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Hydrological Analysis of Tekeze Hydropower System in the Current and Future Climate

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Hydropower Development

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MASTERS THESIS

Hydrological Analysis of Tekeze Hydropower System in the Current and Future Climate

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

Under

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DECLARATION OF AUTHORSHIP

I, Abebe Girmay Adera, declare that this thesis titled, 'Hydrological Analysis of Tekeze Hydropower System in the Current and Future Climate' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for MSc. research degree at Norwegian University of Science and Technology (NTNU)
- Where I have consulted the published work of others, this is always clearly stated.
- Where I have quoted from the work of others, the source is always given.
- Where the thesis is based on work done by myself jointly with my supervisor Knut Alfredsen(Professor), I have made clear what was done by others and what I have contributed myself.
- I have acknowledged all main sources of help.

Signed: Abebe Girmay Adera

Date: 09/06/2015

"Garbage in means garbage out."

Programmer's saying

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Candidate: Abebe Girmay Adera

Title: Hydrological Analysis of Tekeze Hydropower System in the Current and Future Climate

1 BACKGROUND

Climate change is expected to influence runoff and thereby hydropower operation in most regions of the world. Global assessments show both a potential reduction and increase in runoff and production depending on region, and more detailed studies are needed to find how the future climate scenarios will influence production. The purpose of this study is to evaluate the climatic impacts on the Tekeze hydropower plant in Ethiopia by utilizing hydrological and hydropower modelling.

2 MAIN QUESTIONS FOR THE THESIS

1) Perform a literature review on previous studies of climate change impacts in Ethiopia. The study should both review results and findings from the studies and the methods used for the assessment. It is of particular importance to evaluate which climate models and downscaling methods that is used.

2) Data for the current situations should be checked for quality and calibration and validation periods should be selected for the modelling. Missing data should be filled if possible to make complete series. Data should be formatted for the hydrological and hydropower model. Necessary catchment data should be collected according to the need of the model.

3) Calibrate the rainfall-runoff model for a period and run validation for a different period. Evaluate the calibrated values and the quality of the calibration.

4) Prepare the nMag hydropower model for the current situation and make control runs against observed production to set a reservoir operation strategy.

5) Evaluate bias correction methods (e.g. Teutschbein and Seibert, 2010) and prepare climate data for the scenario simulation using the CORDEX RCM data for the region. Evaluate if delta changes or direct simulation should be used, and prepare the data for the hydrological model. There should also be done an evaluation of the scenarios of temperature and precipitation for the future situation.

6) Run the prepared scenarios through the hydrological and hydropower models to generate runoff and production series for the future climate. Evaluate the results and see how the future system might be adapted to any changes.

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)

Department of Hydraulic and Environmental Engineering at NTNU

ABSTRACT

Climate change is expected to intensify the already high hydrological variability and energy production in various regions of the world. This research work investigates the runoff and energy production in the current and future climate for Tekeze hydropower system located in the northern part of Ethiopia. A catchment named Embamadre watershed was delineated and has an area of 44,845km². The rainfall - runoff model (i.e. HBV) and energy production program (i.e. nMAG) were used to generate runoff and production series for the current situation and future climate. The climate data were downscaled to the target catchment using the CORDEX RCM data for the region from Canadian Center for Climate Modelling and Analysis. The mean monthly change computed from the downscaled climate data in both Rcp45 and Rcp85 scenarios showed an increase of precipitation and temperature for the future time (2041 to 2100). Exceptional results showed by Rcp45 and Rcp85 scenarios that both October and December which are the dry months in Ethiopia will have higher mean monthly rainfall than other months in the future time. Besides, Rcp45 scenario showed that rainfall during the future time (2041 - 2100) in July which is the summer month will decrease. This change was applied to the observed precipitation and temperature data to assess the runoff and energy production series using "delta change approach" and "rainy days" scenario application methods. Since the delta change approach applied the mean monthly change factor without considering the dry days, the second method named "rainy days" was found better. The downscaled RCM data was tested on calibration and direct simulations and found that it will not reproduce the observed results. On the other hand, the energy production for the future time showed an increase in annual energy production. However, this increase is not very high and it was found that the spill during the summer months mainly August and September was very high. As a result using reservoir rule curve as operational strategy which implies making empty the reservoir during the dry period and capturing this spill during the summer period will increase the energy production significantly. To sum up, the climate change will affect the runoff and energy production of Tekeze hydropower.

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LIST OF ACRONYMS

CORDEX = Coordinated Regional Downscaling Experiment

DEM = Digital Elevation Model

EEPCo = Ethiopian Electric Power Corporation

EPOT = Potential Evapo-transpiration

GIS = Geographic Information System

HBV = Hydrologiska Byråns Vattenbalansavdelning
(Hydrological Bureau Waterbalance-section)

i.e. = that is

m.a.s.l = mean above sea level

MoWE = Ministry of Water and Energy

NMA = National Meteorology Agency

nMAG = Hydropower Operation Simulation Program

NTH = Norwegian Institute of Technology

NTNU = Norges Teknisk-naturvitenskapelige Universitet
(Norwegian University of Science and Technology)

Ppt = Precipitation

RCM = Regional Climate Model

SINTEF = Stiftelsen for Industriell og Teknisk Forskning
(The Foundation for Scientific and Industrial Research)

UTM = Universal Transverse Mercator

1.1 Background

Ethiopia is a country with abundant water resources that can be harnessed to meet the highly growing energy demands of the society. Despite being non oil producing and landlocked country, hydropower is the most advanced renewable energy technology that provides electricity generation by converting the potential energy of water. This water can be used for irrigation and many other purposes after generating electricity.

Ethiopian government has started a lot of hydropower projects. Currently there are a lot of hydro power projects under constructions including the two largest hydro power plants (i.e. Grand Ethiopian Renaissance Dam and Gilgel Gibe III). Ethiopia has 12 river basins flowing in different regions of the country. Tekeze rive basin is one of the 12 river basins located in the northern part of Ethiopia. It is part of Nile river system, flowing towards Sudan and terminating in the Mediterranean Sea. Tekeze hydropower plant is constructed on this river basin. Tekeze Dam is double curvature concrete arch dam with an overall height of 185m. The power plant is an underground powerhouse with four Francis turbines and four 75 MW generators. The maximum capacity of Tekeze hydropower system is 300 MW in four different units and each unit producing 75 MW. The construction period was from 2002-2007 and started operation in 2009. The reservoir has maximum storage capacity of 9.3 billion cubic meter. However, the live storage capacity is 5.3 billion cubic meter and the rest 4 billion cubic meter is dead storage [2].

1.2 Literature Review

Climate projections using multi-model ensembles show increase in globally averaged mean water vapour, evaporation and precipitation over the 21st century. In part of tropics and high latitudes, nearly all models project an increase in precipitation, while in some subtropical and lower mid-latitude regions, precipitation is projected to decrease. Uncertainties in projected changes in hydrological systems arise from internal variability in climate, uncertainty about future greenhouse gas and aerosol emissions, the translations of these emissions in to climate change by global climate models, and hydrological model uncertainty. Projections become less consistent between models as the spatial scale decreases. The uncertainty of climate model projections for freshwater assessments is often taken into account by using multi-model ensembles [1].

Projections from the global circulation modelling show increased annual mean rainfall and an increase in evapotranspiration to the year 2050, although the magnitude of the variability in these parameters is larger than the change in mean values. The incremental variability of precipitation, which translates as fluctuating rainfall, reduces the availability of a stable water supply and increases the risk of floods. The frequency of low-probable extreme events is expected to increase as well. When these projections are translated into impacts due to water constraints and flood damage, results from multi-market modelling indicate that flood damage mainly influenced by weather variability rather than changes in the mean has a larger depressing effect on overall GDP growth [5]. The main purpose of this research study is to assess the climate change impact on Tekeze hydropower system located in the north part of Ethiopia. This research will also increase understanding of impacts of changes in water usages such as hydropower.

1.3 Description of the Study Area

Using discharge station as an outlet and with the help of ARCGIS software applications, a sub catchment called Embamadre watershed was delineated and considered for this research study. This watershed is from tropical climatic zone and its detail description is written below.

1.3.1 Location and Topography

Embamadre watershed is located in the northern part of Ethiopia, Tigray region. This watershed has an area of $44,845 \text{ Km}^2$ and is sub catchment of Tekeze river basin. Its location ranges from $12^{\circ}30'21''$ to $14^{\circ}05'17''$ N of latitude and $37^{\circ}36'42''$ to $39^{\circ}42'16''$ E of longitude.

Embamadre watershed is part of Tekeze river basin which is located in the northern part of Ethiopia. Tekeze river basin is also part of the Nile river basin system. Embamadre watershed elevation ranges from 869m up to 4502m. The annual rainfall ranges from 500mm up to 1700mm. The mean annual runoff volume for the watershed is 7454 million cubic meter. Embamadre watershed is the biggest catchment for Tekeze hydropower system. Figure 1.1 shows the location of the watershed and other river basins of Ethiopia. This location is prepared using ARCGIS and detail description about the watershed is discussed in Chapter 3.

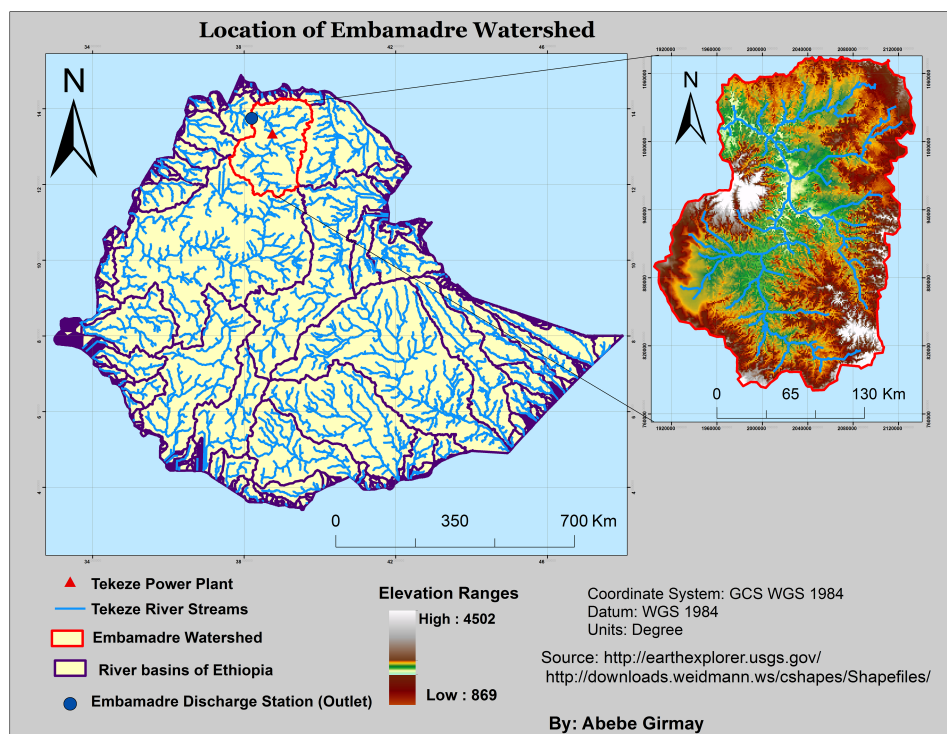


Figure 1.1: Location of Embamadre Watershed

1.3.2 Meteorological Stations

For this research Embamadre watershed consists of total 7 precipitation and temperature gauging stations. From all of the 7 stations one station has only precipitation data. Since there is no snow analysis in this study, temperature is not as influential as precipitation. Regardless of the two stations, the 5 stations are located within the watershed. Even though the two stations are outside of the watershed, they are very close to this watershed. Embamadre watershed has mean annual rainfall of 903 mm and 86277 m³/s of mean annual runoff. The mean temperature of the catchment is 18⁰C. There was no available measured Potential evapo-transpiration for the desired time series. Thus, Thornthwaite equation (1948) were used for calculating mean daily potential evapo-Transpiration in mm per day. Figure 1.2 shows the location of the two discharge stations and the 7 gauging stations.



Figure 1.2: Location of Meteorological Stations

There are three discharge stations within the watershed. The location of the two discharge stations (Embamadre and Yechila) is known. There is discharge data for the third station (Kulmesk) but its location is not mentioned. All discharge data from these three stations have been used for quality control such as accumulation plots, double mass curve and correlation between the stations.

1.4 Objectives

The main objective of this research study is to assess the potential impacts of climate change and make hydrological analysis on Tekeze hydropower system. It is also aimed to evaluate the overall impacts on hydropower production.

The specific objectives of the research are:

- To check quality of the input data and fill missing data.
- To generate catchment parameters using ARCGIS applications.
- Carry out calibration of Rainfall - Runoff model for a period and validate for different period.
- To evaluate calibration results and quality of calibration.
- To asses climate change impacts on runoff and power productions.
- To downscaled climate data from CORDEX RCM for the selected region.
- To generate runoff and production series using hydrological and hydropower models respectively.
- To compare power productions during the current and future time series.

1.5 Methodology

The methodology followed in this research is described below:

Data Quality Control

Before starting any data analysis the quality of all observed inputs mainly runoff, precipitation and temperature were checked.

Catchment Parameters

ARCGIS 10.3 was used to estimate all catchment parameters by delineating the target watershed.

Calibration and Validation on PINEHBV Model

Calibration was used in this study to estimate model parameters and the model was also validated on different year(i.e. the last 3 years from 1999 - 2001). After finding acceptable parameters, runoff was generated for climate study.

Downscaling

Historical and future climate data was downscaled for the selected region (CORDEX - RCM) from Canadian center for climate modelling and analysis. R programming language was also used to process this climate data.

Delta Change and Rainy days Scenario Applications

Both delta change and rainy days application methods were considered to assess the impact of climate change in the future time series.

Hydropower Production

The power production was simulated and compared during the future and current time using nMAG hydropower simulation program.

CHAPTER 2

DATA PREPARATION AND ANALYSIS

2.1 Input Data Preparation

The meteorological data that is necessary input for the rainfall-runoff model were collected from three different offices in Addis Ababa, Ethiopia. Both rain fall and temperature data were collected from National Meteorology Agency (NMA). The rainfall and temperature complete daily data series considered for the research was from 1993 upto 2006 which is 14 years data series. The runoff data for three different stations was collected from Ministry of Water and Energy (MoWE). The complete daily runoff data series ranges from the year 1995 upto 2001 which is 7 years data series.

2.1.1 Rainfall

Precipitation data collected from all of the seven gauging stations was considered for the research study. However, missing data for some years was the issue to take precaution. The missing data is not a big gap data series specially in the rainy season. As a result the missing data within two consecutive days was filled by taking the average value of the days before and after the missing day. Table 2.1 has detail description for all of the 7 gauging stations.

Table 2.1: Precipitation and temperature gauging stations

Station Name	Altitude(m.a.s.l)	Latitude(North)	Longitude(East)	Remark
Adigudom	2100	13 ⁰ 14'48"	39 ⁰ 30'44"	Ppt only
Hawzen	2242	13 ⁰ 58'23"	39 ⁰ 25'53"	Ppt,Temp
Mekelle	2257	13 ⁰ 28'14"	39 ⁰ 31'52"	Ppt,Temp
Alamata	1589	12 ⁰ 25'24"	39 ⁰ 42'51"	Ppt,Temp
Shire	1897	14 ⁰ 06'06"	38 ⁰ 17'40"	Ppt,Temp
Addiszemen	1940	12 ⁰ 06'59"	37 ⁰ 46'23"	Ppt,Temp
Ageregenet	3010	11 ⁰ 48'02"	38 ⁰ 17'55"	Ppt,Temp

Figure 2.1 shows annual precipitation data series for all stations. The rainy season in Ethiopia is consistent and starts from late May up to early September. As a result average value was used to fill the missing precipitation on the rainy season between two different days. However, for the dry period this was not the problem at all.

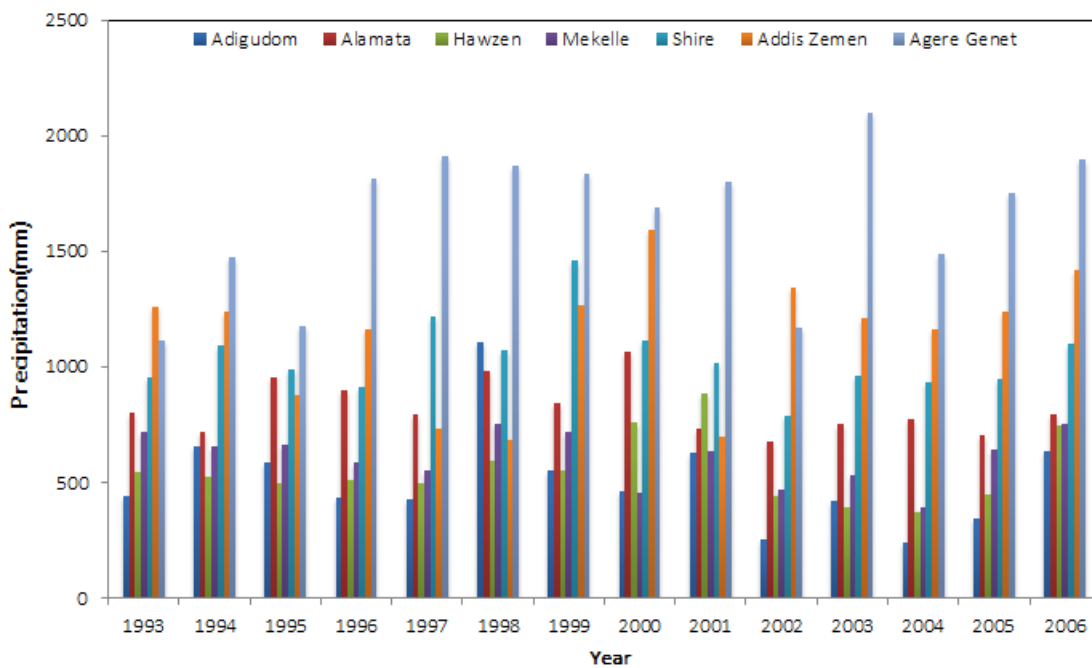


Figure 2.1: Annual precipitation measured at each station

2.1.2 Temperature

Daily maximum as well as minimum complete temperature data series was also available for the same period as precipitation. However, one station (Adigudom) measures precipitation only. So the number of stations for temperature goes down to 6. There is no snow data and snow analysis in this research study at all. Therefore, temperature is not sensitive case but still needs precaution for estimation of potential evaporation which is the main issue in tropical climatic zones. Estimation of the missing maximum and minimum daily temperature was filled similarly to precipitation by taking the average value between two days. As long as the missing data is not a big gap series this method is used for all the data series. The mean monthly maximum and minimum temperature data from all of the 6 stations is shown in Table 2.3.

2.1.3 Runoff

The other main input parameter is runoff. For this research study three different discharge stations were considered for quality control analysis. For all stations the complete daily runoff data series ranges from 1995 up to 2001 which is 7 years in total. Table 2.2 shows detail description of all the three discharge stations. The first station (i.e. Embamadre) is considered for the research study. Even though the third station (i.e. Kulmesk) is in Tekeze River basin, the exact location is not clearly known.

The second station (i.e. Yechila) is poorly gauged station and there is no clear pattern of the whole daily time series. Besides, there is very high runoff (around 6000m³/s) in 1999 which makes it unreliable and untrusted data series. During the pre-feasibility study this station was scaled and filled from neighbouring country (i.e. Sudan) catchment. Thus, the unreliability of the data might come due to lack of precaution in filling the data during scaling. So, this discharge station is no longer useful for the research study and it is not considered for further analysis of this research study. Figure 2.4b show the daily time series pattern for both discharge stations.

Table 2.2: Description of Discharge Stations

Station Name	Altitude(m.a.s.l)	Latitude(North)	Longitude(East)	Area(Km^2)
Embamadre	869	13 ⁰ 43'48"	38 ⁰ 12'00"	44845
Yechila	1000	13 ⁰ 21'00"	38 ⁰ 45'00"	28152
Kulmesk	Unknown	Unknown	Unknown	Unknown

The third station (Kulmesk) time series flow is shown in Figure 2.4a and it is a station with very low runoff than the two other stations. However, the pattern of this station is better than the second stations (i.e. Yechila). As a result the runoff data from Kulmesk station is used to fill the missing gap of Embamadre station by finding very good correlation for overlapped year between the two stations.

2.1.4 Potential Evapo-transpiration

The Potential Evapo-transpiration(EPOT) is computed using Thornthwaite (1948) equation. According to the EPOT equation at (http://en.wikipedia.org/wiki/Potential_evaporation):

$$PET = 1.6 \left(\frac{L}{12} \right) \left(\frac{N}{30} \right) \left(\frac{10 T_a}{I} \right)^\alpha$$

Where

PET is the estimated potential evaporation (cm/month)

T_a is the average daily temperature (degrees Celsius; if this is negative, use 0) of the month being calculated

N is the number of days in the month being calculated

L is the average day length (hours) of the month being calculated

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

$$I = \sum_{i=1}^{12} \left(\frac{T_{ai}}{5} \right)^{1.514}$$

is a heat index which depends on the 12 monthly mean temperatures T_{ai}

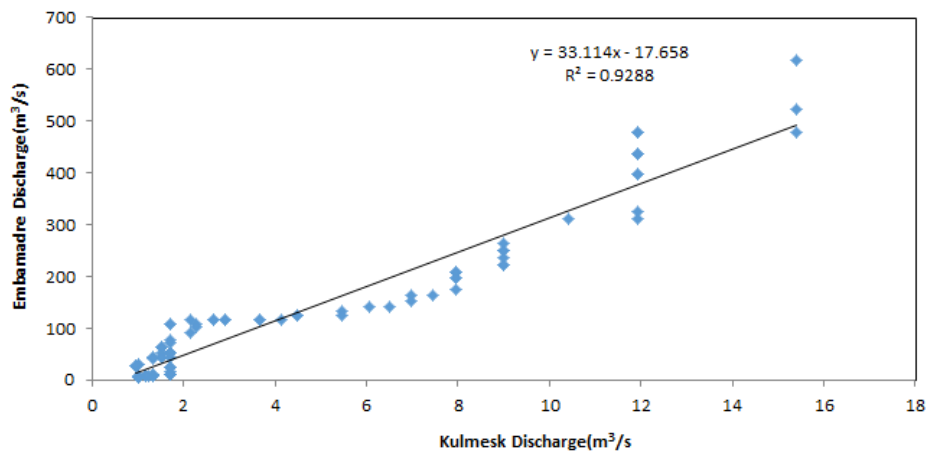


Figure 2.2: Correlation between Embamadre and Kulmesk discharge stations

During filling of the missing runoff for Embamadre discharge station, runoff data with acceptable correlation of +0.96 between both stations (Embamadre and Kulmesk) for the overlapped year of 2000-2001 is considered using the following equation. Figure 2.2 shows correlation between the two stations.

$$Q_{Embamadre} = \frac{AvgQ_{Embamadre}}{AvgQ_{Kulmesk}} * Q_{Kulmesk}$$

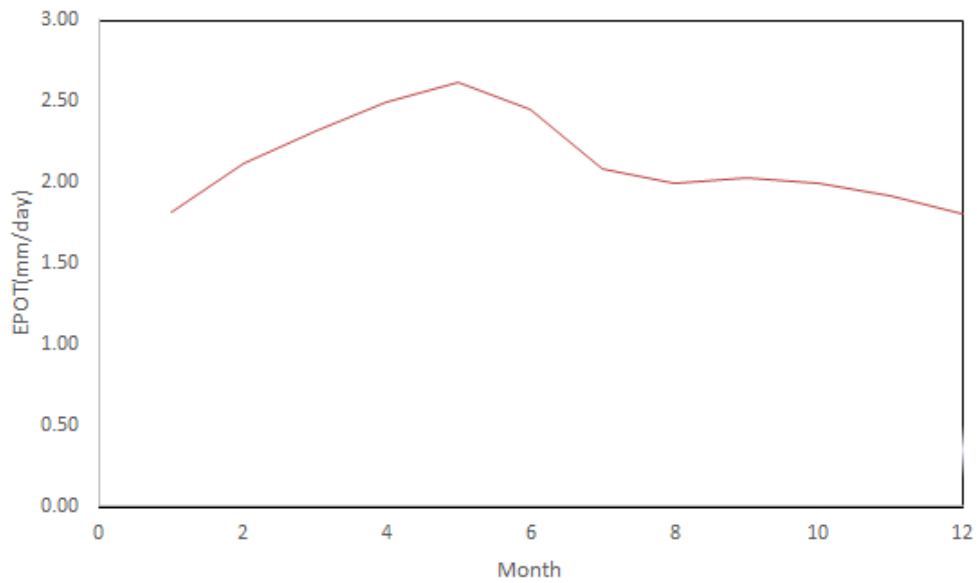
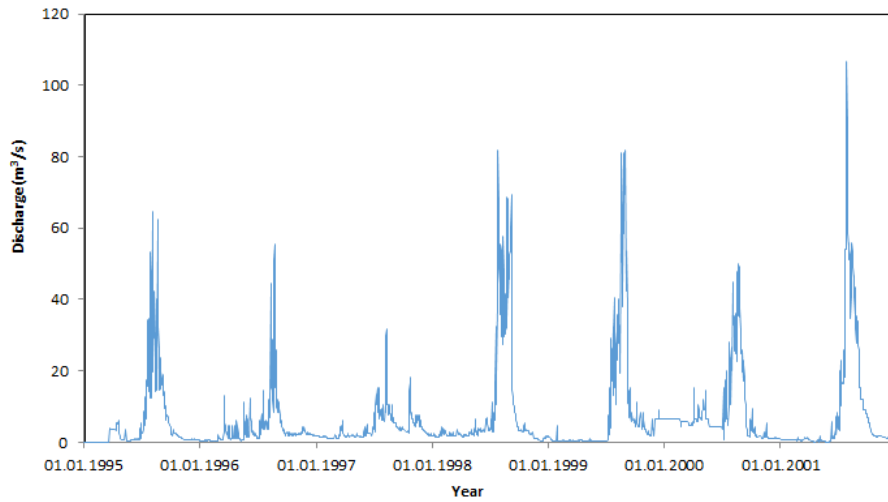


Figure 2.3: Mean monthly potential evapo-transpiration

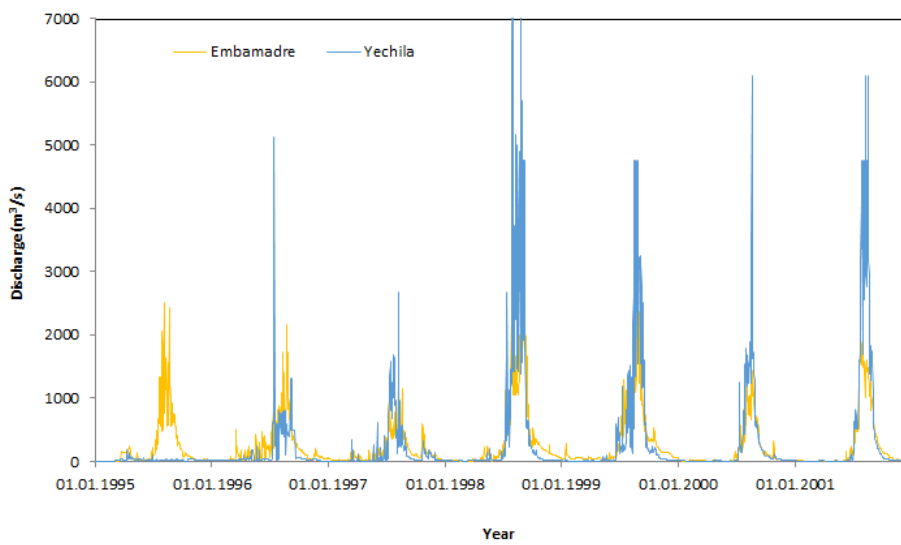
Figure 2.3 shows the mean monthly potential evapo-transpiration in mm per day for the whole time series computed using Thornthwaite equation. This EPOT is the representative of the area which takes mean temperature as an input for the calculations and it is one of the input parameters for HBV model.

