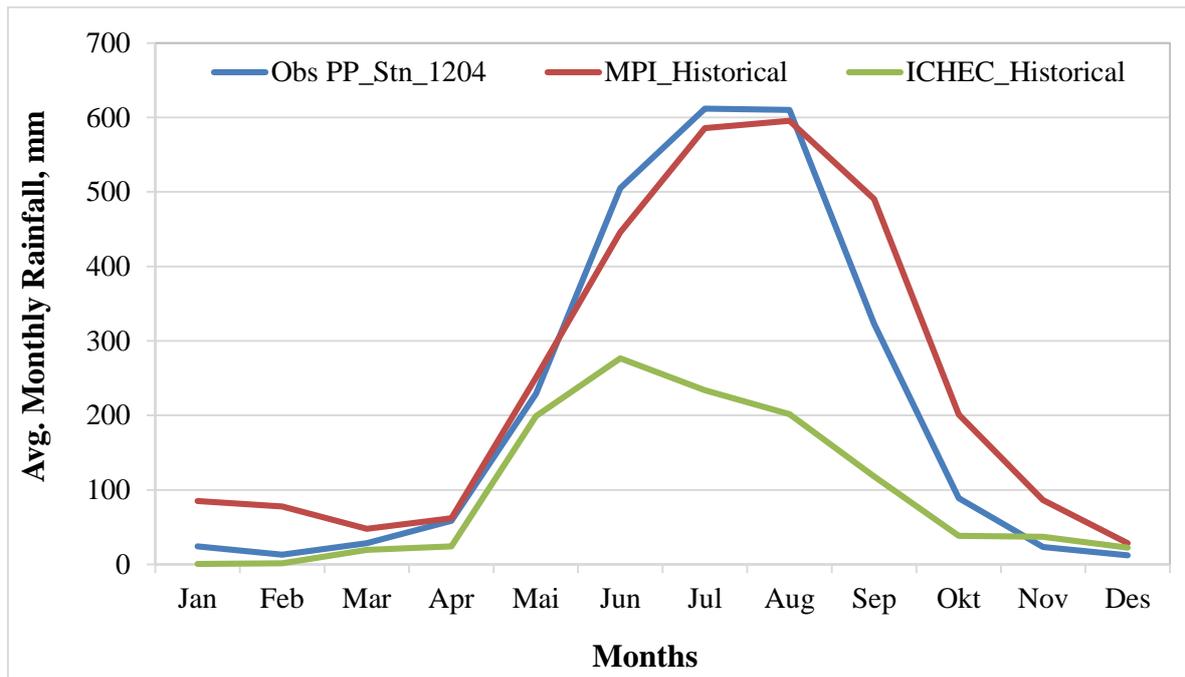
Figure 7-12 Analysis of historical precipitation data from climate models

Referring Figure 7-12, it is clear that the historical data series for model MPI closely follows the observed precipitation trend while model ICHEC highly underestimates the precipitation. Such high discrepancies in historical data might be a reason behind completely different model results. However, this single fact cannot be used to completely deny the projections made by model ICHEC as the temperature and simulation results seem plausible. This discrepancy is a result of comparison done only on a single gird. Further, delta changes are relative calculations and it might be that the future predictions under this model are strong enough to shadow the discrepancies on historical series. Thus, both the model results were used in further analysis with necessary comparisons and justifications wherever required.

7.6   IPCC - AR5 Findings

The future projections for South Asia from IPCC fifth assessment report (AR5) that were relevant with the topic are included in this heading and discussed.
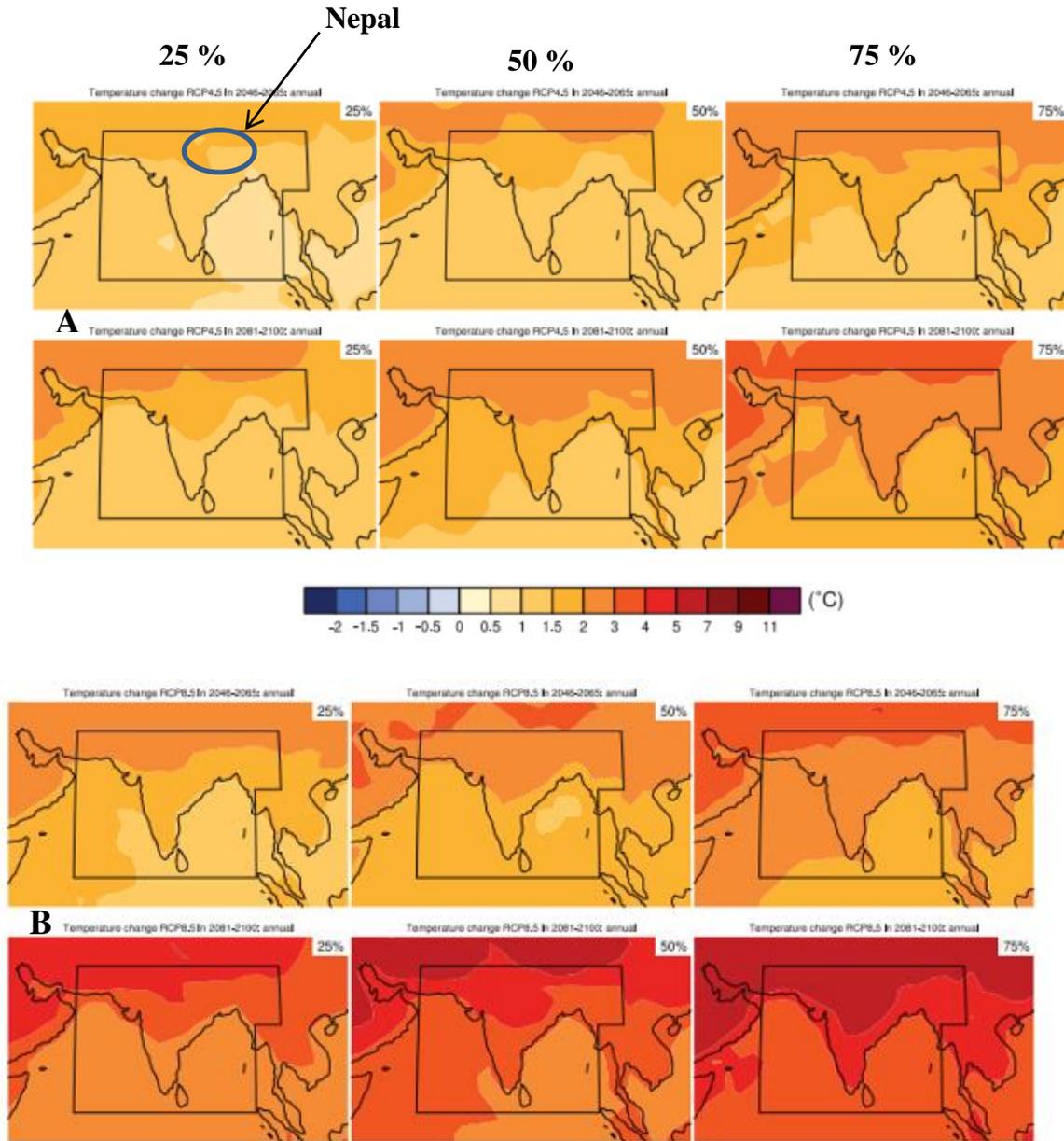
Figure 7-13 Maps of annual temperature change for South Asia from IPCC - AR5 with respect to 1986 - 2005 expressed in percentiles of distribution [21]

(Figure A represents results under RCP 4.5 and figure B under RCP 8.5. First row of each figure represents time frame 2046 - 2065 and second row is to represent 2081 - 2100 while columns represents respective percentiles.)

The temperature change maps around Nepalese boundary (Figure 7-13) shows temperature rise of 2 - 3^{0}C by mid-century and 3 - 6^{0}C by end century with sharp projections under RCP 8.5 compared to RCP 4.5. The maps are thus quite similar to findings from the present work (Refer Table 7-4) in terms of annual temperature change.
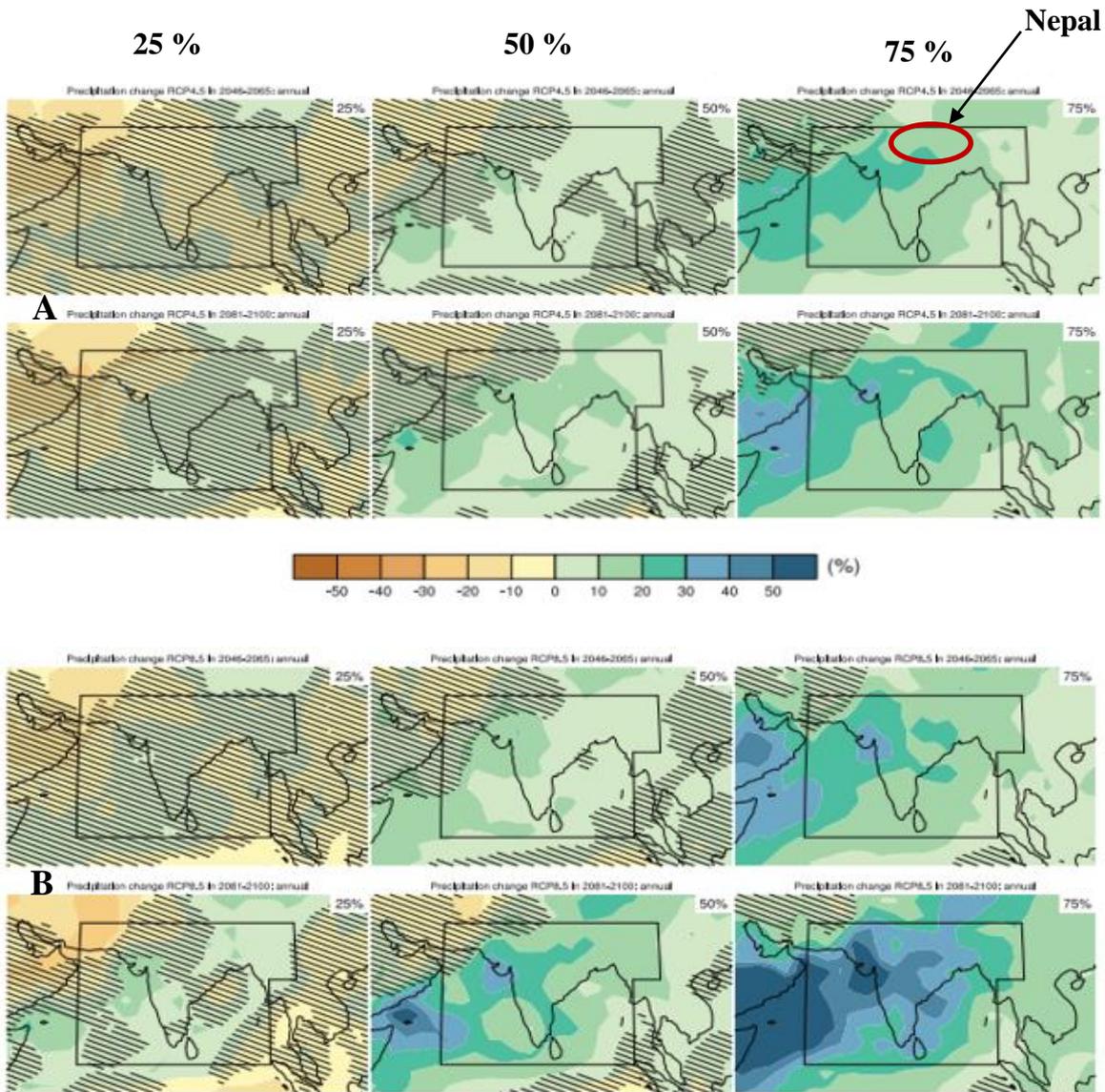
Figure 7-14 Maps of annual precipitation change for South Asia from IPCC - AR5 with respect to 1986 - 2005 expressed in percentiles of distribution [21]

(Figure A represents results under RCP 4.5 and figure B under RCP 8.5. First row of each figure represents time frame 2046 - 2065 and second row represents 2081 - 2100 while columns represents respective percentiles.)

From the figures, it is clear that, IPCC annual precipitation projections for Nepal possess increasing trend under both scenarios, time frames and almost with all percentiles. Precipitation is expected to increase much significantly under RCP 8.5 by end century. These precipitation projections however were found completely different from the results obtained. (Refer Table 7-6) and especially with results from model MPI. Though an increase in precipitation is expected under model ICHEC, the annual projections are not that significant compared to the maps while model MPI suggests a decreasing trend.

Such discrepancies could be a reason of large scale representation through IPCC maps. The present study area is small basin within Nepal and as precipitation is not uniform throughout the country, the change is also not expected to represent entire area. However, this comparison with IPCC findings, to some extent, supports the results from ICHEC.

Projections were found highly uncertain and highly fluctuating with models, methods and scales used for study. Thus, clear selection of single model was not considered and simulations were carried under every scenarios possible.

8. MODEL SIMULATION UNDER CLIMATE CHANGE SCENARIOS

8.1 Background and Input Data

Delta change only gives the expected change individually in terms of precipitation and temperature. But, real field is the combination of this change and influence of many other parameters. So, to see the impact of climate change on hydrology, this delta change driven by several scenarios were applied to the calibrated HBV model and the discharge patterns were observed.

The latest version of HBV model used is more user friendly in applying delta changes. Monthly changes were the input given directly in the form of %, ^{0}C and mm for precipitation, temperature and evaporation, respectively. During simulation, the model divides the monthly value and applies delta change to the daily observation and finally generates corresponding discharge. Delta changes in evaporation were computed using Thornthwaite's equation with the increased temperature. Appendix E: Climate Change - HBV Model Inputs, is the summary of the input given to HBV model to simulate climate change effects.

8.2 Simulation Results

As discussed earlier, HBV model setup 1 was then used for every other simulation. Using the calibrated HBV model, simulations were done under different models, scenarios and periods. Appendix F thus includes the 14 years hydrograph from simulation results.

8.2.1 Monthly Changes

The daily hydrographs for future seems difficult to interpret thus average monthly discharge were computed to see the clear situation in future. With average monthly flow calculation for each condition, percentage deviations from current flow were computed. (Refer Table 8-1).

