CLIMATE CHANGE IMPACT ASSESSMENT OF DIRE DAM WATER SUPPLY

School of Graduate Study, Civil Engineering Department, Hydraulics Engineering Stream

A Thesis Submitted to the School of Graduate Study of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Hydraulics Engineering.

By

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As thesis research advisor, I hereby certify that I have read and evaluated this thesis prepared, under my guidance, by Getu Gemoraw, entitled: **Climate Change Impact Assessment of Dire Dam Water Supply**, Ethiopia. I recommend that it be accepted as fulfilling the thesis requirement.

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As member of the Board of Examiners of the M.Sc. Thesis Open Defense Examination, we certify that we have read, evaluated the thesis prepared by Getu Gemoraw and examined the candidate. We recommended that the thesis be accepted as fulfilling the thesis requirement for the degree of Master of Science in Hydraulics Engineering.

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STATEMENT OF THE AUTHOR

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ABBREVIATIONS

Alfa: Parameter defining the non-linearity of the quick runoff reservoir in the HBV Model
Beta: Parameter in soil moisture routine in the HBV model
DCM: Digital Circulation Model
DEM: Digital Elevation Model
FAO: Food and Agricultural Organizations
FC: Parameter defining the maximum soil moisture storage in HBV model
GCM: General Circulation Model
HadCM3: Hadley Center for Climate Prediction
HBV: Hydrologiska Byråns Vattenbalans-avdelning (Hydrological Bureau Water balance-section)
Hq: Parameter representing the high flow rate in the HBV model
IHMS: Integrated Hydrological Modeling System
IPCC: Intergovernmental Panel on Climate Change
ITCZ: Inter Tropical Convergence Zone
KHQ: Parameter representing a recession coefficient at a corresponding reservoir Volume in HBV model
m.a.s.l.: meters above sea level
NCEP: National Center for Environmental Prediction
NMSA: National Meteorological Service Agency
PERC: Percolation from upper to lower reservoir box [mm/day]
PET: Potential evapotranspiration
R^2: Nash and Sutcliffe coefficient
RCM: Regional Climate Model
RV_E: Relative volume error
SDSM: Statistical Down Scaling Method
SE: Standard error
SHMI: Swedish Metrological and Hydrological Institute.
SRTM: Shuttle Radar Topography Mission
UNFCCC: United Nations Framework Convention on Climate Change

ABSTRACT

Climate change is a major development challenge to Ethiopia. Developing countries are likely to be affected most, and Ethiopia is one of the most vulnerable countries. The issue of climate change and its impacts on water resources is not new but planners are increasingly concerned about the possible negative impacts of climate change on the utilizable yields from dams and water resource systems. Accordingly, making impact assessment can provide information of the situation for which the corresponding solutions to be addressed. Addis Ababa with its ever-increasing population, has reached a state of critical water shortage. To satisfy the rapidly increasing water demands of the city, the Addis Ababa Water and Sewerage Authority, has done Dire Dam rehabilitation works, Dam raising, to provide additional water security by increasing the storage capacity of the reservoir.

The aim of this study is to assess the climate change impact and verify previous hydrological studies carried out to determine the capacity of the reservoir as well as evaluation of supply and demand criteria of Dire Dam Water Supply, which is found in the Northern part of Addis Ababa Metropolitan area.

Projection of the future climate variables were done using General Circulation Model (GCM) which is considered as the most advanced tool for estimating the present and future climatic conditions. Statistical DownScaling Method (SDSM) was applied in order to downscale the climate variables at catchment level. A hydrological model, HBV (the latest version 6.3) was utilized for runoff simulation and hydrological forecasting. The reservoir capacity was assessed based on the detail design reports and re-designing works. Redesigning of the reservoir capacity and comparisons with the results used for the original design purpose was also carried out. In addition, evaluation of demand and supply criteria was also carried out using the newly obtained hydrological results, design criteria set for the original design purpose and national standards.

Accordingly, the projected future climate change shows an increasing trend for both minimum and maximum temperature. Their mean increment reaches by 1.78°C for minimum and 1.98°C for maximum temperature at the end of 21st century. Precipitation variable showed a various trend by an average of 17.2% and 10.25% increment annually for both A2a and B2a scenarios respectively. HBV model was calibrated and validated with the historic data to make water balance of the catchment. As it resulted with R^2=0.78 for the calibration period while R^2 =0.69 was obtained for the validation. Future runoff generation was made by simulating the model with downscaled climatic variables as input. The projected run off had mean annual increasing trend by 21.1%, 21.8% and 19.1% for 2020s, 2050s and 2080s respectively. The current status of the reservoir capacity was assessed and it was found that there is excess surface water potential for Legedadi River (57.54 Mm^3) than previously estimated during detail design phase (47.75Mm^3). As per this study, the anticipated populations to be served from this source were estimated at 949,087, 759,269 and 759,269 in the years 2014, 2020 and 2030 respectively, based on the national standard criterion.

Therefore, the runoff faced variability for all three future time periods. There were increasing trends of temperature, precipitation and runoff, which indicates climate change.

Key words: *Climate Change, GCM, SDSM, HBV, Reservoir Capacity, Dire Dam.*

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1. INTRODUCTION

Under this chapter, background of the study under caption, problem statements which explains why the study is needed, objectives of the study, research questions and the outcome of the study are discussed in details.

1.1 Background

Dire Dam is one of the water supply dams for Addis Ababa metropolis area. The Dam site is located on the perennial Legedadi stream about 40km north of Addis Ababa along the Addis–Dessie road, 8km off-road from Dire town to the left. It is a zoned earth and rock-fill embankment 46m high, with a crest length of 665m. The spillway is located in bedrock adjacent to the right abutment of the dam and contains near-vertical rock cuts measuring up to 4m high.

The main intentions in the construction of Dire Water Supply Dam was to facilitate the supply of water by building a storage dam for the metropolis Addis Ababa on an emergency basis in order to curb the acute domestic water supply shortage. Water Resources Development Authority had done the engineering design work of the emergency Dire Dam Project in August 1993.

The dam and its appurtenance structures, which consist of water abstraction facility, spillway and main transition line to Legedadi treatment plan was designed and implemented as per the design.

The impact of climate change on water resources are the most crucial research agenda in worldwide level (IPCC, 2007). This change in climate causes a significant impact on the water resource by disturbing the normal hydrological processes. Future change in overall flow magnitude, variability and timing of the main flow event are among the most frequently cited hydrological issues (Fredrick, 2002: Wurbs et al., 2005).

The IPCC findings indicate that developing countries, such as Ethiopia will be more vulnerable to climate change. As noted by the World Commission on Dams (2000), it is generally agreed that the future can no longer be assumed to be the same as the past with respect to design and maintenance of dams. It is becoming increasingly recognized that climate change is likely to have significant impact on the water security of existing dams that were designed based on past records.

Ethiopia‟s climate is typically tropical in the South-Eastern and North-Eastern lowland regions, but much cooler in the large central highland regions of the country. Seasonal rainfall in Ethiopia is driven mainly by the migration of the Inter-Tropical Convergence Zone (ITCZ). The exact position of the ITCZ changes over the course of the year, oscillating across the equator from its Northern most position over Northern Ethiopia in July and August, to its Southern most position over Southern Kenya in January and February. The movements of the ITCZ are sensitive to variations in Indian Ocean sea-surface temperatures and vary from year to year, hence the onset and duration of the rainfall seasons vary considerably inter annually, causing frequent drought. The most well documented cause of this variability is the El Niño Southern Oscillation (ENSO). Warm phases of ENSO (El Niño) have been associated with reduced rainfall in the main wet season, July, August and September, in North and central Ethiopia causing severe drought and famine, but also with enhanced rainfalls in the earlier February to April rainfall season which mainly affects Southern Ethiopia.(C. McSweeney, et al, 2012).

Moreover, as per IPCC, the rain also falls within a relatively short period of three to four months, while the rest of the year is relatively dry.

Due to these reasons, it is very likely that climate change has an impact on the quantity and availability of water in Addis Ababa Metropolitan area. Hence, understanding the performance of the Dire Water Supply Reservoir using different climate and hydrological model is of paramount importance.

No one would question the critical importance of safe, sustainable and reliable supply of potable water for human use (SOKOLOV A.A. and T. G. CHAPMAN, 1974). The existing water resources, which serve the city of Addis Ababa, are just inadequate to meet the present and the near future needs of the population.

During the implementation of the project, additional studies were carried out on floods and adequacy of the dam freeboard with proposed technical solutions, which aimed at increasing the storage capacity of the reservoir.

The study (conducted by SEURECA, 2006) showed that there is potential to harvest additional raw water from Dire reservoir that could be treated by expansion of the existing treatment plant at Legedadi.