Table 2.3: Mean monthly temperature at each station from 1993 - 2006

Station	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Alamata	Tmax(⁰ C)	27	29	30	31	33	34	32	30	31	30	29	28
	Tmin(⁰ C)	11	13	14	16	17	18	17	16	14	13	12	11
Hawzen	Tmax(⁰ C)	26	27	28	28	28	28	24	23	26	26	26	26
	Tmin(⁰ C)	8	9	11	12	13	12	13	12	11	9	8	7
Mekelle	Tmax(⁰ C)	23	24	25	26	27	27	23	22	24	24	23	22
	Tmin(⁰ C)	9	10	12	13	14	13	13	13	12	11	10	10
Shire	Tmax(⁰ C)	27	29	30	31	30	28	24	23	26	27	27	27
	Tmin(⁰ C)	11	13	14	17	16	15	15	15	14	13	12	11
Addis Zemen	Tmax(⁰ C)	30	31	31	31	31	28	25	25	26	28	29	29
	Tmin(⁰ C)	10	10	11	11	12	12	12	12	12	10	10	9
Agere Genet	Tmax(⁰ C)	22	23	23	23	23	21	18	18	20	20	21	21
	Tmin(⁰ C)	4	5	6	7	7	8	9	9	7	6	5	5



(a) Kulmesk station



(b) Embamadre and Yechila stations

Figure 2.4: Daily runoff series

2.2 Data Quality Control

Assessment of the quality of the input data is one of the main objectives of this research. The first assessment was visual inspection of the data series. This was done by checking if the data series is complete or not. Secondly, checking was done for some unexpected values (negatives, missing values, variation patterns). As a result filling of the missing values for all of the input data (i.e. precipitation, temperature and runoff) was done by taking average values for precipitation and temperature. For missing in runoff data correlation between two stations was used. In the following sections, the quality control methods used to assess the input data will be described.

2.2.1 Accumulation Plot

The discharge station(i.e. Embamadre) is the only station filled using correlation with the other station(i.e. Kulmesk). The year 2000 - 2001 was filled using correlation $+0.964$ between the two stations. To check if the scaled gap filled values are correct, accumulation plot is shown in Figure 2.5. According to this figure the accumulation plot is continuous and linear.

2.2.2 Double Mass Curve

To detect the inhomogeneities of data series and to check the consistency, double mass curve was plotted for all of the stations with measured precipitation, temperature and runoff. The accumulated development of a time series against the corresponding development of other times series in the same climatic region is plotted to show the double mass curve. This means accumulated values at each station is plotted against the average accumulated values of the other stations. Figure 2.6 shows double mass plot for the two discharge stations (i.e. Embamadre and Kulmesk). The third discharge station(i.e. Yechila) is already left out due to the unreliable data recorded and irregular time series pattern. The double mass curve for both discharge stations shows consistent flow with out any break up.

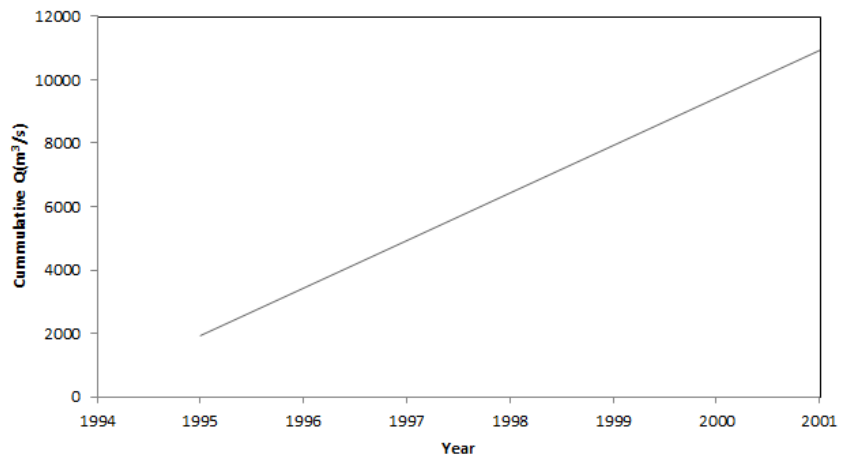


Figure 2.5: Accumulation plot for Embamadre discharge station

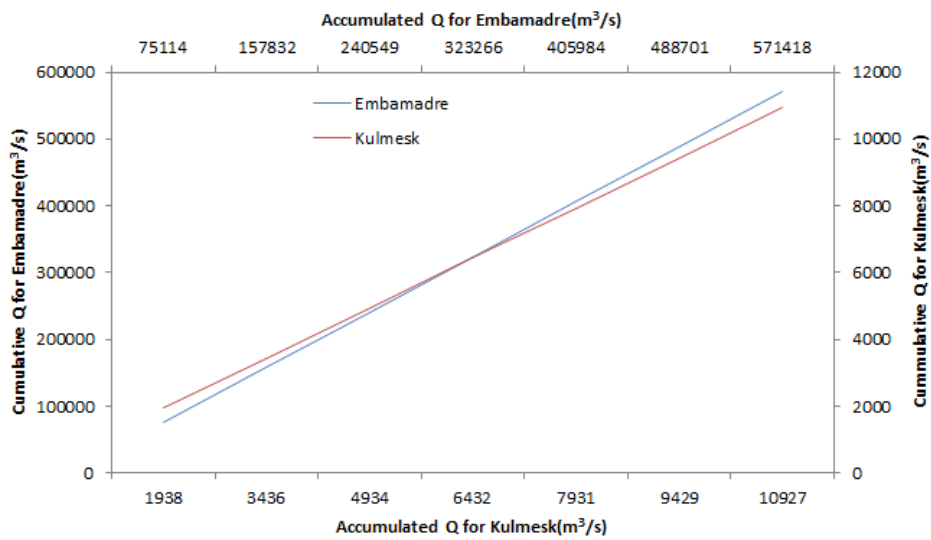


Figure 2.6: Double mass plot for both runoff stations

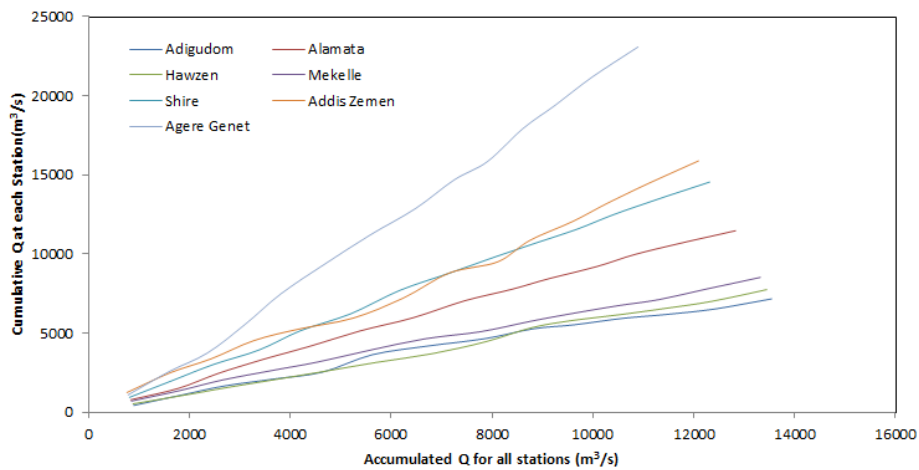
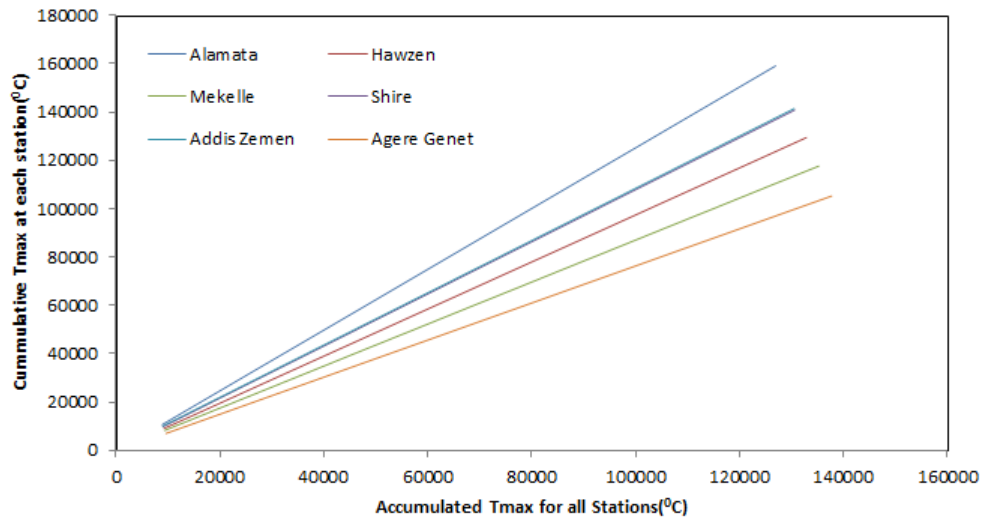
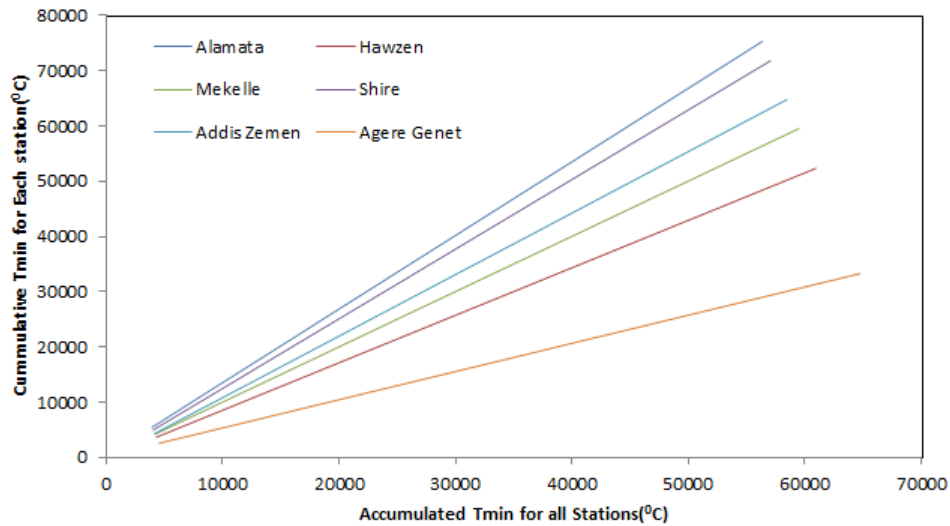


Figure 2.7: Double mass plot of rainfall stations

Figure 2.7 shows double mass plot of all precipitation stations. The graph also shows consistency of each station during the available time series. The graph shows low - high or up - down values. This happened due to some exceptional dry and wet years which comes as a result of climate change. Generally, it shows consistent time series data at each stations with out any break or irregular pattern. Figure 2.8a and 2.8b shows double mass plot for both maximum and minimum temperatures at each station respectively. Even though there is no any snow analysis for the research study, checking consistency of stations is quite important. This temperature is used for calculation of Potential evapo-transpiration which is main input parameter for HBV model.



(a) Maximum temperature



(b) Minimum temperature

Figure 2.8: Double mass plot

CHAPTER 3

CATCHMENT PARAMETERS

ARCGIS has a lot of applications and can be used for many purposes. If it is used carefully, ARCGIS can provide powerful information that will lead to better decision making. One of the applications of ARCGIS is to delineate watershed. For this research study a watershed was delineated using ARCGIS 10.3.

The first task was to delineate the main watershed (i.e. Embamadre Watershed) and for this task DEM is required. The DEM for Africa was used to delineate the watershed which is available from free website at (<http://earthexplorer.usgs.gov/>). Using the discharge station location (i.e. Embamadre station) as an outlet, watershed was delineated easily following few steps in ARCGIS, for example Spatial Analysis tools. To clip and make Ethiopian DEM, shape file of Ethiopia is taken from free website at (<http://downloads.weidmann.ws/cshapes/Shapefiles/>). The final DEM of Ethiopia was obtained By clipping the African DEM with Ethiopia shape file feature. Ethiopia is found in UTM zone 37N and this location is used during changing of the geographic coordinate system to projected coordinate system that helps for measuring area or distance.

In Figure 3.1 the flow chart for running DEM analysis used in the model builder of ARCGIS is shown. After this step then the watershed was delineated and Figure 3.2 shows the flow chart for delineating the watershed using model builder. As shown in the second flow chart projection of the watershed is necessary in order to perform measurements such as area, length or distance, etc.

The second flow chart on Figure 3.2 also shows how the thiesen polygon is generated for each station that leads to compute the areal precipitation. There is detail discussion about thiesen polygons in section 3.1. The delineated watershed is shown in Figure 3.3. This watershed is the final watershed for this research study. All the catchment parameters and discussions are based on this watershed.

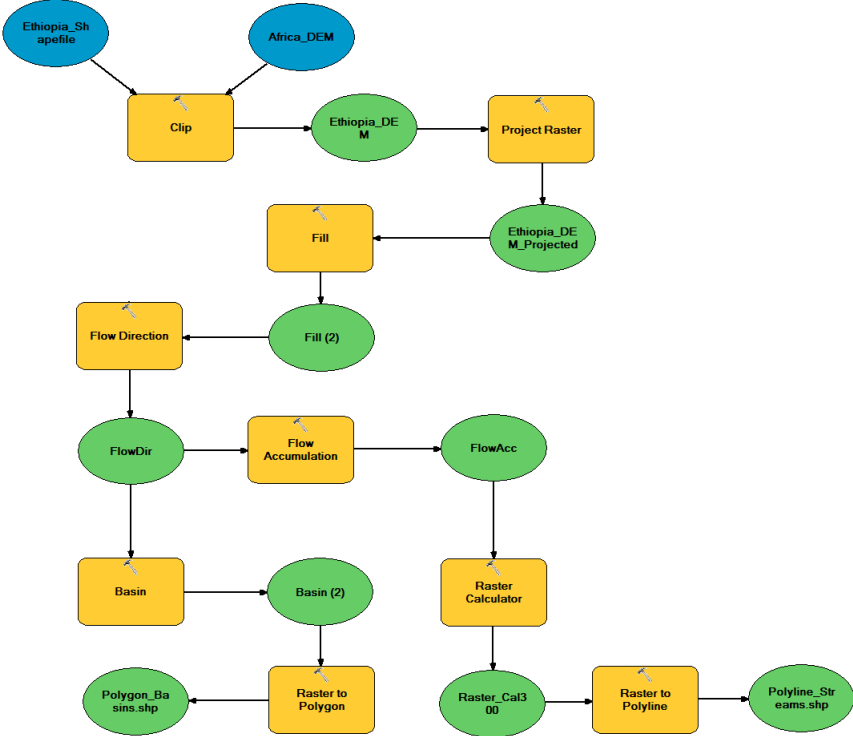


Figure 3.1: Flow chart for Ethiopian DEM analysis

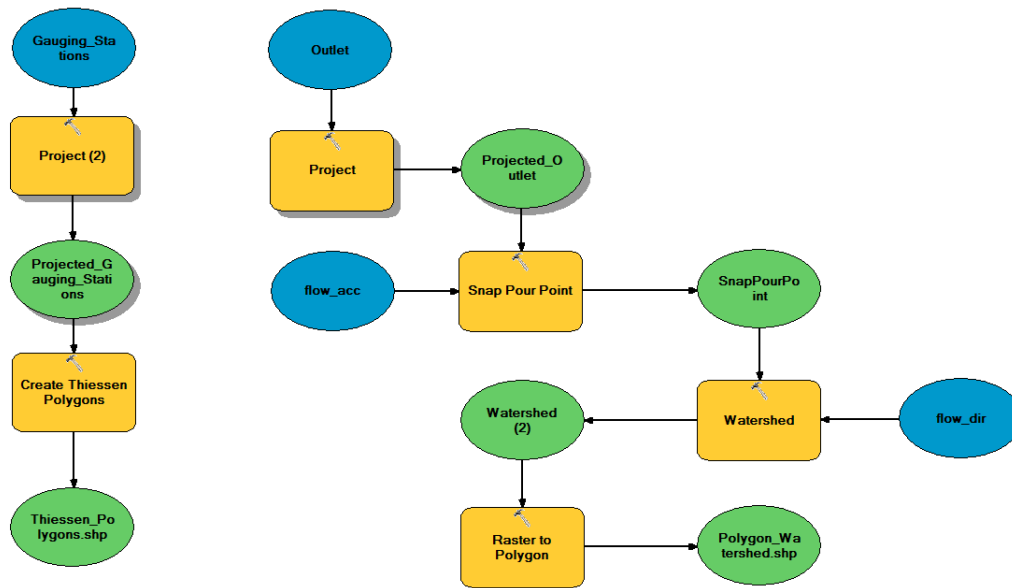


Figure 3.2: Flow chart for watershed delineation and Thiessen polygon

3.1 Areal Precipitation

The precipitation recorded at each station is point precipitation and can not represent the whole catchment unless it is changed in to areal values. Therefore, this point precipitation should be changed in to areal precipitation which is one of the challenging tasks in hydrology. The precipitation stations for Embamadre watershed were located in all directions of the catchment and computation of areal precipitation is not difficult task for this case. There are different methods to compute and change this point precipitation in to areal precipitation. For this research study, a method called Thiessen polygon was used.

The Thiessen polygons were generated with the help of ARCGIS tools using all the 6 selected stations. The flow chart on the left side of Figure 3.2 shows the steps followed for Thiessen polygon after delineating the watershed. Figure 3.4 shows the final outcome of the Thiessen polygons and their respective areas. From the figure, it is shown that gauging station named Mekelle air port is omitted after the first calibration. There is more explanation about this in Chapter 5.

The areal precipitation is calculated using the following equation of Thiessen polygons method:

$$P_{Total} = \frac{A_1}{A_{total}} * P_1 + \frac{A_2}{A_{total}} * P_2 + \frac{A_3}{A_{total}} * P_3 + \frac{A_4}{A_{total}} * P_4 + \frac{A_5}{A_{total}} * P_5 + \frac{A_6}{A_{total}} * P_6$$

Where A = area, and P = precipitation

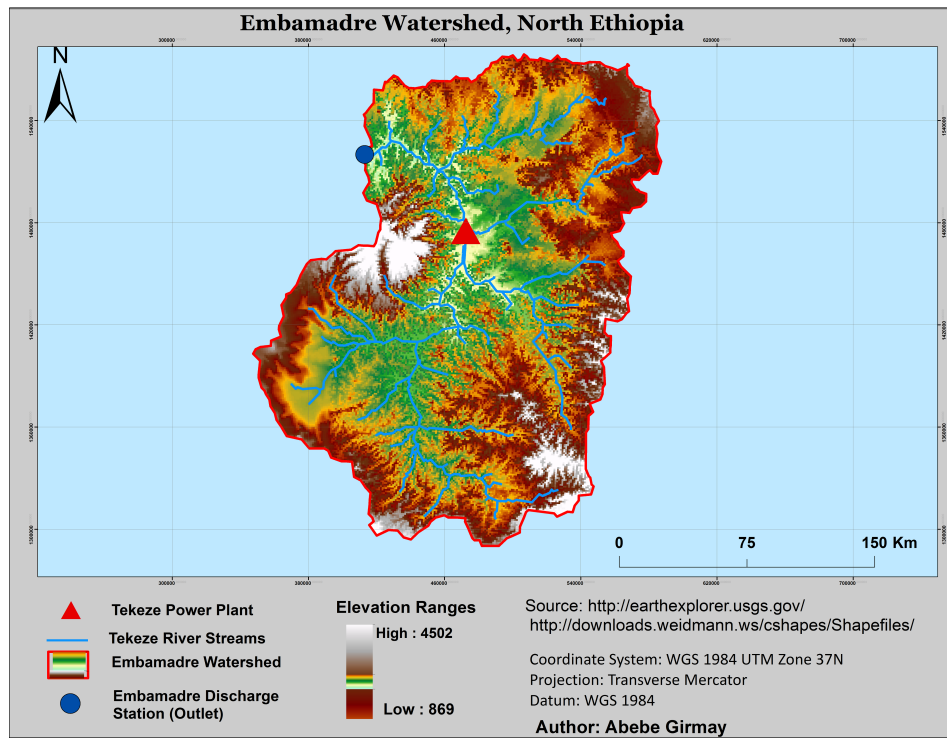


Figure 3.3: Embamadre watershed

The final areal precipitation calculated using thiesen polygon method is shown in Figure 3.6. This is the areal precipitation of the whole watershed and it is also an input data for rainfall-runoff model (HBV).

3.2 Average Temperature

The temperature for the research study is recorded only at 6 stations. Since both maximum and minimum temperatures were available, the mean temperature of all stations is considered for this research study. Unlike precipitation, temperature is mean value. The main purpose of this temperature is to use as an input for calculations of Potential Evapo-transpiration(EPOT) and it is also input data for the model.

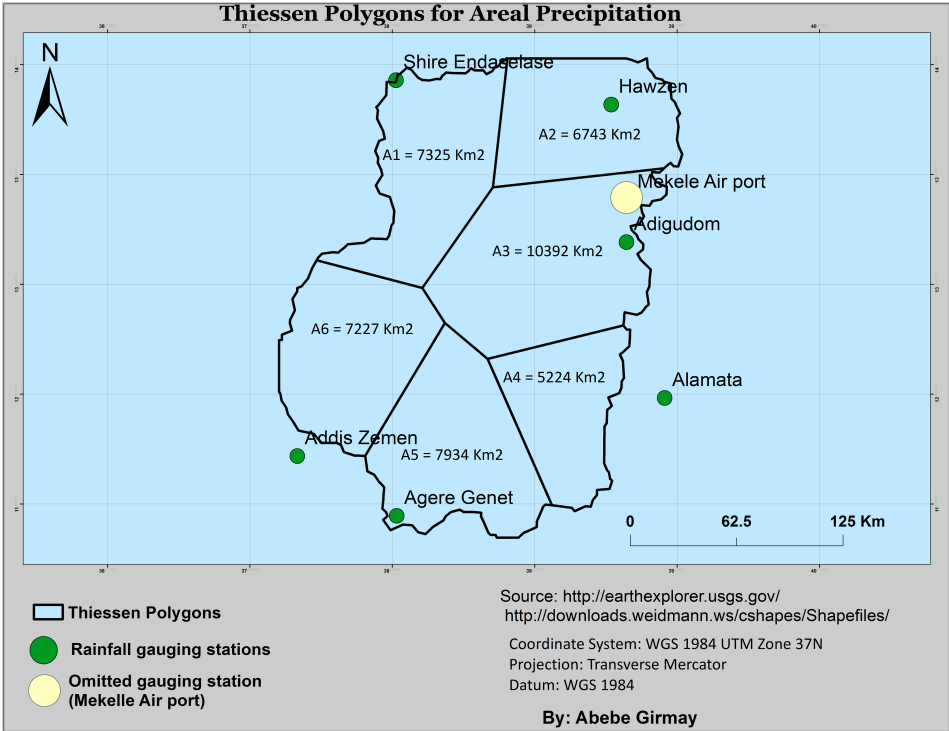


Figure 3.4: Thiessen Polygons

Thus, mean temperature is necessary to take as representative of the area. Additional calculations about EPOT is written in subsection 2.1.4. Figure 3.7 shows average maximum and minimum temperatures of all stations which is one of the input data for the HBV model.