Table 8-1 Percentage deviation in monthly flow under various scenarios

	% Deviation from current flow									
Period	By Mid Century					By End Century				
Model	MPI			ICHEC		MPI			ICHEC	
Months	RCP 2.6	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Jan	1.1	3.0	7.8	7.4	8.8	2.9	5.3	15.5	8.9	16.7
Feb	0.6	2.4	7.0	7.2	8.1	2.8	4.5	15.4	8.8	16.2
Mar	1.0	2.7	7.7	7.8	9.0	3.1	5.0	22.2	9.8	20.5
Apr	2.2	4.8	17.0	15.2	15.7	5.2	12.1	54.4	20.8	48.7
May	-18.3	-20.3	15.7	13.4	27.7	-12.1	-0.7	52.4	16.1	77.7
Jun	-22.9	-23.2	2.3	-16.0	8.3	-16.5	-11.9	-1.7	-8.9	24.5
Jul	-1.2	-0.7	9.5	-10.1	12.5	-0.6	3.8	4.2	5.9	12.5
Aug	6.2	8.8	16.4	6.2	22.6	4.7	11.4	7.3	19.1	21.5
Sep	4.7	15.6	17.6	12.3	18.5	4.2	19.0	19.0	22.2	32.6
Oct	8.3	22.1	27.0	42.0	42.2	13.9	21.2	34.0	45.9	71.7
Nov	1.3	3.7	8.6	8.3	10.7	2.8	5.7	17.1	10.5	17.9
Dec	1.5	3.7	8.7	8.2	9.8	3.1	6.1	16.9	9.7	18.1

Referring the table, in some cases, the percentage deviation seems so high compared to the delta change computed above which is a result of relative calculation. Figure 8-1 & Figure 8-2 clearly shows the average monthly flow and the changes under different scenarios.
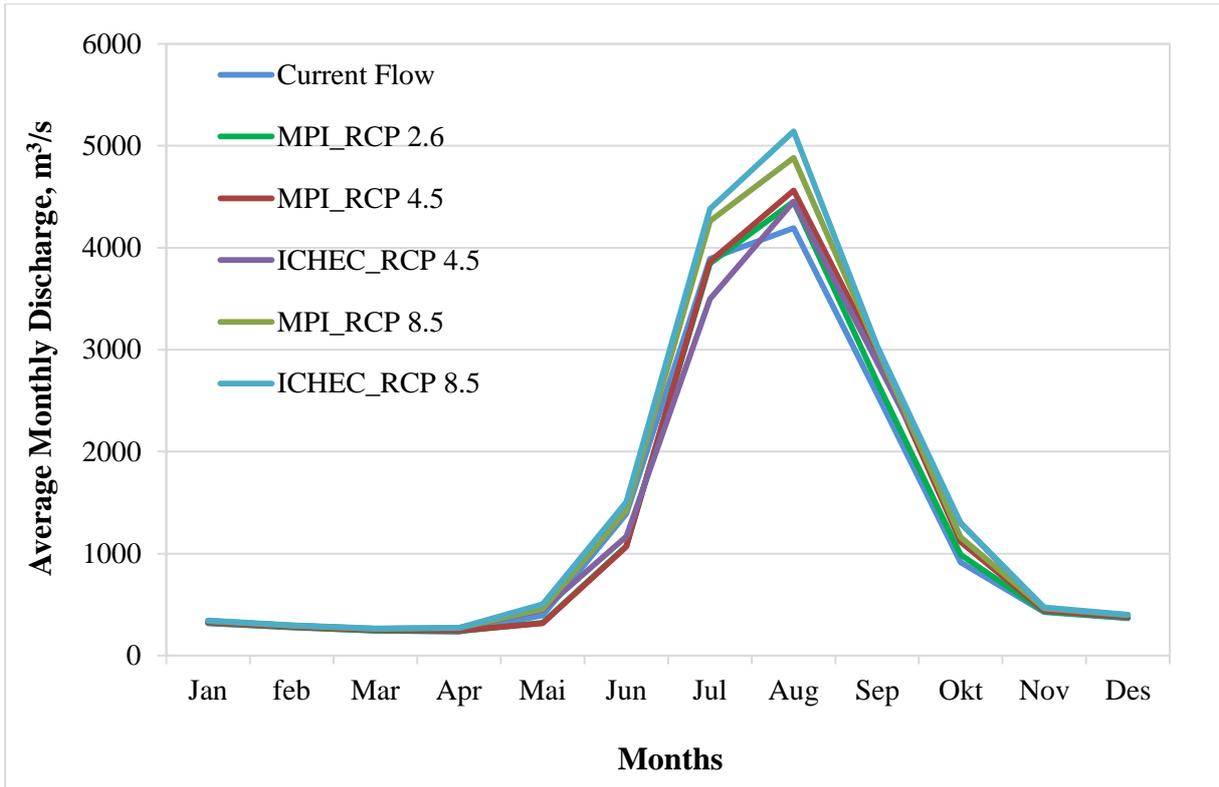
Figure 8-1 Monthly simulation results by mid century
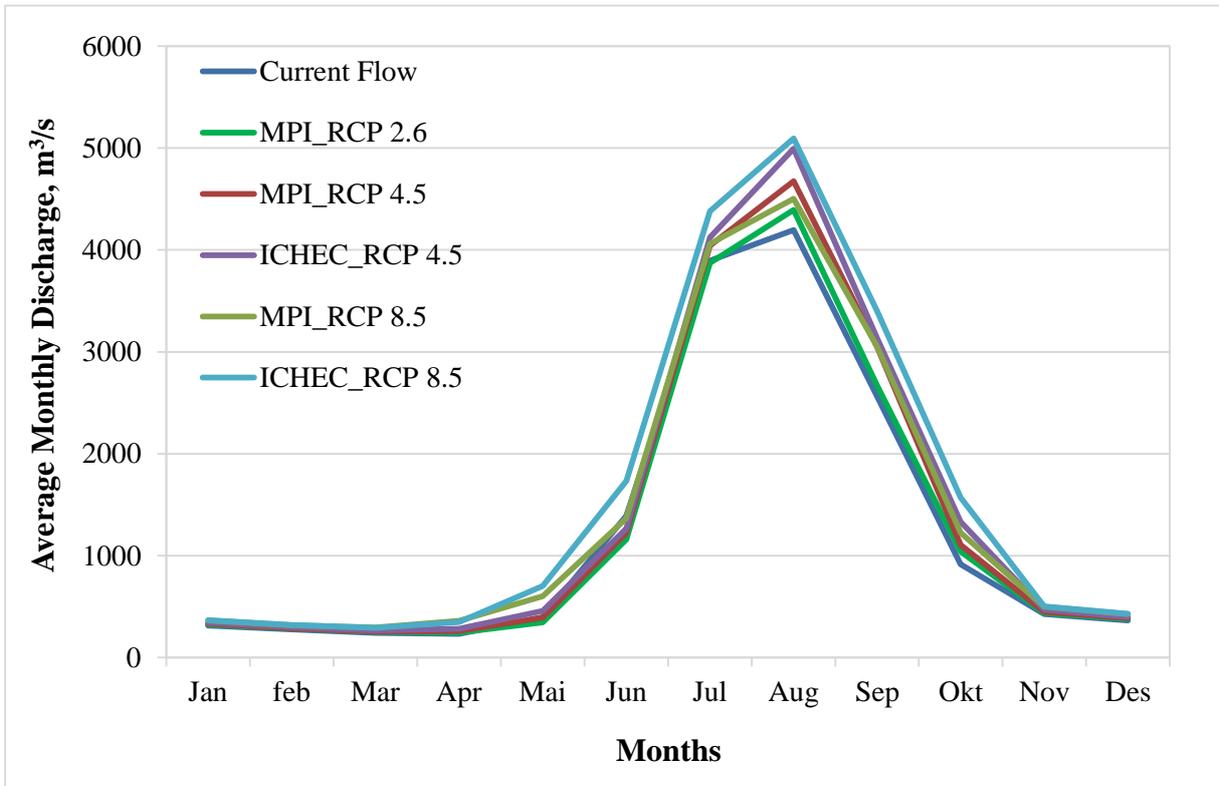
Figure 8-2 Monthly simulation results by end century

Figures show that unlike precipitation delta change, discharge is mostly supposed to increase in future under both models. Flow is supposed to increase more pronouncedly during August - October under every scenario while rest of the months have mixed patterns.

8.2.2 Seasonal Changes

The changes in flow were still difficult to interpret because of wide variations with respect to models, scenarios, months and time periods. Thus this deviation was further averaged to represent seasonal changes. (As described in 7.4.1).

Table 8-2 Percentage deviation in flow with respect to seasons

Time Period	Models	Scenarios	Winter (Dec-Feb)	Premonsoon (Mar-May)	Monsoon (Jun-Sep)	Postmonsoon (Oct-Nov)
Mid Century	MPI	RCP 2.6	1.1	-5.1	-3.3	4.8
		RCP 4.5	3.0	-4.3	0.1	12.9
		RCP 8.5	7.8	13.5	11.5	17.8
	ICHEC	RCP 4.5	7.6	12.1	-1.9	25.2
		RCP 8.5	8.9	17.4	15.5	26.5
End Century	MPI	RCP 2.6	2.9	-1.3	-2.1	8.4
		RCP 4.5	5.3	5.5	5.6	13.4
		RCP 8.5	15.9	43.0	7.2	25.6
	ICHEC	RCP 4.5	9.1	15.6	9.6	28.2
		RCP 8.5	17.0	49.0	22.8	44.8

From the table, it is clear that winter and postmonsoon period are supposed to have more flows in future while premonsoon and monsoon seasons showed mixed patterns under scenarios. During these seasons, model MPI mostly suggested decrease in flow by mid-century while they tend to increase by end century. (Refer Figure 8-3 and Figure 8-4) Like precipitation, the changes are more pronounced under RCP 8.5.
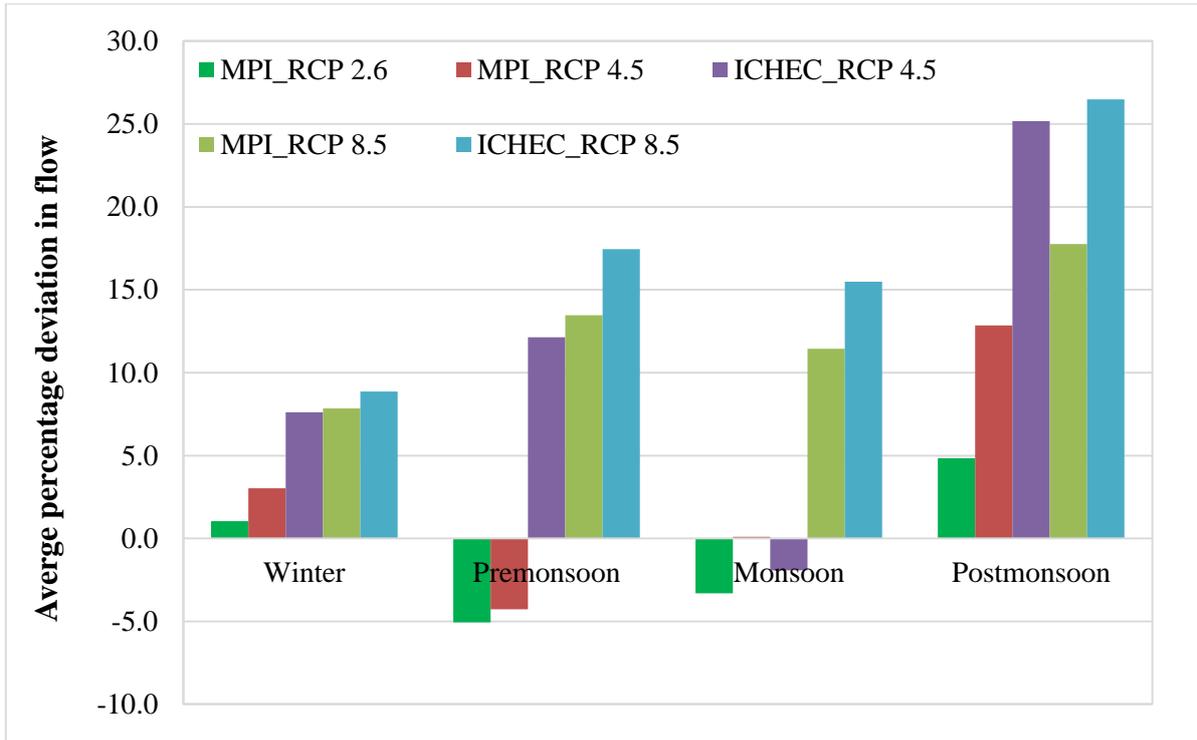
Figure 8-3 Seasonal deviation in flow by mid-century, expressed in percentage
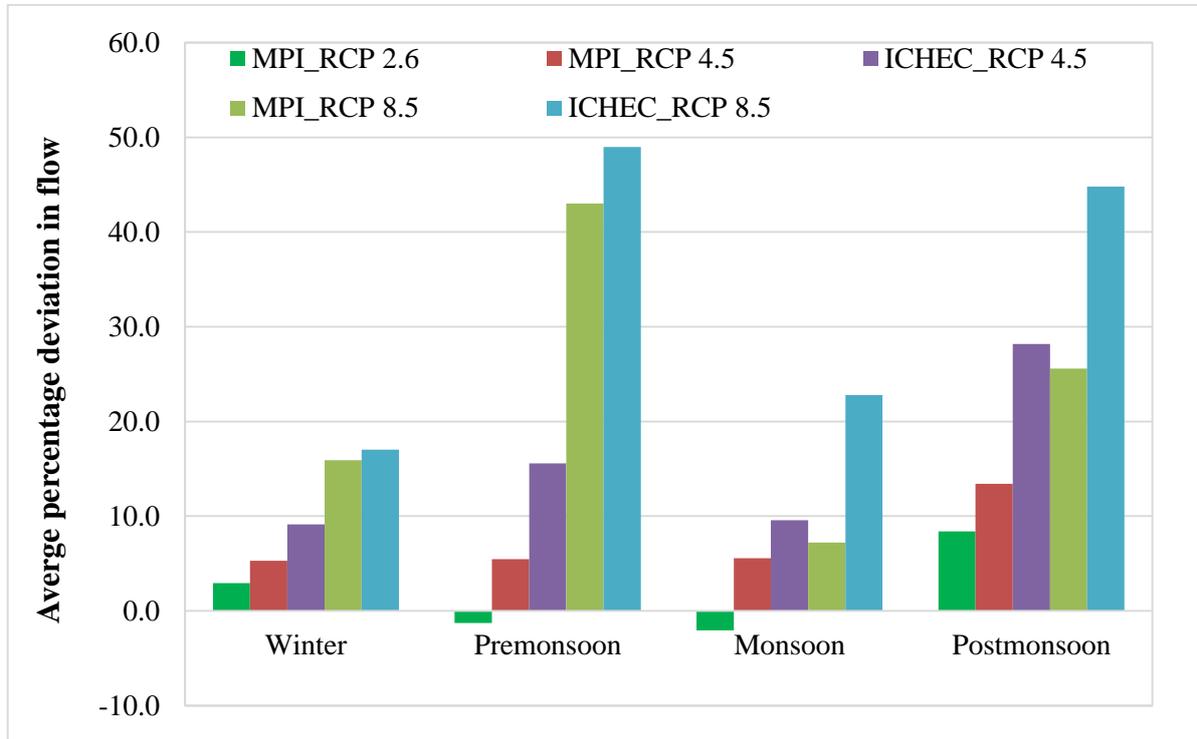
Figure 8-4 Seasonal deviation in flow by end century, expressed in percentage