Moreover, based on the SEURECA‟s conceptual report, a detail design was also carried out by SEURECA-BRLi-TROPICS in the year 2009. Accordingly, the detail design was prepared and the Dam was raised by 1.5m and spillway by 2.5m as per the results obtained from the new design. The main aim of raising the Dam is to increase the storage capacity of the reservoir from 19 Mm^3 to 23 Mm^3 for immediate increase of Addis Ababa water supply. The water demand for the city is increasing tremendously and this indicates clearly for a need to provide additional water security and a study was commissioned to augment the supply by the raising of the existing dam.

In recent years, the scientific and practical importance of water balance problems has been highlighted by predictions of freshwater shortages in many areas of the world, due to industrial development, urbanization, and increase in agricultural production. (SOKOLOV A. A. and T. G. CHAPMAN, 1974)

Hence, in order to assess the reservoir capacity, the hydrological analysis of the catchment (supply) was done and make comparisons between the two formerly carried out hydrology reports for the design purpose. Moreover, the supply and demand analysis was also done according to the results obtained from the newly designed hydrological results, the original results used for the design purpose and the formulated national and international standards respectively. Comparison was also made with the supply and demand criteria set for the design works.

1.2 Problem Statement

Climate change is the sever problem that the whole world facing today. Besides, global climate changes effect, some studies conducted in Abay and Awash basins show that the basins are climate sensitive (TAHEL, 2000). Dire catchment is in the upper North Western part of Awash basin; therefore, climate change should be a big concern and should be considered to evaluate the future climate effect on the reservoir which are the main sources of water supply of Addis Ababa. It has been clearly seen that climate change has huge influence to impose on the water availability of the water sources of Addis Ababa by bringing *seasonal shift to rainfall pattern* so that changing the magnitudes of hydrologic components of the reservoir (Oziranski, 2009). This implies the political center of Ethiopia and Africa is under water shortage stress. This shortage is mainly a result of lack of water supply to meet the real demand of the city.

Addis Ababa with its ever-increasing population, has reached a state of critical water shortage. To satisfy the rapidly increasing water demands of the city, the Addis Ababa Water and Sewerage Authority, has done Dire Dam rehabilitation works, dam raising, major expansions of the water treatment plant, transmission and distribution facilities.

The water demand for the city is increasing tremendously and this indicates clearly for a need to provide additional water security and a study was commissioned to augment the supply by the raising of the existing dam. Accordingly, raising works of Dire Dam is undertaken by the Authority to increase the storage capacity of the reservoir. As it has been seen the situations on the ground as well based on the reports of Addis Ababa Water and Sewerage Authority, the Dam still could not attain to meet the expected requirements for it has been re-designed for.

The aim of this study is to assess the climate change impact of Dire Dam Water Supply and verify previous hydrological studies carried out to determine the capacity of Dire reservoir. Moreover, it also deals with the assessment of supply and demand criteria to allow the planners, decision makers and any concerned persons to know the situations there.

1.3 Objectives of the Study

The general objective of this study is to assess the climate change impact of Dire Dam Water Supply, addressing water security for the beneficiaries of Addis Ababa Metropolitan area. The specific objectives are:

- To assess the impact of climate change on major climate and hydrological parameters of Dire Dam
- To assess the reservoir capacity and water supply and demand criteria

1.4 Research Questions

Generally, the study was attempted to give answer for the following questions:

- Is there any climate change impact on the climate parameters (rainfall & temperature)?
- Is there any climate change impact on hydrological parameters (runoff)?
- Does the reservoir capacity satisfy the hydraulic requirements as per the design criteria?
- Does the reservoir meet its supply and demand criteria?

1.5 Outcome of the Study

The major significance of this study is to allow the planners, decision makers and any concerned persons to know the consequences of climate change on climate and hydrological variables and the impacts on reservoir water resource planning management and accordingly device decision and management support tools. Moreover, it also allows creating awareness, the current status of the reservoir capacity and supply and demand conditions.

2. LITERATURE REVIEW

The following literature review is focused on the relevant topics in terms of the assessment of the current status of the reservoir capacity, evaluation of demand and supply criteria and assessment of the impact of climate change on the Dam, using detail design documents, re-designing works and HBV and GCMs models are of interest of this study.

2.1 Review of Documents

2.1.1 Hydrology Report, Detail Design of Dire Dam Project (1995 Study)

At the stage of this study, a review of the previous works by Water Resources Development Authority has been undertaken. The Authority prepared detail hydrological report used for the detail design purpose. In this report, HEC-1 model, rational formula method, regionalization analysis (area-ratio method), Boldakov‟s and B.D. Richard‟s methods were used to estimate the probable maximum flood. For the safe engineering design purpose, results obtained using B.D. Richards method was adapted and used for the detail engineering design, which is 570m^3/s.

2.1.2 SEURECA (2006 Study)

In this study, a review of the previous works by SEURECA has also been undertaken. The feasibility study conducted by SEURECA in 2006 concluded that there is potential to harvest additional raw water from Dire reservoirs that could be treated by expansion of the existing treatment plant at Legedadi. This report recommended increase of the treatment capacity at Legedadi plant by construction of an additional pulsator clarifier of new 30,270m^3/day capacity for immediate increase of Addis Ababa water supply.

2.1.3 SEURECA-BRLi-TROPICS (2009)

In 2009, SEURECA-BRLi Consulting Engineers in association with Tropics Consulting has carried out a hydrological study for raising the existing Dam. The study was carried out based on the conceptual report carried out by SEURECA in 2006. During the conceptual and detail designs of the project, further hydrological assessments were carefully conducted in order to evaluate the estimates of additional raw water availability in the reservoirs at Dire and Legedadi dams. As per their report, the 10,000-year flood hydrograph estimated by SCS (Soil Conservation Service) model is found to be 563 m^3/s which is very close to the estimation for the original dam design study (570 m^3/s) carried out by Water Resources Development Authority.

Accordingly, the detail design was prepared and the construction for the raise of the Dam by 1.5m and spillway by 2.5m had been performed as per the results obtained from the new design. The main aim of raising the Dam is to increase the storage capacity of the reservoir from 19 Mm^3 to 23 Mm^3 for immediate increase of Addis Ababa water supply.

Figure 2-1: Spillway under & after construction

2.2 Over View of Climate Change

Climate change is the sever problem that the whole world facing today. It is now widely accepted that climate change is already happening and further change is inevitable; over the last century (between 1906 and 2005), the average global temperature rose by about 0.74 ^{o}C. This has occurred in two phases, from 1910s to 1940s and more strongly from the 1970s to the present (IPCC, 2007a).

Many studies into the detection and attribution of climate change have found that most of the increase in average global surface temperature over the last 50 years is attributable to human activities (IPCC, 2001a).

It is estimated that, for the 20th Century, the total global mean sea level has risen 12-22 cm, this rise has been caused by the melting of snow cover and mountain glaciers (both of which have decline on average in both hemispheres)(IPCC, 2007a). The IPCC also notes that observations over the past century shows, changes are occurring in the amount, intensity, frequency and types of precipitation globally (IPCC, 2007a).

2.3 Impacts of Climate Change on Water Resource and Reservoir

Findings of the IPCC 2001, strongly suggests that water resource respond to global warning in ways that will negatively impacted the water availability and water supplies. The climate change has also the potential to deteriorate the surface water quality due to increased evapotranspiration, lower flows and rivers becoming warmer, making the management of water treatment works (and subsequent compliance with the drinking water quality regulations) more challenging. The reduction in the runoff volume will lead to the decrease in the inflow to the reservoirs consequently; longer period might be required to fill the reservoir. As result of the increase in temperature, the rate of evaporation from the reservoir open water surface may increase and this may create the reservoir to fail to supply at least the required amount of demand because of its depletion or decrease in the active storage volume and/or water level.

2.4 Climate Change in Ethiopia

According to the Ethiopian National Meteorological Services Agency (NMSA, 2001) study for 42 meteorological stations, the country has experienced both dry and wet years over the last 50 years. Trend analysis of the annual rainfall show that, there was a declining trend in the northern half of the country and southern Ethiopia, while there is an increasing trend in the central part of the country. However, the overall trend in the entire country is more or less constant.

The study of NMSA at the same year for 40 stations showed that there have been very warm and very cold years. However, the general trend showed there was an increase in temperature over the last 50 years. The study also noted that the minimum temperature is increasing at a higher rate than the maximum temperature.

Associated with rainfall and temperature change and variability, there was a recurrent draught and flood events in the country. There was also observation of water level rise and dry up of lakes in some parts of the country depending on the general trend of the temperature and rainfall pattern of the regions.

2.5 Previous Studies on the Potential Impact of Climate Change on the Dire Water Supply Dam

Regarding the subject matter, it was tried to investigate literatures from different sources. But it was difficult to locate climate impact study reports for this specific area with the exception of the following thesis reports.