3.3 Elevation Zones

The area is divided into 10 elevation zones which will be taken as an input parameter for the hypsography part of Rainfall-Runoff model. The hypsographic curve is accumulated curve over the 10 elevation zones and shows the elevation distribution of the catchment. Figure 3.5 shows hypsography curve of Embamadre watershed.

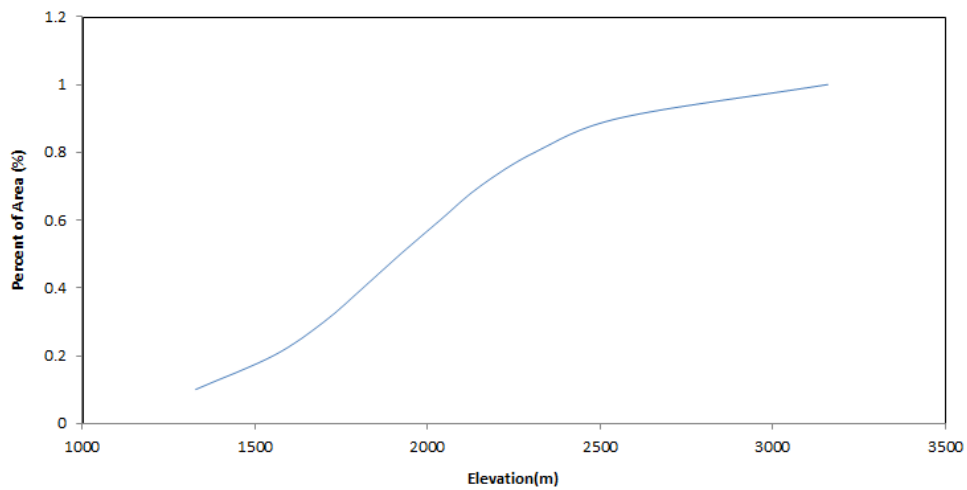


Figure 3.5: Hypsographic Curve for 10 Elevation Zones at Embamadre Watershed

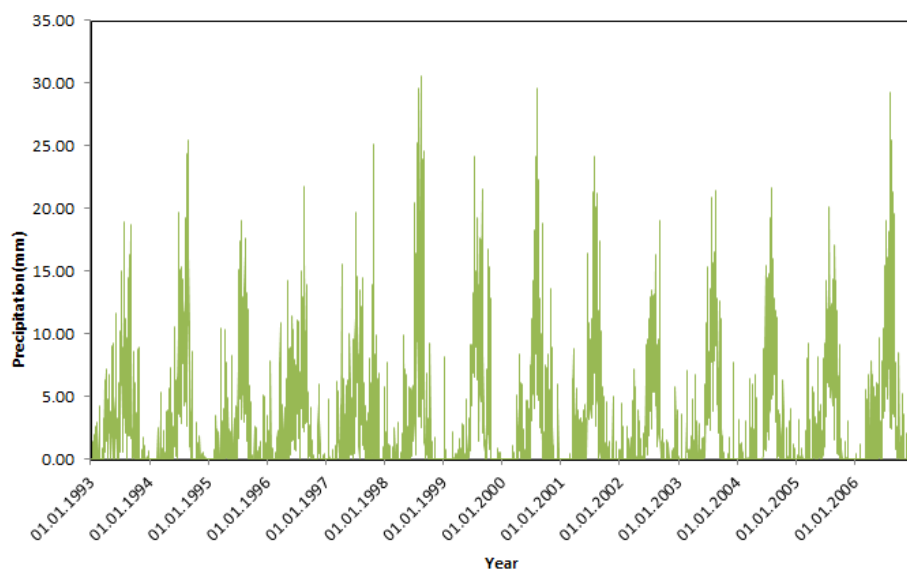


Figure 3.6: Areal Precipitation

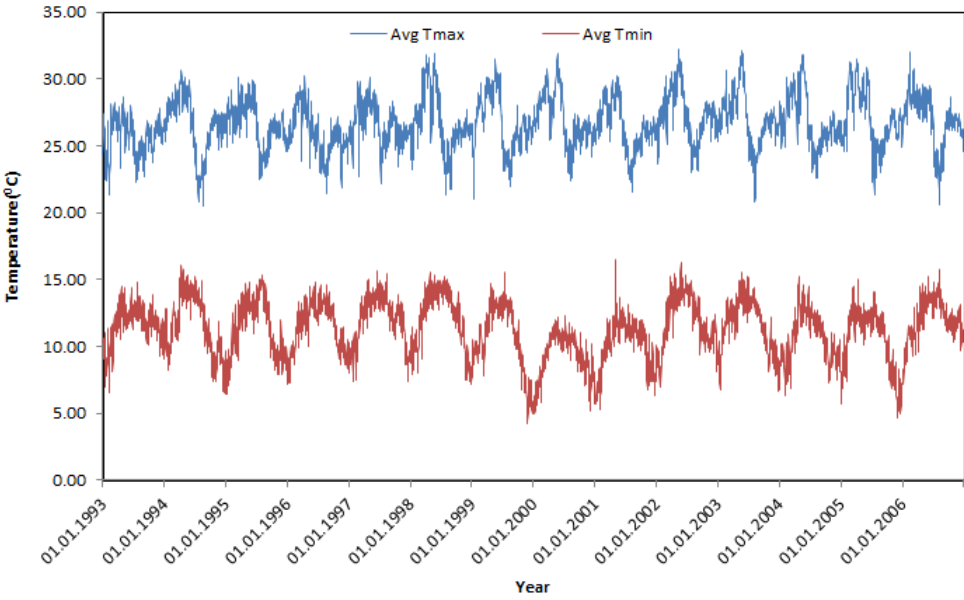


Figure 3.7: Average maximum and minimum temperature

Models are representation of a portion of the natural or human constructed world which produces an output or series of outputs in response of an input or series of inputs. In this chapter, there is description and some explanation about models and types of models to use for this research study.

4.1 Types of Model

There are different types of hydrological models used nowadays that ranges from simple conceptual models upto more complex models. The diagram shown in Figure 4.1 is about the types of hydrological models used for different purposes. The model type is chosen depending on the purpose and objective or aims of the tasks [3].

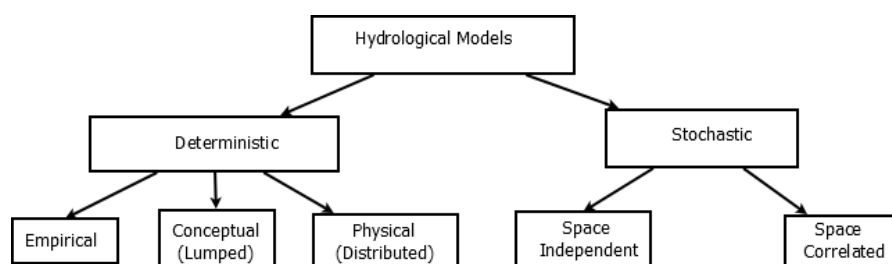


Figure 4.1: Types of Hydrological Models

4.2 HBV (Rainfall - Runoff Model)

Rainfall-Runoff models are most of the time used for inflow and flood forecasting, and to fill or extend missing data in runoff series. Besides catchment is the basic unit for generation of runoff in most hydrological models. There are two important concepts for any rainfall-runoff model. Firstly, how much of the rainfall becomes runoff(runoff generation). Secondly, the distribution of this runoff with time to form runoff hydrograph at the outlet(runoff routing).

The main purpose of using rainfall-runoff model for this research study is for calibration of model parameters and to generate runoff series for climate change impact analysis. Although it is possible to use any hydrological model, PINEHBV is the model considered for this research study. The HBV model is a conceptual rainfall-runoff model used to simulate runoff process in a catchment based on an input data such as precipitation, temperature and potential evapotranspiration.

The HBV model was developed by Dr. Sten Bergstrom at the Swedish Meteorological and Hydrological Institute (SMHI), at the Hydrologiska Byråns avdelning for Vattenbalans (HBV). The main structure of HBV is shown in Figure 4.2. Despite the absence of snow in Ethiopia, from this diagram the snow parameters are not considered during this research study. However, all the other parameters were taken in to considerations [3].

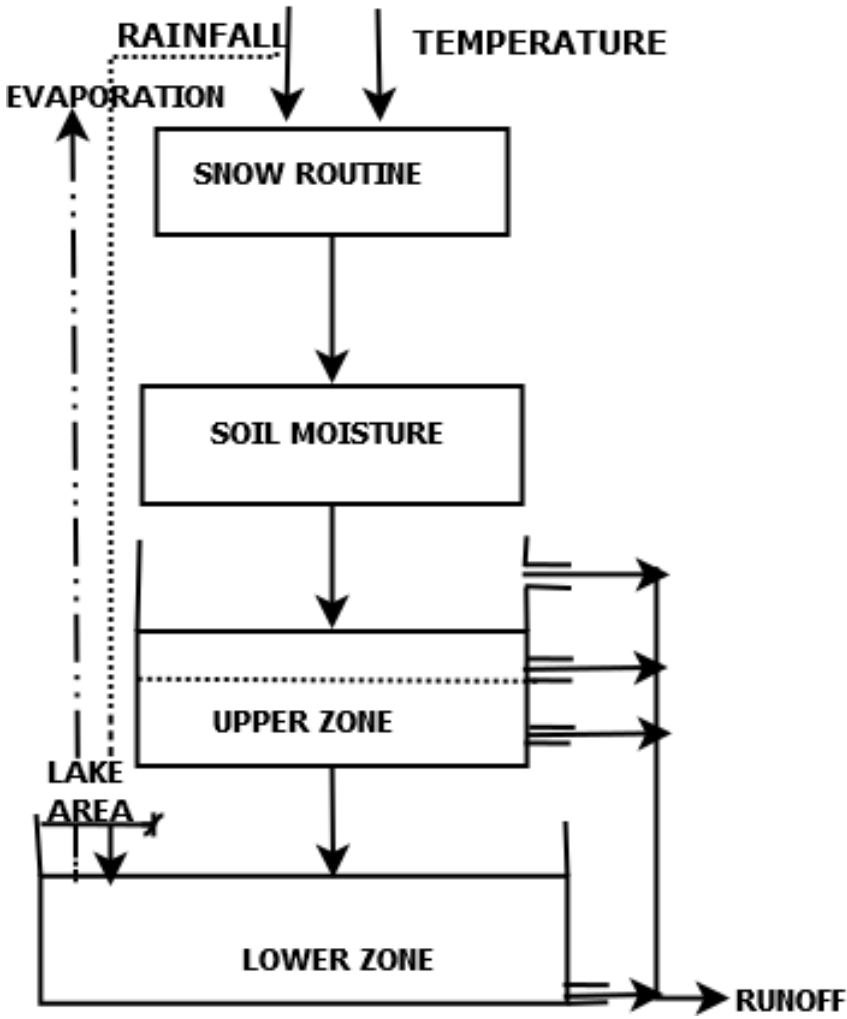


Figure 4.2: HBV model structure

4.3 Hydropower Simulation Model(nMAG)

Simulation model of the hydropower project is important for obtaining and setting reservoir operational strategy. The operation can be simulated over several years with different hydrological conditions. It is also possible to compare the model simulation of the current situations with the measured ones to check how the model responses.

Operation simulation will lead to the following outcomes:

- Average Annual Energy Production, E_A
- Firm Energy Production, E_F
- Average Annual Income, I

Another good reason for making operation simulation is to estimate production due to the variation of inflow within a given year or between different years. Simulation models will simulate different conditions of the system such as:

- Inflow conditions,
- Power demand, energy prices, water consumption, and
- Operational strategy of reservoirs.

For this research study, hydropower simulation model program called nMAG is used to generate the power production. nMAG is one of hydropower simulation models developed at NTH/SINTEF in the mid 1980's. This model is based on detailed description of inflow conditions and production systems. The nMAG model for Tekeze hydropower system case is only one reservoir system. Figure 4.3 shows the schematic representation of nMAG model. According to this diagram the main inflow conditions are the main components for the model and the production system [3]. For simulation of energy production the mean annual runoff from Embamadre watershed was downscaled to the reservoir catchment by the area ratio (i.e. 0.66) to get mean annual runoff of the reservoir. Table 4.1 shows summarized basic design parameters used during nMAG simulation for energy production [2].

Table 4.1: Design parameters used during nMAG simulation

Parameter	Quantity
Nominal Head	162.8m
Lowest regulated level	1096masl
Highest regulated level	1140masl
Volume	5289Mill.m3
Maximum discharge	220m ³ /s
Energy equivalent	0.37kwh/m ³
Intake level	1096masl
Tail Water level	933masl
Firm power	981GWh/yr

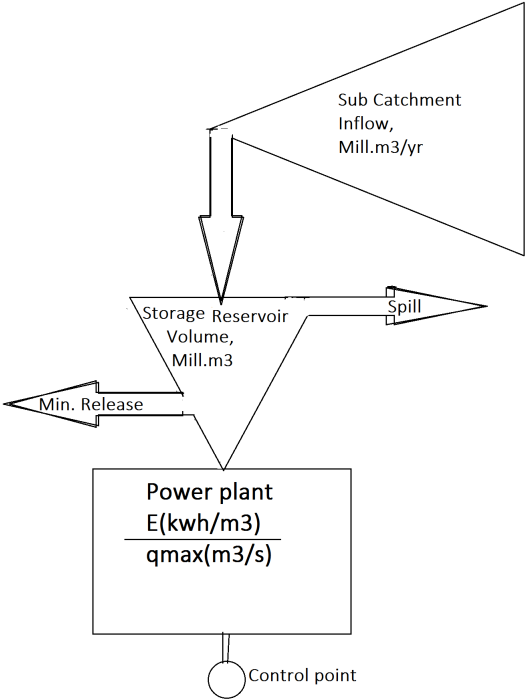


Figure 4.3: nMAG model structure for Tekeze hydropower system

CHAPTER 5

HBV CALIBRATION AND SIMULATION

Before starting to generate runoff for climate study, it is necessary to calibrate the model parameters. After setting up all model input parameters, the next step is to check quality and results of calibration. Calibration can be manual or automatic. Since HBV can do automatic calibration which is time efficient and produces parameter sensitivity, it is easy to do automatic calibration in HBV model. For this research study, two different calibration cases has been made. In the next sections there is detail discussions on both calibration cases and their quality assessment.

5.1 Calibration and Simulation

Calibration is estimating of model parameters otherwise not possible to measure. The summary of the input parameters is written below:

- The observed runoff data available was for total of 7 years (1995 - 2001). So this is splited in to two parts. The first 4 years are taken for calibration and the last 3 years for model verification or validation.
- The observed areal precipitation data was recorded for 14 years (1993 - 2006). For the calibration and validation only the overlapped year (1995 - 2005) was considered.
- The observed maximum and minimum temperature data was recorded the same as precipitation, for 14 years (1993 - 2006). For calibration and validation, average temperature of all the stations for the same year (1995 - 2001) was considered.
- The potential evapo-transpiration was computed using Thornthwaite (1948) equation as average monthly value in mm per day.

- The catchment parameters (i.e. hypsography, elevation of both temperature and precipitation stations, total area) were obtained using ARCGIS applications.
- The remaining parameters are left as the default values and ready to start automatic calibration. In the next sections there is result and comparison of the two different calibration cases.

5.1.1 First Case Calibration

In the first case the precipitation and temperature from all the stations were used. This first case was to check how all the stations response and produces calibration result. The final summary of parameters result obtained from this first case is presented in Table 5.1.

Table 5.1: Parameter results of first calibration

Paramters	Value	Remark
RCORR	1.6	little bit higher
SCORR	1.8	high
FC	26.1	Low
Beta	0.1	Low
R2	0.635	Low
ACC_DIFF	(-1876.8mm)	Very large

Another calibration were also done on this first case to improve the first results. There is difference in the results of the parameters between the two calibrations. The summary of this second calibration is shown in Table 5.2.

Table 5.2: Parameter results of second calibration

Paramters	Value	Remark
RCORR	2.475	Very high
SCORR	2.5	Very high
FC	21.6	Low
Beta	1.172	Ok
R2	0.78	Ok
ACC_DIFF	(-86.6mm)	Medium

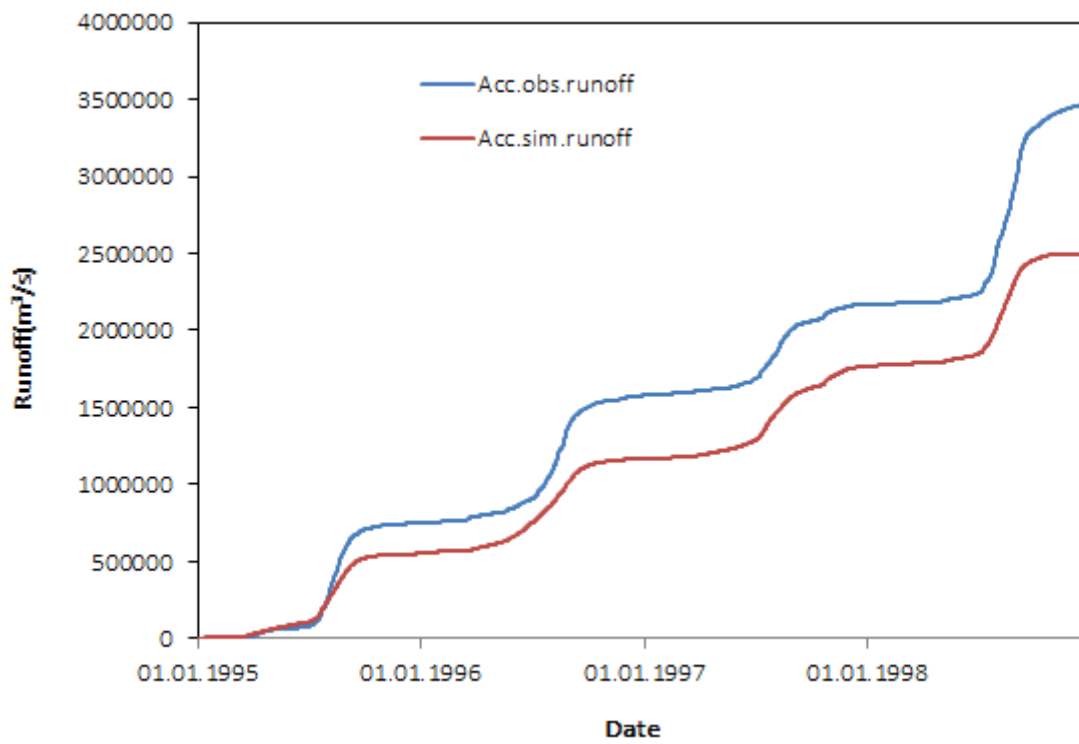


Figure 5.1: Accumulated difference for first calibration

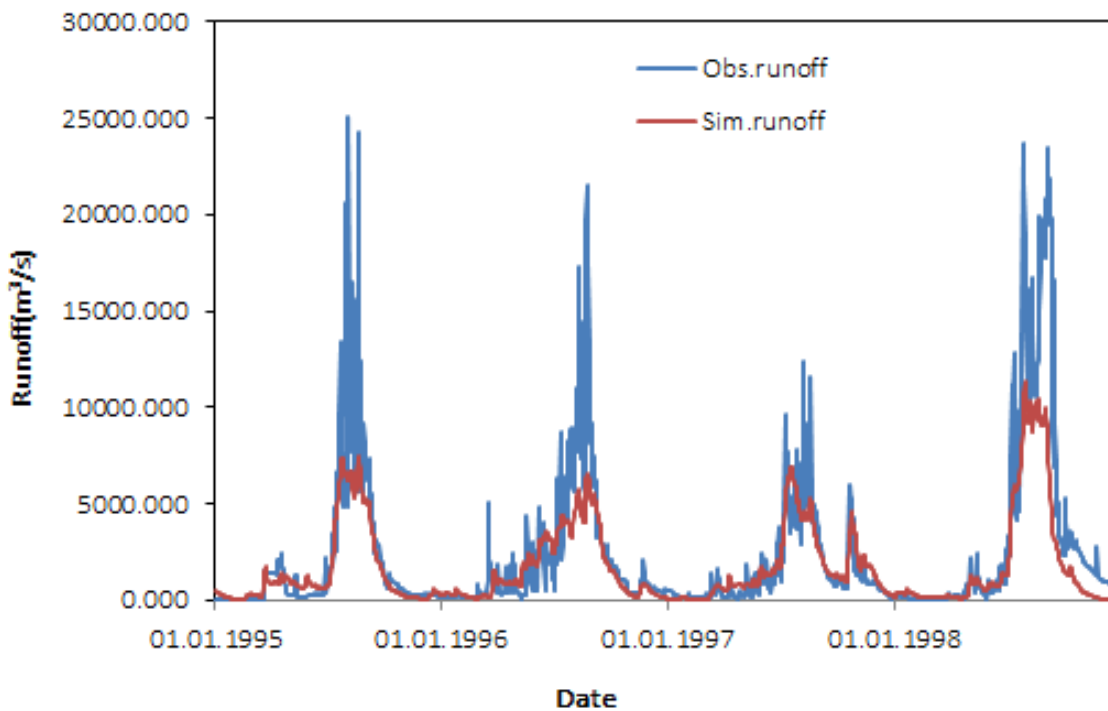


Figure 5.2: Simulated and observed runoff of first calibration

Evaluation of First Case Model Calibration

From Table 5.1 which is the first calibration test, the R^2 value was very low and it is not acceptable. The accumulated difference between simulated and observed runoff was also very large. As a result second calibration was done and shown in Table 5.2. For the second calibration test, in order to improve the R^2 value, the RCORR were extended beyond the limit up to 3 and the final value after calibration becomes RCORR of 2.475. This RCORR value is very high and this high value indicates that the input precipitation to the model was very low and as a result the model takes high correction factor (i.e. $RCORR = 2.475$). The possible solution for this was to check the input precipitation data to the model. There is second case calibration in (subsection 5.1.2) which describes this condition.

The accumulated difference between simulated and observed runoff for both calibrations are shown in Figure 5.1 and Figure 5.3. In the first calibration (Figure 5.1) the accumulated difference is very large as compared to the second (Figure 5.3). Thus the second calibration test is better with low accumulated difference than the first calibration. However, the accumulated difference is not the only criteria to evaluate calibration quality.

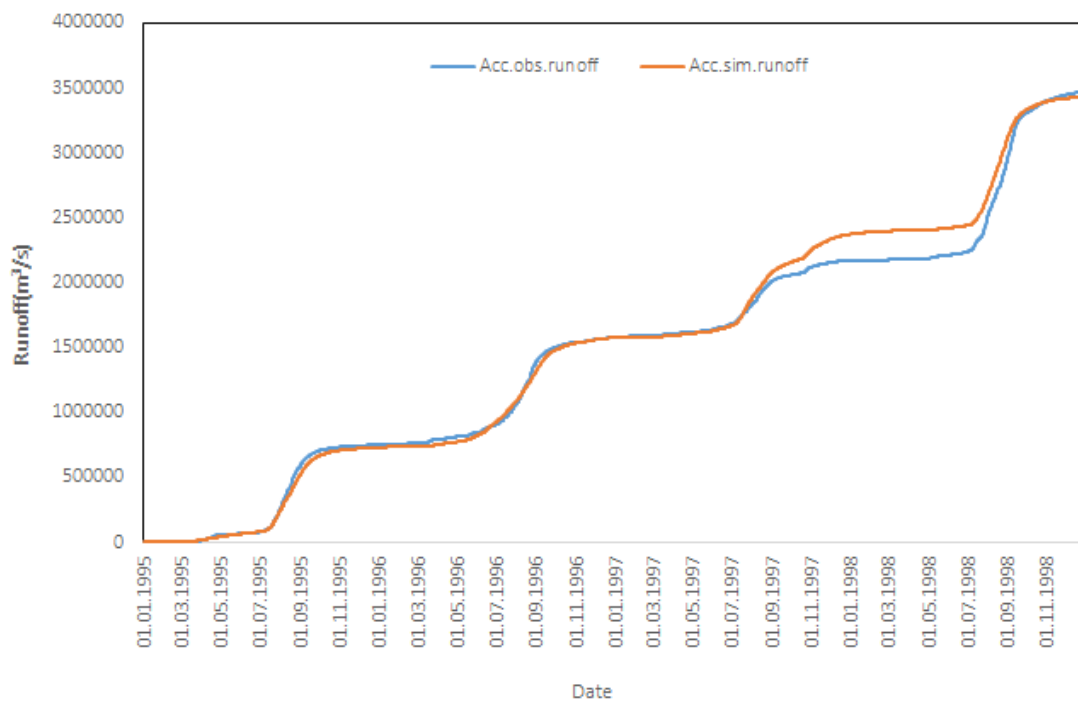


Figure 5.3: Accumulated difference for second calibration

The simulated and observed runoff for the first case is shown in Figure 5.2 and Figure 5.4. In both calibrations the timing and magnitude for all episodes is not good. On the other hand the recession curvatures also shows deviations and not correct at all. Even though the second graph in Figure 5.4 is better still due to unrealistic parameter values specially rainfall correction factor of 2.4, this calibration is no longer useful. In the next subsection 5.1.2 a second calibration case is described which is the accepted one to generate runoff series for climate studies.