8.2.3 Annual Changes

In addition to daily, monthly and seasonal patterns, annual discharge pattern were equally interesting to observe thus are included through Figure 8-5 & Figure 8-6.
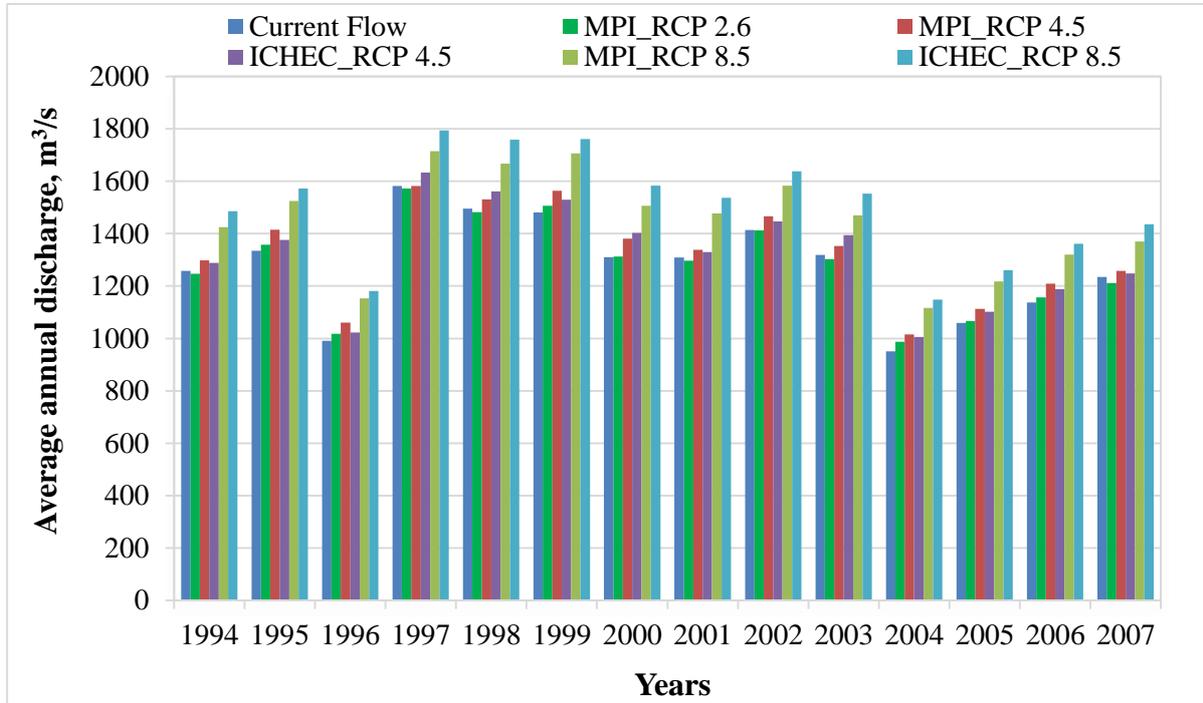
Figure 8-5 Average annual discharge by mid century
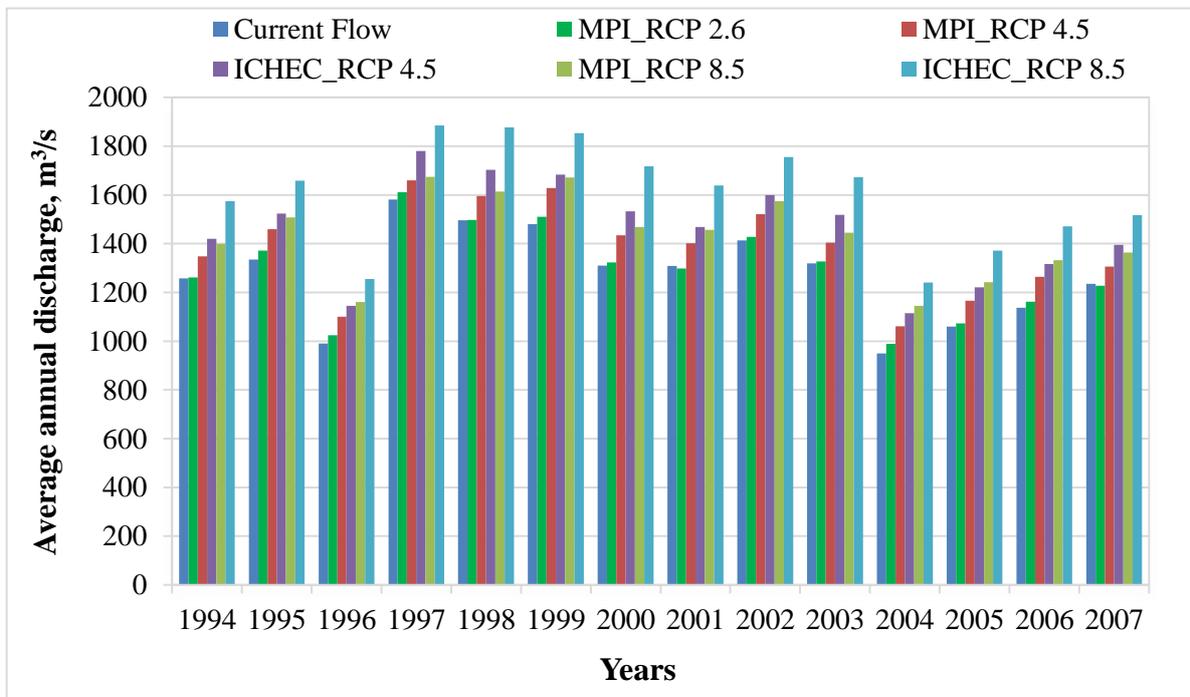
Figure 8-6 Average annual discharge by end century

Figures show that the average annual discharge increases in almost all cases with small increase under RCP 2.6 but considerable increase under RCP 8.5 in future. While the changes under RCP 4.5 were found more pronounced by end century compared to mid-century. Table 8-3 proves the same and again shows that projections with ICHEC are much higher than with model MPI.

Table 8-3 Percentage deviation from current situation in average annual flow

% deviation in average annual flow				
Time Frame	Mid Century		End Century	
Scenarios / Models	MPI	ICHEC	MPI	ICHEC
RCP 2.6	0.3	-	1.3	-
RCP 4.5	4	3.6	8.3	14.2
RCP 8.5	13.3	17.9	12.2	25.8

8.3   Discussions

The simulation results show that average annual flow is expected to increase in future with almost no change under RCP 2.6 and noticeable change under RCP 8.5 (Refer Table 8-3). The percentage change is different with different models, higher with ICHEC compared to MPI with an exception in mid-century. In addition, flow is projected to increase during both the time frames even higher by end century which may have overcome the fear of less water availability due to glacier retreat as discussed in Chapter 2.

Projected seasonal changes are however more significant and complex compared to annual change. Table 8-2 suggests that the driest winter period and post monsoon seasons are supposed to have higher flows than current situation which is an advantage against possible droughts in future though the increase in winter is not high. Meanwhile, the premonsoon and monsoon seasons have different projections depending on models and scenarios. During these periods, future flow seems decreasing under RCP 2.6 while RCP 8.5 suggests an increasing trend for both the time frames. Model MPI suggests decrease in flow by mid-century followed by increase during end century under RCP 4.5, while Model ICHEC under the same scenario suggests increase in flow for both the time frames (with an exception of very slight decrease in monsoon during mid-century). In any case, the reduction in flow volume is very less and the period is during monsoon when water is abundant, thus might not have huge impact in water

availability. The simulation results obtained were different from projected precipitation change especially for winter period which could be a contribution from snow melt due to high rate of temperature rise during winter.

The projections however had no change in seasonal distribution of flow, means the peak flows are always in July, August and monsoon always has the major contribution in hydrology. Earlier snow melt were expected due to temperature rise and was supposed to have impact on seasonal distribution of flow but the results show no significant change in seasonal distribution. It might be a reason of large basin scale analysis on which the changes were not that significant but if done on sub basin scale might be prominent.

Overall, the annual flow is supposed to increase in future under the scenarios studied. Changes are more pronounced in seasonal basis rather than in annual. Dry periods are to receive more flows while wet periods may have decreased flow under some scenarios but not in huge quantity. Thus, the future water availability doesn't seem that depressing with the current study being made. But still sub basin scale studies are to be made in order to see changes in local level.

9. THE nMAG MODEL

9.1 Introduction

The nMAG model is a hydropower simulation model developed at the Norwegian Hydro technical Laboratory, affiliated to SINTEF and Norwegian Institute of Technology, Trondheim in 1984 - 86. The nMAG model is the updated version of ENMAG done in 90's. The model is based on detailed description of hydrological conditions and production systems, while consumer systems and operation strategy are described with simpler model. Thus, this model is best suited for planning and less for optimising the operation of a hydropower plant. [11] The model used in the present study is last updated version i.e. nMAG 2004, updated in 2004.

9.2 Model Structure

Figure 9-1 outlines the basics of hydropower simulation model structure.
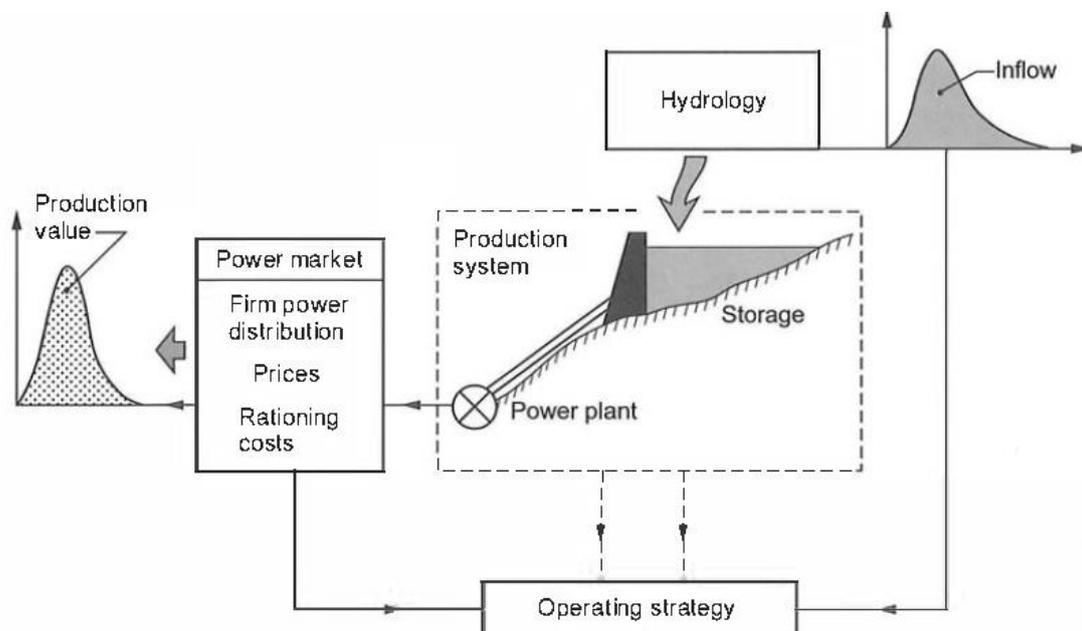
Figure 9-1 Main components of a Hydropower system simulation [11]

The main components of a hydropower system are; Reservoir, Power Plant and Diversions. These components are represented by modules which are connected by connecting lines often referred as nodes and links in a simulation model. Besides the hydropower components another module termed as checkpoint is used. Checkpoint can be certain place in watercourse where, for an example, a minimum discharge is to be imposed, or where it is desirable to compute the discharge. In short, nMAG is a simulation model represented by modules and linked together with certain operation strategies.

9.3   Use of the model

The aim of the study is to see the impacts of climate change on power potential. Thus to meet the scope, nMAG model has been used. The main purpose of using the model in present study is to simulate the production and other related features for a hydropower system under varying hydrological conditions brought by climate change.

9.4   Model Setup

In order to do meet the aim of study, a model setup is necessary. Besides hydrology, an nMAG model setup requires;

- ➢ A production system
- ➢ The power market
- ➢ Restrictions data and
- ➢ Operation strategy

Establishing a complete new setup following all the planning phases were behind the time frame of the study. Thus, an available model setup for a system within the study basin has been used with necessary modifications.

9.4.1 The Likhu Hydroelectric Project Setup

The Likhu HEP is a planned peaking run of river (PROR) project in Likhu River in eastern Nepal. The project is a result of study made for academic purpose. Coincidently, the location of headworks and power house for the project are similar with commercial project named Likhu IV HEP. [22] Operational planning of the Likhu project has been done by Subarna Shrestha by establishing nMAG model setup for the project, as a thesis to Msc at NTNU. As the project lies in the same study basin, Likhu setup has been used for further study with changes in hydrology through scaling.