2.5.1 Evaluation of Climate Change Impact on Extreme Hydrological Event (Case study: Addis Ababa and surrounding catchment)

In May 2011, Abayneh Alemu has carried out a case study for the partial fulfillment for the degree of Masters of Science in Civil Engineering at Addis Ababa University. The study findings indicate that, for the coming 90 years, the mean monthly precipitation may both increase and decrease. The mean monthly precipitation indicates a decreasing up to 51% in 2030s and an increasing trend up to 131% in 2090s. The maximum and minimum temperature indicates an increasing trend. Based on the simulated result, he forwarded that, the maximum river flows in the study area will be high and more variable in terms of magnitude, and irregular of occurrence, than they are at present. He also set that, the climate change has negligible effect on the low flow condition of the Akaki River flow.

2.5.2 Climate Change Effect on Surface Water Sources of Addis Ababa(A Case Study in Legedadi-Dire-Gefersa Catchments and Reservoirs, January 2012)

In this study, a review of the previous works, carried out by Endalkachew Girma for the partial fulfillment for the degree of Masters of Science in Water Supply and Environmental Engineering at Addis Ababa University has also been undertaken. As per his study findings the following conclusions are forwarded. The projected daily mean, maximum and minimum temperature of the Legedadi, Dire and Gefersa shows an increasing trend in comparing with respect to the observed period. The projected areal rainfall also shows an increasing trend in both future time horizons of Legedadi,Dire and Gefersa catchments. Evapotranspiration also shows an increasing trend in all catchments. In the case of Dire catchment, surface water potential increases by 9% and 3% respectively in 2030‟s and 2090‟s time horizons respectively. The effect of climate change on the three reservoirs storage and expected spillway discharge was evaluated and the three reservoirs have a tendency of increasing reservoir storage and spillway discharge in both future time horizons.

2.6 Determination of the Capacity of the Reservoir

The main function of the reservoir is to store water and thus stabilize the flow of water. Therefore, the most important characteristics of the reservoir is nothing but the Storage Capacity. The capacity of the reservoir, at the dam site, can be determined from the contour maps of the area (Thomas A. McMahon, February 2007).

The yield of the reservoir and its storage capacity are very much dependent upon each other. Since the inflow to a reservoir is variable, water is stored in the reservoir to cater to the firm (safe) yield during the critical periods. Capacity of the reservoir certainly depends upon the demand. If more water is required, more capacity has to be provided based on the catchment yield.

The capacity of the reservoir is determined by determining the storage needed to accommodate the given inflow minus the given outflow, besides determining the inflow to the reservoir and the outflow (demand and other releases) from the reservoir.

Further, the construction of the reservoir creates an exposed area of water surface thus, evaporation losses take place. Seepage from the reservoir is also added to the loss resulting from the reservoir.

Finally, an approximate reservoir capacity corresponding to different size of users has been obtained. Fixation of the required reservoir capacity can be determined on the basis of the proposed demand or the principle of utilizing the optimum capacity of the reservoir site.

The reservoir physical capacity and yield can also be verified by applying reservoir mass curve analysis and sequent peak algorithm method (Thomas A. McMahon, February 2007).

2.6.1 Mass Curve Diagram Approach

In the process of determining the initial capacity of the storage required, using the mass curve techniques, an analytical approach for determining the spill and the reservoir has to be developed. This method gives the mass curve graphical techniques. The data requirements for this method are the river flows, evaporation and other losses and the demand. The advantage of this method is that, it is simple and can be used in preliminary design (Thomas A. McMahon, February 2007).

From the previous reports(SEURECA-BRLi-TROPICS, 2009), the estimated demand was 900 l/s at low level and 1000 l/s at high level. For the analysis of the mass curve diagram, it was taken the maximum demand, which is 1000l/s. The transmission capacity was also set to pass these amounts of discharge per second.

2.6.1 Sequent Peak Algorithm Approach

With the standard assumptions of known inflows and requirements and final storage equal to or exceeding initial storage, the linear programming approach to determining the capacity of a single reservoir is equivalent to the sequent peak algorithm in that they must produce the same reservoir capacity(Thomas A. McMahon, February 2007).

2.7 Potential Evapo-Transpiration

F. Bautista et al. (2009) discussed, reference Crop Evapotranspiration (ETo) is a key component in hydrological studies. ETo is used for agricultural and urban planning, irrigation scheduling, regional water balance studies and agro-climatological zoning. Various equations are available for estimating ETo. These equations range from the most complex energy balance equations requiring detailed climatological data

(Penman-Monteith) to simpler equations requiring limited data (Blaney-Criddle, Hargreaves-Samani). The Penman-Monteith equation is widely recommended because of its detailed theoretical base and its accommodation of minor periods. However, the detailed climatological data required by the Penman-Monteith, are not often available especially in developing nations. For example, in the continent of Africa, there is one such weather station for every three million hectares. Even in more developed nations, the climatological data are often limited.

2.8 Climate Scenario

Scenarios can be described as pertinent, plausible, alternative futures. Their pertinence, in the case of climate change, is in providing information on how future human activities are expected to alter the composition of the atmosphere, how this may affect the global climate and how changes in climate may affect natural systems and human activities. This information is required to assist decision-makers in controlling future emissions of greenhouse gases and in managing resources that may be affected by climate change.

Climate scenarios are plausible representations of the future that are consistent with assumptions about future emissions of greenhouse gases and other pollutants and with our understanding of the effect of increased atmospheric concentrations of these gases on global climate. A range of scenarios can be used to identify the sensitivity of an exposure unit to climate change and to help policy makers decide on appropriate policy responses. It is important to emphasize that climate scenarios are not predictions, like weather forecasts are. Weather forecasts make use of enormous quantities of information on the observed state of the atmosphere and calculate, using the laws of physics, how this state will evolve during the next few days, producing a prediction of the future - a forecast. In contrast, a climatic scenario is a plausible indication of what the future could be like over decades or centuries, given a specific set of assumptions. These assumptions include future trends in energy demand, emissions of greenhouse gases, land use change as well as assumptions about the behavior of the climate system over long time scales. It is largely the uncertainty surrounding these assumptions, which determines the range of possible scenarios (Carter *et al*., 1999).

Climate scenarios are sets of time series or statistical measures of climate variables, such as temperature and precipitation, that represent alternative climate conditions for past, present or future conditions. A variety of methods have been developed to generate climate scenarios for use in the assessment of the impacts of climate variability and change. These methods are typically categorized as being empirical or process model based. The empirical approaches use information about the past to estimate possible future conditions, whereas model-based approaches attempt to use the underlying physical laws of atmospheric processes to simulate climate under changed conditions (Van Dam, 2003).

Climate change scenarios provide the best-available means of exploring how human activities may change the composition of the atmosphere, how this may affect global climate, and how the resulting climate changes may impact upon the environment and human activities. They should not be viewed as predictions or forecasts of future climate, but as internally consistent pictures of possible future climates, each dependent on a set of prior assumptions (Goodess, 2000).

2.8.1 Types of Climate Scenarios

According to Carter *et al*., (1999), climate scenarios fall into three main classes, which are mentioned as follows:

- **Synthetic scenarios:** Synthetic scenarios describe techniques where particular climatic (or related) elements are changed by a realistic but arbitrary amount, often according to a qualitative interpretation of climate model simulations for a region. For example, adjustments of baseline temperatures by +1, 2, 3 and 4^{O}C and baseline precipitation by $\pm$5, 10, 15 and 20 percent could represent various magnitudes of future change.
- **Analogue scenarios:** Analogue scenarios are constructed by identifying recorded climate regimes, which may resemble the future climate in a given region. These records can be obtained either from the past (temporal analogues) or from another region at the present (spatial analogues).
- **Scenarios from general circulation model outputs:** Climate models at different spatial scales and levels of complexity provide the major source of information for constructing scenarios. GCMs and a hierarchy of simple models produce information at the global scale.

2.9 Special Report on Emission Scenarios (SRES)

Four different narrative storylines were developed to describe consistently the relationships between emission driving forces and their evolution and add context for the scenario quantification. Each storyline represents different demographic, social, economic, technological, and environmental developments, which may be viewed positively by some people and negatively by others. The scenarios cover a wide range of the main demographic, economic, and technological driving forces of greenhouse gas and sulfur emissions. Each scenario represents a specific quantitative interpretation of one of four storylines. All the scenarios based on the same storyline constitute a scenario “family” (IPCC, 2000).

According to IPCC (2007) notification, the Emissions Scenarios of the IPCC Special Report on Emissions Scenarios (SRES) includes:

A1: The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies.

A2: The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1: The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid- century and declines thereafter, as in the A1 storyline but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2: The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

Storyline- a narrative description of a scenario (or a family of scenarios), highlighting the main scenario characteristics and dynamics, and the relationships between key driving forces (Carter *et al*., 1999).