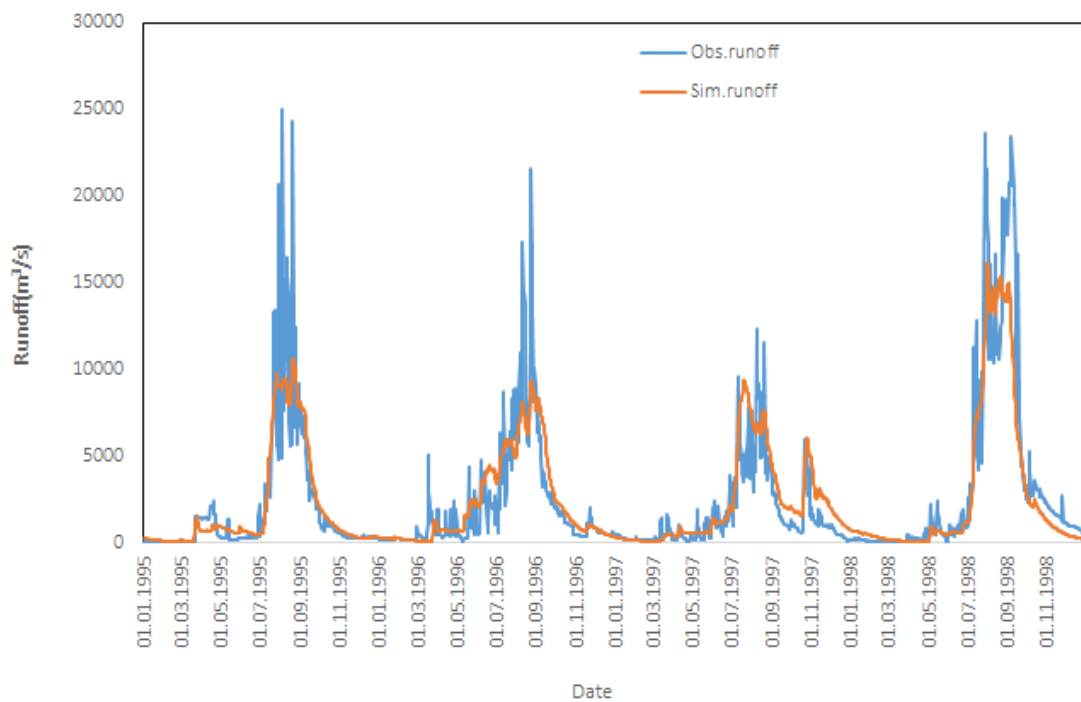


Figure 5.4: Simulated and observed runoff for second calibration

5.1.2 Second Case Calibration

There is low precipitation coming in to the model according to the first case. So for the second case, one of the three stations with low annual precipitation is omitted (i.e. Mekelle Airport) in order to increase the precipitation coming in to the model. As a result 6 precipitation stations were used. Table 5.3 shows the summary of the parameters result obtained in the final calibration case.

Table 5.3: Parameter results of final calibration

Paramters	Value	Remark
RCORR	0.42	Ok
SCORR	0.58	OK
FC	77.2	Low
Beta	0.352	Low
R2	0.804	Very Good
ACC_DIFF	(-4.9mm)	Low = Ok

The simulated and observed runoff after calibration is better than the previous two calibrations and is shown in Figure 5.6. Besides, the accumulated difference between both simulated and observed is very low and it is an accepted value. In this case the R^2 is 0.8 which is much better than all the previous calibration tests. After accepting this calibration case results, validation was made for the last three years (i.e. 1999 - 2001). The validation result gives the value of R^2 (0.73).

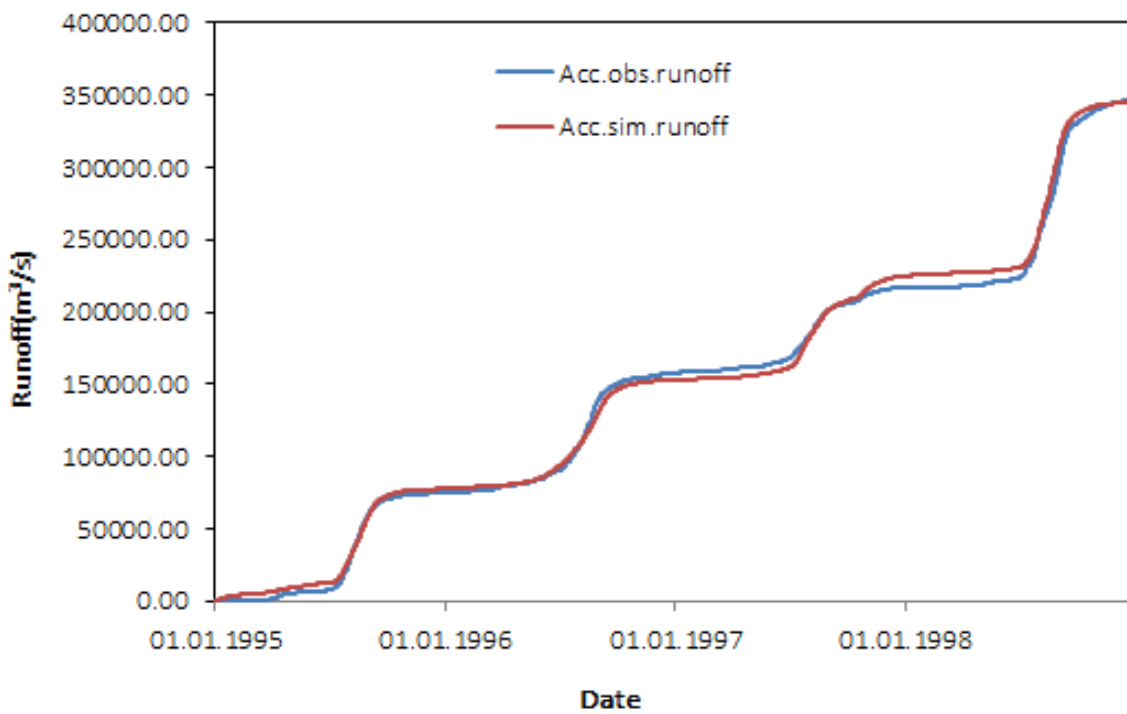


Figure 5.5: Accumulated difference for final calibration

Evaluation of Second Case Model Calibration

The second case calibration results are better than all the previous calibrations. This calibration results shows R^2 value of 0.8 and accumulated runoff difference of (-4mm). The timing and magnitude of the calibration is good and better than the first case. Besides the produced recession curvatures were correct for every episodes. The calibration also simulated correct overall volume with very low accumulated difference. Thus, this calibration case was taken as the final and acceptable one for this research study and all the generated runoff are based on this calibration parameter results.

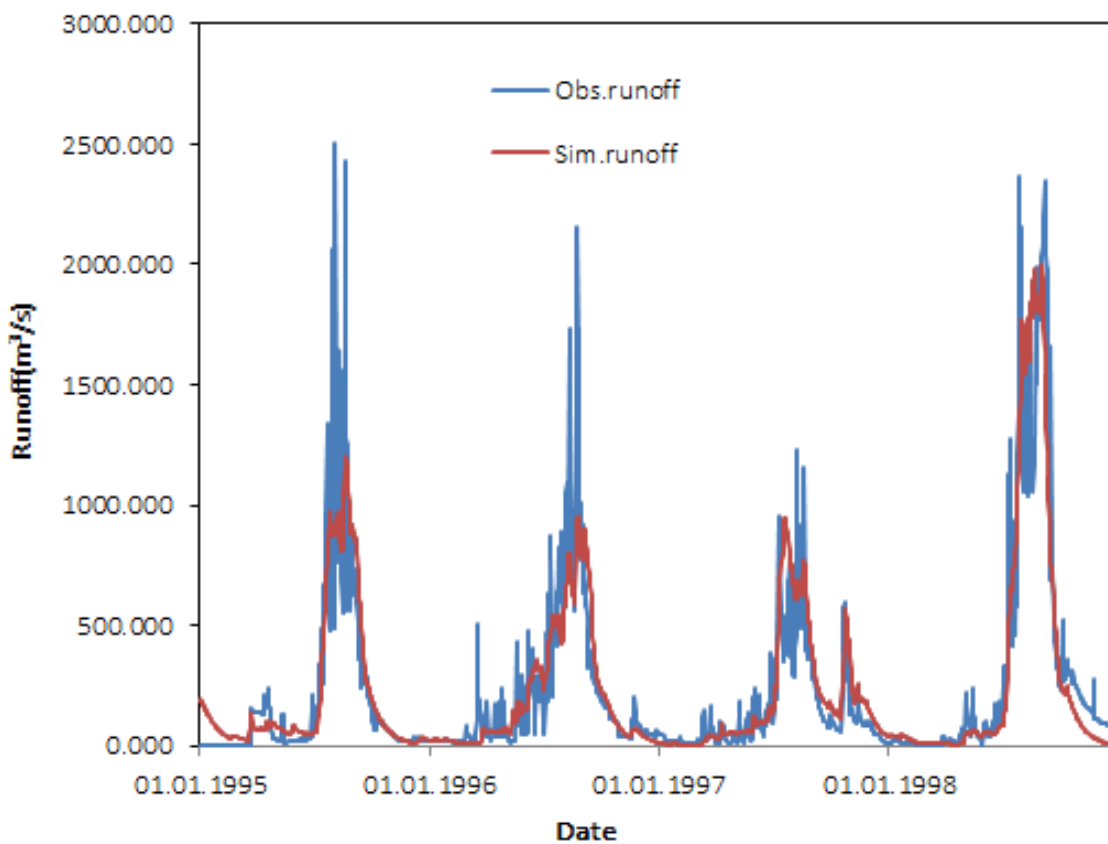


Figure 5.6: Simulated and observed runoff for final calibration

5.2 Runoff Series for Climate Change Analysis

After taking all the parameters from second case calibration (final calibration), 14 years runoff data were simulated for climate studies. Initially the observed runoff data were only for 7 years. By extending up to 14 years starting from 1993 up to 2006, the model generated new runoff series which is going to be used for climate studies. The generated runoff series is shown in Figure 5.7.

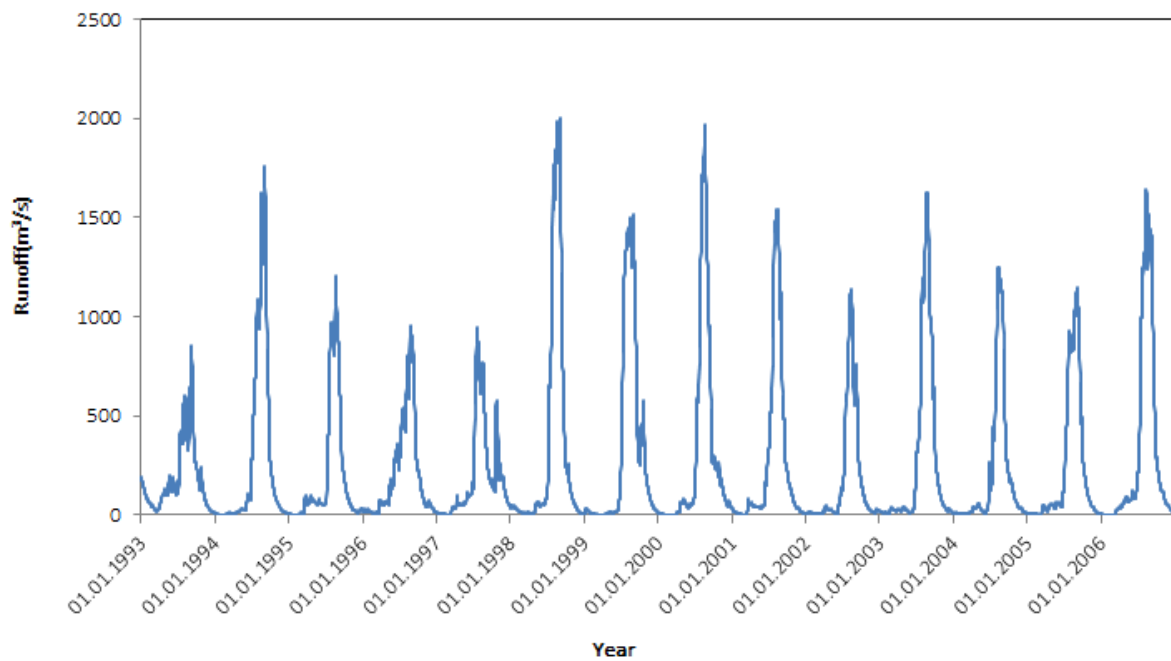


Figure 5.7: Simulated runoff for climate studies

CHAPTER 6

MODELLING CLIMATE CHANGE IMPACTS ON HYDROPOWER

The other main purpose of this research is to downscale climate data and make assessment on it. The climate data was taken from Canadian Center for Climate Modelling and Analysis (CCCma). CCCma has developed a number of climate models. However, the only model available for free for African continent and some other continents is the Canadian Regional Climate Model (CanRCM4). The model has only two future scenarios (i.e. Rcp45 and Rcp85) for African region, 0.22° horizontal grid resolution of approximately 25km. The data is freely available at (<http://www.cccma.ec.gc.ca/data/data.shtml>). The same website is used for precipitation and rainfall. The climate data were for 30 years slices. For historical the data started from 1976 up to 2005. In addition, for the future the data starts from 2041 - 2070 and 2071 - 2100.

6.1 Regional Circulation Models - Selection and Downscaling

A Global Climate Model (GCM) can provide reliable prediction information on scales of around 1000 by 1000km. However, Regional Climate Models (RCM) and Empirical Statistical Downscaling (ESD), applied over a limited area and driven by GCMs can provide information on much smaller scales. Since the impacts of climate change and adaptation strategies required to deal with them occur more on regional and national scales, it is important to use Regional climate downscaled data that provide much greater detail and more accurate representation of localised extreme events.

To downscale the RCM data CORDEX were considered. CORDEX is coordinated regional downscaling experiment which is an international project founded by the World Climate Research Programme, and aims to coordinate international efforts in regional climate downscaling. The downscaling and selection of precipitation and temperature data has been done by writing scripts in R programming language.

6.1.1 Delta Change Approach

After downloading climate data from the Canadian Center for Climate Modelling and Analysis website, the delta change was calculated. Delta change is the mean monthly change in precipitation or temperature between historical and future downscaled climate data. For calculation of delta change R programming language were used. The scripts of R programming languages were written and the following three main steps were followed to compute delta change factor:

- The first step was to find and select location of grid points based on the catchment. This will give index of matrix points in the catchment. The total number of grid points for the catchment were 120. Figure 6.1 shows location of all grid points within the catchment.

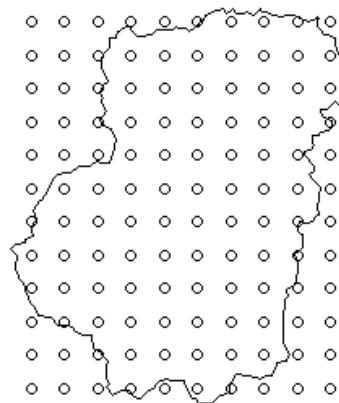
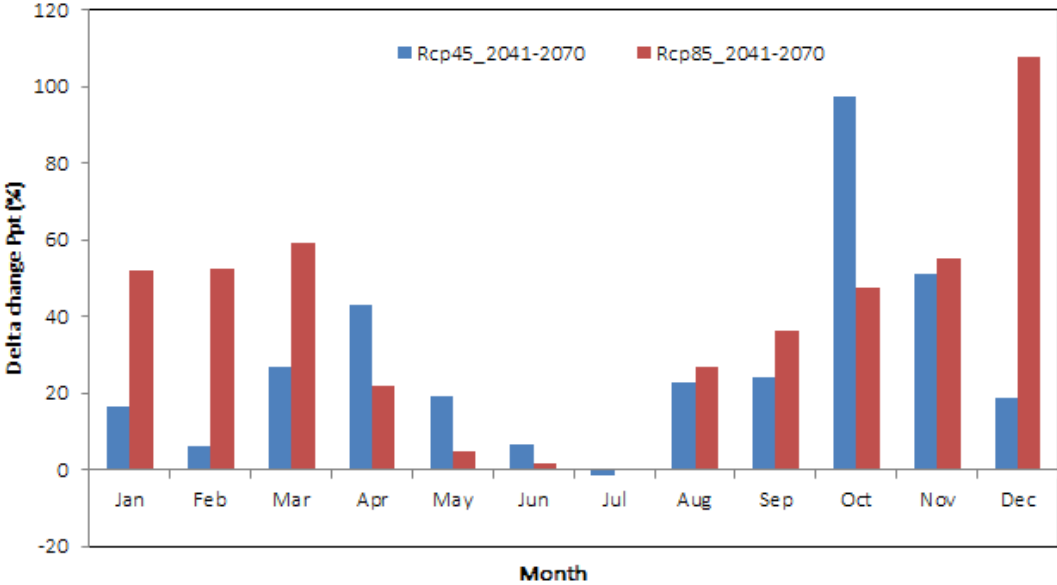


Figure 6.1: Location of grid points During downscaling

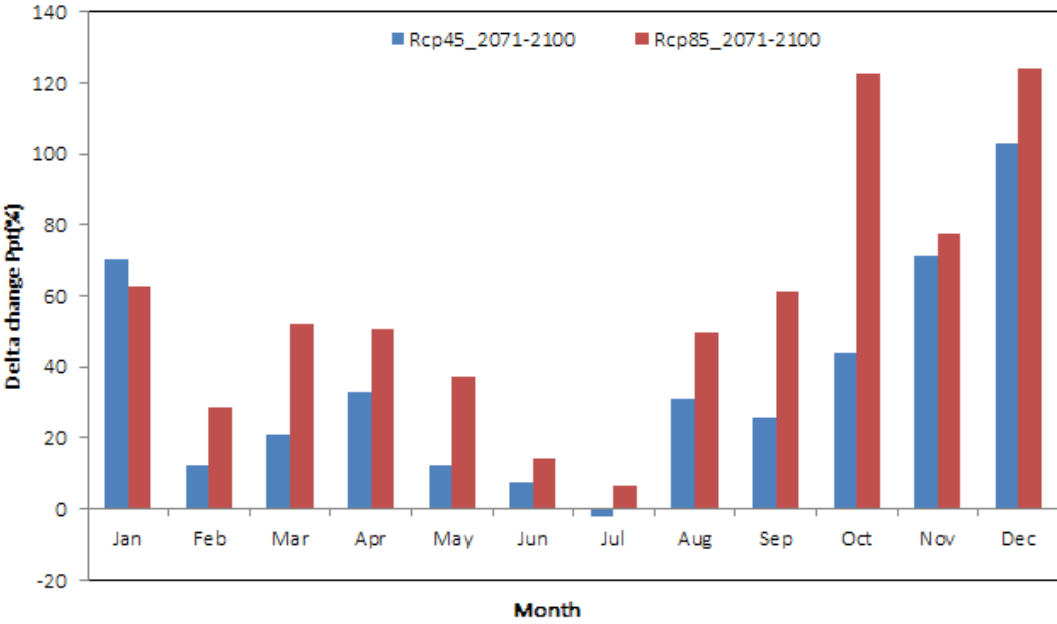
- The second step was to extract relevant daily precipitation and temperature data for the selected points of step one.
- The third and final step was to calculate delta change for both scenarios. In this step the daily data is change in to mean monthly data before calculation of delta change. The delta change is monthly percentage change value.

The delta change of rainfall during the first 30 years computed for both scenarios (Rcp45 and Rcp85) is shown in Figure 6.2a. The delta change result ranges from (-1%) up to maximum (+108%). Exceptionally October and December shows very high delta change values. However, these months are dry months in Ethiopia. In Rcp45 the delta change is negative for the month July. The negative number indicates decrease in rainfall for the future according to the first scenario. However, the delta change in Rcp85 is zero indicating that the rainfall will not change for July month. The delta change during the next 30 years of rainfall computed for both scenarios (Rcp45 and Rcp85) is shown in Figure 6.2b. Here again the delta change ranges from (-2%) up to maximum (+124%). From this graph the delta change is positive for all months for Rcp85 and exceptionally very high for October and December months which implies an increase monthly rainfall. In contrast Rcp45 shows negative delta change value for the rainy month of Ethiopia (i.e. July) which implies decrease of rainfall in the future time.

On the other hand, the delta change of temperature computed during the first 30 years (2041-2070) for both scenarios is shown in Figure 6.3a. The delta change values ranges from (-8⁰C) up to maximum (+3.25⁰C). This figure shows that the future temperature will decrease for the first 30 years according to the first scenario (Rcp45). However, this is not the case for the second scenario (Rcp85). Besides the delta change of temperature for both scenarios during the last 30 years (2071-2100) is shown in Figure 6.3b. Unlike the previous 30 years, the delta change is positive ranging from (+2.7⁰C) up to maximum (+5⁰C). Both graphs shows increase of temperature in the future time with positive values in all months.

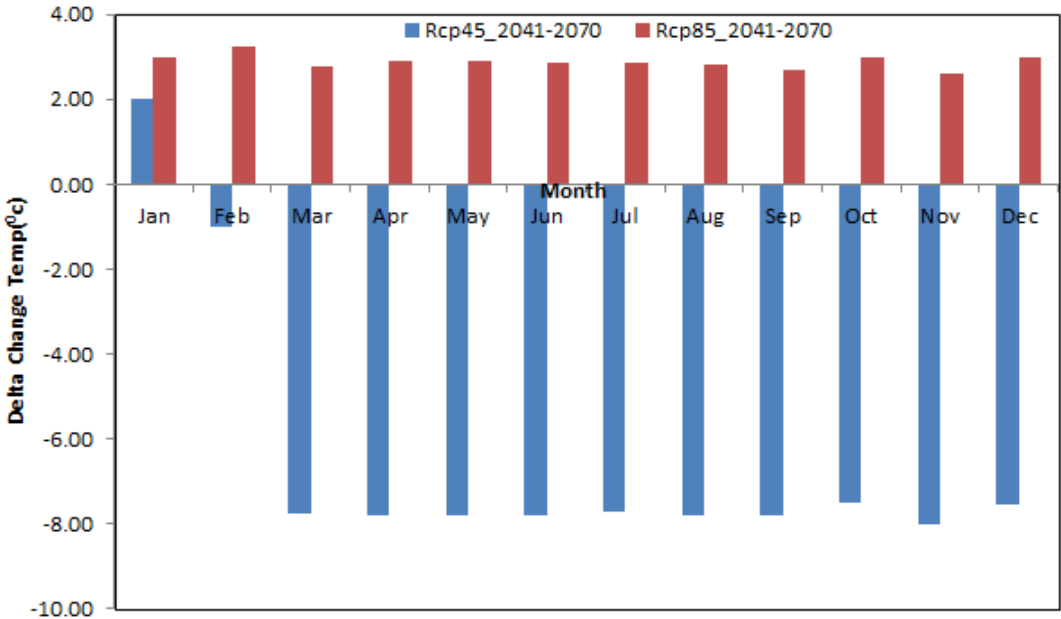


(a) 2041 - 2070

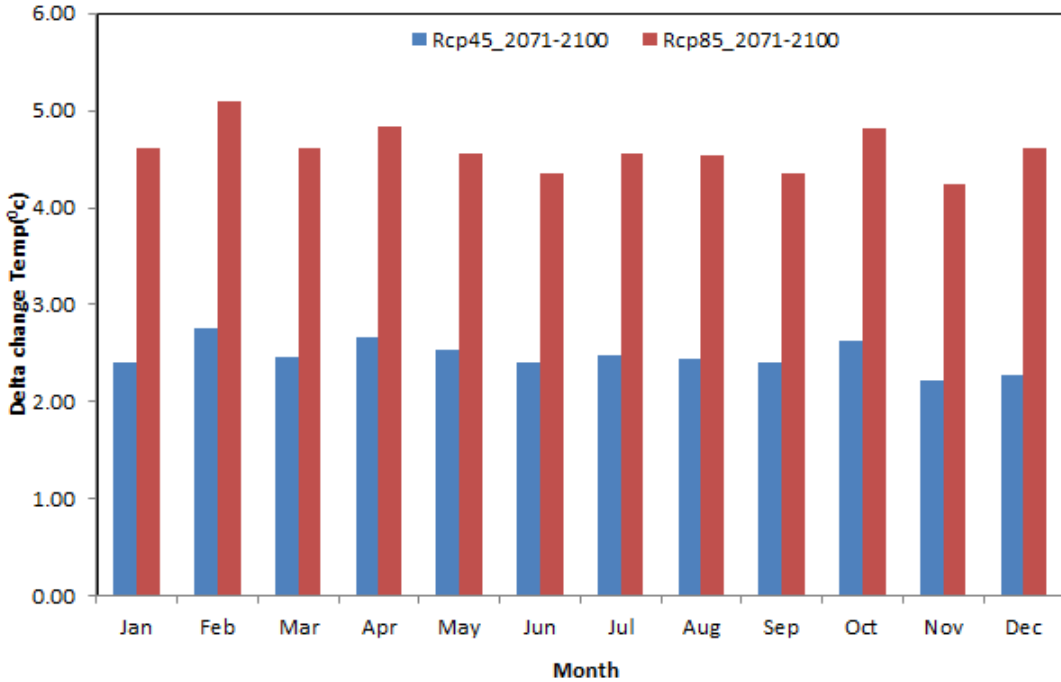


(b) 2071 - 2100

Figure 6.2: Delta change for rainfall



(a) 2041 - 2070



(b) 2071 - 2100

Figure 6.3: Delta change for temperature

All of the previous delta changes of rainfall were used for the first method during application of scenarios. However, for the second method mean monthly change has been computed. There is more discussion on application of scenarios in section 6.2.