Some basic features of the project as extracted from the study are;

Location of Project: Khiji Chandeshwari, Okaldhunga, Nepal

Type of Scheme: Peaking ROR

Catchment Area (Upto Dam site): 640.2 km^2

Location of Headworks: Latitude $27^0 28$' N & Longitude $86^0 18$' E

Gross Head: 232 m

Design Discharge: 20.8 m³/s
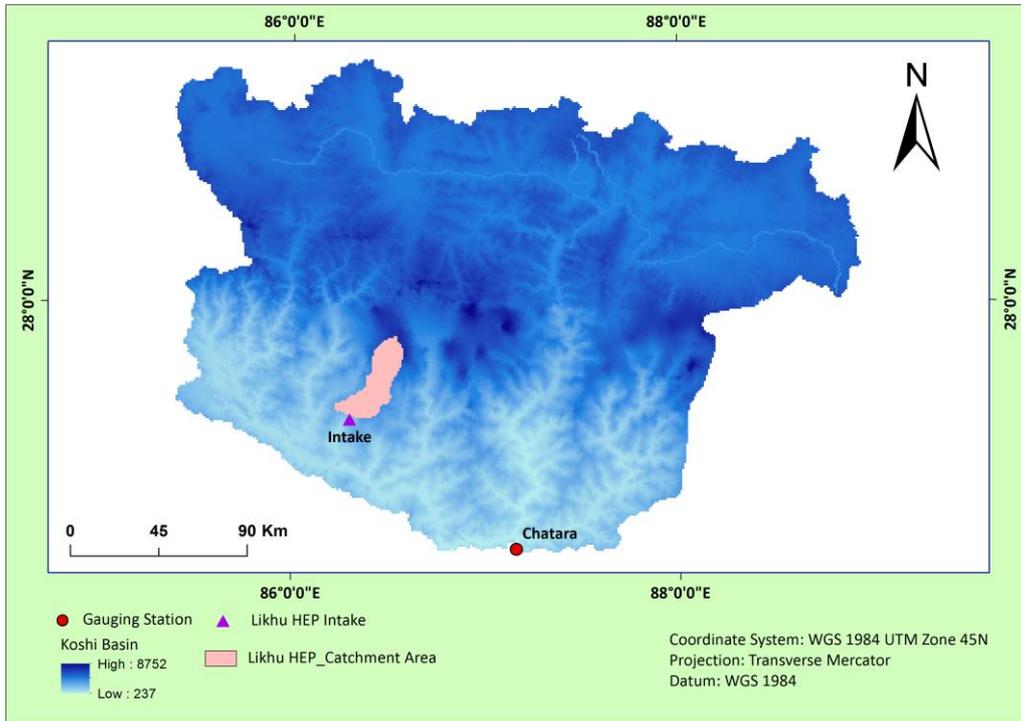
Figure 9-2 Location Map of Likhu Project on Koshi Basin

The Likhu HEP is simple and small system with one catchment, small daily peaking reservoir and one power system. Figure 9-3 is an overview of model setup for Likhu.
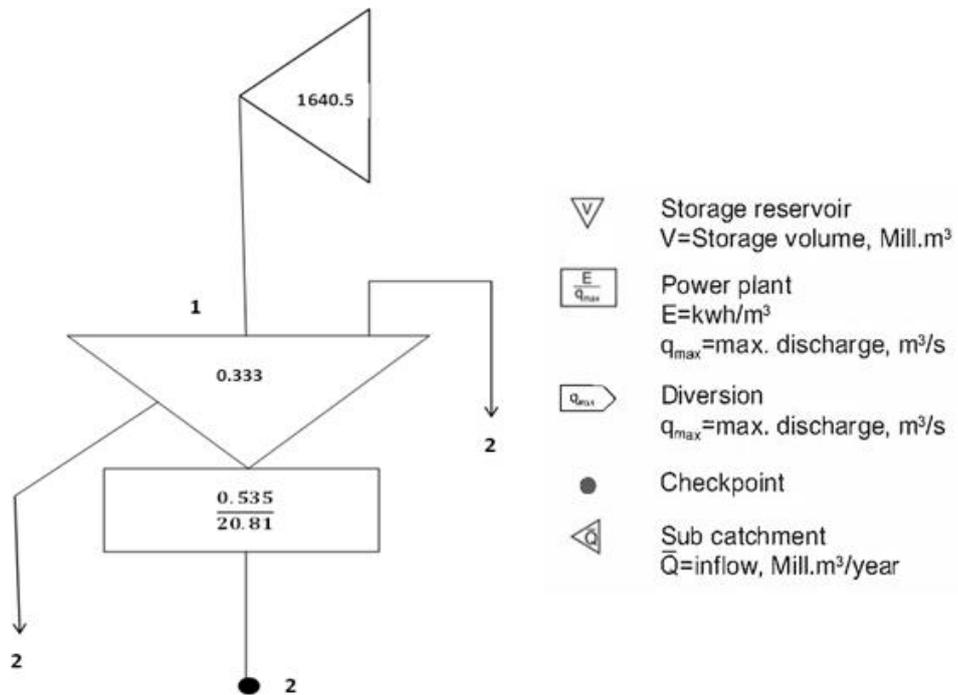
Figure 9-3 nMAG model of Likhu HEP system

Module Parameters

The main parameters from Likhu system which were adopted without any changes from previous studies are;

Table 9-1 Module Parameters of Likhu HEP System

Reservoir Data	LRWL	1034	masl
	HRWL	1042	masl
	Volume	0.332	mill m^3
Power Plant	Maximum Discharge	20.81	m^3/s
	Energy Equivalent	0.5346	kwh/m^3
	Nominal Head	221.94	m^3/s
	Intake Level	1030	masl
	Tailwater Level	807	masl
	Head Loss Coefficient	0.0186	s^2/m^5
Operation Strategy	Peaking Schedule	5 hours	
	Automatic Reservoir Balancing	(from 18 - 23 hours)	
Energy Market	Firm Power Level	175.06	GWh/year
	Firm Power Price	4.56	NPR/KWh
Restriction Data	Bypass Release (Throughout Year)	1.21	m^3/s

Table 9-2 Water Level - Volume relationship for Likhu HEP system

Water Level	masl	1034	1035	1036	1038	1039	1040	1041	1042
Volume Storage	Mill m^3	0	0.03	0.07	0.15	0.19	0.24	0.28	0.33

9.4.2 Hydrological Data

Simulation results from HBV model for Koshi basin were downscaled to get the hydrological data at intake site. Daily discharge data from 1994 - 2007 under current and future scenarios were scaled to get the hydrological input for nMAG model. Correspondingly, annual inflows under each scenario were computed.

Scaling Factor

Scaling factor is required to scale the flow obtained through simulation at Koshi basin to the intake site.

Table 9-3 Scaling factor calculation

	Likhu	Koshi	Remarks
Area, km^2	642.00	57,811.00	Results from ArcGIS
Specific Discharge, m^3/s/km^2	0.082	0.022	Computed from data series used in model setup
Scaling Factor	**0.0414**		

To check the quality of scaling, graphs between flows at intake site used for the model setup previously and the downscaled flow from Koshi basin were plotted.
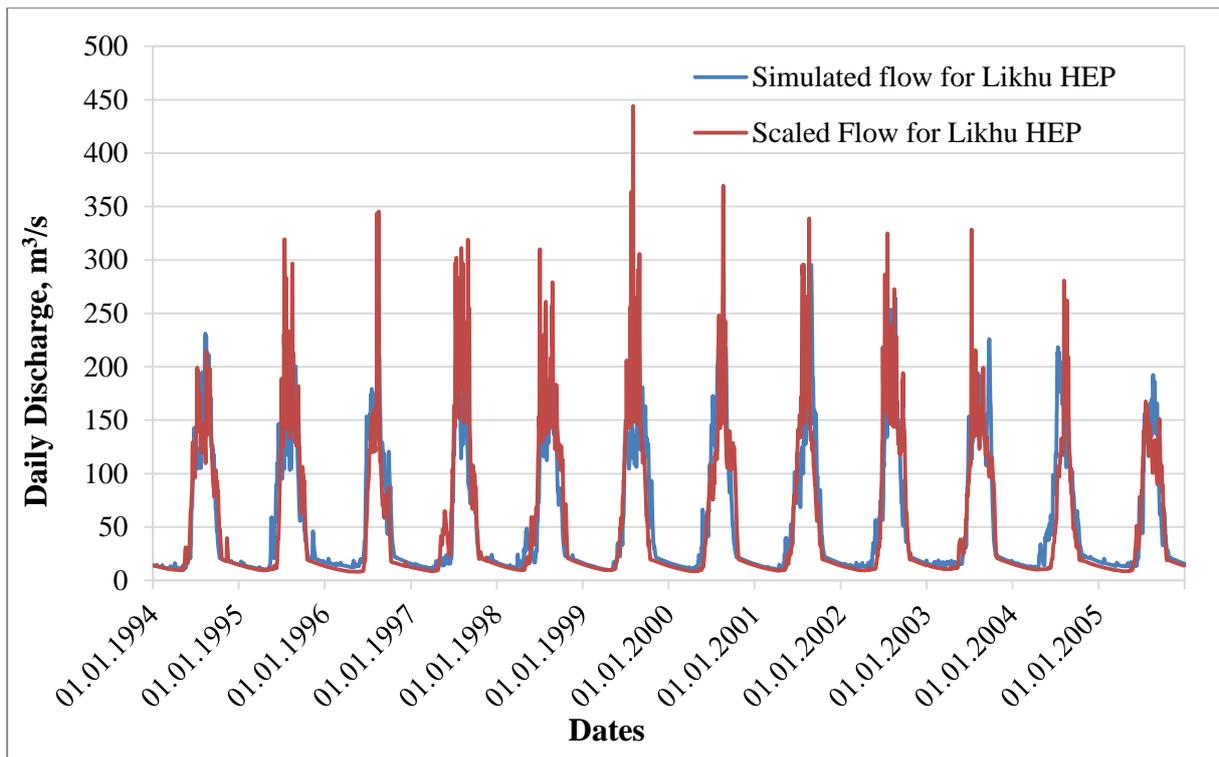
Figure 9-4 Graphs between simulated and scaled flow at Likhu HEP intake

Observing the graph, quality of scaling seems good enough. Moreover, the aim is to make an analysis on present and future conditions rather planning and optimisation thus the simple procedure of scaling looks good enough. The scaling factor was then used to downscale all the simulated flows under scenarios at Koshi basin outlet to represent Likhu.

9.4.3 Evaporation Data

The reservoir storage for the project is very small such that reservoir evaporation did not make any significant difference in power production thus was omitted in previous study. However, this is only the present situation which might not be true in future. Higher evaporation under temperature rise due to climate change may have considerable effect on power production. Considering this fact, reservoir evaporation data were applied to the model setup for every scenario. Evaporation data for present situation were used as from previous study while for future cases under scenarios; corresponding delta changes (Appendix E: Climate Change - HBV Model Inputs obtained for the basin were applied.

The reservoir evaporation data as tested initially for the model setup were;

Table 9-4 Reservoir Evaporation data for Likhu, mm/day

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.33	0.72	1.20	1.84	2.42	3.12	3.12	2.96	2.67	1.73	1.01	0.48

9.5   Model Simulation

The nMAG model simulation was done for current and future setup for time period of 14 years i.e. 1994 - 2007. Power production results, spill volume and through flow were noted for each different setup to see the changes with time frame.

9.5.1 Power Production

Annual power productions were found to follow the increasing trend of flow in future. The average annual production of 267 GWh/yr at present situation is expected to increase to a maximum level of 285 GWh/yr by mid-century and 304.5 GWh/yr by end century, both driven by scenario RCP 8.5 under ICHEC model.

Table 9-5 Average annual power production under scenarios, GWh/yr

Current	Time Frame	Mid Century		End Century	
	Scenarios / Models	MPI	ICHEC	MPI	ICHEC
266.9	RCP 2.6	266.6	-	269.9	-
	RCP 4.5	269.6	280.8	277.6	284.6
	RCP 8.5	284.2	285.2	304.7	304.5
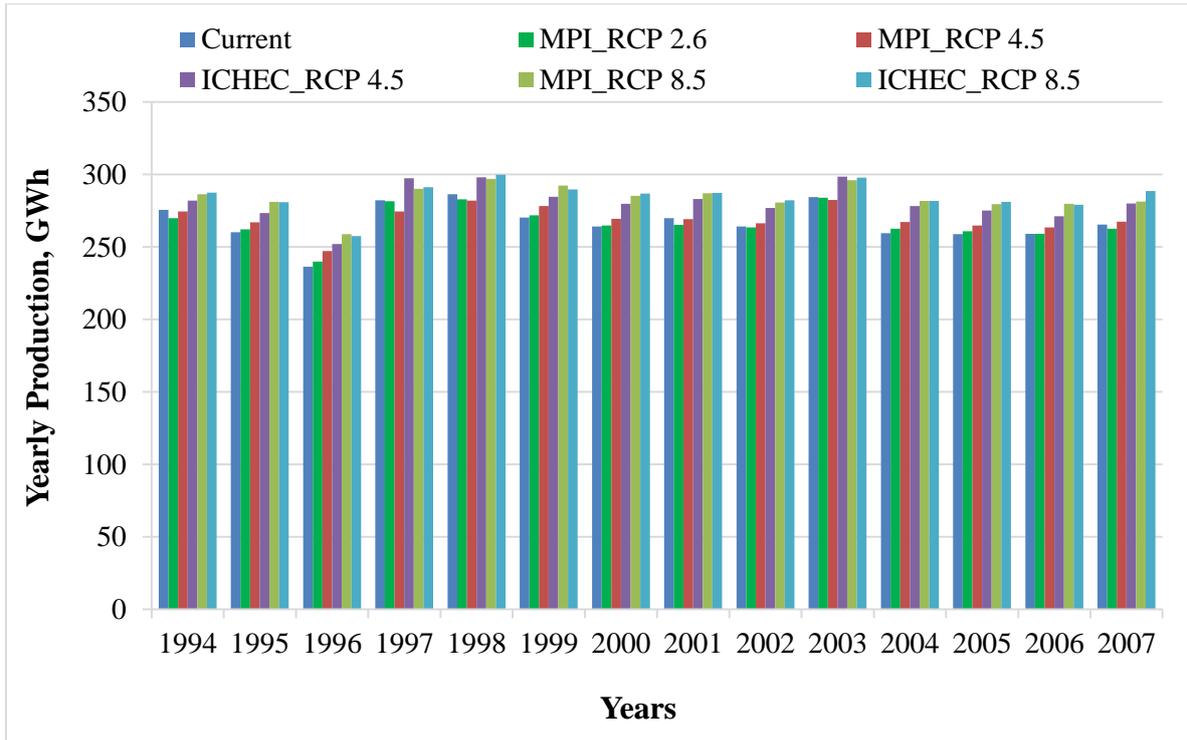
Figure 9-5 Power production by mid century
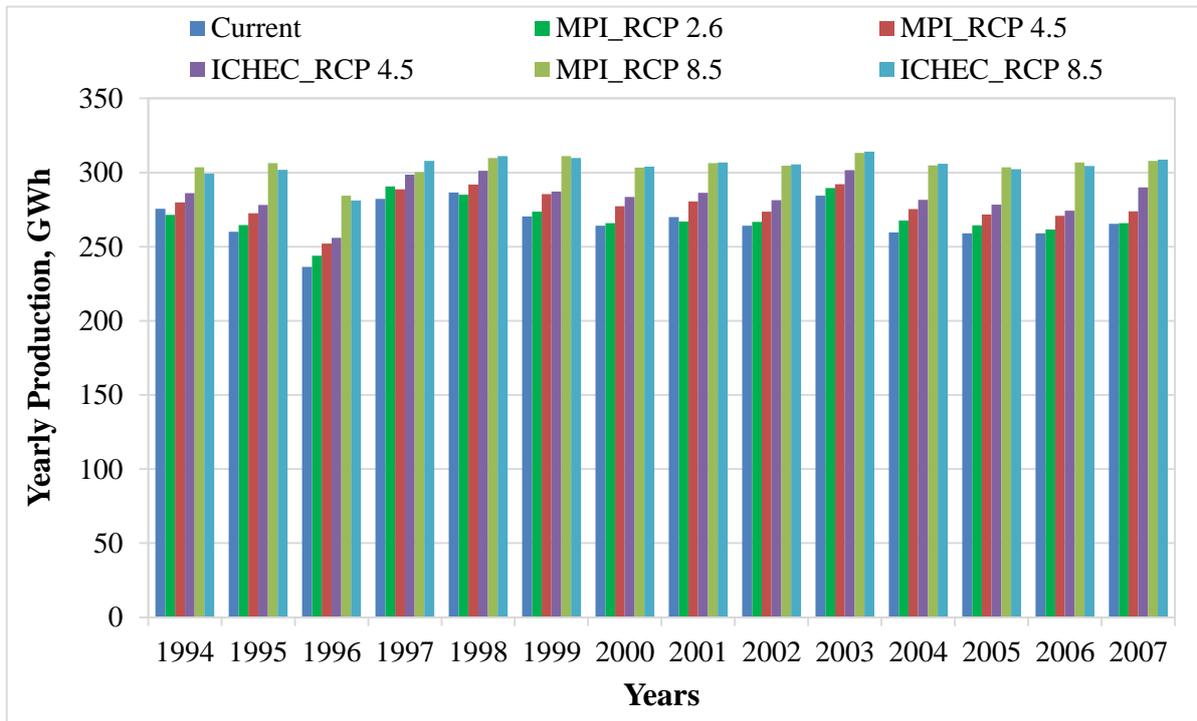
Figure 9-6 Power production by end century