2.10 Modeling Climate Change

The earth‟s climate is governed by the interaction between many processes in the atmosphere, ocean, land surface and cryosphere. The interactions are complex and extensive so that quantitative predictions of the climate of greenhouse gas increase cannot be made through simple intuitive reasoning. For this reason, computer models have been developed which try to mathematically simulate the climatic system, including the interaction between the system component (Coulibaly and Dibike, 2004). For climate simulation, the major components of the climate system that must be represented in sub-models are atmospheric, ocean, land surface, cryosphere and biosphere along with the processes that go on within and between them.

The mathematical models generally used to simulate the present climate and project future climate with forcing by greenhouse gases and aerosols are generally referred to as GCMS (General Circulation Models). General circulation models in which the atmosphere and ocean components have been coupled are also known as Atmosphere-Ocean General Circulation Models (AOGCMs). Currently, the resolution of the atmospheric part of a typical model is about 250 km in the horizontal and about 1km in the vertical above the boundary layer. The resolution of a typical ocean model is about 200 to 400 m in the vertical, with a horizontal resolution of about 125 to 250 km. Many physical processes, such as those related to clouds or ocean convection, take place at much smaller spatial scales than the model grid and therefore cannot be modeled and resolved explicitly. Their average effects are approximately included in a simple way by taking advantage of physically based relationships with the larger-scale variables through the techniques of parameterizations (Houghton, 2001).

2.10.1 General Circulation Model (GCM)

The climate model is a mathematical description of the earth‟s climate system, broken into a number of grid boxes and levels in the atmosphere, ocean and land. At each of these grid points equations are solved which describe the large-scale balances of the momentum, heat and moisture. Based on this, a wide range climate models are developed.

When GCMs comes to quantifying the potential impacts of climate change on water resources, more problems arise. GCMs generally operate at coarse resolutions across the continents, but much smaller scales (in both time and space) are required for catchment hydrological modeling (Bergkamp et al. 2003).

Generally, coarse spatial resolution of GCMs also presents a significant problem when rainfall is being considered. GCMs usually generate an estimate of the average rainfall over a large grid square for the GCM time step, but they fail to take into account localized temporal and spatial variations in rainfall which, on a smaller scale, can produce highly significant results (Calder, 2005). Even though, GCMs has the above main limitations, currently it has been recognized to be able to represent reasonably well the main futures of global distribution of the basic climate parameters (Gates et al., 1999; Lambert and Boer, 2001). In order to decrease the uncertainty related to coarse resolution of GCMs, usually, most climate impact assessment researches use different downscaling methods such as dynamic downscaling method and/or statistical downscaling method. These two fundamental approaches exist for the downscaling of large-scale GCM output to a finer spatial resolution. The dynamical approach is used where a higher- resolution climate model is embedded within a GCM. The other approach is to use statistical methods to establish empirical relationships between GCM-resolution climate variables and local climate (Fowler et al., 2007).

According to Wilby and Dawson (2007) discussion, Downscaling is the term given to the process of deriving finer resolution data (e.g., for a particular site) from coarser resolution GCM data. It may be possible to define a relationship, or relationships, between site climate and large-scale (i.e., GCM grid box scale) climate which can then be used to derive more realistic values of the future climate at the site scale.

2.10.1.1 Dynamical Downscaling

According to Fowler et al. (2007) notification, dynamical downscaling refers to the use of regional climate models (RCMs), or limited-area models (LAMs). These use large-scale and lateral boundary conditions from GCMs to produce higher resolution outputs. These are typically resolved at the approximate 0.5° latitude and longitude scale and parameterize physical processes.

2.10.1.2 Statistical Downscaling

Statistical downscaling provides a way to utilize output of climate models for local-scale applications. Typical grid size for global-scale simulations are of the order of 100 – 200 km, and the raw global-scale model output is of limited use when information is required at local scales. The objective of downscaling is to overcome this scale mismatch and to use the skill in atmospheric forecasts at local scales. In short, statistical downscaling develops relationships between large-scale atmospheric circulation variables and local climate information (e.g. precipitation and temperature observations at individual stations). Regional or local climate information is derived by first determining a statistical model which relate large scale climate variables (or" predictors ") to regional and local variables (or “predictands"). Using these observed relationships, forecasts of atmospheric variables can be translated into forecasts of local climate variables. Several methods of varying complexity have been used in performing statistical downscaling (Gangopadhyay et al., 2005).

Many statistical downscaling techniques have been developed to translate large-scale GCM output onto a finer resolution (Fowler et al., 2007).

According to Wilby and Dawson (2007), the SDSM software reduces the task of statistically downscaling daily weather series into seven discrete steps: Quality control and data transformation, screening of the predictor variables, model calibration, weather generator, data analysis, graphical analysis, and scenario generations.

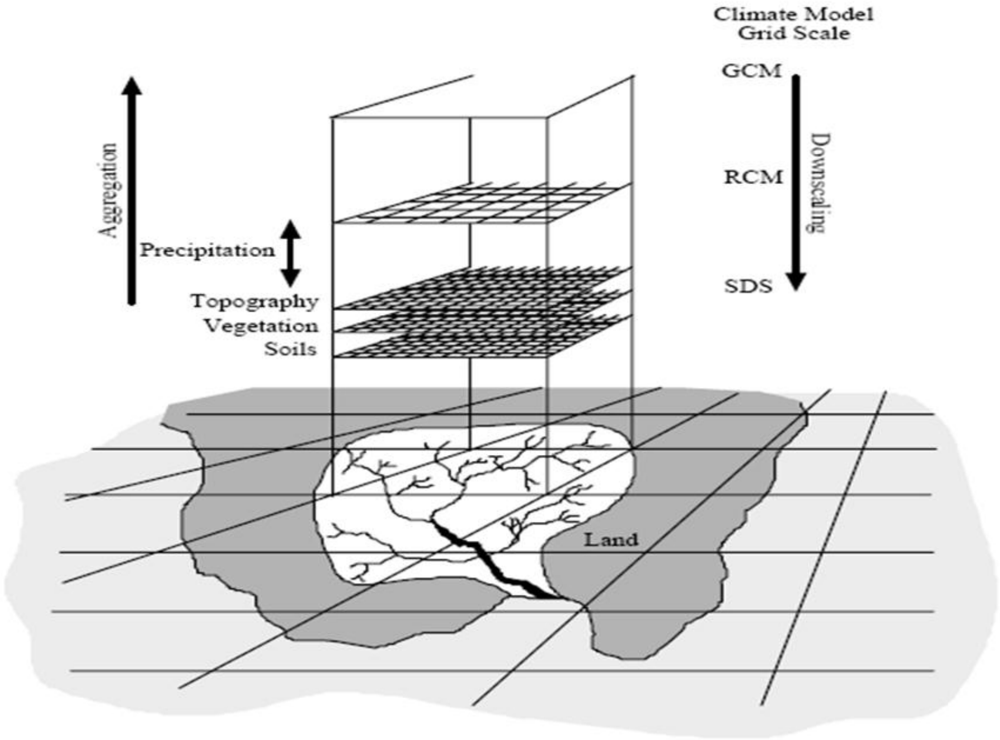


Figure 2-2: A schematic diagram illustrating the general approach to downscaling (Dawson & Wilby, 2007)