The mean monthly change of rainfall computed for the whole time series is summarized in Table 6.1. This table shows the mean monthly change that is going to be added based on the second method of scenarios application. During the month July there is negative mean monthly change values which indicates the reduction of future rainfall.

Table 6.1: Mean monthly change rainfall for all scenarios in mm

Month	RCP45_4170	Rcp_85_4170	Rcp_45_7100	Rcp_85_7100
Jan	0.0	0.1	0.1	0.2
Feb	0.0	0.2	0.0	0.1
Mar	0.2	0.5	0.1	0.4
Apr	0.8	0.4	0.6	0.7
May	0.4	0.1	0.3	0.8
Jun	0.2	0.0	0.3	0.5
Jul	-0.2	-0.2	-0.3	0.3
Aug	1.7	1.9	2.2	3.6
Sep	0.9	1.5	1.0	2.4
Oct	1.2	0.6	0.6	1.4
Nov	0.2	0.2	0.3	0.3
Dec	0.1	0.3	0.3	0.3

6.2 Application of Scenarios

After calculating the delta change values, the next step was to compare different methods for applying the scenarios. Two ways of applying the monthly rainfall scenarios to daily rainfall time series were considered [4].

6.2.1 Proportional Change - Delta Change

The first method applies the monthly percentage change (i.e. Delta change) to each day's rainfall within a given month. Therefore, this will give a 'proportional change' rainfall scenario. The change in temperature was applied in the same way to give proportional change during calculation of potential evapo-transpiration. The application of this delta change method has drawbacks. For example, the delta change in Figure 6.2a during October and December shows an increase in rainfall for future scenarios. However, these months are dry month in Ethiopia and application of any delta change factor will not change the future since it is multiplied with dry days (i.e. 0 mm rainfall). Thus, to overcome this drawbacks of Delta change method a second method were considered and applied.

6.2.2 Rainy Days - Mean Monthly Change

According to the second method [4] ('change in rain days') applies the scenario by changing the number of rain days in each month. From September up to May, the number of rain days per month was increased if the scenario showed an increase monthly rainfall. This increase in rainfall was attained by adding the change in mean monthly rainfall, divided equally, to every third dry day. For example, if the month had nine dry days (i.e. days with 0mm precipitation) then the mean monthly change is divided in to three and applied to every third dry day. If there were no dry days then the change was applied proportionally.

On the other hand, if the mean monthly rainfall decreases (i.e. negative value), the number of rain days was kept constant and a proportion of this mean monthly decreased value was subtracted from each day. In the summer the percentage decrease was applied proportionally to each day. This method of applying the scenario have an effect of reducing wet days during dry periods and increasing during wetter periods but the overall applied volume is the same.

CHAPTER 7

RESULTS AND DISCUSSIONS

The calibrated model were assumed stationary through out the future time. Thus, all simulation results were based on this calibrated model of the catchment. The simulated runoff for different cases, for different time series and different scenarios are discussed in detail in this chapter.

7.1 Model Results and Discussions

In the following sections, rainfall after applying both application methods and all simulated runoff results are presented. Three different cases were considered during runoff simulation using PINEHBV model. The first case is based on the first method for application of scenarios (section 6.2.1). This was done by applying delta change factor for each month and new runoff were generated afterwards. The second case is based on direct simulation from the downscaled RCM data for the target catchment. The third case is based on the second method for application of scenarios (section 6.2.2). This was done by adding mean monthly change for each month and new runoff generated afterwards.

7.1.1 Rainfall - Runoff Modelling

Using the calibrated model, an extended time series runoff were generated by PINEHBV model. This generated runoff is shown in Figure 5.7. The annual runoff volume is shown in Figure 7.1. This Figure shows higher volume in the year 1998, 1999, 2000 and 2006 as compared to other years. Besides the volume were lower in the year 1993, 1995, 1996, 1997 and 2002.

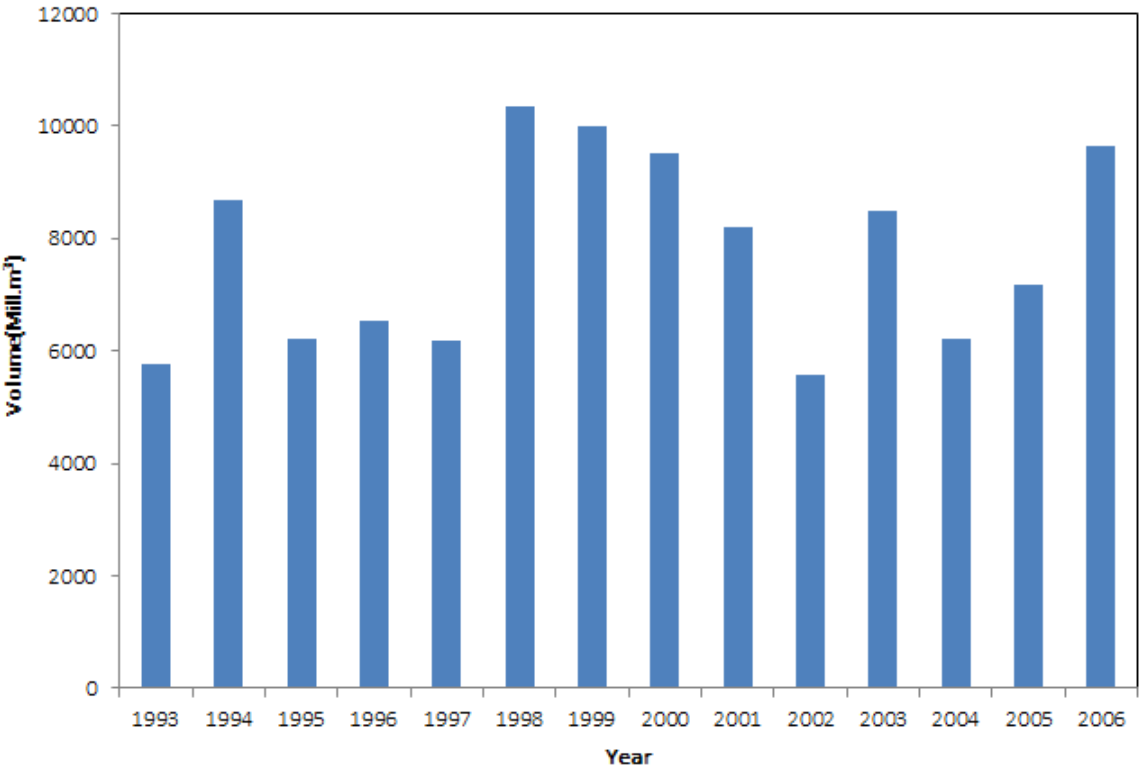


Figure 7.1: Current simulated annual runoff volume (1993 - 2006)

7.1.2 Rainfall After Applying Delta Change Method

The new mean monthly rainfall computed after applying delta change factor is shown in Figure 7.2. This graph shows too much variation of rainfall within each days of the month. It shows deviations since it will not change the dry days (i.e. days with 0mm rainfall).

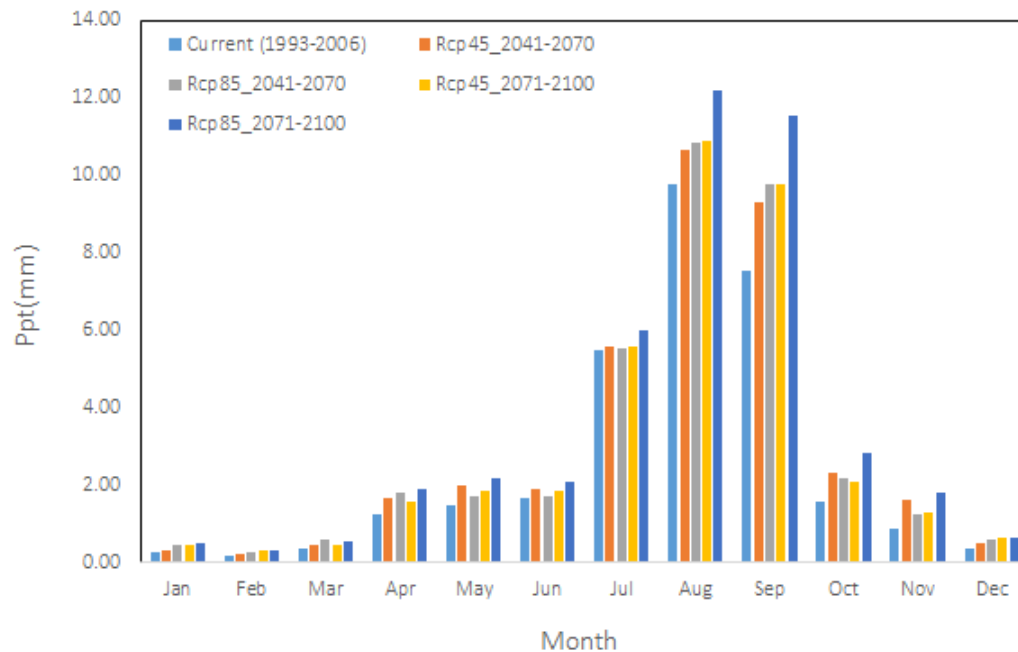
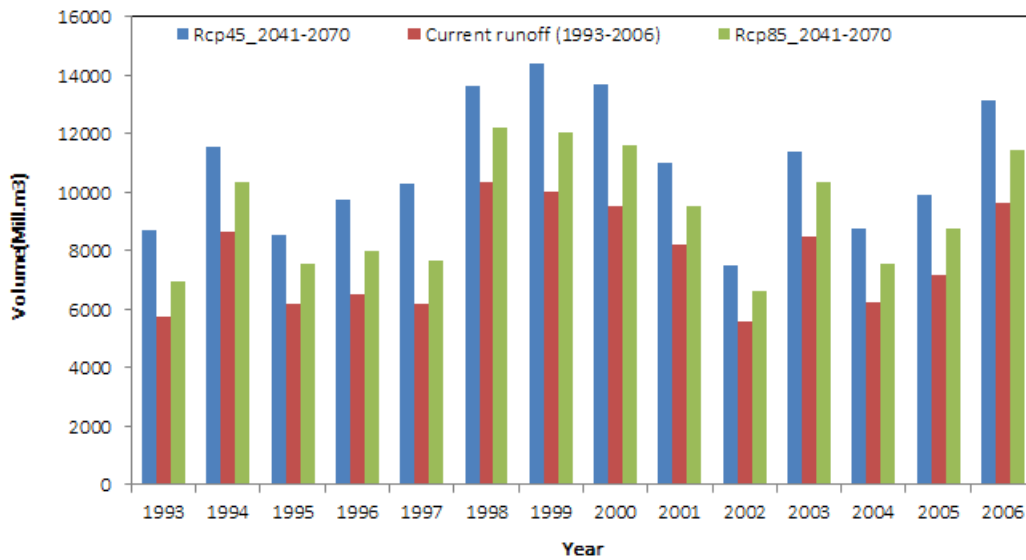


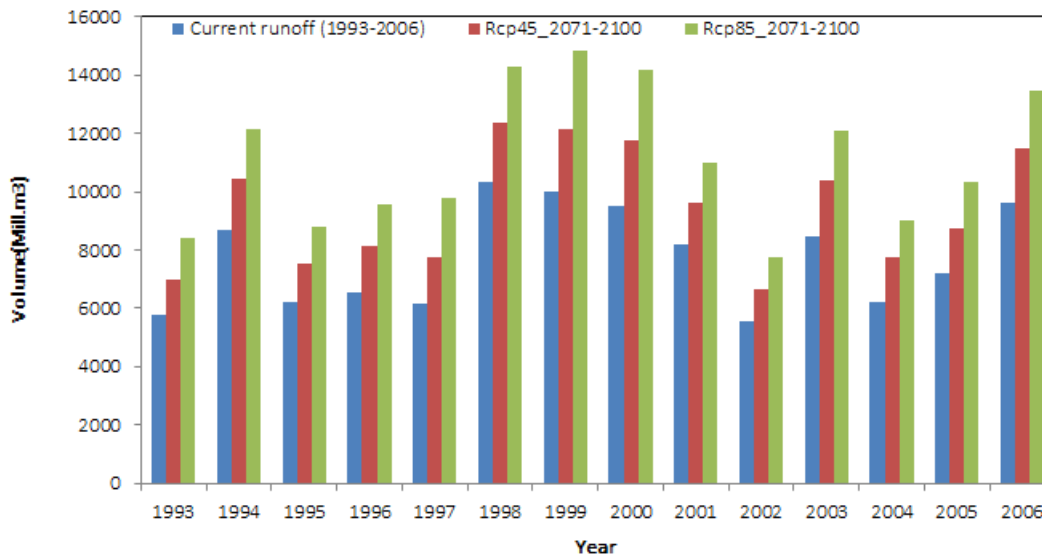
Figure 7.2: Mean monthly rainfall after applying delta change

7.1.3 Runoff After Applying Delta Change Method

The monthly delta change factors are shown in section 6.1.1. In this section the simulated runoff after application of delta change factor will be described. The annual runoff volume after application of both Rcp45 and Rcp85 scenarios during the first 30 years (2041-2070) is shown in Figure 7.3a. The comparison was made with the simulated runoff using the same calibrated model. The graph shows change in annual runoff volume for the future time due to the climate which was applied as delta change factor. From this graph the annual volume was increased from the current time for both scenarios during the first 30 years. Besides, Rcp45 shows higher annual runoff volume than Rcp85 for the same time step. For the daily time series another graph was also made and is shown in Figure 7.8. The timing and recessions shows similar pattern for both scenarios and current runoff with difference in peaks. In this graph Rcp45 shows higher runoff peaks than Rcp85.



(a) 2041 - 2070



(b) 2071 - 2100

Figure 7.3: Annual runoff volume after applying delta change

On the other hand the same procedure were followed to simulated the runoff for the last 30 years (i.e. 2071 - 2100). The annual runoff volume after application of delta change factor is shown in Figure 7.3b. Rcp85 shows higher annual runoff volume than Rcp45. However, both scenarios produces higher runoff volume than the current simulated runoff (i.e. runoff during 1993 - 2006). The graph also shows the simulated runoff with out any delta change applications for comparison. In addition to show the daily time series graph was made and is shown on Figure 7.9. This time series graph shows similar pattern for both scenarios and simulated runoff with difference in the peaks. Here again Rcp85 shows higher peak values than Rcp45 in the daily time series.

7.1.4 Direct Simulations

Another result to compare was whether the runoff generated by the model using the downscaled RCM precipitation and temperature represents the catchment. For this condition the extended 14 years current runoff and the runoff from downscaled RCM data for the same period (i.e. 1993 - 2005) were compared. Figure 7.12 shows the daily time series runoff between the current and RCM runoff. From this graph the RCM runoff is not fitted well with the current runoff. However, it shows similar recession and rise pattern which implies similarity between them. In addition Figure 7.4 shows annual runoff volume for both current and RCM runoff. From this graph in most time steps the generated runoff from RCM shows higher volume than the current runoff. However, still there is similarity which can be taken as representative values for the target catchment. Generally, it is possible to say that the RCM data can represent the catchment according to these graphs.

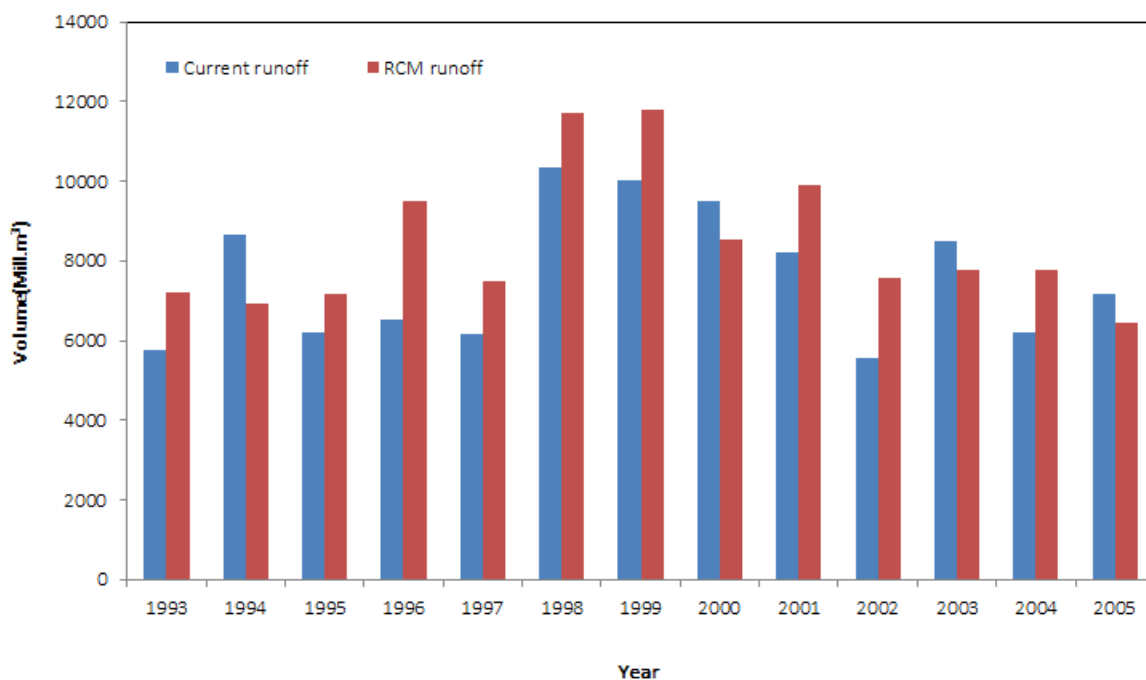


Figure 7.4: Annual runoff volume for current and RCM during 1993 - 2005

For both future scenarios, direct simulations was also made to check how the RCM data varies during the period 1976 - 2004 and the future time 2041 - 2069. Figure 7.13 shows the daily time series runoff from RCM during historical and future time steps for both Rcp45 and Rcp85 scenarios. This graph do not show any shift in time for the runoff during past and future time. The graph also shows an increase runoff in the future time for both scenarios than the historical runoff (i.e. 1976 - 2004). Similar procedure were followed for the last 30 years (i.e. 2071 - 2100) and historical RCM (1976-2005). The generated RCM runoff data both in the past and future time was compared for Rcp45 and Rcp85. There is an increase runoff in the future time for both scenarios and it is shown in Figure 7.14. On the other hand annual runoff volume was drawn for the same time step and is shown in Figure 7.6a and Figure 7.6b. In Figure 7.6a Rcp45 shows higher annul runoff volume than the others. Besides, in Figure 7.6b Rcp85 shows higher annual runoff volume than the others.

7.1.5 Rainfall After Applying 'Rainy Days Method'

Unlike delta change, this method produces consistent rainfall. In addition, the change is applied evenly considering dry days within each month(i.e. days with 0mm rainfall) as outlined in Figure 7.5. Thus, this method gives better distribution of change in rainfall for every days within a given month.

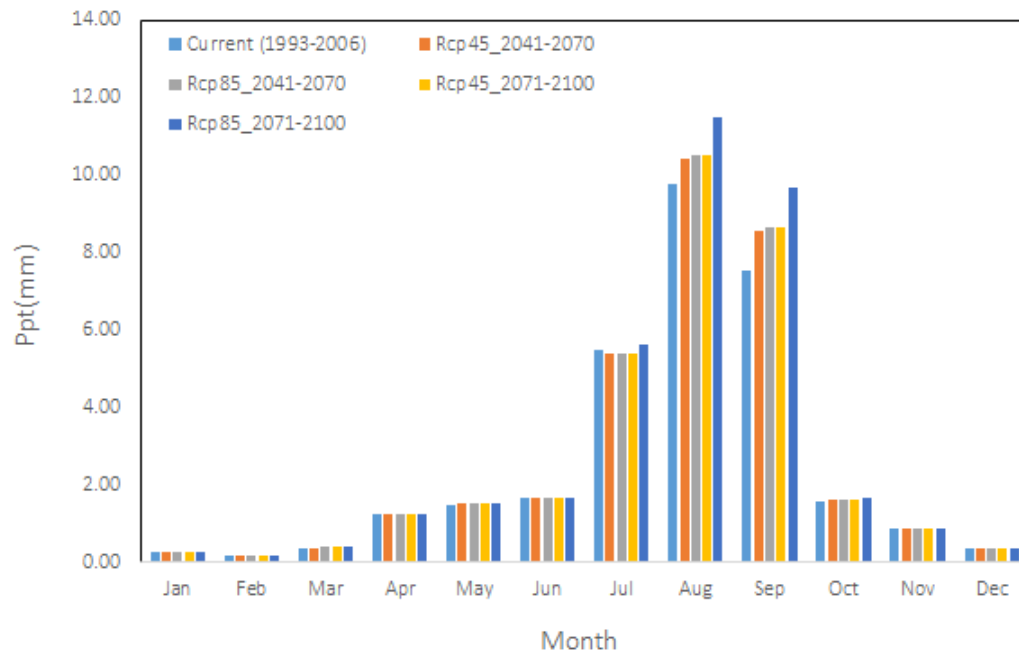
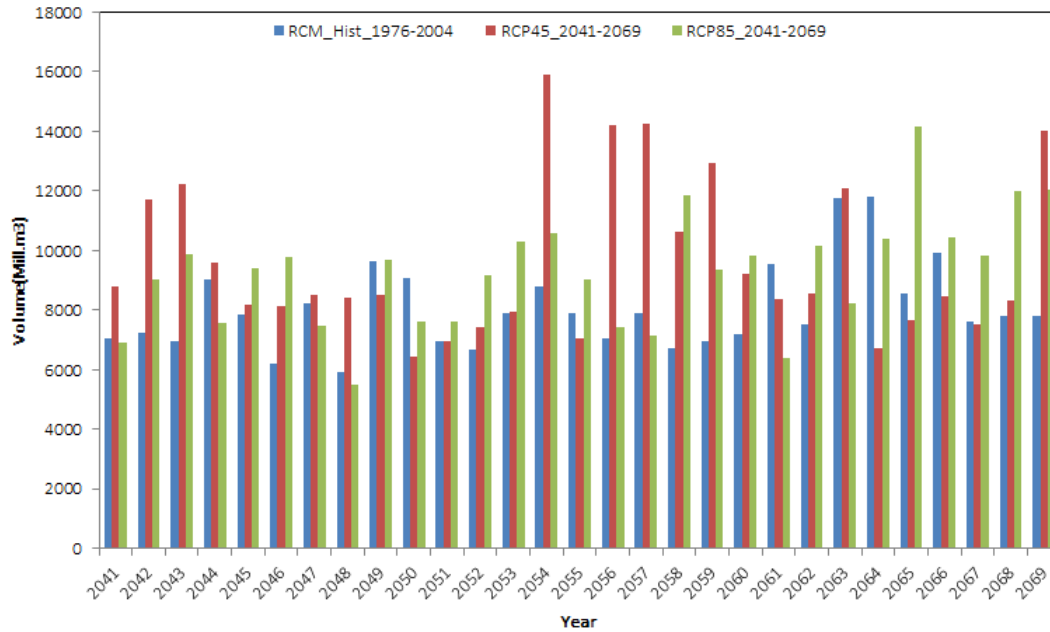


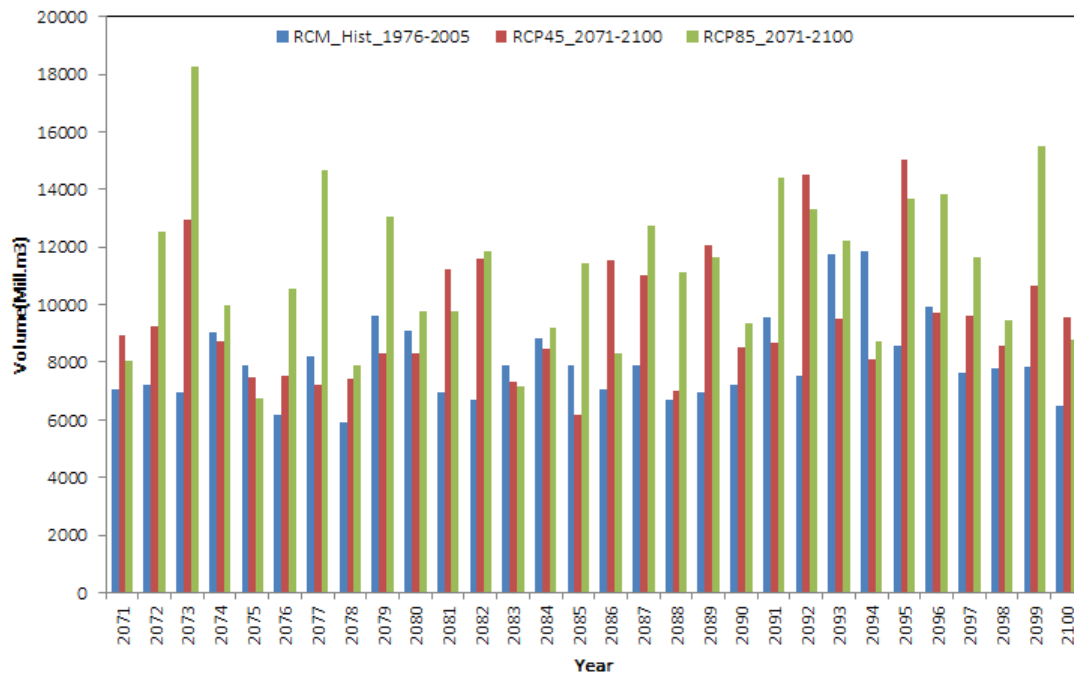
Figure 7.5: Mean monthly rainfall after applying rainy days

7.1.6 Runoff After Applying Rainy Days Method

The mean monthly change added to every month during the future time for both scenarios is shown in Table 6.1. The runoff generated for this case is based on the second method of application scenarios described in section 6.2.2. The generated annual runoff volume during the first 30 years starting from 2041 - 2070 is shown in Figure 7.7a. From this figure Rcp45 shows higher annual runoff volume. Similarly the generated annual runoff volume for the last 30 years starting from 2071 - 2100 is also shown in Figure 7.7b. Here again Rcp45 shows higher annual runoff volume than others.