9.5.2 Flood Spill

The power system remaining the same, increased flow will definitely result in more flood spill which can be clearly seen through the figures below;
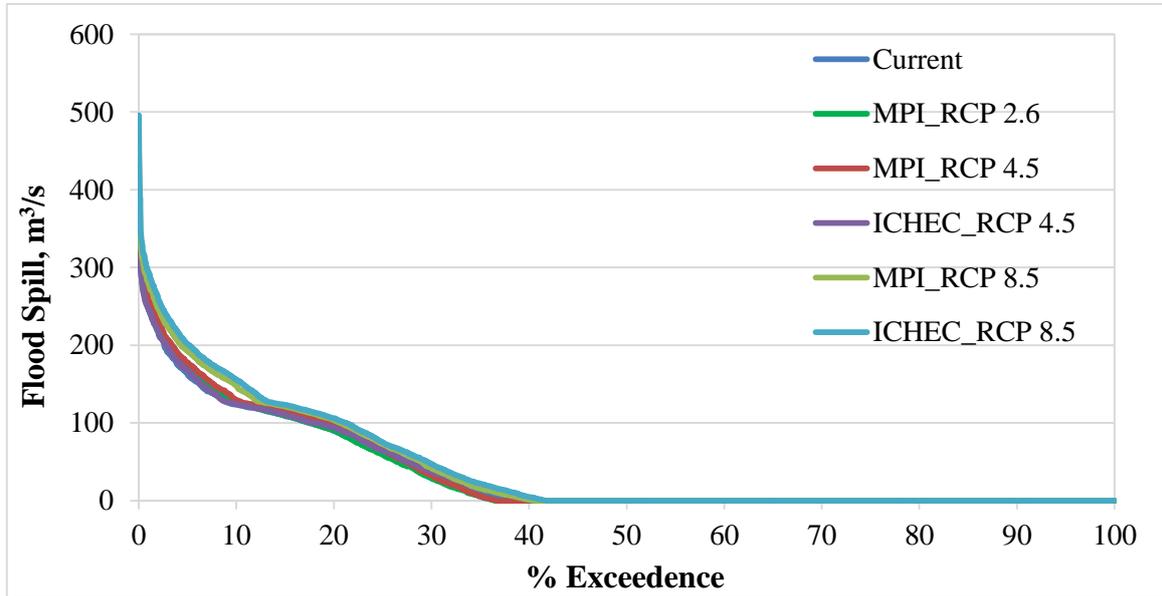
Figure 9-7 Flow duration curve of flood spill by mid century
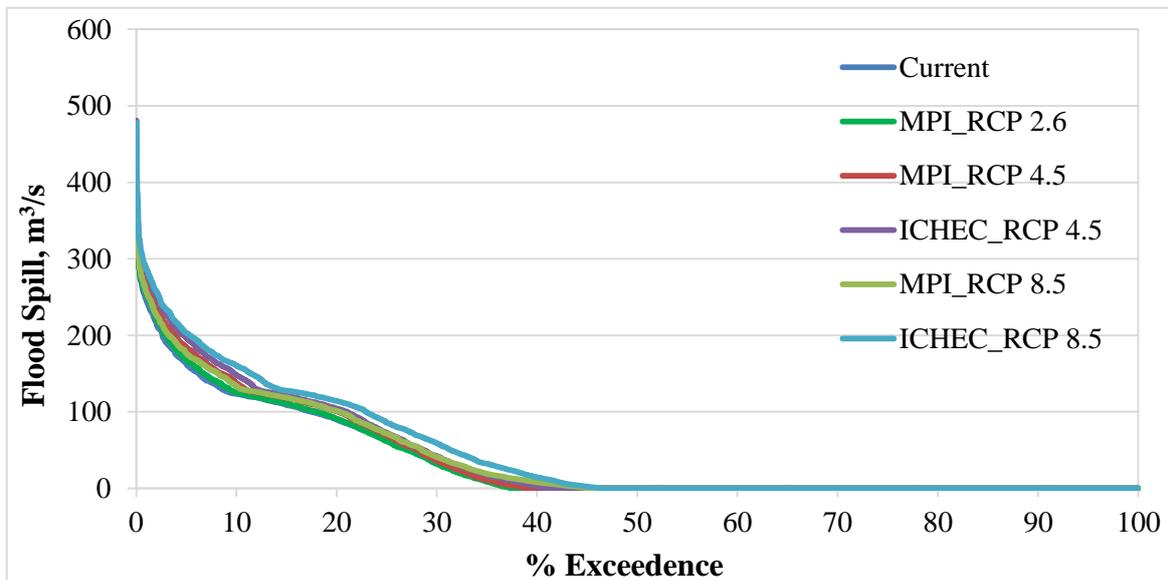
Figure 9-8 Flow duration curve of flood spill by end century

It should be noticed that overflow is higher and more distinct by end century compared to mid-century. This entire overflow occurs during wet periods of the year. So, in order to have an overview of this overflow distribution throughout the year, average monthly flood spill graphs were plotted as below;
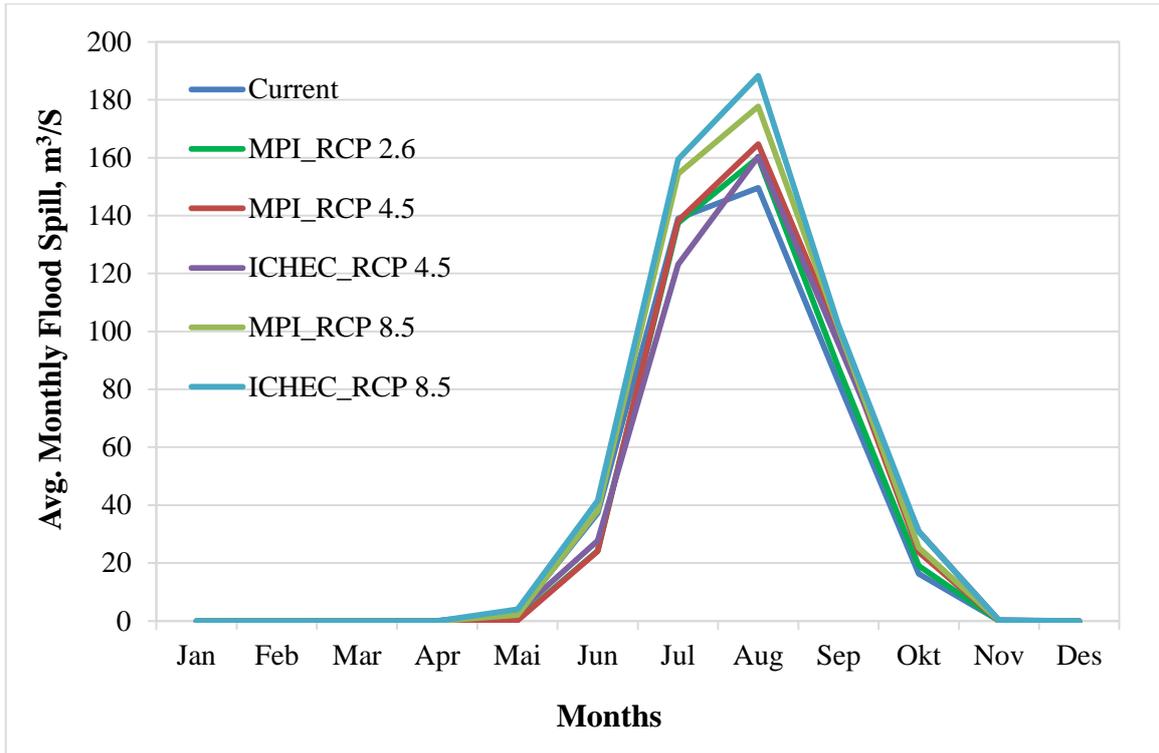
Figure 9-9 Average monthly flood spill by mid century
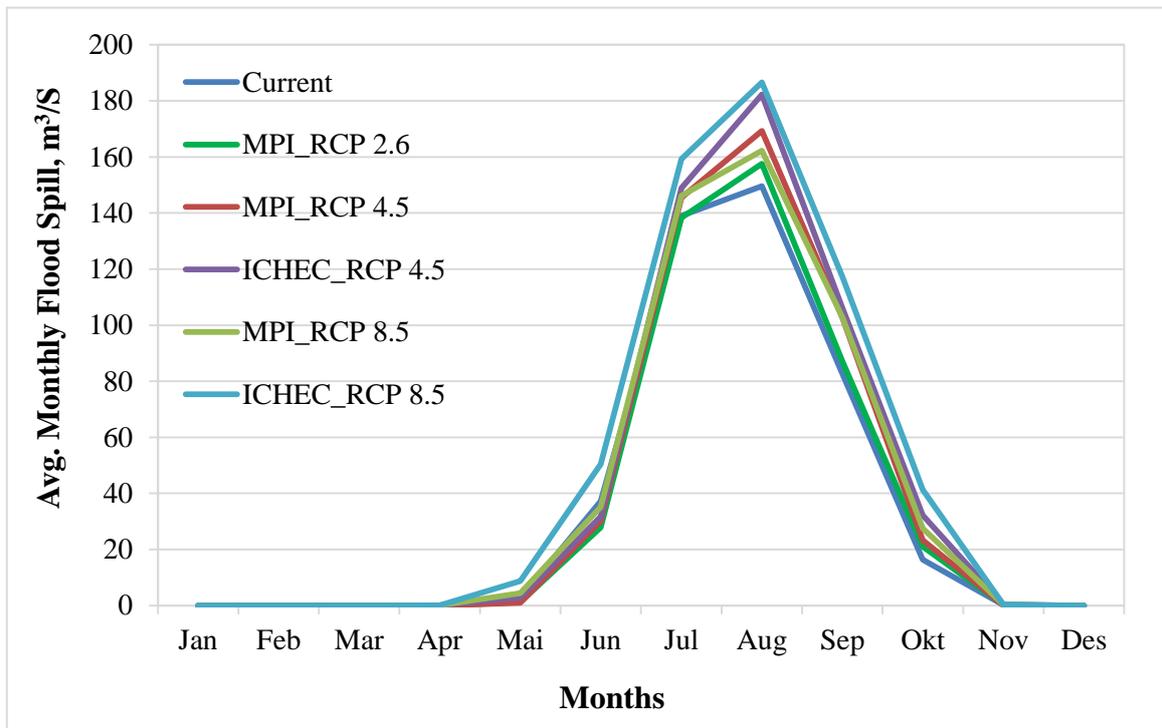
Figure 9-10 Average monthly flood spill by end century

9.6   Discussions

A good simulation of future conditions on power production was successful through the use of nMAG model. Though model set up covered a small area of the basin, a good overview of impact of climate change on power potential was obtained. For the discussed setup, it has been found that the annual power production increases in future under almost every scenario. Similar to discharge trend, increase in production is more distinct by end century compared to mid-century. Simulation results under RCP 8.5 shows higher production in future compared to RCP 4.5 while production under RCP 2.6 was found to be almost same as present situation.

The more interesting events were with flood spill. Simulation results show that, in future with increase in flow, flood spill during wet seasons also increases. As the storage system is very small and only focuses on daily peaking production, the flood spill cannot be utilised by having optimum reservoir planning for future. However, the increased flow and extra spill can be utilised for upgrading the same power system in future which can be very helpful to meet the increased demand with only few investment. It should also be noted that this is just a discussion made through simple simulation of future conditions on a small power system neglecting a number of parameters like sediment flow conditions, turbines efficiency and so on in future. Thus, comprehensive study and planning is required to see if the increased flow could certainly be utilised for upgrading the power plant in future.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

Every chapter includes discussions related to the corresponding heading. However, this is a summary and a sequential link to all those discussions made throughout the study.

The main aim of the study was to observe the likely impact of climate change on water availability in Koshi basin and simulate its consequent effect on power potential. To do so, the main methodology adopted was to establish HBV model for the study basin, use climate models to make future projections and simulate future flows under scenarios using the calibrated HBV model. Those current and future flows simulated were then fed to nMAG model setup made to see the impacts on power potential due to climate change.

The results show that a good basin scale HBV model has been established to represent the hydrology of Koshi basin. Despite the challenges; like lack of uniformly distributed meteorological stations, very less information for the Tibetan part of catchment and uncertain precipitation patterns in high Himalayas, model calibration has been satisfactorily done with an average R^2 of 0.86 and good fit between the observed and simulated discharge graphs. The model performance was found satisfactory even outside the period of calibration also with an average R^2 of 0.85. However, the model failed to catch peak in some years which could be a reason of average daily data storage system. Besides, the performance may be improved through better model handling experience.

Climate change assessment in Koshi basin showed a significant monthly and seasonal variation compared to annual changes. The results also presented the fact that climate change is highly uncertain as the results were varying widely with models, scenarios and time frames. Almost consistent results were obtained on projected temperature changes with the models. It was found that temperature in future is supposed to increase on average by 2.56^0 and 3.58^0 than the current situation, by mid and end century, respectively. These results were in fact comparable with IPCC projections for Nepal. However, the rate of increase were found higher in winter and postmonsoon seasons with small increment in monsoon period and projections under MPI were higher than under ICHEC (exception in postmonsoon), for both time frames. The two models projected completely different precipitation patters with MPI suggesting mostly a decreasing trend while increasing trend under model ICHEC. The decrease in rainfall were mostly observed during winter and premonsoon, highly pronounced by mid-century compared to end

century. However, the flow simulation gave a different results. Flow in future is expected to increase throughout the year for both time frames with few exceptions. Quantity and time of snow melt could be a reason behind increased flow even on decreased precipitation period. No change were observed on distribution of flow i.e. monsoon remaining the prominent source of water in future also.

The effect of these changes in flow patterns on hydropower potential were studied using an nMAG set up already made for Likhu HEP system which lies in Koshi basin, with necessary downscaling and changes. With increased flow under almost all scenarios, annual power productions are expected to increase in future, with an assumption of all other conditions remaining the same. Flood spill are supposed to be increasing in future. Being ROR system, there was no point on effective reservoir planning, thus focus can be made on possibility of extension of capacity of the plant in future in order to utilise the extra spill and to meet higher demand.