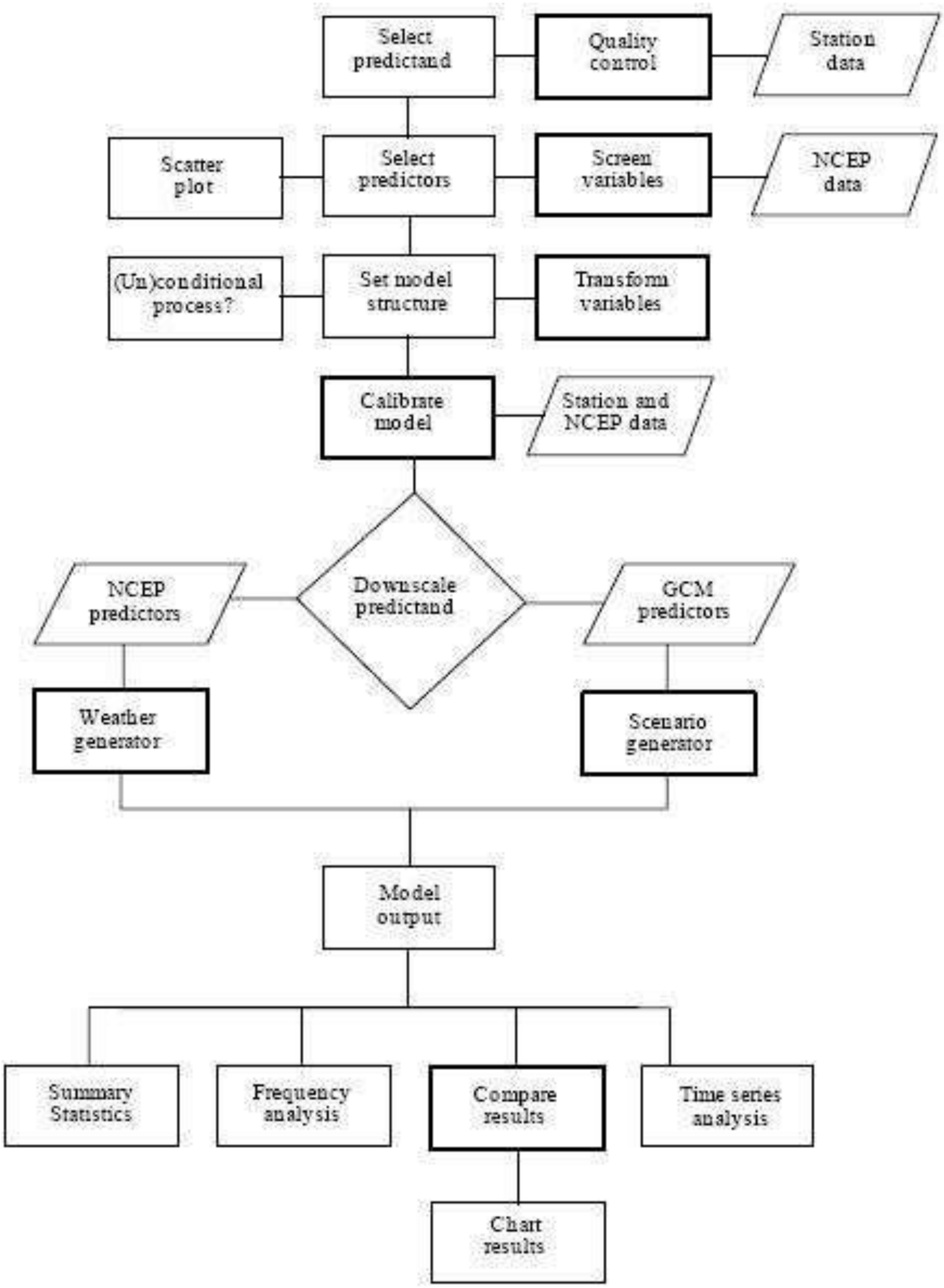


Figure 2-3: SDSM Version 3.1 climate scenario generations (Dawson & Wilby, 2007)

2.11 Hydrological Model Selection

There are many different reasons why modeling of the rainfall-runoff processes of hydrology is needed. The main reasons behind are a limited range of hydrological measurement techniques and a limited range of measurements in space and time (Beven, 2000). Therefore, it is necessary to develop a means of extrapolating from those available measurements in space and time to un-gauged catchments and in to the future to assess the likely impact of the real world system. The researchers use a wide range of hydrological, models; however, the applications of those models are highly dependent on the purposes for which the modeling is made. (Beven, 2000) stated that many rainfall- runoff models are carried out purely for research purposes as a means of enhancing knowledge about hydrological systems. He also added that other types of models are developed and employed as tools for simulation and prediction aiming ultimately to allow decision makers to improve decision making about hydrological problems. Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding hydrologic processes.

2.12 Factors to be considered in Model Selection

There are a range of possible model structures within each class of models. Hence, choosing a particular model structure for a particular application is one of the challenges of the model user community. (Beven, 2000) suggested four criterions for selecting model structures as below.

1. Consider models which are readily available and whose investment of time and money appeared worthwhile.
2. Decide whether the model under consideration will produce the outputs needed to meet the aims of a particular project.
3. Prepare a list of assumptions made by the model and check the assumptions likely to be limiting in terms of what is known about the response of the catchment. This assessment will generally be a relative one, or at best a screen to reject those models that are obviously based on incorrect representations of the catchment processes.
4. Make a list of the inputs required by the model and decide whether all the information required by the model can be provided within the time and cost constraints of the project.

2.13 Hydrologic Modeling

Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding hydrologic processes. Without going into too much detail, *deterministic hydrologic models* can be classified into three main categories (Juraj M, 2003)

1. **Lumped models**. Parameters of lumped hydrologic models do not vary spatially within the basin and thus, basin response is evaluated only at the outlet, without explicitly accounting for the response of individual sub-basins. Parameters of lumped models often do not represent physical features of hydrologic processes and usually involve certain degree of empiricism. The impact of spatial variability of model parameters is evaluated by using certain procedures for calculating effective values for the entire basin. The most commonly employed procedure is an area-weighted average (Haan et al., 1982). Lumped models are not usually applicable to event-scale processes. If the interest is primarily in the discharge prediction only, then these models can provide just as good simulations as complex physically based models (Beven, 2000).

2. **Semi-distributed models.** Parameters of semi-distributed (simplified distributed) models are partially allowed to vary in space by dividing the basin into a number of smaller sub-basins. There are two main types of semi-distributed models: 1) kinematic wave theory models (KW models, such as HEC-HMS), and 2) probability distributed models (PD models, such as TOPMODEL). The KW models are simplified versions of the surface and/or subsurface flow equations of physically based hydrologic models (Beven, 2000). In the PD models spatial resolution is accounted for by using probability distributions of input parameters across the basin.

3. **Distributed models.** Parameters of distributed models are fully allowed to vary in space at a resolution usually chosen by the user. Distributed modeling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of this distribution on simulated precipitation-runoff behavior. Distributed models generally require large amounts of (often unavailable) data for parameterization in each grid cell. However, the governing physical processes are modeled in detail, and if properly applied, they can provide the highest degree of accuracy.

2.13.1 HBV Rainfall-Runoff Model

The Hydrologiska Byrans Vattenbalansavdelning (HBV) model was developed at Swedish Metrological and Hydrological Institute (SMHI) during the early 1970‟s. The HBV is a semi – distributed conceptual rainfall-runoff model for continuous simulation of catchment runoff and out flow from reservoirs, the model consistence of subroutines for precipitation and snow accumulation, soil moisture accounting, actual evaporation and uses simple transformation functions routine procedures. Soil moisture accounting is governed by two simple relations that are parameterized by *FC*, which is the maximum soil moisture storage (mm) in the model, and *LP* that is the limit for potential evapo-transpiration and *Beta* control the contribution of the soil moisture storage, *SM*, to the response function ΔQ/ΔP.

$$\frac{\Delta Q}{\Delta P} = \left[\frac{SM}{FC}\right]^{Beta} ----------------2.1$$

Q denotes the discharge and *P* denotes the precipitation while Δ*Q*/ Δ*P* is to be interpreted as runoff coefficient. Actual evapo-transpiration, *Ea*, which is controlled by the soil moisture routine, is linearly related to the potential evapo-transpiration, *Ep* , and reads;

$$Ea = Ep * min\left\{\left(\frac{SM}{(lp * FC)}\right), 1\right\} -----------2.2$$

In HBV-IHMS the runoff routine comprises two reservoirs that distribute generated runoff over time to obtain quick and slow part of catchments runoff hydrograph. Runoff generated from the upper reservoir represents quick runoff discharges while runoff from the lower reservoir represents ground water discharges.

$$Qo = K * UZ^{(1+alfa)} ---------------2.3$$

Where Q_o *is* the direct runoff from upper reservoir the parameters *UZ* and *KHQ* are the upper reservoir storage and the quick flow recession coefficient while Alfa is a measure for the nonlinearity of the flow. The lower reservoir is a simple linear reservoir that simulates base flow contributions by percolation from upper reservoir.

$$Q_1 = K_4 * LZ ---------------- 2.4$$

Q_1denotes the outflow from lower reservoir; *LZ* is the lower reservoir storage while K4is the recession coefficient. Obviously, the combination of the parameters control runoff contribution over time that affects the shape of hydrograph.

The general HBV water balance can be described as:

$$P - E - Q = \frac{d}{dt}[SP + SM + UZ + LZ + lakes] - - - - - - - - 2.5$$

Where: P = precipitation
E = evapotranspiration
Q = runoff
SP = snow pack
SM = soil moisture
UZ = upper groundwater zone
LZ =lower groundwater zone
lakes = lake volume
dt = time step.

The left side of the equation describes hydrological dynamic processes and right side change of the storages including snow, soil, groundwater and lake storages.

The time step is usually one day, but it is possible to use shorter time steps. The input information to the HBV model is: Precipitation records (on daily or shorter time step) Air temperature records (if snow is present) Evapotranspiration (can be also calculated from for instance minimum and maximum temperatures) Runoff record (catchment outlet discharge) for calibration Geographical information about the river catchment

The model consists of subroutines for meteorological interpolation, snow accumulation and melt, evapotranspiration estimation, soil moisture accounting procedure and routines for runoff generation. It is possible to run the model separately for several subbasins and then add the contributions from all subbasins. Calibration as well as forecasts can be made for each subbasin.