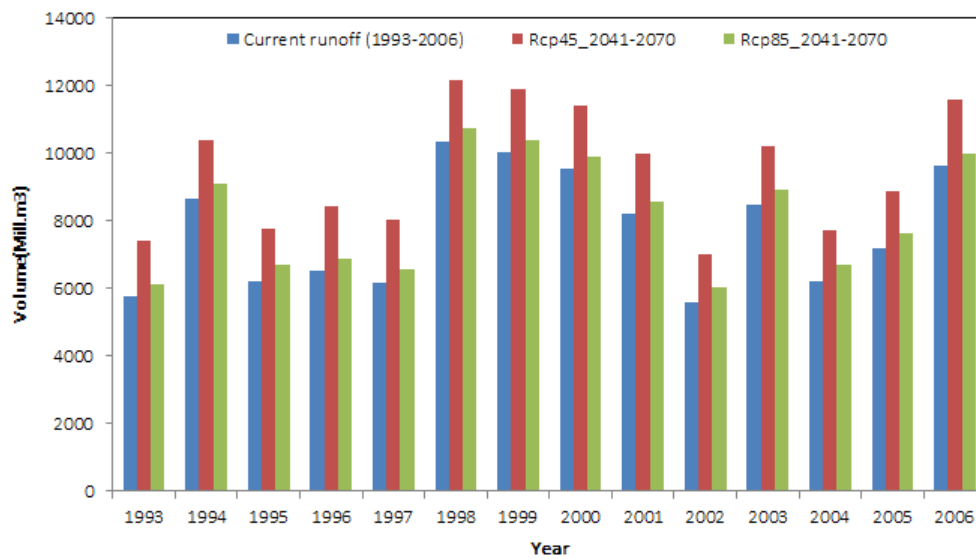


(a) 2041 - 2069

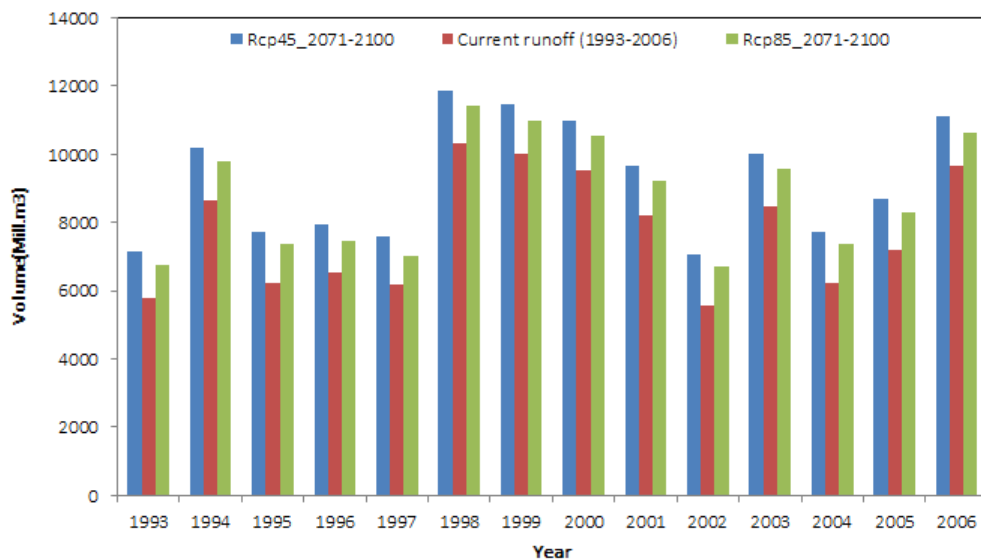


(b) 2071 - 2100

Figure 7.6: Annual runoff volume for RCM



(a) 2041 - 2070



(b) 2071 - 2100

Figure 7.7: Annual runoff volume after applying rainy days method

For daily time series, Figure 7.15 shows generated runoff during the first 30 years (i.e. 2041 - 2071) for Rcp45 and Rcp85. All the hydrographs show similar rising and recession pattern for all time series. However, the peaks are different. Similar graph is also shown in Figure 7.16. In this graph the rising as well as the recession pattern have similarity with the others. However, there is difference in peaks between current simulated runoff and future scenarios.

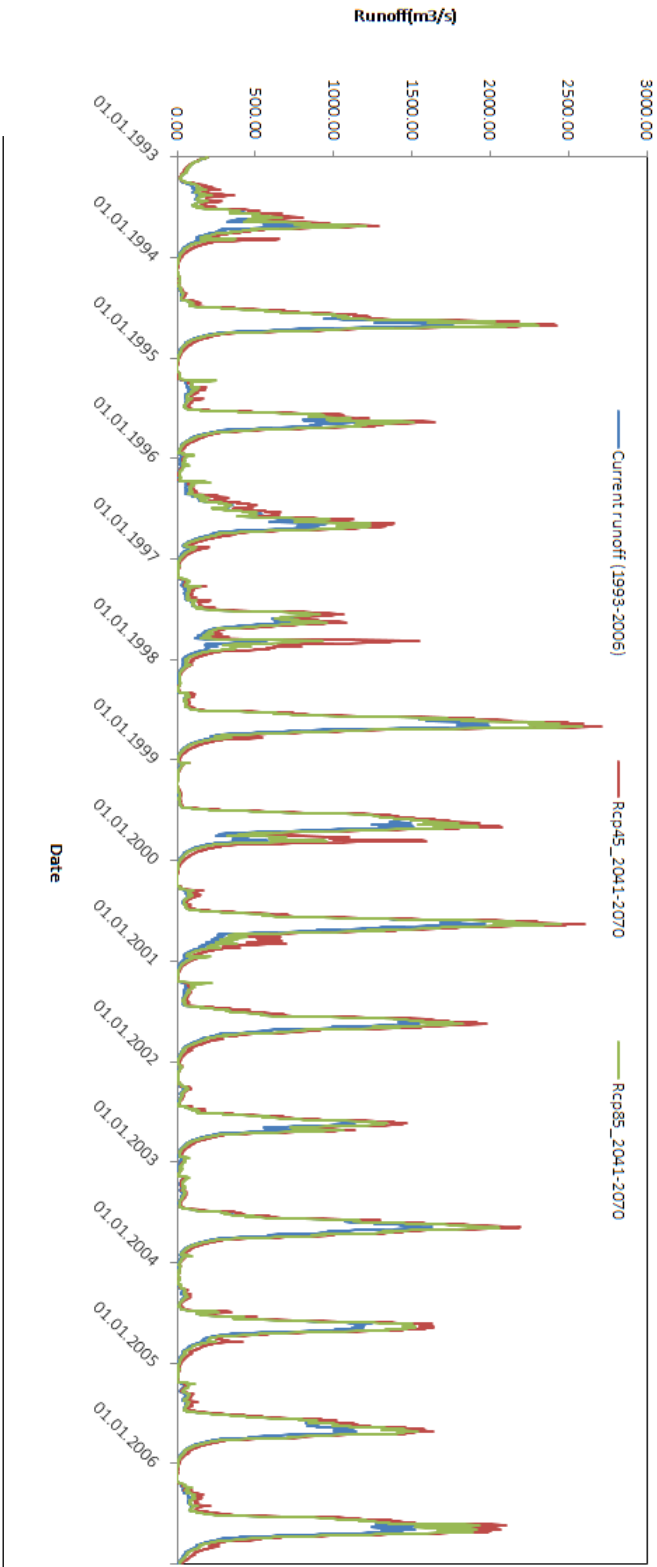


Figure 7.8: Daily time series runoff after applying delta change (2041 - 2070)

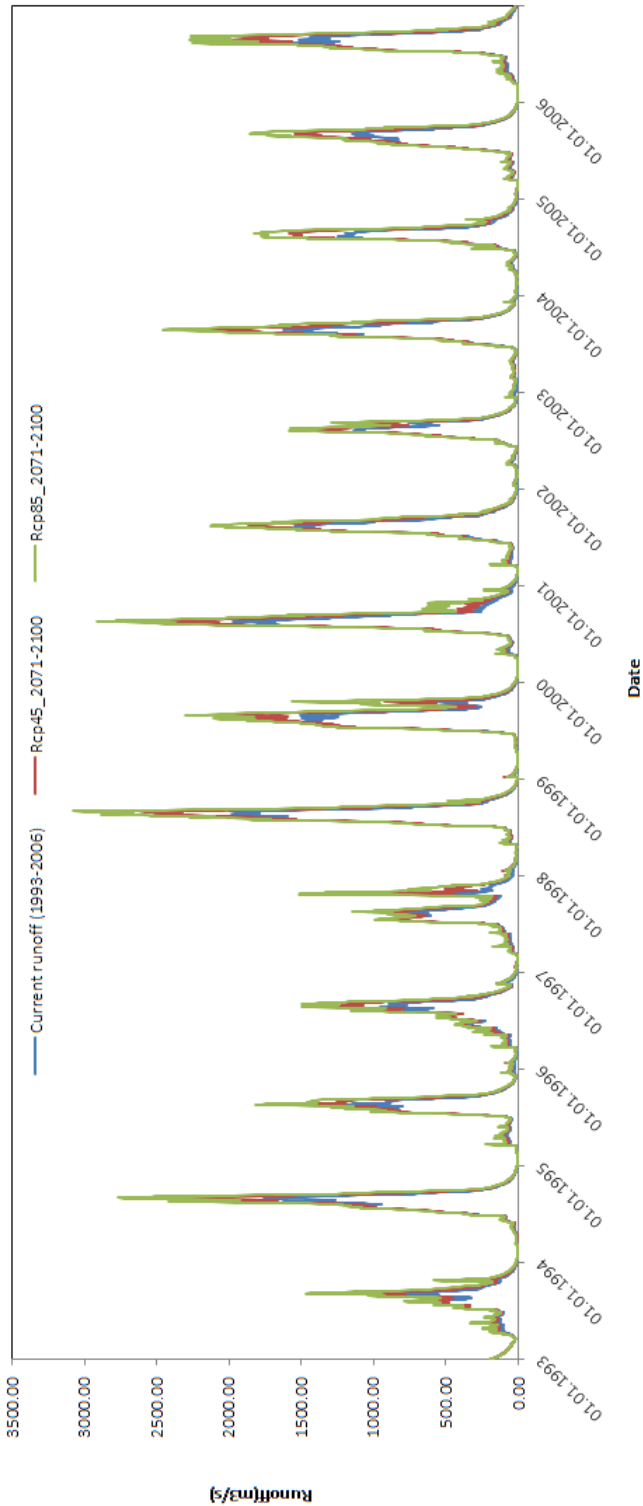


Figure 7.9: Daily time series runoff after applying delta change (2071 - 2100)

7.2 Calibration - Test on RCM Data

Using the downscaled RCM precipitation and temperature data, calibration test was done to check whether the RCM data reproduces better model parameters than the final calibration results using observed runoff during the year(1995-2001). The final parameter results of this calibration test are shown in Table 7.1. All the parameter results are not unrealistic rather they are within the range. However, the simulated runoff and observed runoff do not fit well and are not better than the second case calibration (i.e. Section 5.1.2). The simulated and observed runoff for this RCM calibration test is shown in Figure 7.11. The graph shows that both simulated and observed runoff of the RCM data do not fit very well. However, it shows similarity and it is reasonable to trust the RCM data because of the similar runoff pattern shown on this graph. The accumulated difference between observed and simulated RCM runoff is also shown in Figure ???. This graph shows still there is significant difference between RCM and observed runoff data.

Table 7.1: Parameter results of RCM calibration test

Parameters	Value	Remark
RCORR	0.32	Ok
SCORR	0.44	Ok
FC	48.6	Low
Beta	0.4	Ok
R2	0.54	Low
ACC_DIFF	(-98.2mm)	Medium

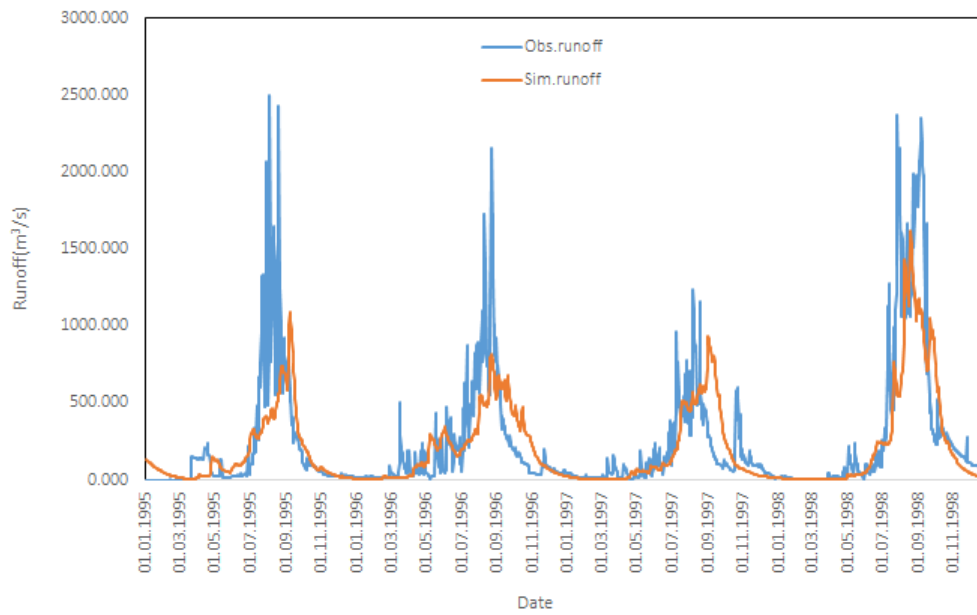


Figure 7.10: Simulated and observed runoff for RCM calibration test

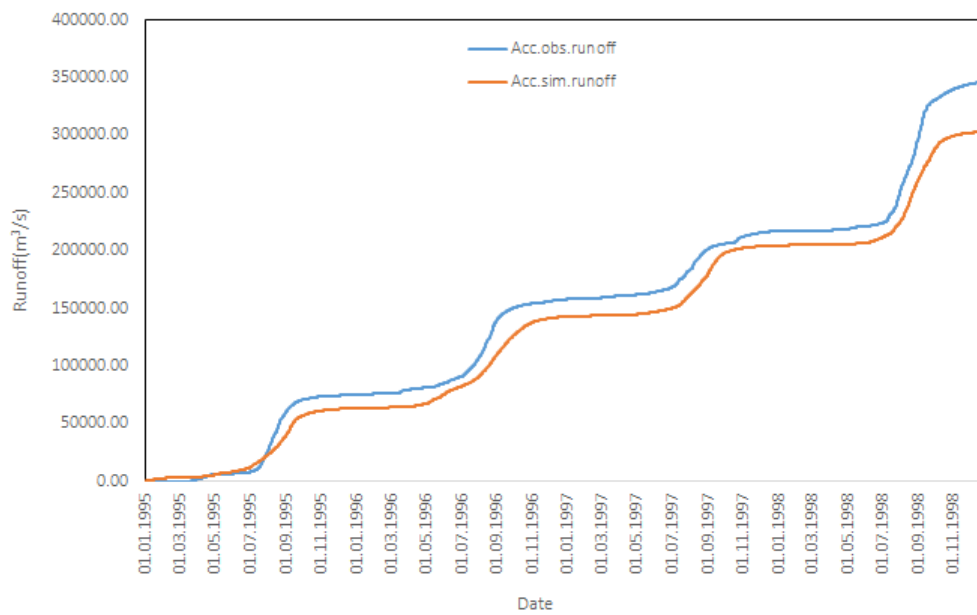


Figure 7.11: Accumulated difference between RCM and observed runoff

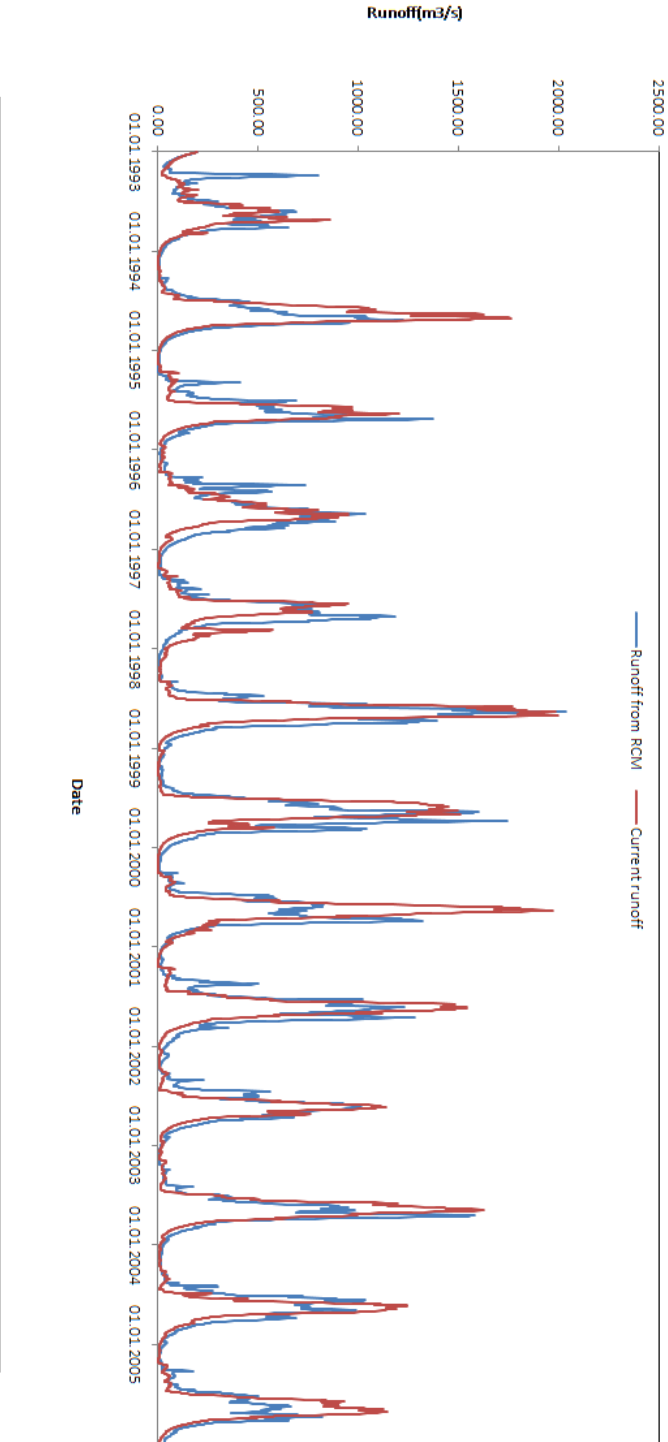


Figure 7.12: Daily time series runoff for current and RCM in 1993 - 2005

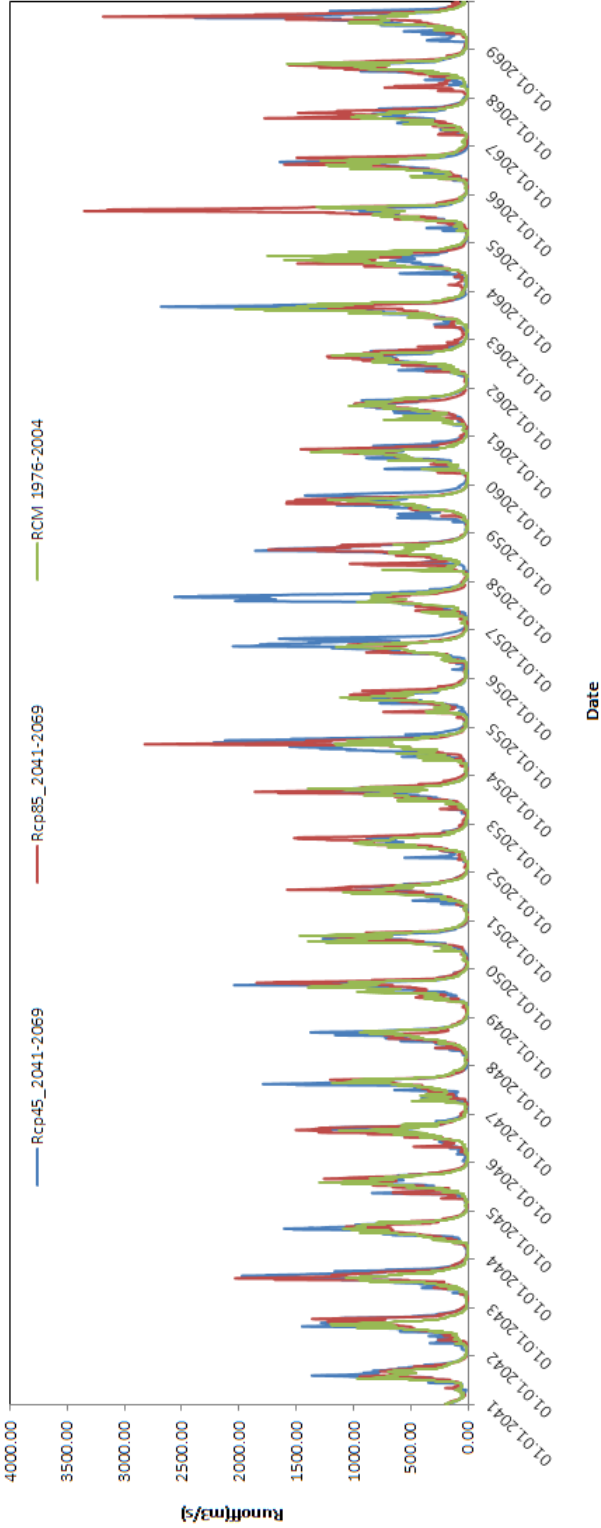


Figure 7.13: Runoff generated from RCM historical 1976-2004 and future 2041 - 2069

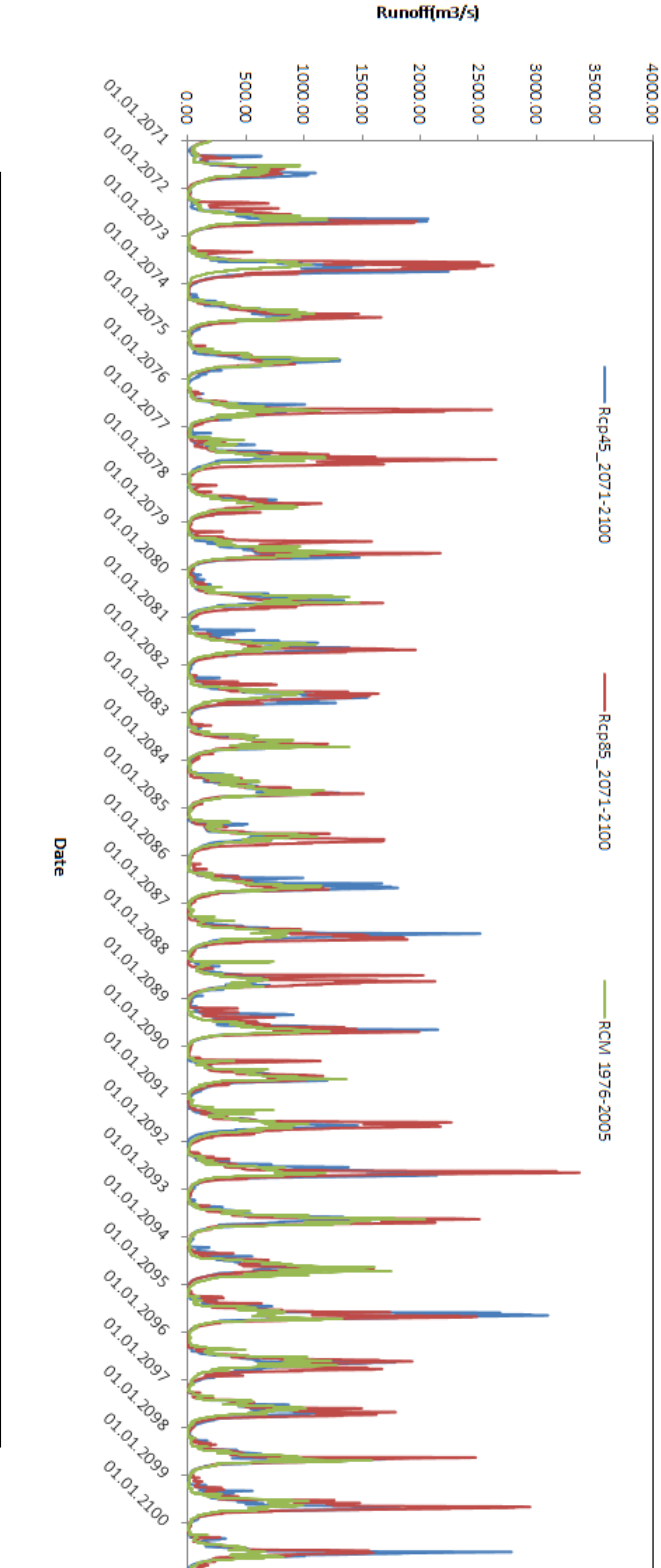


Figure 7.14: Runoff generated from RCM historical 1976-2005 and future 2071 - 2100