In conclusion, climate change has been an interesting and important topic on relation with water availability and utilisation, also with equal uncertainty associated. Basin scale studies on climate change for the selected area has been satisfactorily done but are left with questions about impacts on sub basin scale. The basin area being large enough needs to have sub basin scale study to get more detail impact assessment and visualise the local changes which are very important for hydropower planning and potential.

10.2 Recommendations

The recommendations based on the present study experience are;

➢ Uniformly distributed precipitation stations are very necessary to uplift the quality of studies in Nepalese catchments. The precipitation patterns are so complex and influenced by a number of factors like topography, elevation, windward/leeward side that makes estimation of areal precipitation very challenging and if done, is mixed with uncertainties.

➢ Most of the river basins of Nepal have their catchment areas out of the country's boundary. It is therefore equally important to have information and data access for that part of catchment. Thus, more time and effort needs to be applied to study such basins. An interesting part in this study could have been to see if the historical climate data for the grids could be used to represent Tibetan part of catchment.

➢ HBV model failed to catch the peak especially during flood periods which could be a reason of average daily data storage system. Monsoon season being the most dominant period for water availability, precise measurement of flow especially during this season is recommended.

➢ Sub basin scale study is highly recommended particularly in this basin because of wide variation in altitude and environment within the basin.

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Appendix A: Hydro - Meteorological Stations in Koshi Basin

Precipitation Stations:

S.N	Station name	Index No.	District	Elevation, m.a.s.l	Latitude	Longitude
1	Gumthang	1006	Sindhupalchok	2000	$27^052'0"$	$85^052'0"$
2	Nawalpur	1008	Sindhupalchok	1592	$27^048'0"$	$85^037'0"$
3	Chautara	1009	Sindhupalchok	1660	$27^047'0"$	$85^043'0"$
4	Sarmathang	1016	Sindhupalchok	2625	$27^057'0"$	$85^036'0"$
5	Dubachaur	1017	Sindhupalchok	1550	$27^052'0"$	$85^034'0"$
6	Baunepati	1018	Sindhupalchok	845	$27^047'0"$	$85^034'0"$
7	Mandan	1020	Kabhre	1365	$27^042'0"$	$85^039'0"$
8	Dolal ghat	1023	Kabhre	710	$27^038'0"$	$85^043'0"$
9	Dhulikhel	1024	Kabhre	1552	$27^037'0"$	$85^033'0"$
10	Dhap	1025	Sindhupalchok	1240	$27^055'0"$	$85^038'0"$
11	Bahrabise	1027	Sindhupalchok	1220	$27^047'0"$	$85^054'0"$
12	Pachuwar ghat	1028	Kabhre	633	$27^034'0"$	$85^045'0"$
13	Panchkhal	1036	Kabhre	865	$27^041'0"$	$85^038'0"$
14	Khopasi	1049	Kabhre	1517	$27^035'0"$	$85^031'0"$
15	Tarke ghyang	1058	Sindhupalchok	2480	$28^00'0"$	$85^033'0"$
16	Sangachok	1062	Sindhupalchok	1327	$27^042'0"$	$85^043'0"$
17	Thokarpa	1063	Sindhupalchok	1750	$27^042'0"$	$85^047'0"$
18	Dhap	1078	Sindhupalchok	1310	$27^054'0"$	$85^038'0"$
19	Nagdaha	1101	Dolkha	850	$27^041'0"$	$86^006'0"$
20	Charikot	1102	Dolkha	1940	$27^040'0"$	$86^003'0"$
21	Jiri	1103	Dolkha	2003	$27^038'0"$	$86^014'0"$
22	Melung	1104	Dolkha	1536	$27^031'0"$	$86^003'0"$
23	Sindhuli gadhi	1107	Sindhuli	1463	$27^017'0"$	$85^058'0"$
24	Bahun tilpung	1108	Sindhuli	1417	$27^011'0"$	$86^010'0"$
25	Nepalthok	1115	Sindhuli	1098	$27^027'0"$	$85^049'0"$
26	Manthali	1123	Ramechhap	495	$27^028'0"$	$86^005'0"$
27	Chaurikhark	1202	Solukhumbu	2619	$27^042'0"$	$86^043'0"$

28	Pakarnas	1203	Solukhumbu	1982	$27^0$26'0"	$86^0$34'0"
29	Aisealukhark	1204	Khotang	2143	$27^0$21'0"	$86^0$45'0"
30	Okhaldhunga	1206	Okhaldhunga	1720	$27^0$19'0"	$86^0$30'0"
31	Mane bhanjyang	1207	Okhaldhunga	1576	$27^0$29'0"	$86^0$25'0"
32	Kurule ghat	1210	Khotang	497	$27^0$08'0"	$86^0$26'0"
33	Khotang bazar	1211	Khotang	1295	$27^0$02'0"	$86^0$50'0"
34	Salleri	1219	Solukhumbu	2378	$27^0$30'0"	$86^0$35'0"
35	Diktel	1222	Khotang	1623	$27^0$13'0"	$86^0$48'0"
36	Sirwa	1224	Solukhumbu	1662	$27^0$33'0"	$86^0$23'0"
37	Num	1301	Sankhuvwasabha	1497	$27^0$33'0"	$87^0$17'0"
38	Chainpur (east)	1303	Sankhuvwasabha	1329	$27^0$17'0"	$87^0$20'0"
39	Pakhribas	1304	Dhankuta	1680	$27^0$03'0"	$87^0$17'0"
40	Leguwa ghat	1305	Dhankuta	410	$27^0$08'0"	$87^0$17'0"
41	Munga	1306	Dhankuta	1317	$27^0$02'0"	$87^0$14'0"
42	Dhankuta	1307	Dhankuta	1210	$26^0$59'0"	$87^0$21'0"
43	Mul ghat	1308	Dhankuta	365	$26^0$56'0"	$87^0$20'0"
44	Tribeni	1309	Dhankuta	143	$26^0$56'0"	$87^0$09'0"
45	Terhathum	1314	Terhathum	1633	$27^0$08'0"	$87^0$33'0"
46	Chepuwa	1317	Sankhuvwasabha	2590	$27^0$46'0"	$87^0$25'0"
47	Tumlingtar	1321	Sankhuvwasabha	303	$27^0$17'0"	$87^0$13'0"
48	Machuwaghat	1322	Dhankuta	158	$26^0$58'0"	$87^0$10'0"
49	Dingla	1325	Bhojpur	1190	$27^0$22'0"	$87^0$09'0"
50	Lungthung	1403	Taplejung	1780	$27^0$33'0"	$87^0$47'0"
51	Taplejung	1405	Taplejung	1732	$27^0$21'0"	$87^0$40'0"
52	Memeng jagat	1406	Panchther	1830	$27^0$12'0"	$87^0$56'0"
53	Phidim	1419	Panchther	1205	$27^0$09'0"	$87^0$45'0"
54	Dovan	1420	Taplejung	763	$27^0$21'0"	$87^0$36'0"

Hydrological Stations:

S.N	Stn No.	River	Location	Elevation, m.a.s.l	Latitude	Longitude
1	600.1	Arun River	Uwa Goan	1294	$27^0 36'0''$	$87^0 20'06''$
2	602.5	Hinwa Khola	Pipletar	300	$27^0 17'45''$	$87^0 13'30''$
3	604.5	Arun River	Turkeghat	414	$27^0 20'00''$	$87^0 11'30''$
4	606	Arun River	Simle	152	$26^0 55'30''$	$87^0 09'30''$
5	610	Bhote Koshi	Barhbise	840	$27^0 47'10''$	$85^0 53'20''$
6	620	Balephi Khola	Jalbire	793	$27^0 48'20''$	$85^0 46'10''$
7	627.5	Melanchi Khola	Helambu	2134	$28^0 02'30''$	$85^0 32'00''$
8	630	Sunkoshi River	Pachuwarghat	589	$27^0 33'30''$	$85^0 45'10''$
9	647	Tamakoshi	Busti	849	$27^0 38'05''$	$86^0 05'12''$
10	650	Khimati Khola	Rasnalu	1120	$27^0 34'30''$	$86^0 11'50''$
11	652	Sunkoshi River	Khurkot	455	$27^0 20'00''$	$86^0 00'00''$
12	660	Likhu Khola	Sangutar	543	$27^0 20'10''$	$86^0 13'10''$
13	670	Dudhkoshi River	Rabuwa Bazar	460	$27^0 16'00''$	$86^0 39'50''$
14	681	Sunkoshi River	Hampachuwar	150	$26^0 55'15''$	$87^0 08'45''$
15	684	Tamor River	Majhitar	533	$27^0 09'30''$	$87^0 42'45''$
16	690	Tamur River	Mulghat	276	$26^0 55'50''$	$87^0 19'45''$
17	695	Saptakoshi River	Chatara	140	$26^0 52'00''$	$87^0 09'30''$

Temperature Stations:

S.N.	Station Name	Index No.	District	Elevation m.a.s.l	Latitude	Longitude
1	Dhulikhel	1024	Kabhre	1552	$27^0$37'0"	$85^0$33'0"
2	Panchkhal	1036	Kabhre	865	$27^0$41'0"	$85^0$38'0"
3	Jiri	1103	Dolkha	2003	$27^0$38'0"	$86^0$14'0"
4	Sindhuli gadhi	1107	Sindhuli	1463	$27^0$17'0"	$85^0$58'0"
5	Okhaldhunga	1206	Okhaldhunga	1720	$27^0$19'0"	$86^0$30'0"
6	Chainpur (East)	1303	Sankhuvwasabha	1329	$27^0$17'0"	$87^0$20'0"
7	Pakhribas	1304	Dhankuta	1680	$27^0$03'0"	$87^0$17'0"
8	Dhankuta	1307	Dhankuta	1210	$26^0$59'0"	$87^0$21'0"
9	Terhathum	1314	Terhathum	1633	$27^0$08'0"	$87^0$33'0"
10	Taplejung	1405	Taplejung	1732	$27^0$21'0"	$87^0$40'0"
11	Phidim (Panchther)	1419	Panchther	1205	$27^0$09'0"	$87^0$45'0"

Evaporation Stations:

S.N	Index No.	District	Elevation m.a.s.l	Latitude	Longitude
1	1103	Dolkha	2003	$27^0$38'0"	$86^0$14'0"
2	1304	Dhankuta	1680	$27^0$03'0"	$87^0$17'0"

Appendix B: R Scripts for Data Processing

Precipitation Data Processing

```
setwd("D:/Thesis/Data/from DHM/Rainfall") # working directory
install.packages("hydroTSM") # Installation of packages required
library(hydroTSM)
library(zoo)
fold=list.files(pattern="*.*") # list files in the folder
for ( j in 1:length(fold)){ #Loop
ls=list.files(path=paste(getwd(), fold[j], sep="/"), pattern="*.*",full.names = T)
datf=data.frame() #variable setting
for( i in 1:length(ls)){ #second loop (to read all the years data from a folder)
dat= read.table(ls[i], na.strings =  "DNA",  stringsAsFactors =F) # read the data from file
dat[,2]=as.numeric(dat[,2])
dat[,2][dat[,2]=="T"] <- 0
datf= rbind(datf, dat)            }#binding data as per rows
std =as.Date("1994-01-01") # start date
series=zooreg(datf[,2], start=std) # daily timeseries creation
mont= hydroTSM::daily2monthly(series, FUN=sum, na.rm=TRUE)
flnam= paste("D:\\Thesis\\Result_fig\\",fold[j], ".pdf", sep="") #graph storage folder
pdf(file=flnam,width=8,height=6.1,pointsize=12)
par(oma=c(2,1,1,1),mar=c(4,6,2,1)+0.1, mfrow=c(3,1)) ## Make enough room for both labels
plot(series, ylab="daily RR, mm", xlab="",las=1)
grid()
dyr= daily2annual(series, FUN=sum, na.rm=T) #daily to annual
yr= format(index(dyr), "%Y")
cd=coredata(dyr)
mids=barplot(cd, xlab="", ylab="Annual RR, mm", ylim=c(0,5000), las=1)
axis(1, at=mids, labels=yr, las=3)
mn=monthlyfunction(mont, FUN=mean )
barplot(mn, ylab="monthly RR, mm", ylim=c(0,1000), las=1)
grid()
dev.off()          }
```

Discharge Data Processing

```r
setwd("D:\\Thesis\\Data\\from DHM\\Discharge\\")

library(zoo)

library(hydroTSM)

lsf=list.files( ) # list folder

for( k in 1:19){ #this loop for the flow stations

ls=list.files(lsf[k], full.names = T) # list file inside folder

yrf=list.files(lsf[k], full.names = F)

yrf=substr(yrf, 1,4)

yr=list.files(lsf[k], full.names = F)[1] # list file inside folder

styr=substr(yr, 1,4) #start of the year

vec_f=c()

for (j in 1:length(ls)) {

ft=read.delim(ls[j],header=F, skip=0,nrows=31,  stringsAsFactors =F)

write.table(ft, "test.txt", row.name=F)

 rr=read.table("test.txt", stringsAsFactors=F , header=T,sep="\t")

dim(str)

names(rr)

str(rr)

 unlink("test.txt")

cn= c("day",month.abb)

myvec=rr[1,1] # it reads first row as rr is data frame with 1 variable but 31 rows

res=do.call(rbind, strsplit(myvec, " ")) ## read the first and split and make character vector

str(res)

rb=res[!res==""] #remove the un ncessary doubl quote

 for (i in 2:28){    # consider 28 rows from second row as first row is already taken care of

 myvec=rr[i,1]

 res=do.call(rbind, strsplit(myvec, " "))

 res1=res[!res==""]

length(res1)

 rb=rbind(rb,res1)     }

 # processing the 31th days row equivalent

 myvec=rr[31,1]

 res=do.call(rbind, strsplit(myvec, " "))
```

```r
 res1=res[!res==""]
length(res1)
 dy31=c(res1[1],res1[2], -999,res1[3], -999, res1[4], -999, res1[5], res1[6], -999, res1[7], -999,
res1[8] )
  dy31
# processing the 30th days row equivalent
myvec=rr[30,1]
res=do.call(rbind, strsplit(myvec, " "))
res1=res[!res==""]
length(res1)
dy30=c(res1[1],res1[2], -999,res1[3], res1[4],   res1[5], res1[6],   res1[7],   res1[8],res1[9],
res1[10], res1[11], res1[12] )
# processing the 29th days row equivalent
myvec=rr[29,1]
res=do.call(rbind, strsplit(myvec, " "))
res1=res[!res==""]
length(res1)
if(length(res1)==13){ # this check for the leap year
  dy29=res1     }else {
  dy29=c(res1[1],res1[2], -999,res1[3], res1[4],   res1[5], res1[6],   res1[7],   res1[8],res1[9],
res1[10], res1[11], res1[12] )          }
rbf=rbind(rb, dy29, dy30,dy31)
colnames(rbf)=cn
row.names(rbf)=NULL
vec=as.vector(rbf[,-1]) # put in long list that make a lost of vector by each month
mode(vec)="numeric"
vec1=as.numeric(vec)
vec2 <- vec1[vec1 != -999]
vec_f=c(vec_f,vec2)            }
dt=paste(styr,"-01-01", sep="")
zoo(vec2, as.Date(dt)+1:length(vec2)-1)
zp=zoo(vec_f, as.Date(dt)+1:length(vec_f)-1)
plot(zp)
zp[zp==-99] <- NA
```

```r
write.zoo(zp, "test.txt")
plot(zp)
Sys.sleep(3)
save(zp, file=paste("D:\\Thesis\\Result_fig\\Discharge\\", lsf[k], ".Rdata", sep=""))
write.zoo(zp, paste(file="D:\\Thesis\\Result_fig\\Discharge\\", lsf[k], ".txt", sep=""))
}
# Merge zoo
rd=list.files(path="D:\\Thesis\\Result_fig\\Discharge\\",pattern="*.Rdata",  full.names = T)
rd1=list.files(path="D:\\Thesis\\Result_fig\\Discharge\\",pattern="*.Rdata",  full.names = F)
plot(get(load(rd[1])), ylim=c(0,8000), ylab="flow, m3/s")
np=get(load(rd[1]))
nm=substr(rd1, 1,(nchar(rd1)-6))
nm #station_Name
plot(get(load(rd[1])), ylim=c(0,8000), ylab="flow, m3/s")
np=get(load(rd[1]))
for (m in (2:19)){
  lines(get(load(rd[m])), col=colors()[m])
  np1=get(load(rd[m]))
  np=merge(np, np1)      }
names(np)<- nm
#save in excel file
write.zoo(np,"D:\\Thesis\\Result_fig\\Discharge\\flow1.csv")
pdf("D:\\Thesis\\Result_fig\\Discharge\\Discharge_plot.pdf")
plot(get(load(rd[1])), ylab="flow, m3/s",main=paste("station_", nm[1], sep=""))
for (m in (2:19)){
 plot(get(load(rd[m])), ylab="flow, m3/s", main=paste("station_", nm[m], sep=""))
}
dev.off()
```