The standard model uses a rather crude weighting routine and lapse rates for computation of areal precipitation and air temperatures.

The runoff generation routine is the response function which transforms excess water from the soil moisture zone to runoff. It also includes the effect of direct precipitation and evaporation on a part which represents lakes, rivers and other wet areas. The function consists of one upper, non-linear, and one lower, linear, reservoir. These are the origin of the quick (superficial channels) and slow (base-flow) runoff components of the hydrograph. Level pool routing is performed in lakes located at the outlet of a subbasin.

HBV has been used for the following applications:

- flood warnings - stream flow and volume forecasting for appraisal of flood risks, and development of flood risk maps
- hydropower - short term inflow forecasts for operational hydropower planning at dispatch centers and volume forecasts of up to a year for seasonal reservoir planning
- pre-feasibility studies - quality control of water stage and discharge records, extension of historical records and ground water simulations
- irrigation - determination of evapotranspiration and forecasting inflow to reservoirs and storage pounds to aid regulation of irrigation schemes
- dam safety - design flood computations including reservoir management strategies
- climate change - studies of the effect of changing climate conditions on run-off patterns, soil moisture, ground water change and evapotranspiration

2.13.1.1 Model Structure

The HBV model can best be described as a semi-distributed conceptual model. Over the years only minor changes in the basic model structure have been made. Input data have been kept as simple as possible, normally only daily mean-values of temperature and precipitation and runoff data for calibration are used. Despite its simplicity, its simulation performance is commendable, and the original use for hydrological forecasting has expanded to applications such as filling gaps in measured time-series, simulation of stream-flow in ungauged rivers, design flood calculations and water quality studies input data. The flexible structure of the HBV/IHMS system allows the model to make necessary sub-divisions with respect to different climate zones, land-use, density of the hydro-meteorological network etc. In connection with spillway design studies for hydropower reservoirs in Sweden, SMHI has worked with river models for regulated rivers including up to 200 sub-catchments.

During 2004-2005 a completely revised version of the Graphical User Interface (GUI) for the HBV-model has been developed called IHMS 5 (Integrated Hydrological Modeling system). The Swedish version was released in February 2005 and the English version during autumn of 2005. The system is continuously developed and the latest version is 6.3.

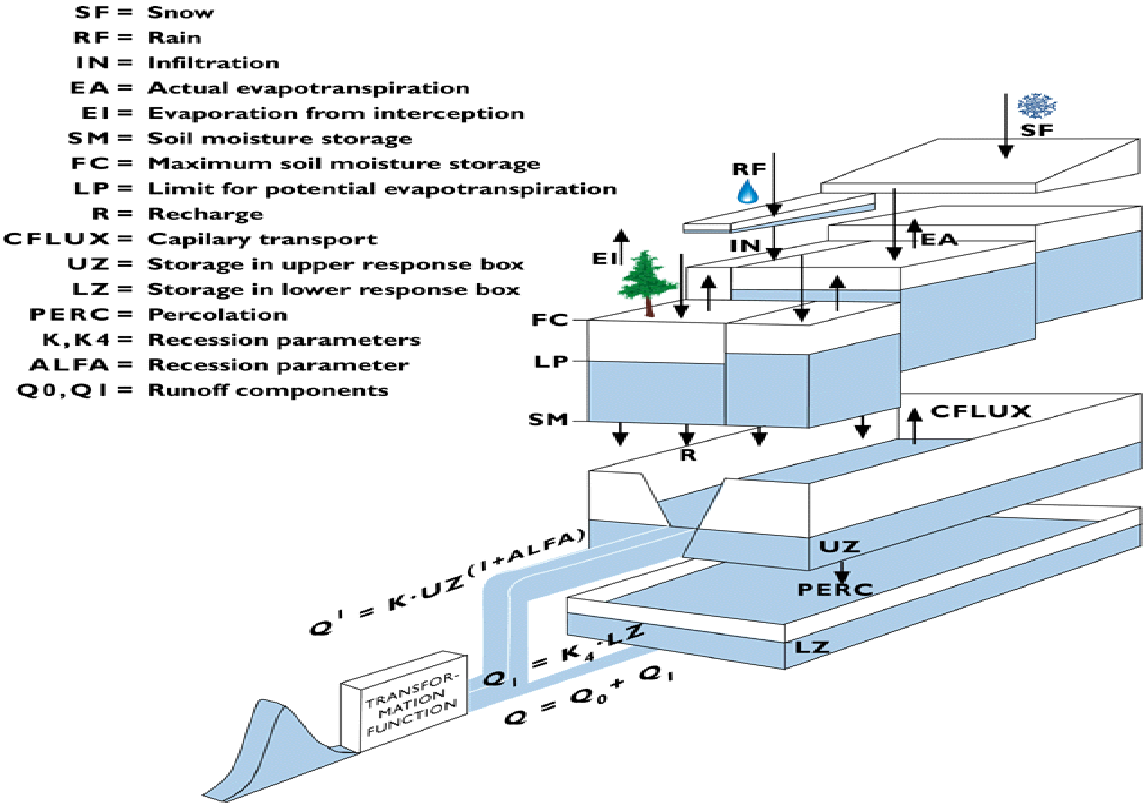


Figure 2-4: Schematic presentation of the HBV model for one sub-basin

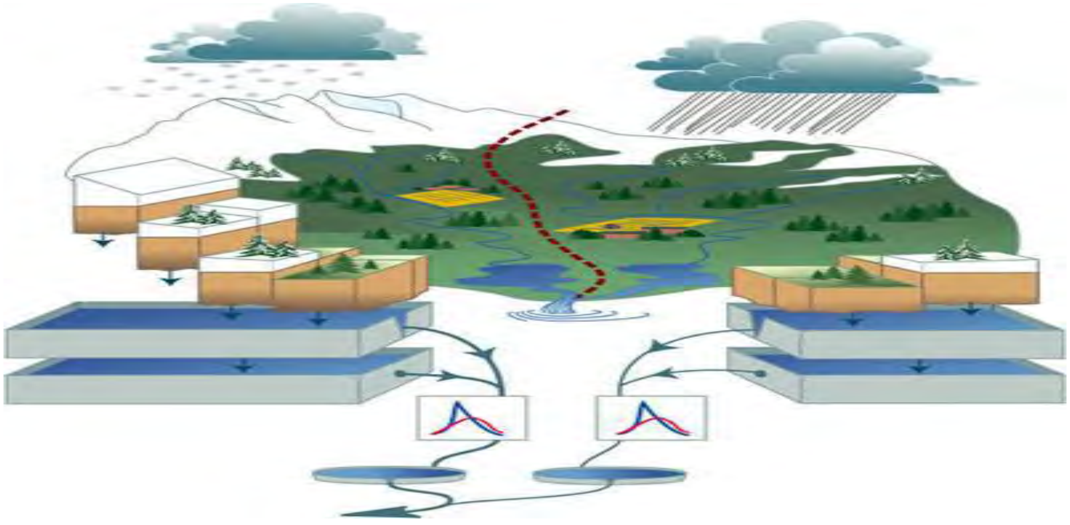


Figure 2-5: Schematic representation of the HBV model structure (SMHI, 2012)

Each catchment area receives precipitation which can be divided into different areas and into snow and water fractions. The precipitation is routed through surface and deep storages (base flow) to the catchment outlet (SMHI, 2012).

The model is available free of charge for research purposes at Universities, given that user agrees to give feed-back about progress and results described in report to SMHI /Swedish Meteorological and Hydrological Institute/.

2.14 Evaluation of Model Simulation

2.14.1 Model Calibration and Validation

Calibration is the process by which optimal parameters are determined by the model user in order to produce the most accurate models in comparison to measured data. Calibration is means of adjusting or fine tuning model parameters to match with the observed data as much as possible with limited deviations accepted (Neitsch, 2002). This greatly improves the accuracy of a model. Parameters estimation for calibration is various techniques designed to reduce uncertainty in the estimates of the process parameters. A typical approach is to first select an initial estimate for the parameters, somewhere inside the ranges previously specified. The parameter values then adjusted to move closely matches the model behavior to that of the catchment. The process of adjustment can be done manually or using computer based automatic methods.

Whilst Model validation is the process of rerunning the simulation, using a different time-series for input data, without changing any parameter values which may have been adjusted during calibration. It is testing of calibrated model results with independent set without any further adjustment at different spatial and temporal scales (Neitsch, 2002).