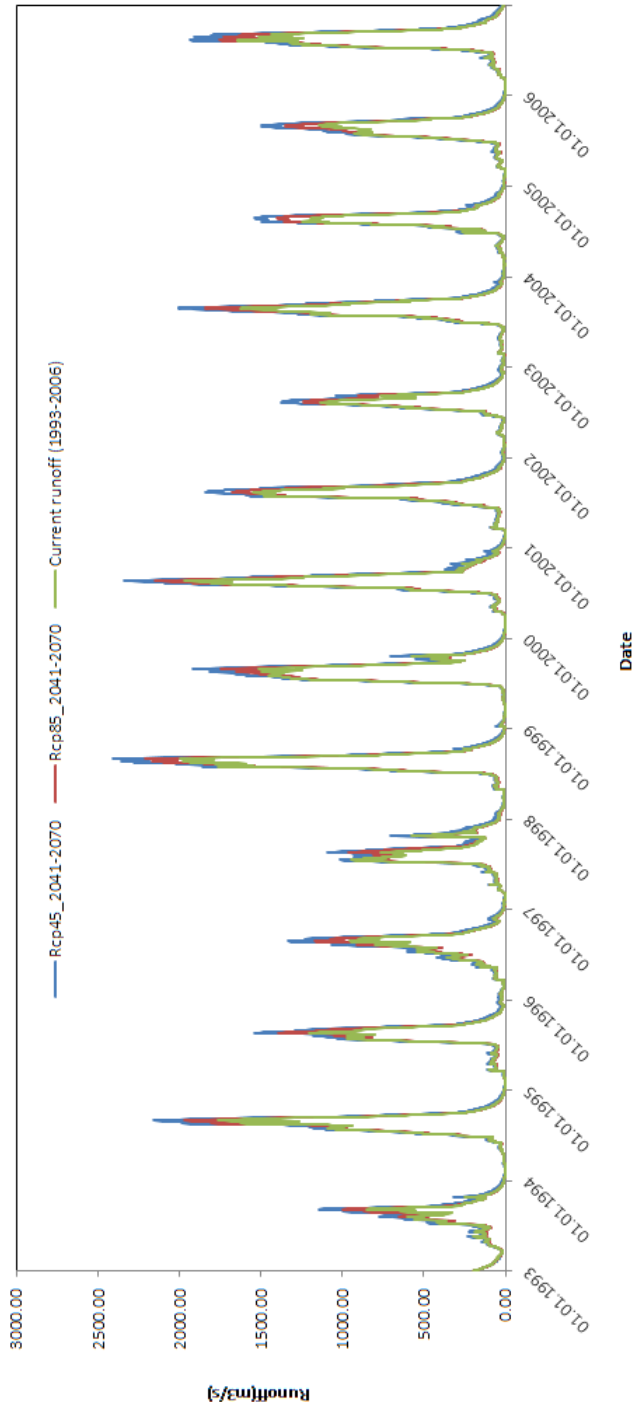


Figure 7.15: Daily generated runoff after applying rainy days method in 2041 - 2070

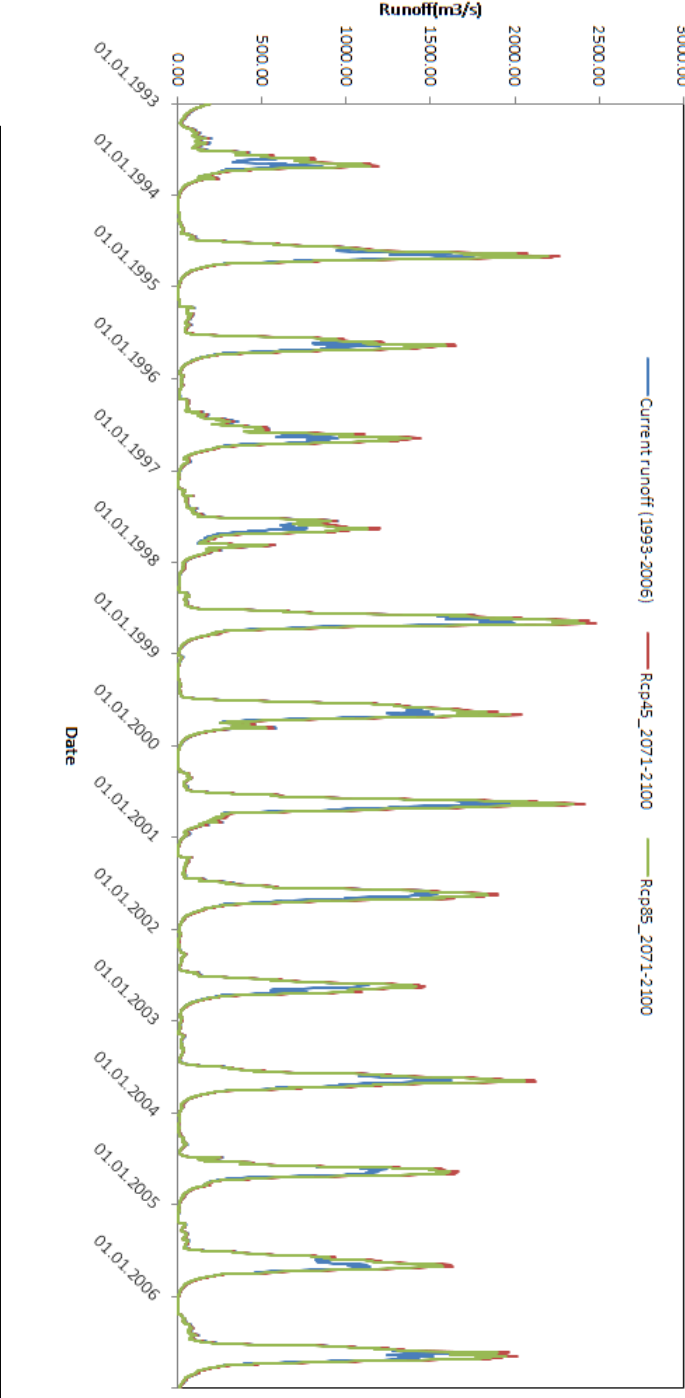


Figure 7.16: Daily generated runoff after applying rainy days method in 2071 - 2100

7.3 Hydropower Simulation Modelling

The runoff generated during the Rainy days case is used for comparing hydropower production in the future time series for both scenarios. In this section the production is going to be compared during the current situation and future time step. There is also a current measured energy production for Tekeze Hydropower plant and this production will be compared with the one generated from nMAG hydropower simulation model.

For comparison of Energy production in the current and future climate, the first task was to check whether the hydropower simulation program (nMAG) produces the currently observed energy production of the system. For this comparison observed energy production for two years was collected from Ethiopian Electric Power Corporation (EEPCo). The annual observed energy production for 2011/2012 was 1296GWh and for 2012/2013 it was 1657GWh. Figure 7.17 shows both graphs for annual observed energy production and simulated annual energy production from observed runoff using nMAG. The graph indicates that nMAG can produce the observed energy production with average annual production of 1224 for the observed 7 years runoff.

After checking energy production from nMAG simulation program then it is possible to proceed with the extended current runoff simulated by PINEHBV and simulate the energy production from that runoff. The annual energy production for the extended 14 years of runoff was simulated first and thereafter the future 60 years of runoff using nMAG program. Figure 7.18 shows the annual energy production for the extended 14 years runoff and the future 60 years runoff. The first scenario (Rcp45) for the first 30 years starting from 2041 - 2070 shows highest energy production in every years than the others. This means the production will increase from the current time (i.e. 1993-2006) to the future time (i.e. 2041-2070) according to Rcp45 scenario and this is also true for Rcp85. Similarly Rcp45 shows higher energy production for the last 30 years (i.e 2071-2100) and this is also the same for Rcp85 but the increase amount is not the same as Rcp45. To conclude, both scenario shows increase of energy production but the increase is more for Rcp45 than Rcp85.

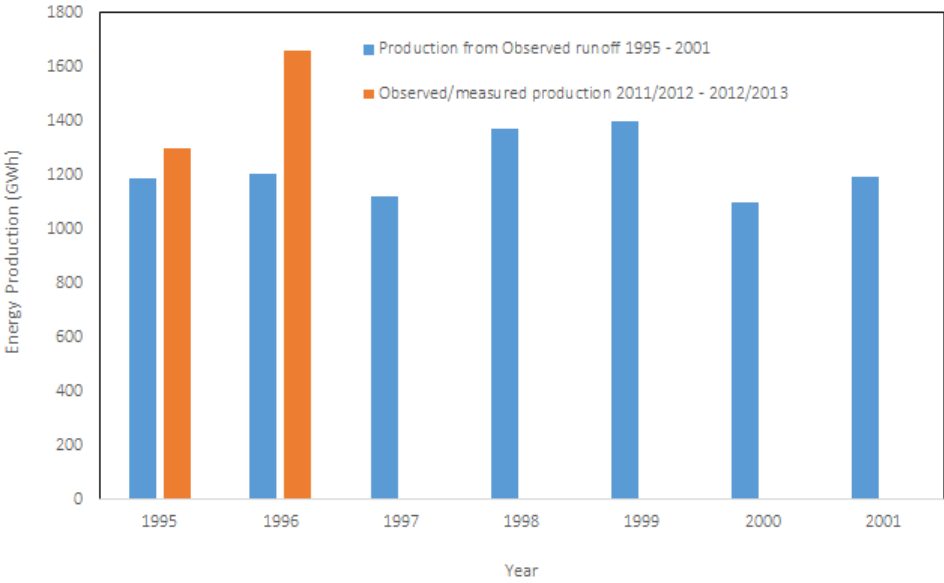


Figure 7.17: Observed and simulated energy production

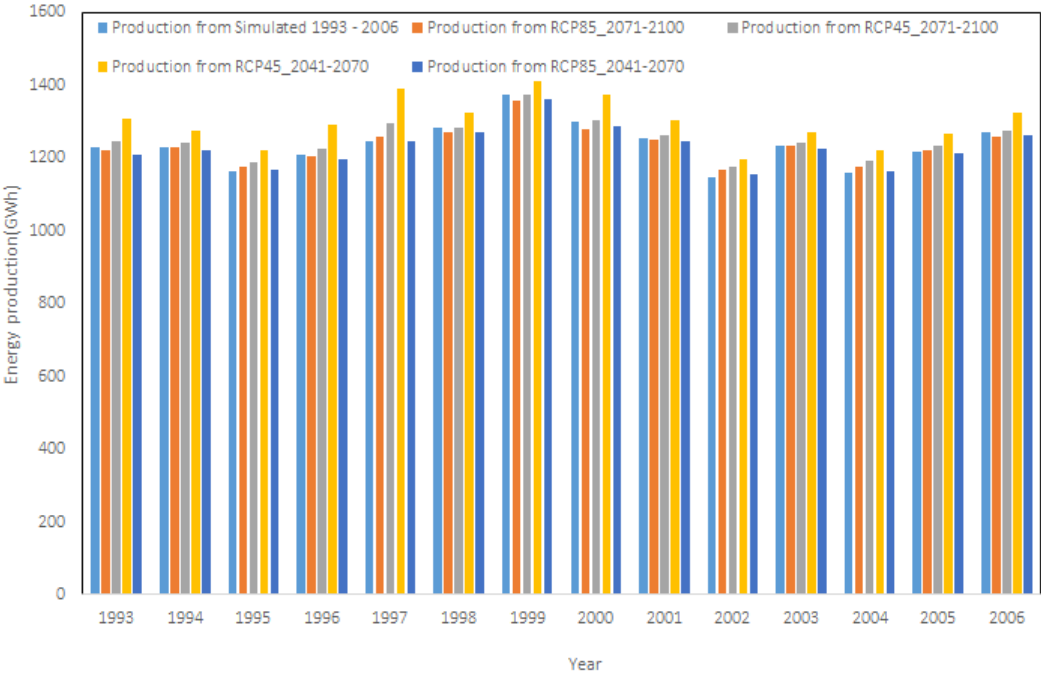


Figure 7.18: Current and future annual energy production

The energy production do not show big difference in the future time. So, the mean monthly flood spill was simulated using nMAG as outlined in Figure 7.19. From this graph the spill is common and high during August and September. By using reservoir rule curve which implies making empty the reservoir during the dry season and filling it during this high spill time will give more energy production.

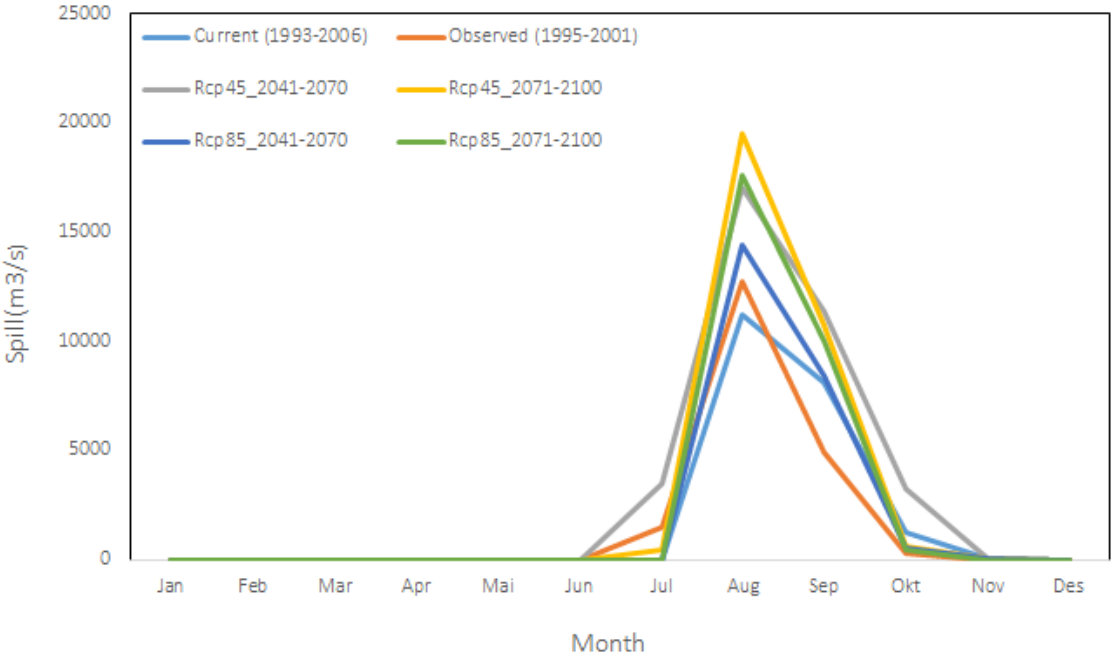


Figure 7.19: Mean monthly spill for current and future time

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Input data

The precipitation and temperature input data were good and the missing values were not difficult to fill. However, in the case of runoff data it is possible to say a poorly gauged stations specially the second station (i.e. Yechila station). The daily time series runoff measured at this station shows poor results. As a result this station was excluded from any further analysis.

Quality of calibration results

Three different calibration test were done to get improved parameters result. The final and accepted calibration result for this research study had R^2 value of 0.8 and an accumulated difference of (-4.9mm) between the simulated and observed runoff. These results are the better ones than the other two calibration results. As long as the input data to the model is reasonable it is possible to get very good parameter results. On the other hand, calibration test was done using downscaled RCM data in order to check whether the RCM data gives better or the same parameter results than the final accepted calibration test using the same observed runoff data. However, the result from this RCM calibration test was lower than the result from the final accepted calibration test.

Climate modelling

Downscaling of RCM data for the target catchment was one of the main tasks in this research. Total of 120 grid points were found within the catchment to downscale precipitation and temperature. The climate issue was found very important during this research study. In order to detect the future climate changes impacts on inflow and energy production, delta change and rainy days application methods were used. The delta change application do not capture the rainy days. For example, the delta change value for dry months (October and December) shows positive value which means an increase in rainfall for the future time. However, applying this positive value to the current dry days will not distribute the change of rainfall evenly for each days because those months are dry months in Ethiopia. To resolve this problem, another method called 'Rainy days' was found much better and gives much reasonable result. This method applies mean monthly change values divided equally by counting number of dry days first and applies to every third dry day and distribute the change evenly for each dry days. This method was concluded as better method for this research study.

Direct simulation

Another important result was on the case of direct simulation. The downscaled RCM data was checked whether it reproduces the extended 14 years runoff which was obtained from observed data using the same calibrated model for the catchment. However, the simulated runoff from this RCM data shows little deviation in annual runoff volume than the simulated runoff from observed data. It implies more precipitation data due to the selection of grid points with very good resolution. Despite that the data is much similar and representative for the catchment. From this result it is also quite acceptable to trust the RCM data. However, it is concluded that the runoff generated from the observed precipitation and temperature as an acceptable result for this research.

Runoff after applying delta change method

The delta change approach is one of the commonly applied and used approach in climate studies. In this research delta change was computed for both precipitation and temperature data. The delta change of temperature was used to calculate the new potential evapotranspiration. However, the main task was for runoff simulations after applying delta change factor during the future time. In this research the delta change values showed how the rainfall will vary for the future time and most months showed an increase in rainfall.

Even though this method was not taken for simulation of energy production, the runoff reflects the change of climate for the future time. To conclude the climate impact will change the flow and energy production for the future time and this is shown in both application methods (i.e. rainy days and delta change methods).

Runoff after applying rainy days method

Rainy days application method was the second and accepted method for simulation of energy production for this research study. The main reason for choosing this method is due to its ability to capture the rainy days of the future time. This will distribute the increase of rainfall evenly during each day though the volume applied for both methods is the same. So, this method applies the change of rainfall for each day which will give reasonable change of energy production. As a result the energy production for the future was simulated using runoff simulated after applying this method on the current observed precipitation and temperature.

Energy production

The energy production simulated by nMAG for the observed runoff data was similar to the current observed energy production. Since the observed runoff data was only for 7 years, then the number of years was extended up to 14 years and new runoff was simulated using the calibrated model for the catchment. The energy production from this extended year runoff shows similar with the one from observed runoff. However, the energy production increases for the future time (2041 - 2071) as shown by both Rcp45 and Rcp85 though the increase is not the same for both scenarios. So, it is possible to conclude that the energy production will increase for the future and this increase in energy production might not be the maximum or peak energy production expected but there is an increase in production. Since there is flood spill during the rainy season, it is also possible to increase energy production by following reservoir rule curve which implies making empty the reservoir during dry period and filling during rainy period. This will increase energy production significantly.

8.2 Recommendations for Future Study

According to the results obtained from this research and other important issues, the following recommendations have been made for the future time research studies:

- The observed runoff was only for 7 years. It will be better to check the calibration with more runoff though this 7 years is enough to start calibration. So, for the future it is recommended to work and check the calibration results with 10 years or more and see the results.
- The evapotranspiration for this research was computed using Thornthwaite (1948) formula which gives an approximation value but not exact value. It will be better to use measured evapotranspiration specially for tropical climate zones which gives the exact value. So for the future study it is recommended to use measured or observed evapotranspiration as an input for the rainfall-runoff model.
- During the climate study analysis one model and two scenarios were used due to the availability of the climate data for the continent. It will be better to use more than one model and three scenarios though the current results were satisfactory. For future study it is recommended to use two models and three scenarios and check the outcome.
- The rainfall-runoff model was assumed as stationary for the future time. However, this might not be the real case because the vegetation and land use of the environment will not stay stationary. So it is recommended to assess more on this land use part for the future study.
- The energy production was the only parameter compared for the future time. However, the price is also an important issue to assess. So, it is recommended to check the cost and benefit of this simulation result obtained from nMAG though the main objective for this research was to assess only the energy production.
- The spill also shows that it is possible to increase the energy production by using the flood spill in a systematic way. I would recommend to use reservoir guide curve or rule curve as an operational strategy which helps to increase the energy production.

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APPENDIX A

APPENDIX

A.1 Scripts for Downscaling RCM Data

A.1.1 Step-1

```
1
2 # this script find the location of the points based on the catchment and
   The output of this script is the index of the matrix of variables by
   which we can extraction only those location within the basin
3
4 #Needed packages:
5
6 library(ncdf4)
7 library(ncdf)
8 library(rgdal)
9 library(sp)
10 library(maptools)
11
12
13 #Establish working directory
14
15 setwd ("D:\\CORDEX_R\\Step_1")
16
17
18 #Read shapefile (selected map or study area)
19
20 sp <- readShapeSpatial("D:\\CORDEX_R\\SHP_CA\\EmbamadreWatershed.shp")
21
22
```

```

23 #Read nc file to get the structure of the points , this can be done with any
    .nc file (RCM)
24
25 mycdf <- nc_open("tas_AFR-22_CCCma-CanESM2_historical_r1i1p1_CCCma-CanRCM4_
    r2_day_19760101-19801231.nc", verbose = TRUE, write = FALSE)
26
27
28
29 # This method is to find a cell number of data set , therefore this cell
    number is needed only once
30
31 ##Grab the longitude (lon) and latitude (lat) and other data (tm, pr) from
    RCM
32
33 lat <- ncvar_get(mycdf,"lat")
34 lon <- ncvar_get(mycdf,"lon")
35
36
37 tm <- ncvar_get(mycdf,"time_bnds")
38 pr <- ncvar_get(mycdf, varid="tas", start=NA, count=NA, verbose=FALSE,
39                 signedbyte=TRUE, collapse_degen=TRUE)
40
41 ##Construct a data frame from RCM data structure , then they will be filled-
    in with lat , long and .nc other data
42
43
44 lat_lng <- data.frame()
45 prg_f <- data.frame()
46
47
48 ## Define lat and long for each of the points existing in the .nc
49
50 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)
51   latg <- round(lat[,i],2)
52   latg
53
54   long <- round(lon[,i],2)
55   long
56
57   # precipitation is extracted only for one day
58   prg <- pr[, i,1]
59
60   prg <- data.frame(prg)

```

```

61
62 prg_f <- rbind(prg_f, prg)
63
64 latlong <- cbind(long, latg)
65 lat_lng <- rbind(lat_lng, latlong)
66 }
67
68 ## Convert above data into spatial data framework (for the whole Africa)
69
70 dat <- SpatialPointsDataFrame(lat_lng, data=prg_f,
71                               proj4string=CRS("+proj=longlat +datum=WGS84 "
72                                               ))
73 #plot Whole Africa
74 #spplot(dat)
75
76
77 ## Write above data as shape file (it goes into a folder node_Shapefile)
78
79 writeOGR( dat, dsn = 'node_Shapefile', layer = 'node_Shapefile', driver='
      ESRI Shapefile', overwrite_layer=T)
80
81
82 ## Read above data for later use (read the data from the created node_
      Shapefile)
83
84 xx <- readShapePoints("node_Shapefile\\node_Shapefile.shp")
85 #plot(xx)
86
87
88 # Overlay xx (whole Africa) with sp (our catchment), so we will extract
      only relevant points to be used in the project
89
90
91 ## Get overlaid coordinates
92
93 op_1 = overlay(xx, sp)
94 poly1<- cbind(xx@ coords, xx@data, op_1) # 1 is inside polygon and NA is
      outside polygon
95
96 pt_1 <- poly1[(!is.na(poly1$op_1)) ,] #remove NA rows selects only # pt_1
      _ latitude , longitude
97 rr <- pt_1[, -4]
98

```

```

99 rr
100
101
102 #-----
103
104 lati <- round(lat,2)
105 longi <- round(lon,2)
106
107 fl <- c()
108 ft <- c()
109 for (i in 1:dim(rr)[1]){
110   l <- which(longi==rr[i,1]) #to find index in the matrix longitude
111   t <- which(lati==rr[i,2]) # to find index in the matrix latitude
112   fl <- c(fl,l)
113   ft <- c(ft, t)
114 }
115
116 idx <- intersect(fl,ft) # the same index for latitude and logitude based on
   which the
117 save(idx, file=".\\index_of_the_3d_matrix.Rdata")
118 lon[idx] # this is check for the index
119 lat[idx]
120
121 idx
122 plot(sp)
123 points(lon[idx], lat[idx])
124
125 rr_final<-rr[,-3]
126 rr_final
127 names(rr_final)
128
129 colnames(rr_final)[1]<-"latitude"
130 colnames(rr_final)[2]<-"longitude"
131 names(rr_final)
132
133 write.table(rr_final, file=".\\index_of_the_3d_matrix.txt", col.names = T)