Appendix C: Results of HBV Model Calibration and Validation - Model Setup 1
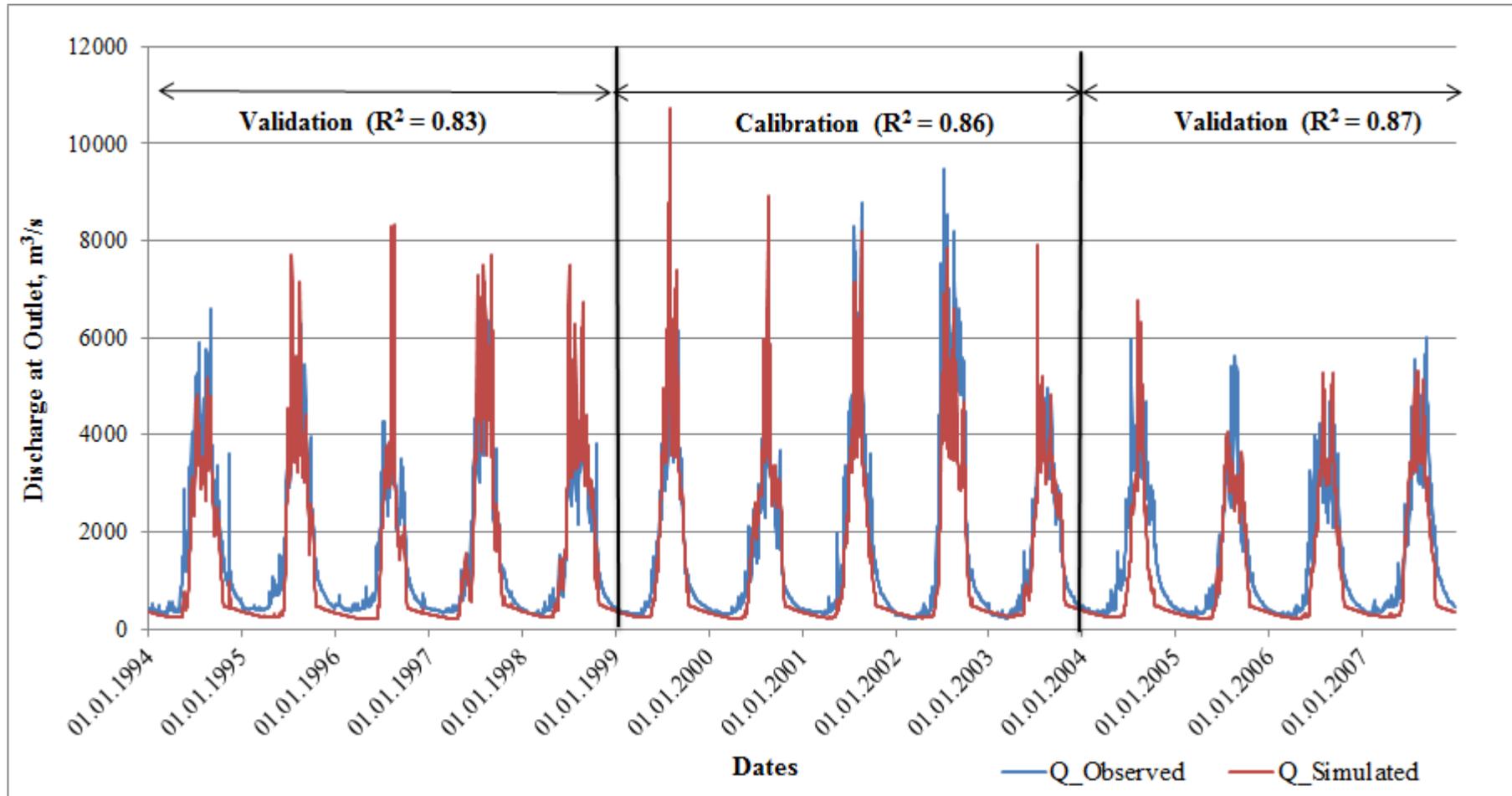
Appendix D: R Scripts used for Climate Data Processing

Step 1: Extraction of grid points within catchment

#Needed packages:

library(ncdf4)

library(ncdf)

library(rgdal)

library(sp)

library(maptools)

setwd ("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_1")

#Read shapefile (selected map or study area)

Sp =

readShapeSpatial("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Catchment\\Koshi_CA.shp")

#Read nc file to get the structure of the points, this can be done with any .nc file (RCM)

mycdf   <-   nc_open("tas_WAS-44_MPI-M-MPI-ESM-LR_rcp26_r1i1p1_MPI-CSC-
REMO2009_v1_day_20510101-20551231.nc", verbose = TRUE, write = FALSE)

This method is to find a cell number of data set, therefore this cell number is needed only
once

##Grab the longitude (lon) and latitude (lat) and other data (tm, pr) from RCM

lat <- ncvar_get(mycdf,"lat")

lon <- ncvar_get(mycdf,"lon")

tm <- ncvar_get(mycdf,"time_bnds")

pr <- ncvar_get(mycdf, varid="tas", start=NA, count=NA, verbose=FALSE,
signedbyte=TRUE, collapse_degen=TRUE)

##Construct a data frame from RCM data structure, then they will be filled-in with lat, long and
.nc other data

lat_lng <- data.frame()

prg_f <- data.frame()

Define lat and long for each of the points existing in the .nc

for (i in 1:412) { # 412 is the raster dimension (equal for all all the raster has same dimension
(this is the reason for 412)

latg <- round(lat[,i],2)

long <- round(lon[,i],2)

precipiation is extracted only for one day

```
prg <- pr[, i,1]

prg <- data.frame(prg)

prg_f <- rbind(prg_f, prg)

latlong <- cbind(long,latg)

lat_lng <- rbind(lat_lng, latlong)

}
```

Convert above data into spatial data framework

```
dat <- SpatialPointsDataFrame(lat_lng, data=prg_f,

proj4string=CRS("+proj=longlat +datum=WGS84 "))
```

Write above data as shape file (it goes into a folder node_Shapefile)

```
writeOGR( dat, dsn = 'node_Shapefile', layer = 'node_Shapefile', driver='ESRI
Shapefile',overwrite_layer=T)
```

Read above data for later use (read the data from the created node_Shapefile)

```
xx <- readShapePoints("node_Shapefile\\node_Shapefile.shp")
```

Get overlayed coordinates

```
op_1 = overlay(xx,sp)

poly1<- cbind(xx@ coords,xx@data,op_1) # 1 is inside polygon and NA is outside polygon

pt_1 <- poly1[(!is.na(poly1$op_1)) ,  #remove NA rows selects only # pt_1_ latitude, longitude

rr <- pt_1[,-4]

lati <- round(lat,2)

longi <- round(lon,2)

fl <- c()

ft  <- c()

for (i in 1:dim(rr)[1]){

l <- which(longi==rr[i,1])  #to find index in the matrix longitude

t <- which(lati==rr[i,2]) # to find index in the matrix latitude

fl <- c(fl,l)

ft <- c(ft, t)

}

idx <- intersect(fl,ft) # the same index for latitude and logitude based on which the

save(idx, file=".\\index_of_the_3d_matrix.Rdata")

plot(sp)

points(lon[idx],lat[idx])

rr_final<-rr[,-3]
```

names(rr_final)

colnames(rr_final)[1]<-"latitude"

colnames(rr_final)[2]<-"longitude"

names(rr_final)

write.table(rr_final, file=".\\index_of_the_3d_matrix.txt",col.names = T)

Step 2: Extraction of daily data from .NC files

➢ **For Rainfall Data**

```
#This script will have to be ran for each of the models and RCPs + historical data

rm(list=ls())

memory.limit(50000)

library(ncdf4)

library(rhdf5)

library(raster)

setwd("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_2\\RR\\Historical")

#setwd("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_2\\RR\\RCP_26") and so on

lst <- list.files(getwd(), pattern="\\.nc$")

# this loop for the nc files

for (k in 1:length(lst)){

rm(nc)

nc <- nc_open(lst[k], verbose = TRUE, write = FALSE)

#List the content of the HDF5 file.

 fname=lst[k]

long <- h5read(fname, "lon")

lat <- h5read(fname, "lat")

rm(pr)

pr <- h5read(lst[k], "pr")

 h5read(lst[k], "time_bnds")

# create data based on file name

idx <-

get(load("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_1\\index_of_the_3d_matrix.Rdata

"))

fn <- lst[k]
```

```r
dt <- substr(fn, (nchar(fn)-19),(nchar(fn)-3))
st <- as.Date(paste(substr(dt,1,4), substr(dt,5,6), substr(dt,7,8) , sep="-"))
ed <- as.Date(paste(substr(dt,10,13), substr(dt,14,15), substr(dt,16,17) , sep="-"))
d_dt <- seq(st, ed, by="1 day")
length(d_dt)
dim(pr)[3]
rr_f <- data.frame()
for (j in 1:dim(pr)[3]) {# hope j=1 means first day
rr <- pr [, , j] [idx]
rr <- as.data.frame(rr)
colnames(rr)<- d_dt[j]
rr <- t(rr)
rr_f <-  rbind(rr_f,rr)   }
lat <- lat[idx]
long <- long[idx]
rr_f <- round(rr_f*24*3600,3)
rr_ff <- rbind(long, lat,rr_f)
rownames(rr_ff)[1]<- "Longitude"
rownames(rr_ff)[2]<- "Latitude"
fn_txt <- substr(fn, 1, nchar(fn)-3)
fn_txt <- paste(fn_txt,".txt", sep="")
write.table(rr_ff, fn_txt,col.names = F)
library(zoo)
rr_zoo<- zoo(rr_f, d_dt)
fn_zoo <- paste(fn_txt,".Rdata", sep=" ")
save(rr_zoo,file=fn_zoo)
}
```

➢ For Temperature Data

```
rm(list=ls())
memory.limit(50000)
library(ncdf4)
library(rhdf5)
library(raster)
setwd("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_2\\TEMP\\Historical")
lst <- list.files(getwd(), pattern="\\.nc$")
# this loop for the nc files
for (k in 1:length(lst)){
rm(nc)
nc <- nc_open(lst[k], verbose = TRUE, write = FALSE)
#List the content of the HDF5 file.
fname <- lst[k]
h5ls(fname) # to access variable
fname=lst[k]
long <- h5read(fname, "lon")
long <- round(long,3)
lat <- h5read(fname, "lat")
lat <- round(lat, 3)
rm(pr)
pr <- h5read(lst[k], "tas")
# create data based on file name
idx <-
get(load("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_1\\index_of_the_3d_matrix.Rdata
"))
fn <- lst[k]
dt <- substr(fn, (nchar(fn)-19),(nchar(fn)-3))
st <- as.Date(paste(substr(dt,1,4), substr(dt,5,6), substr(dt,7,8) , sep="-"))
ed <- as.Date(paste(substr(dt,10,13), substr(dt,14,15), substr(dt,16,17) , sep="-"))
d_dt <- seq(st, ed, by="1 day")
rr_f <- data.frame()
for (j in 1:dim(pr)[3]) {# hope j=1 means first day
rr <- pr [, , j] [idx]
```

```r
rr <- as.data.frame(rr)
colnames(rr)<- d_dt[j]
rr <- t(rr)
rr_f <-  rbind(rr_f,rr)            }
lat <- lat[idx]
long <- long[idx]
rr_f <- rr_f-273.15
rr_f <- round(rr_f,3)
rr_ff <- rbind(long, lat,rr_f)
rownames(rr_ff)[1]<- "Longitude"
rownames(rr_ff)[2]<- "Latitude"
fn_txt <- substr(fn, 1, nchar(fn)-3)
fn_txt <- paste(fn_txt,".txt", sep="")
write.table(rr_ff, fn_txt,col.names = F)
library(zoo)
rr_zoo<- zoo(rr_f, d_dt)
fn_zoo <- paste(fn_txt,".Rdata", sep=" ")
save(rr_zoo,file=fn_zoo)
}
```