2.14.2 Model Efficiency

Although, the main objective of the study is not to evaluate the model performance, the model outputs have to be evaluated to use the output for further analysis with better confidence. There are various methods for measuring models predictions for goodness-of-fit during the calibration and validation periods. Calibration aimed at the water balance and over all shape agreement of the observed discharge using RVE (relative volume error) and R^2 (Nash and Sutcliffe coefficient). The Nash - Sutcliffe simulation efficiency, ENS, indicates that the degree of fitness of the observed and simulated plots with the 1; 1 line (Santhi et al, 2002).

Relative Volume Error

The relative volume error can vary between -∞and ∞ but performs best when a value of 0 is generated since no difference between simulated and observed discharge occurs. However, at the same time the distribution of the discharge throughout the calibration period can be completely wrong. Therefore, this objective function should always be used in combination with another objective function that considers the overall shape agreement.

$$RV_E = \left[\frac{\sum_{i=1}^{n} Q_{sim(i)} - \sum_{i=1}^{n} Q_{obs(i)}}{\sum_{i=1}^{n} Q_{obs(i)}}\right] * 100\% --------2.6$$

Where:

RV_E: Relative volume error, $Q_{sim(i):}$ Simulated flow, and $Q_{obs(i})$: Observed flow

A relative volume error less than +5% or -5% indicates that a model performs well while relative volume errors between +5% and +10% and -5% and -10% indicates with a reasonable performance.

Nash-Sutcliffe Coefficient

Nash-Sutcliffe Coefficient measures the efficiency of the model by relating the goodness-of-fit of the model to the variance of the measured data. Nash-Sutcliffe Coefficients can range from -∞to 1. An efficiency of 1 corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 indicates that the model predictions are an accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty < NS < 0$) occurs when the observed mean is a better predictor than the model. Besides, due to frequent use of this coefficient, it is known that when values between 0.6 and 0.8 are generated, the model performs reasonably. A value between 0.8 and 0.9 tells that the model performs well and values between 0.9 and 1 indicates that the model performs extremely well (Deckers, 2006).

$$NS = 1 - \frac{\sum_{i=1}^{n}\left(Q_{sim(i)} - Q_{obs(i)}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs(i)} - \bar{Q}_{obs}\right)^2} ------------2.7$$

Where:

NS: Nash-Sutcliffe Coefficient, $Q_{sim(i):}$ Simulated flow, $Q_{obs(i)}$: Observed flow and Q_{obs}: Average of observed flow.

3. MATERIALS AND METHODS

Under this section, description of the study area, materials to be used for the study purpose, data availability and its collection methods were discussed in detail. Furthermore, the overall methodology to be employed to undertake the study was also explained in detail.

3.1 Study Area Description

3.1.1 Location

The study area lies at an elevation varying from 2512 to 2557 m.a.s.l. The Dam site is located on the perennial Legedadi stream about 40km north of Addis Ababa along the Addis–Dessie road, 8km off-road from Addis-Dessie high way to the left. The overall catchment area is 77km^2 with an annual rainfall of 1000mm. the land use/land cover of the area is composed of forest, scanty bush, and light-to-light dense bush cover with the sizeable cultivable and grazing land.

The existing dam was constructed along the Legedadi River and has a height of 46m at crest level of 2558.5m. The summarized detail description of the old Dem and related matters are presented as follows:

i. Location

❖ Latitude	9^0 09"
❖ Longitude	38^0 40"
❖ Nearest Township	Sendafa
❖ Regional Sub-district	Bereh Woreda
❖ Mean Sea Level Elevation	2540 m – 3140 m

ii. Hydrology

❖ Catchment Area	77 Km^2
❖ Mean Catchment Slope	23.2%
❖ Land Use of Catchment	-Large part is covered by small drain And mountain chain is lightly forested and some portion is left as fallow
❖ Physiography of Catchment	-highly with steep-slope topography
❖ Mean Annual Rainfall	1000 m
❖ Mean Annual Runoff	-i) Regional analysis(area ratio)=43.606*10^{6}m^3 -ii) SCS Model = 33.972 * 10^6 m^3
❖ 90% Probable Annual Flow	-i)Regional analysis(area ratio)=30.5*10^{6}m^3

-ii) SCS Model = 27 * 10^6 m^3

iii. Reservoir

❖ Active Storage	17 x 10^6 m^3
❖ Dead Storage	2 x 10^6 m^3
❖ Gross Storage	19 x 10^6 m^3
❖ Normal Water Level	2554.5 m.a.s.l
❖ Lowest Inlet Level	2520.0m.a.s.l
❖ Maximum Water Level	2557.0m.a.s.l
❖ Dead Storage Level	2532.0m.a.s.l

iv. Spillway

❖ Design flood	-i)un routed = 570 m^3/sec -ii) routed = 495.6 m^3/sec
❖ Crest Length	60 m
❖ Crest Level	2554.5 m.a.s.l
❖ Maximum Flood Level	2557.0m.a.s.l
❖ Surcharge	2.5 m
❖ Freeboard	1.5 m

v. Bottom Outlet

❖ Inlet Invert Level	2519.1m.a.s.l
❖ Design Discharge capacity	34.86m^3/sec

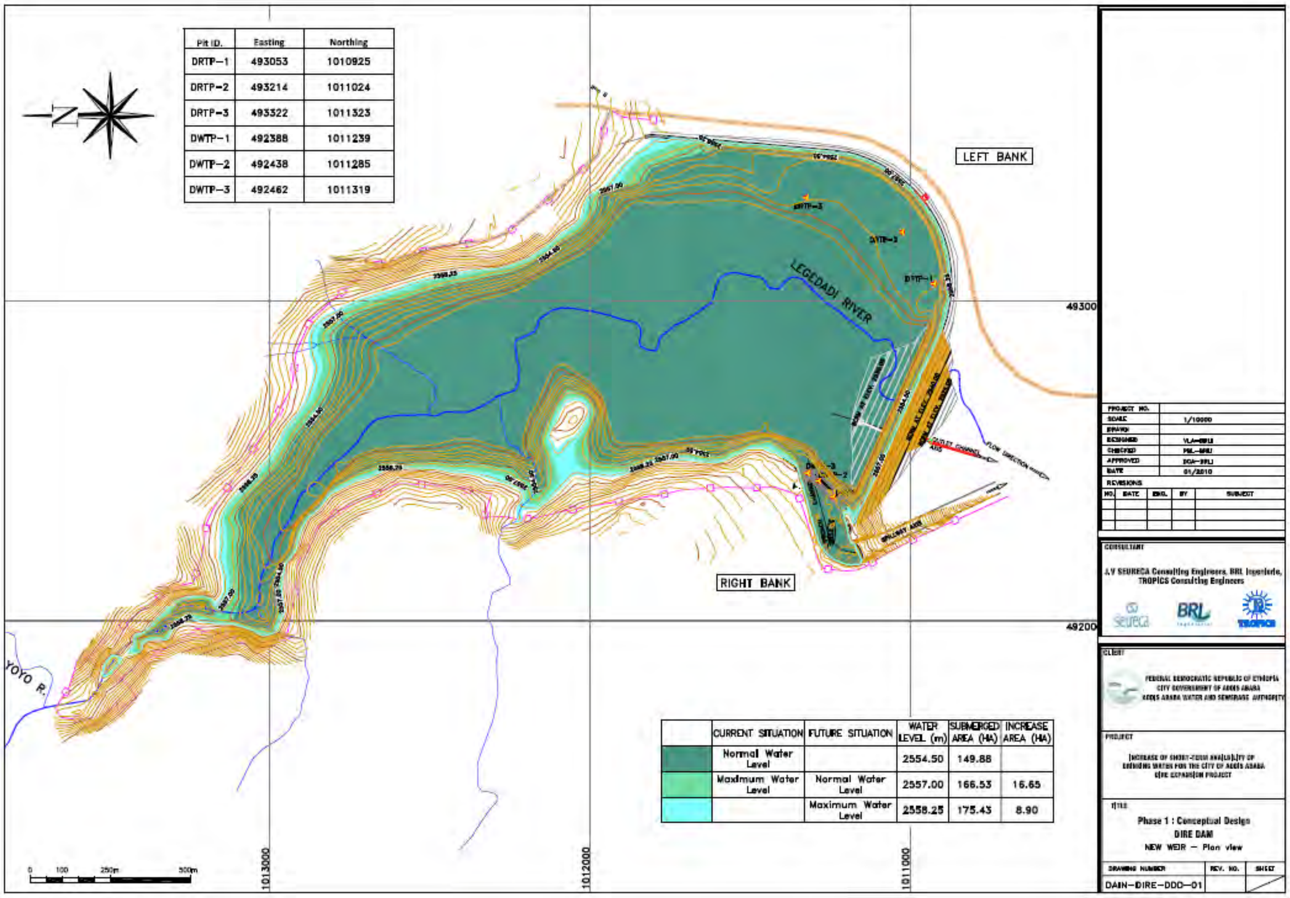
vi. Dam

❖ Embankment Length	-i)Dyke = 1318m -ii) Main dam body = 665m
❖ Upstream Slope	1:4.0
❖ Downstream Slope	1:2.5
❖ Top Width	7m
❖ Volume of Fill	2.1 x 10^6 m^3
❖ Crest Level	2558.5 m
❖ Max. Height	46 m

vii. Water Supply Requirement

❖ Design Period	25 years

- Average Daily Water Demand 6.3 x 10^4 m^3
- Annual Water Demand 1.7 x 10^7 m^3
- Release for downstream users 45 l/s (0.045 m^3/s)