```

A.1.2 Step-2: Rainfall

```
1
2
3
4 #This script will have to be run for one model and RCPs + historical data,
   that they will be found in D:\CORDEX_R\Step_2\RR
5
6 ##Note: Both input data (*.nc) and output data (*.txt, *.RData) will be
   found in each of the used folders (see below)
7
8 rm(list=ls())
9 memory.limit(50000)
10 library(ncdf4)
11 library(rhdf5)
12 library(raster)
13 library(zoo)
14
15 #user input
16 setwd("D:\\CORDEX_R\\Step_2\\RR\\CCCma_CanESM2_hist")
17 #setwd("D:\\CORDEX_R\\Step_2\\RR\\CCCma_CanESM2_RCP_45")
18 #setwd("D:\\CORDEX_R\\Step_2\\RR\\CCCma_CanESM2_RCP_85")
19
20
21
22
23 lst <- list.files(getwd(), pattern="\\.nc$")
24
25 # this loop for the nc files
26 for (k in 1:length(lst)){
27   rm(nc)
28   nc <- nc_open(lst[k], verbose = TRUE, write = FALSE)
29
30
31 #List the content of the HDF5 file.
32
33   lat <- ncvar_get(nc, "lat")
34   lon <- ncvar_get(nc, "lon")
35
36
37   pr <- ncvar_get(nc, varid="pr", start=NA, count=NA, verbose=FALSE,
38     signedbyte=TRUE, collapse_degen=TRUE)
39
40
```

```

41 # create data based on file name
42 idx <- get(load("D:\\CORDEX_R\\Step_1\\index_of_the_3d_matrix.Rdata"))
43
44
45 fn <- 1st[k]
46 dt <- substr(fn, (nchar(fn)-19),(nchar(fn)-3))
47 dt
48 st <- as.Date(paste(substr(dt,1,4), substr(dt,5,6), substr(dt,7,8) , sep=
    "-"))
49 ed <- as.Date(paste(substr(dt,10,13), substr(dt,14,15), substr(dt,16,17)
    , sep="-"))
50 d_dt <- seq(st, ed, by="1 day")
51 length(d_dt)
52 dim(pr)[3]
53 rr_f <- data.frame()
54 for (j in 1:dim(pr)[3]) {# hope j=1 means first day
55   rr <- pr [, , j] [idx]
56   rr <- as.data.frame(rr)
57   colnames(rr)<- d_dt[j]
58   rr <- t(rr)
59
60   rr_f <- rbind(rr_f, rr)
61 }
62 lat <- round(lat[idx],2)
63 lon <- round(lon[idx],2)
64 rr_f <- round(rr_f*24*3600,3)
65 rr_ff <- rbind(lon, lat, rr_f)
66 rownames(rr_ff)[1]<- "Longitude"
67 rownames(rr_ff)[2]<- "Latitude"
68 fn_txt <- substr(fn, 1, nchar(fn)-3)
69 fn_txt <- paste(fn_txt, ".txt", sep="")
70 write.table(rr_ff, fn_txt, col.names = F)
71 rr_zoo<- zoo(rr_f, d_dt)
72 fn_zoo <- paste(fn_txt, ".Rdata", sep=" ")
73 save(rr_zoo, file=fn_zoo)
74 #plot(rr_zoo[,1])
75
76 }

```

A.1.3 Step-2: Temperature

```
1
2 #This script will have to be run for one model and RCPs + historical data,
   that they will be found in D:\CORDEX_R\Step_2\TEMP
3
4 ##Note: Both input data (*.nc) and output data (*.txt, *.RData) will be
   found in each of the used folders (see below)
5
6 rm(list=ls())
7 memory.limit(50000)
8 library(ncdf4)
9 library(rhdf5)
10 library(raster)
11 library(zoo)
12
13 setwd("D:\\CORDEX_R\\Step_2\\TEMP\\CCCma_CanESM2_hist")
14 setwd("D:\\CORDEX_R\\Step_2\\TEMP\\CCCma_CanESM2_RCP_45")
15 setwd("D:\\CORDEX_R\\Step_2\\TEMP\\CCCma_CanESM2_RCP_85")
16
17
18
19 lst <- list.files(getwd(), pattern="\\.nc$")
20
21 # this loop for the nc files
22 for (k in 1:length(lst)){
23   rm(nc)
24   nc <- nc_open(lst[k], verbose = TRUE, write = FALSE)
25
26
27   #List the content of the HDF5 file.
28
29   lat <- ncvar_get(nc, "lat")
30   lon <- ncvar_get(nc, "lon")
31
32
33   tm <- ncvar_get(nc, "time_bnds")
34   pr <- ncvar_get(nc, varid="tas", start=NA, count=NA, verbose=FALSE,
35                   signedbyte=TRUE, collapse_degen=TRUE)
36
37
38   # create data based on file name
39   idx <- get(load("D:\\CORDEX_R\\Step_1\\index_of_the_3d_matrix.Rdata"))
40
```

```

41
42 fn <- lst[k]
43 dt <- substr(fn, (nchar(fn)-19),(nchar(fn)-3))
44 dt
45 st <- as.Date(paste(substr(dt,1,4), substr(dt,5,6), substr(dt,7,8) , sep=
    "-"))
46 ed <- as.Date(paste(substr(dt,10,13), substr(dt,14,15), substr(dt,16,17)
    , sep="-"))
47 d_dt <- seq(st, ed, by="1 day")
48
49 rr_f <- data.frame()
50 for (j in 1:dim(pr)[3]) {# hope j=1 means first day
51   rr <- pr [, , j] [idx]
52   rr <- as.data.frame(rr)
53   colnames(rr)<- d_dt[j]
54   rr <- t(rr)
55
56   rr_f <- rbind(rr_f, rr)
57 }
58 lat <- round(lat[idx],2)
59 long <- round(lon[idx],2)
60 rr_f <- rr_f-273.15
61 rr_f <- round(rr_f,3)
62 rr_ff <- rbind(long, lat, rr_f)
63 rownames(rr_ff)[1]<- "Longitude"
64 rownames(rr_ff)[2]<- "Latitude"
65 fn_txt <- substr(fn, 1, nchar(fn)-3)
66 fn_txt <- paste(fn_txt, ".txt", sep="")
67 write.table(rr_ff, fn_txt, col.names = F)
68 rr_zoo<- zoo(rr_f, d_dt)
69 fn_zoo <- paste(fn_txt, ".Rdata", sep=" ")
70 save(rr_zoo, file=fn_zoo)
71 #plot(rr_zoo[,1])
72
73 }

```


A.1.4 Step-3: Rainfall

```
1
2 #This script will convert daily data to monthly data for CCCma_CanESM2,
   first for the historical data, and then for each of the scenarios (45
   and 85)
3
4
5 rm(list=ls())
6 library(zoo)
7 require(hydroTSM)
8 library(raster)
9 library(sp)
10 library(rgdal)
11
12 scn <- "Delta_cal_RR_step_3.R"
13
14
15 # CanESM2
16
17 ## CanESM2_hist
18
19 setwd("D:\\CORDEX_R\\Step_2\\RR\\CCCma_CanESM2_hist")
20
21 lst <- list.files(getwd(), pattern="\\.Rdata$")
22 a <- get(load(lst[1]))
23
24
25 for (k in 2:length(lst)){
26
27   b <- get(load(lst[k]))
28   names(b) <- names(a)
29   a <- rbind(a, b)
30 }
31
32 #Creating the file where all data is together
33
34 a<- window(a, start=as.Date("1976-01-01"), end=as.Date("2005-12-31"))
35 nm <- ("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_hist\\pr_daily_CCCma_
   CanESM2_hist_1976-05.Rdata")
36 save(a, file=nm)
37 write.zoo(a, file="D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_hist\\pr_daily_
   CCCma_CanESM2_hist_1976-05.txt")
38
```

```

39 #Creation of .Rdat and pdf outputs:
40
41 setwd("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_hist")
42
43 mnth <- monthlyfunction(a, FUN="mean")
44 save(mnth, file="mean_monthly_CCCma_CanESM2_hist_1976-2005.Rdata")
45
46 # - this is for checking purpose whether the location are correctly placed
47 #lat_lon <- read.table("pr_EUR-11_CNRM-CERFACS-CNRM-CM5_historical_r1i1p1_
      SMHI-RCA4_v1_day_20010101-20051231.txt", stringsAsFactors = F)[1:2,]
48 #lon_lat <- t(lat_lon[, -(1)])
49 #mode(lon_lat) <- "numeric"
50
51
52
53
54 ## CanESM2_RCP_45
55
56 setwd("D:\\CORDEX_R\\Step_2\\RR\\CCCma_CanESM2_RCP_45")
57
58 lst <- list.files(getwd(), pattern="\\.Rdata$")
59 a <- get(load(lst[1]))
60
61
62 for (k in 2:length(lst)){
63   b <- get(load(lst[k]))
64   names(b) <- names(a)
65   a <- rbind(a, b)
66 }
67
68
69 r1<- window(a, start=as.Date("2041-01-01"), end=as.Date("2070-12-31"))
70 r2<- window(a, start=as.Date("2071-01-01"), end=as.Date("2100-12-31"))
71 nm1<- ("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_45\\pr_daily_CCCma_
      CanESM2_RCP_45_2041-70.Rdata")
72 nm2 <- ("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_45\\pr_daily_CCCma_
      CanESM2_RCP_45_2071-00.Rdata")
73
74 save(r1, file=nm1)
75 save(r2, file=nm2)
76
77 write.zoo(r1, file="D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_45\\pr_
      daily_CCCma_CanESM2_RCP_45_2041-70.txt")

```

```

78 write.zoo(r2, file="D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_45\\pr_
    daily_CCCma_CanESM2_RCP_45_2071-00.txt")
79
80
81 setwd("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_45")
82
83 mnth1 <- monthlyfunction(r1, FUN="mean")
84 save(mnth1, file="mean_monthly_CCCma_CanESM2_RCP_45_2041-2070.Rdata")
85 mnth2 <- monthlyfunction(r2, FUN="mean")
86 save(mnth2, file="mean_monthly_CCCma_CanESM2_RCP_45_2071-2100.Rdata")
87
88
89
90 #calculate delta change CCCma_CanESM2_RCP_45-----
91
92 crrm_hist <- load("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_hist\\mean_
    monthly_CCCma_CanESM2_hist_1976-2005.Rdata")
93 CCCma_CanESM2_hist <- mnth
94
95 CCCma_CanESM2_41_70<- load("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_
    45\\mean_monthly_CCCma_CanESM2_RCP_45_2041-2070.Rdata")
96 CCCma_CanESM2_41_70 <- mnth1
97
98 delta_CCCma_CanESM2_4170_to_hist_rcp_45 <- (CCCma_CanESM2_41_70-CCCma_
    CanESM2_hist)/CCCma_CanESM2_hist*100
99
100
101 CCCma_CanESM2_71_21 <- load("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_
    45\\mean_monthly_CCCma_CanESM2_RCP_45_2071-2100.Rdata")
102 CCCma_CanESM2_71_21<- mnth2
103
104 delta_CCCma_CanESM2_7100_to_hist_rcp_45 <- (CCCma_CanESM2_71_21-CCCma_
    CanESM2_hist)/CCCma_CanESM2_hist*100
105
106 rp1 <- apply(delta_CCCma_CanESM2_4170_to_hist_rcp_45,2, "mean")
107 save(rp1, file="D:\\CORDEX_R\\Step_3\\RR\\All_DELTA\\delta_CCCma_CanESM2_
    rcp45_1976-2005_vs_2041-2070.Rdata")
108 rp2 <- apply(delta_CCCma_CanESM2_7100_to_hist_rcp_45,2, "mean")
109 save(rp2, file="D:\\CORDEX_R\\Step_3\\RR\\All_DELTA\\delta_CCCma_CanESM2_
    rcp45_1976-2005_vs_2071-2100.Rdata")
110 write.table(rp1, file="D:\\CORDEX_R\\Step_3\\RR\\All_DELTA\\delta_CCCma_
    CanESM2_rcp45_1976-2005_vs_2041-2070.txt")
111 write.table(rp2, file="D:\\CORDEX_R\\Step_3\\RR\\All_DELTA\\delta_CCCma_
    CanESM2_rcp45_1976-2005_vs_2071-2100.txt")

```

```

112
113
114
115 #-----CCCma_CanESM2_RCP_85-----
116
117 setwd("D:\\CORDEX_R\\Step_2\\RR\\CCCma_CanESM2_RCP_85")
118
119 lst <- list.files(getwd(), pattern="\\.Rdata$")
120 a <- get(load(lst[1]))
121
122 for (k in 2:length(lst)){
123   b <- get(load(lst[k]))
124   names(b) <- names(a)
125   a <- rbind(a, b)
126 }
127 r1<- window(a, start=as.Date("2041-01-01"), end=as.Date("2070-12-31"))
128 r2<- window(a, start=as.Date("2071-01-01"), end=as.Date("2100-12-31"))
129 dir.create("res")
130 nm1<- ("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_85\\pr_daily_CCCma_
      CanESM2_RCP_rcp85_2041-70.Rdata")
131 nm2 <- ("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_85\\pr_daily_CCCma_
      CanESM2_RCP_rcp85_2071-00.Rdata")
132 save(r1, file=nm1)
133 save(r2, file=nm2)
134 write.zoo(r1, file="D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_85\\pr_
      daily_CCCma_CanESM2_RCP_85_2041-70.txt")
135 write.zoo(r2, file="D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_85\\pr_
      daily_CCCma_CanESM2_RCP_85_2071-00.txt")
136
137
138 setwd("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_RCP_85")
139
140 mnth1 <- monthlyfunction(r1, FUN="mean")
141 save(mnth1, file="mean_monthly_CCCma_CanESM2_rcp85_2041-2070.Rdata")
142 mnth2 <- monthlyfunction(r2, FUN="mean")
143 save(mnth2, file="mean_monthly_CCCma_CanESM2_rcp85_2071-2100.Rdata")
144
145
146 #calculate delta change CCCma_CanESM2_RCP_85-----
147 CCCma_CanESM2_hist <- load("D:\\CORDEX_R\\Step_3\\RR\\CCCma_CanESM2_hist\\
      mean_monthly_CCCma_CanESM2_hist_1976-2005.Rdata")
148 CCCma_CanESM2_hist <- mnth
149

```

```

150 CCCma_CanESM2_41_70 <- load("D:\\CORDEX_R\\ Step_3\\RR\\CCCma_CanESM2_RCP_
      85\\mean_monthly_CCCma_CanESM2_rcp85_2041-2070.Rdata")
151 CCCma_CanESM2_41_70<- mnth1
152
153 delta_CCCma_CanESM2_4170_to_hist_rcp_85 <- (CCCma_CanESM2_41_70-CCCma_
      CanESM2_hist)/CCCma_CanESM2_hist*100
154
155
156 CCCma_CanESM2_71_21 <- load("D:\\CORDEX_R\\ Step_3\\RR\\CCCma_CanESM2_RCP_
      85\\mean_monthly_CCCma_CanESM2_rcp85_2071-2100.Rdata")
157 CCCma_CanESM2_71_21<- mnth2
158
159 delta_CCCma_CanESM2_7100_to_hist_rcp_85 <- (CCCma_CanESM2_71_21-CCCma_
      CanESM2_hist)/CCCma_CanESM2_hist*100
160
161
162 rp1 <- apply(delta_CCCma_CanESM2_4170_to_hist_rcp_85,2, "mean")
163 save(rp1 ,file="D:\\CORDEX_R\\ Step_3\\RR\\ All_DELTA\\ delta_CCCma_CanESM2_
      rcp85_1976-2005_vs_2041-2070.Rdata")
164 rp2 <- apply(delta_CCCma_CanESM2_7100_to_hist_rcp_85,2, "mean")
165 save(rp2 ,file="D:\\CORDEX_R\\ Step_3\\RR\\ All_DELTA\\ delta_CCCma_CanESM2_
      rcp85_1976-2005_vs_2071-2100.Rdata")
166 write.table(rp1 ,file="D:\\CORDEX_R\\ Step_3\\RR\\ All_DELTA\\ delta_CCCma_
      CanESM2_rcp85_1976-2005_vs_2041-2070.txt")
167 write.table(rp2 ,file="D:\\CORDEX_R\\ Step_3\\RR\\ All_DELTA\\ delta_CCCma_
      CanESM2_rcp85_1976-2005_vs_2071-2100.txt")

```

A.1.5 Step-3: Temperature

```
1
2 #This script will convert daily data to monthly data for CCCma_CanESM2,
   first for the historical data, and then for each of the scenarios (45
   and 85)
3 then calculates delta change
4
5
6
7 rm(list=ls())
8 library(zoo)
9 require(hydroTSM)
10 library(raster)
11 library(sp)
12 library(rgdal)
13 library(proj4)
14 library(maptools)
15 gpclibPermit()
16
17
18 scn <- "Delta_cal_TEMP_step_3.R"
19
20
21 # CanESM2
22
23 ## CanESM2_hist
24
25 setwd("D:\\CORDEX_R\\Step_2\\TEMP\\CCCma_CanESM2_hist")
26
27 lst <- list.files(getwd(), pattern="\\.Rdata$")
28 a <- get(load(lst[1]))
29
30
31 for (k in 2:length(lst)){
32
33   b <- get(load(lst[k]))
34   names(b) <- names(a)
35   a <- rbind(a, b)
36 }
37
38 #Creating the file where all data is together
39
40 a<- window(a, start=as.Date("1976-01-01"), end=as.Date("2005-12-31"))
```

```

41 nm <- ("D:\\CORDEX_R\\Step_3\\TEMP\\CCCma_CanESM2_hist\\tas_daily_CCCma_
      CanESM2_hist_1976-05.Rdata")
42 save(a, file=nm)
43 write.zoo(a, file="D:\\CORDEX_R\\Step_3\\TEMP\\CCCma_CanESM2_hist\\tas_
      daily_CCCma_CanESM2_hist_1976-05.txt")
44
45
46 #Creation of .Rdat and pdf outputs:
47
48 setwd("D:\\CORDEX_R\\Step_3\\TEMP\\CCCma_CanESM2_hist")
49
50 mnth <- monthlyfunction(a, FUN="mean")
51 save(mnth, file="mean_monthly_CCCma_CanESM2_hist_1976-2005.Rdata")
52
53 # - this is for checking purpose whether the location are correctly placed
54 #lat_lon <- read.table("pr_EUR-11_CNRM-CERFACS-CNRM-CM5_historical_r1i1p1_
      SMHI-RCA4_v1_day_20010101-20051231.txt", stringsAsFactors = F)[1:2,]
55 #lon_lat <- t(lat_lon[, -(1)])
56 #mode(lon_lat) <- "numeric"
57
58
59
60
61 ## CanESM2_RCP_45
62
63 setwd("D:\\CORDEX_R\\Step_2\\TEMP\\CCCma_CanESM2_RCP_45")
64
65 lst <- list.files(getwd(), pattern="\\.Rdata$")
66 a <- get(load(lst[1]))
67
68
69 for (k in 2:length(lst)){
70   b <- get(load(lst[k]))
71   names(b) <- names(a)
72   a <- rbind(a, b)
73 }
74
75
76 r1<- window(a, start=as.Date("2041-01-01"), end=as.Date("2070-12-31"))
77 r2<- window(a, start=as.Date("2071-01-01"), end=as.Date("2100-12-31"))
78 nm1<- ("D:\\CORDEX_R\\Step_3\\TEMP\\CCCma_CanESM2_RCP_45\\tas_daily_CCCma_
      CanESM2_RCP_45_2041-70.Rdata")
79 nm2 <- ("D:\\CORDEX_R\\Step_3\\TEMP\\CCCma_CanESM2_RCP_45\\tas_daily_CCCma_
      CanESM2_RCP_45_2071-00.Rdata")

```

```

80 save(r1, file=nml)
81 save(r2, file=nm2)
82 write.zoo(r1, file="D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_45\\tas_
    daily_CCCma_CanESM2_RCP_45_2041-70.txt")
83 write.zoo(r2, file="D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_45\\tas_
    daily_CCCma_CanESM2_RCP_45_2071-00.txt")
84
85
86 setwd("D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_45")
87
88 mnth1 <- monthlyfunction(r1, FUN="mean")
89 save(mnth1, file="mean_monthly_CCCma_CanESM2_RCP_45_2041-2070.Rdata")
90 mnth2 <- monthlyfunction(r2, FUN="mean")
91 save(mnth2, file="mean_monthly_CCCma_CanESM2_RCP_45_2071-2100.Rdata")
92
93
94
95 #calculate delta change CCCma_CanESM2_RCP_45-----
96
97 CCCma_CanESM2_hist <- load("D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_hist
    \\mean_monthly_CCCma_CanESM2_hist_1976-2005.Rdata")
98 CCCma_CanESM2_hist <- mnth
99
100 CCCma_CanESM2_41_70<- load("D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_
    45\\mean_monthly_CCCma_CanESM2_RCP_45_2041-2070.Rdata")
101 CCCma_CanESM2_41_70 <- mnth1
102
103 delta_CCCma_CanESM2_4170_to_hist_rcp_45 <- (CCCma_CanESM2_41_70-CCCma_
    CanESM2_hist)
104
105
106 CCCma_CanESM2_71_21 <- load("D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_
    45\\mean_monthly_CCCma_CanESM2_RCP_45_2071-2100.Rdata")
107 CCCma_CanESM2_71_21<- mnth2
108
109 delta_CCCma_CanESM2_7100_to_hist_rcp_45 <- (CCCma_CanESM2_71_21-CCCma_
    CanESM2_hist)
110
111 rp1 <- apply(delta_CCCma_CanESM2_4170_to_hist_rcp_45,2, "mean")
112 save(rp1, file="D:\\CORDEX_R\\ Step_3\\TEMP\\ A11_DELTA\\ delta_CCCma_CanESM2_
    rcp45_1976-2005_vs_2041-2070.Rdata")
113 rp2 <- apply(delta_CCCma_CanESM2_7100_to_hist_rcp_45,2, "mean")
114 save(rp2, file="D:\\CORDEX_R\\ Step_3\\TEMP\\ A11_DELTA\\ delta_CCCma_CanESM2_
    rcp45_1976-2005_vs_2071-2100.Rdata")

```



```

115 write.table(rp1 ,file="D:\\CORDEX_R\\ Step_3\\TEMP\\ All_DELTA\\ delta_CCCma_
      CanESM2_rcp45_1976-2005_vs_2041-2070.txt")
116 write.table(rp2 ,file="D:\\CORDEX_R\\ Step_3\\TEMP\\ All_DELTA\\ delta_CCCma_
      CanESM2_rcp45_1976-2005_vs_2071-2100.txt")
117
118
119
120 #-----CCCma_CanESM2_RCP_85-----
121
122 setwd("D:\\CORDEX_R\\ Step_2\\TEMP\\CCCma_CanESM2_RCP_85")
123
124 lst <- list.files(getwd(), pattern="\\.Rdata$")
125 a <- get(load(lst[1]))
126
127 for (k in 2:length(lst)){
128   b <- get(load(lst[k]))
129   names(b) <- names(a)
130   a <- rbind(a, b)
131 }
132 r1<- window(a, start=as.Date("2041-01-01"), end=as.Date("2070-12-31"))
133 r2<- window(a, start=as.Date("2071-01-01"), end=as.Date("2100-12-31"))
134 dir.create("res")
135 nm1<- ("D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_85\\tas_daily_CCCma_
      CanESM2_RCP_rcp85_2041-70.Rdata")
136 nm2 <- ("D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_85\\tas_daily_CCCma_
      CanESM2_RCP_rcp85_2071-00.Rdata")
137 save(r1 , file=nm1)
138 save(r2 , file=nm2)
139 write.zoo(r1 , file="D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_85\\tas_
      daily_CCCma_CanESM2_RCP_85_2041-70.txt")
140 write.zoo(r2 , file="D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_85\\tas_
      daily_CCCma_CanESM2_RCP_85_2071-00.txt")
141
142
143 setwd("D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_85")
144
145 mnth1 <- monthlyfunction(r1 , FUN="mean")
146 save(mnth1 , file="mean_monthly_CCCma_CanESM2_rcp85_2041-2070.Rdata")
147 mnth2 <- monthlyfunction(r2 , FUN="mean")
148 save(mnth2 , file="mean_monthly_CCCma_CanESM2_rcp85_2071-2100.Rdata")
149
150
151 #calculate delta change CanESM2_RCP_85-----

```

```

152 CCCma_CanESM2_hist <- load("D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_hist
    \\mean_monthly_CCCma_CanESM2_hist_1976-2005.Rdata")
153 CCCma_CanESM2_hist <- mnth
154
155 CCCma_CanESM2_41_70 <- load("D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_
    85\\mean_monthly_CCCma_CanESM2_rcp85_2041-2070.Rdata")
156 CCCma_CanESM2_41_70<- mnth1
157
158 delta_CCCma_CanESM2_4170_to_hist_rcp_85 <- (CCCma_CanESM2_41_70-CCCma_
    CanESM2_hist)
159
160
161 CCCma_CanESM2_71_21 <- load("D:\\CORDEX_R\\ Step_3\\TEMP\\CCCma_CanESM2_RCP_
    85\\mean_monthly_CCCma_CanESM2_rcp85_2071-2100.Rdata")
162 CCCma_CanESM2_71_21<- mnth2
163
164 delta_CCCma_CanESM2_7100_to_hist_rcp_85 <- (CCCma_CanESM2_71_21-CCCma_
    CanESM2_hist)
165
166
167 rp1 <- apply(delta_CCCma_CanESM2_4170_to_hist_rcp_85,2, "mean")
168 save(rp1 ,file="D:\\CORDEX_R\\ Step_3\\TEMP\\ All_DELTA\\ delta_CCCma_CanESM2_
    rcp85_1976-2005_vs_2041-2070.Rdata")
169 rp2 <- apply(delta_CCCma_CanESM2_7100_to_hist_rcp_85,2, "mean")
170 save(rp2 ,file="D:\\CORDEX_R\\ Step_3\\TEMP\\ All_DELTA\\ delta_CCCma_CanESM2_
    rcp85_1976-2005_vs_2071-2100.Rdata")
171 write.table(rp1 ,file="D:\\CORDEX_R\\ Step_3\\TEMP\\ All_DELTA\\ delta_CCCma_
    CanESM2_rcp85_1976-2005_vs_2041-2070.txt")
172 write.table(rp2 ,file="D:\\CORDEX_R\\ Step_3\\TEMP\\ All_DELTA\\ delta_CCCma_
    CanESM2_rcp85_1976-2005_vs_2071-2100.txt")

```