Step 3: Computation of Delta Changes

➢ For Rainfall Data

```r
#This script will convert daily data to monthly data, first for the historical data, and then for each of the scenarios
rm(list=ls())
library(zoo)
require(hydroTSM)
library(raster)
library(sp)
library(rgdal)
scn <- "Delta_cal_RR_step_3.R"
setwd("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_2\\RR\\Historical")
lst <- list.files(getwd(), pattern="\\.Rdata$")
a <- get(load(lst[1]))
```

```r
for (k in 2:length(lst)){
b <- get(load(lst[k]))
names(b) <- names(a)
a <- rbind(a, b)
}
#Creating the file where all data is together
a<- window(a, start=as.Date("1971-01-01"), end=as.Date("2000-12-31"))
nm <-
("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\Historical\\pr_daily_Remo_2009_
hist_1971-00.Rdata")
save(a, file=nm)
write.table(a,
"D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\Historical\\pr_daily_Remo_2009_h
ist_1971-00.txt")
#Creation of .Rdat and pdf outputs:
mnth <- daily2monthly(a, FUN="sum")
mnth <- monthlyfunction(a, FUN="mean")
save(mnth,
file="D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\Historical\\mean_monthly_Re
mo_2009_hist_1971-2000.Rdata")
## Remo_2009_RCP_85
setwd("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_2\\RR\\RCP_85")
lst <- list.files(getwd(), pattern="\\.Rdata$")
a <- get(load(lst[1]))
for (k in 2:length(lst)){
b <- get(load(lst[k]))
names(b) <- names(a)
a <- rbind(a, b)
}
r1<- window(a, start=as.Date("2041-01-01"), end=as.Date("2070-12-31"))
r2<- window(a, start=as.Date("2071-01-01"), end=as.Date("2100-12-31"))
nm1<-
("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\RCP_85\\pr_daily_Remo_2009_rc
p85_2041-70.Rdata")
```

```
nm2 <-
("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\RCP_85\\pr_daily_Remo_2009_rc
p85_2071-00.Rdata")
save(r1, file=nm1)
save(r2, file=nm2)
setwd("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\RCP_85")
mnth1 <- monthlyfunction(r1, FUN="mean")
save(mnth1, file="mean_monthly_Remo_rcp85_2041-2070.Rdata")
mnth2 <- monthlyfunction(r2, FUN="mean")
save(mnth2, file="mean_monthly_Remo_rcp85_2071-2100.Rdata")
#calculate delta change Remo_2009_RCP_85------------------------------------------------
remo_hist <-
load("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\Historical\\mean_monthly_Re
mo_2009_hist_1971-2000.Rdata")
remo_hist <- mnth
remo_41_70<-
load("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\RCP_85\\mean_monthly_Rem
o_rcp85_2041-2070.Rdata")
remo_41_70 <- mnth1
delta_remo_4170_to_hist_rcp_85 <- (remo_41_70-remo_hist)/remo_hist*100
remo_71_21 <-
load("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\RCP_85\\mean_monthly_Rem
o_rcp85_2071-2100.Rdata")
 remo_71_21<- mnth2
delta_remo_7100_to_hist_rcp_85 <- (remo_71_21-remo_hist)/remo_hist*100
write.table(delta_remo_7100_to_hist_rcp_85, "delta.txt")
rp1 <-  apply(delta_remo_4170_to_hist_rcp_85,2, "mean")
 save(rp1
,file="D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\ALL_DELTA\\delta_Remo_2
009_rcp85_1971-2000_vs_2041-2070.Rdata")
 rp2 <- apply(delta_remo_7100_to_hist_rcp_85,2, "mean")
save(rp2
,file="D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\ALL_DELTA\\delta_Remo_2
009_rcp85_1971-2000_vs_2071-2100.Rdata")
```

```r
write.table(rp1,
file="D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\ALL_DELTA\\delta_Remo_2
009_rcp85_1971-2000_vs_2041-2070.txt")
write.table(rp2, file=
"D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\RR\\ALL_DELTA\\delta_Remo_2009_
rcp85_1971-2000_vs_2071-2100.txt")
```

> **For Temperature Data**

```r
rm(list=ls())
library(zoo)
require(hydroTSM)
library(raster)
library(sp)
library(rgdal)
library(proj4)
gpclibPermit()
scn <- "Delta_cal_TEMP_step_3.R"
## Remo_2009_hist
setwd("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_2\\TEMP\\Historical")
lst <- list.files(getwd(), pattern="\\.Rdata$")
a <- get(load(lst[1]))
for (k in 2:length(lst)){
b <- get(load(lst[k]))
names(b) <- names(a)
a <- rbind(a, b)                    }
#Creating the file where all data is together
a<- window(a, start=as.Date("1971-01-01"), end=as.Date("2000-12-31"))
nm <-
("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\Historical\\tm_daily_Remo_20
09_hist_1971-00.Rdata")
save(a, file=nm)
#Creation of .Rdat and pdf outputs:
setwd("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\Historical\\")
mnth <- monthlyfunction(a, FUN="mean")
```

```r
save(mnth, file="mean_monthly_Remo_2009_hist_1971-2000.Rdata")
## Remo_2009_RCP_26
setwd("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_2\\TEMP\\RCP_26")
rm(a)
rm(lst)
lst <- list.files(getwd(), pattern="\\.Rdata$")
a <- get(load(lst[1]))
for (k in 2:length(lst)){
b <- get(load(lst[k]))
names(b) <- names(a)
a <- rbind(a, b)
}
r1<- window(a, start=as.Date("2041-01-01"), end=as.Date("2070-12-31"))
r2<- window(a, start=as.Date("2071-01-01"), end=as.Date("2100-12-31"))
nm1<-
("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\RCP_26\\tm_daily_Remo_200
9_rcp26_2041-70.Rdata")
nm2 <-
("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\RCP_26\\tm_daily_Remo_200
9_rcp26_2071-00.Rdata")
save(r1, file=nm1)
save(r2, file=nm2)
setwd("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\RCP_26")
mnth1 <- monthlyfunction(r1, FUN="mean")
save(mnth1, file="mean_monthly_Remo_2009_rcp26_2041-2070.Rdata")
mnth2 <- monthlyfunction(r2, FUN="mean")
save(mnth2, file="mean_monthly_Remo_2009_rcp26_2071-2100.Rdata")
#calculate delta change Remo_2009_RCP_26---------------------------------------------
remo_hist <-
load("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\Historical\\mean_monthly_
Remo_2009_hist_1971-2000.Rdata")
remo_hist <- mnth
```

```
remo_41_70<-
load("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\RCP_26\\mean_monthly_
Remo_2009_rcp26_2041-2070.Rdata")
remo_41_70 <- mnth1
delta_remo_4170_to_hist_rcp_26 <- (remo_41_70-remo_hist)
remo_71_21 <-
load("D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\RCP_26\\mean_monthly_
Remo_2009_rcp26_2071-2100.Rdata")
remo_71_21<- mnth2
delta_remo_7100_to_hist_rcp_26 <- (remo_71_21-remo_hist)
rp1 <-  apply(delta_remo_4170_to_hist_rcp_26,2, "mean")
save(rp1
,file="D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\All_DELTA\\delta_Remo_
2009_rcp26_1971-2000_vs_2041-2070.Rdata")
write.table(rp1,
file="D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\All_DELTA\\delta_Remo_
2009_rcp26_1971-2000_vs_2041-2070.txt")
rp2 <- apply(delta_remo_7100_to_hist_rcp_26,2, "mean")
save(rp2
,file="D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\All_DELTA\\delta_Remo_
2009_rcp26_1971-2000_vs_2071-2100.Rdata")
write.table(rp2,
file="D:\\Thesis\\CORDEX_Data\\REMO_2009\\Step_3\\TEMP\\All_DELTA\\delta_Remo_
2009_rcp26_1971-2000_vs_2071-2100.txt")
```

Appendix E: Climate Change - HBV Model Inputs

	Precipitation in %						Temperature in degree						Evaporation(Daily) in mm					
Model : MPI																		
Scenarios	RCP 2.6		RCP 4.5		RCP 8.5		RCP 2.6		RCP 4.5		RCP 8.5		RCP 2.6		RCP 4.5		RCP 8.5	
Period	Mid	End	Mid	End	Mid	End	Mid	End	Mid	End	Mid	End	Mid	End	Mid	End	Mid	End
Jan	16.4	67.3	-10.6	-30.3	-28.2	-37.6	2.5	1.7	3.1	3.9	4.0	7.1	0.2	0.1	0.2	0.2	0.2	0.4
Feb	-39.6	-29.8	-21.6	-39.3	-27.8	-39.6	2.3	1.5	3.1	4.2	4.0	7.2	0.2	0.1	0.2	0.3	0.2	0.5
Mar	26.1	8.7	-13.2	3.5	-8.2	-23.0	1.9	1.5	2.9	3.3	3.8	7.0	0.2	0.1	0.2	0.3	0.3	0.7
Apr	-8.5	-7.8	-26.8	2.9	-0.5	-48.8	1.5	1.4	2.8	3.4	4.0	6.4	0.1	0.1	0.3	0.4	0.5	0.9
May	-24.0	-28.4	-28.7	-16.4	-5.1	-23.1	1.2	1.4	2.1	2.7	3.4	5.9	0.1	0.2	0.3	0.3	0.5	1.1
Jun	-9.9	-2.2	-7.7	-5.6	1.8	-9.5	1.6	1.5	2.1	2.6	3.0	5.2	0.3	0.3	0.3	0.5	0.5	1.2
Jul	5.8	3.1	5.8	7.5	8.0	11.7	1.3	1.3	2.0	2.4	2.9	4.9	0.2	0.2	0.4	0.4	0.6	1.2
Aug	4.6	3.9	5.7	7.0	12.9	3.3	1.4	1.3	2.0	2.3	2.8	4.8	0.2	0.2	0.3	0.4	0.5	1.1
Sep	-0.7	-0.8	12.0	15.3	8.2	14.4	1.7	1.0	1.9	2.3	3.2	4.6	0.2	0.1	0.2	0.3	0.5	0.8
Oct	6.9	18.8	11.5	-3.7	10.9	-7.3	1.4	1.3	2.0	2.8	3.3	5.7	0.1	0.1	0.1	0.3	0.3	0.7
Nov	-15.7	-9.3	-24.1	-36.2	-28.1	19.4	1.3	1.3	2.3	2.8	4.2	5.8	0.0	0.1	0.1	0.1	0.3	0.4
Dec	-1.7	64.7	-34.6	26.1	8.2	-19.1	2.4	2.1	3.3	3.5	4.3	6.5	0.2	0.1	0.2	0.2	0.2	0.3
Model: ICHEC																		
Jan			43.1	55.5	-41.4	-11.9			2.5	2.1	3.9	5.8			0.1	0.1	0.2	0.3
Feb			6.4	42.5	21.9	5.3			1.5	2.0	2.7	5.4			0.0	0.0	0.1	0.3
Mar			-15.1	-17.9	17.6	-29.7			2.2	2.5	3.1	6.1			0.2	0.2	0.2	0.6
Apr			9.0	25.1	4.6	33.3			2.4	2.5	2.8	5.4			0.3	0.2	0.3	0.6
May			6.4	-3.3	18.0	24.4			1.8	2.2	2.8	4.7			0.2	0.3	0.4	0.7

Jun		-15.5	-9.5	-0.4	2.0		1.6	2.2	2.6	4.3		0.2	0.4	0.4	0.9
Jul		-3.2	8.5	9.4	8.5		1.7	2.0	2.2	4.0		0.3	0.3	0.4	0.8
Aug		6.5	15.2	19.1	16.9		1.6	2.2	2.4	4.1		0.3	0.4	0.4	0.8
Sep		3.8	12.6	5.6	19.8		1.5	1.9	2.3	3.9		0.2	0.2	0.3	0.6
Oct		55.3	43.7	37.9	61.4		2.4	3.1	3.8	5.5		0.3	0.4	0.5	0.7
Nov		-3.9	4.5	8.3	-31.6		2.3	3.6	4.1	6.5		0.2	0.3	0.4	0.6
Dec		61.6	10.6	-35.6	35.2		2.8	3.1	3.3	6.2		0.2	0.2	0.2	0.4

Appendix F: Daily Hydrograph at Basin Outlet - Under Scenarios

Daily Hydrograph by Mid Century
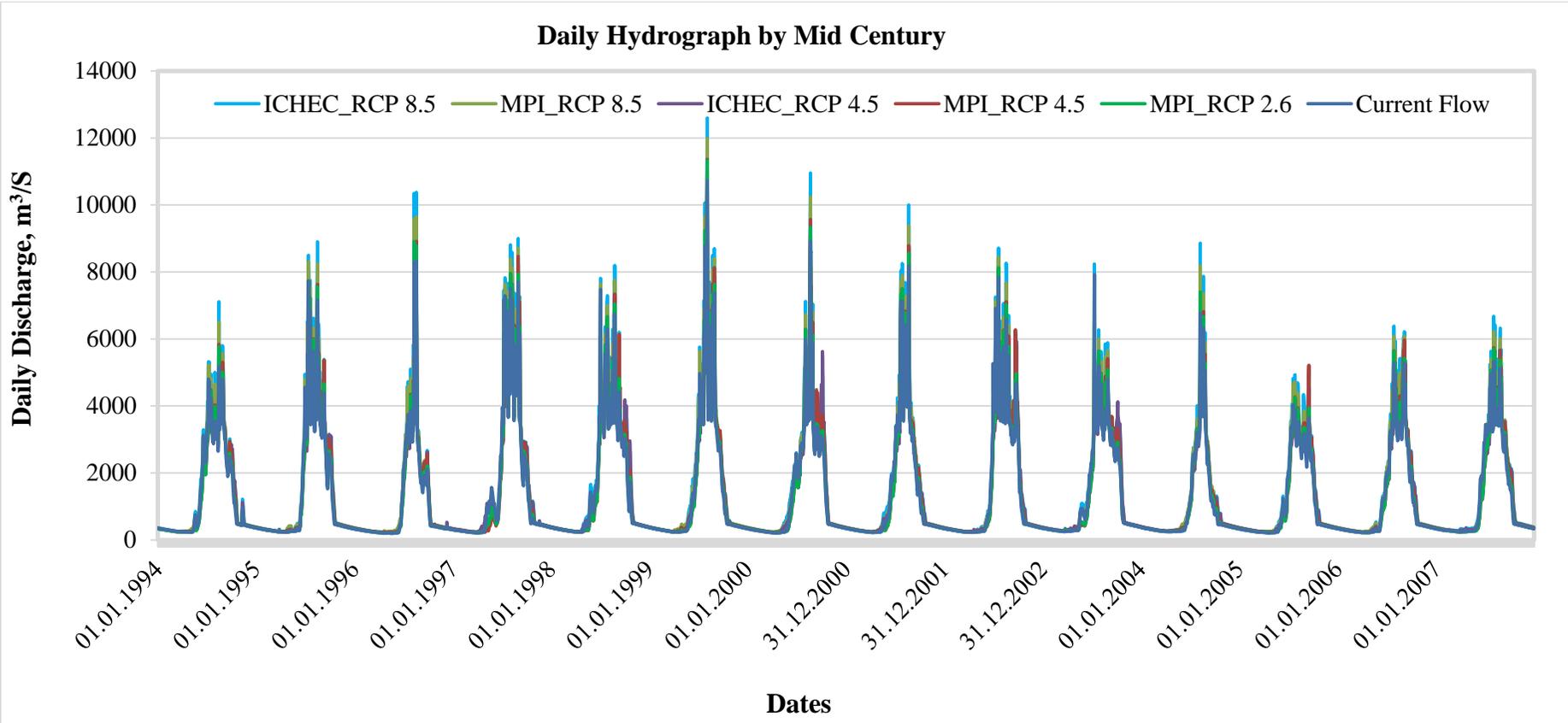
Daily Hydrograph by End Century