Pit ID.	Easting	Northing
DRTP–1	493053	1010925
DRTP–2	493214	1011024
DRTP–3	493322	1011323
DWTP–1	492388	1011239
DWTP–2	492438	1011285
DWTP–3	492462	1011319

	CURRENT SITUATION	FUTURE SITUATION	WATER LEVEL (m)	SUBMERGED AREA (HA)	INCREASE AREA (HA)
🟩	Normal Water Level		2554.50	149.88	
🟩	Maximum Water Level	Normal Water Level	2557.00	166.53	16.65
🟦		Maximum Water Level	2558.25	175.43	8.90

PROJECT NO.	
SCALE	1/10000
DRAWN	
DESIGNED	VLA–BRLI
CHECKED	PML–BRLI
APPROVED	DGA–BRLI
DATE	01/2010

REVISIONS

NO.	DATE	ENG.	BY	SUBJECT

CONSULTANT

J.V SEURECA Consulting Engineers, BRL Ingenierie, TROPICS Consulting Engineers

CLIENT

FEDERAL DEMOCRATIC REPUBLIC OF ETHIOPIA
CITY GOVERNMENT OF ADDIS ABABA
ADDIS ABABA WATER AND SEWERAGE AUTHORITY

PROJECT

INCREASE OF SHORT-TERM AVAILABILITY OF DRINKING WATER FOR THE CITY OF ADDIS ABABA
DIRE EXPANSION PROJECT

TITLE

Phase 1 : Conceptual Design
DIRE DAM
NEW WEIR – Plan view

DRAWING NUMBER	REV. NO.	SHEET
DAIN–DIRE–DDD–01		

Figure 3-1: Contour map of Dire water supply reservoir

3.1.2 Climate of the Study Area

High annual rainfalls in the region of Addis Ababa occur where moist winds are forced to rise in order to pass over mountains. Such conditions prevail especially along the mountain ranges that extend nearly at right angles to the prevailing storm movements. The rainfall patterns in the region of the project areas have a bimodal profile with strong peaks in the summer months and minor rainfalls in the months of March and April. In the summer months, mainly from July to September, a strong air current moves from the southwest towards the northeast. This current brings moisture from the Gulf of Guinea to the Upper Awash and Abay (Blue Nile) watersheds. Thus, there are two seasonal weather patterns in the region of Addis Ababa, and these are clearly observed and reflected by the weather observation records. The weather is relatively cool in the wet season of July to September when the main rains fall, while the more or less rainless season of October to June has warmer temperatures with easterly winds. Rainfall usually occurs in the form of localized thunderstorms due to convective heating of the air masses during the day and rapid cooling at night (TAHEL, 2000).

3.1.3 Dire Catchment and Land Use/Land Cover

Catchment area is the area of land draining into a stream at a given location (Chow, 1990). The catchment area under consideration is the Dire catchment. It is located in the upper northwestern narrow part of the Awash basin. The population of the catchment, by large, ekes out its existence from rain fed crops and livestock, which may be categorized as subsistence agriculture. High population growth and environmental degradation, limited resources, and inadequate land use and water policies have increased raw water degradation in the area (TAHEL, 2000).

The land use and land cover types mapped in the Dire catchment area consist of: moderately cultivated land, intensively cultivated land, eucalyptus woodland (matured and young); grass and other natural vegetation (woody), shrub land, grassland, bare soil and built-up areas (paved roads, dam, concrete buildings, etc.). The Eucalyptus woodland, bare soil and intensively cultivated areas were mapped with very good accuracy (>95%). Land cover classes, such as moderately cultivated land, wet and dry grassland, shrub land and wooded shrub land and farms with small size villages, were mapped with only moderate accuracy (~80%).The major physiographic units on which the various land cover types are found are: the mountains of Bereh, Bura and Tenkole, foothills, the foot and side slopes of the mountains and hills, steep stream embankments, and narrow undulating valley bottoms and sides. Tributaries of the Doyo and Yeso rivers on which the Dire dam is constructed have deeply dissected mountains from the north-west direction to the north-east. Thus, the tributaries of the river form deeply incise gorges in the mountains and undulating and relatively wide valley bottoms at the foot slopes in the northern and southern parts of the catchment area. The altitude in the catchment area ranges from 2,460 to 3,300 m.a.s.l. The 660 m elevation difference demonstrates the steepness of the catchment area (TAHEL, 2000).

3.2 Materials Used

This study was conducted using the following materials and tools:

- Detail design documents, data obtained from field investigations, contour map of the reservoir area and criteria for demand and supply analysis, related literatures and books

- GIS software Arc map version 9.3 to obtain hydrological and physical parameters and related information
- Statistical downscaling Model
- DEM Data
- Hydrological Data
- Meteorological Data
- HBV Latest Hydrological Model(Version 6.3)

3.3 Data Availability

The data was collected from different sources of which some was browsed and collected from the internet. Moreover, topographic map, GPS and Digital camera were also used for the study.

Table 3-1: Available hydro-meteorological data

Station	Coverage period	Available data	Remark
Dire Dam	Jan 2002-Feb 2009	Daily water level	Observed at 6 o‟clock every day
Beke hydrometric station	1986 - 2006	Daily flow	Catchment: 50 km²
Mutincha hydrometric station	1990 - 2014	Daily flow	Catchment: 172.4 km²
Addis Ababa Bole rainfall station	1983 - 2014	Daily rainfall	Monthly data 1983-2014
Sendafa rainfall station	2008 - 2014	Daily rainfall	Monthly data 2008-2014
Intoto rainfall station	1988-2014	Daily rainfall	Monthly data 1988-2014

3.3.1 Design Documents

Engineering documents like hydrology, dam and dam appurtenance structures, topographic maps, working drawings, environmental and socio-economic reports were collected from Addis Ababa Water and Sewerage Authority.

3.3.2 Meteorological Data

For HBV simulation and SDSM long years‟ climatic data was required. They are daily mean-values of temperature and precipitation. Daily Precipitation and Temperature data was collected from the National Meteorological Service Agency for relevant station, possibly from first class meteorological station of Addis Ababa Bole Airport (1983-2013) and Intoto Meteorological station.

Three rainfall stations of having various classes were selected for analysis. The basic hydro-meteorological data collected are listed in the Table 3-2.

Table 3-2: List of rainfall stations selected (Daily Data)

Name of Station	Easting	Northing	Length of Record	Period	Percent of Data Missing
Addis Ababa Bole	476590	993272	32	1983 - 2014	1.1
Sendafa	502651	1011388	7	2008 - 2014	
Intoto	473907	1004831	27	1988-2014	4.1

3.3.3 Hydrological Data

The river was not gauged before the implementation of Dire Dam. However, staff-gauging station was established near Dire Village and measurements were being taken for two years beginning from August 1993. Flow data, Kessem at Beke and Mutincha stations, at daily bases were collected from Ministry of Water, Irrigation and Energy.

Table 3-3: List of river gauging stations selected (Daily Data)

Name of Station	Easting	Northing	Length of Record	Period	Percent of Data Missing
Beke	543686	1005413	21	1986 - 2006	2.9
Mutincha	450604	1027704	25	1990 - 2014	1.2

3.3.4 Land Use/Land Cover Data

Land use/land cover data was required to get understanding the current land cover/land use condition of the catchment required for the model. The land cover/land use data was taken from the previous design reports.

Intoto mountain chains with steep slopes partly forested bound the watersheds of the Dam area in the North. This may contribute towards reducing the erosion that could result from relatively high intensity of rainfall, which is inherent to the area. Some portions of the catchment areas are cultivated and have little vegetation cover.

3.3.5 Catchment Delineation

DEM of the catchment required to delineate the catchment and sub catchments and generate topographic maps and stream networks. Topographic map of the study area was required to determine the specific location of the catchment, gauging station and dam sites. The topographic map of the study area prepared during the previous detail design was used. The catchment area was also delineated using the digital elevation model to identify the stream networks and sub catchments of the study area.

3.4 Methodology

For any research works, identifying clear and efficient methodology is crucial for the effectiveness of the study not only from time budget point of view, but also from the quality of the research result.

Conceptual Frame Works for the Study

The overall procedure adopted for the study can be described by the following flow charts.

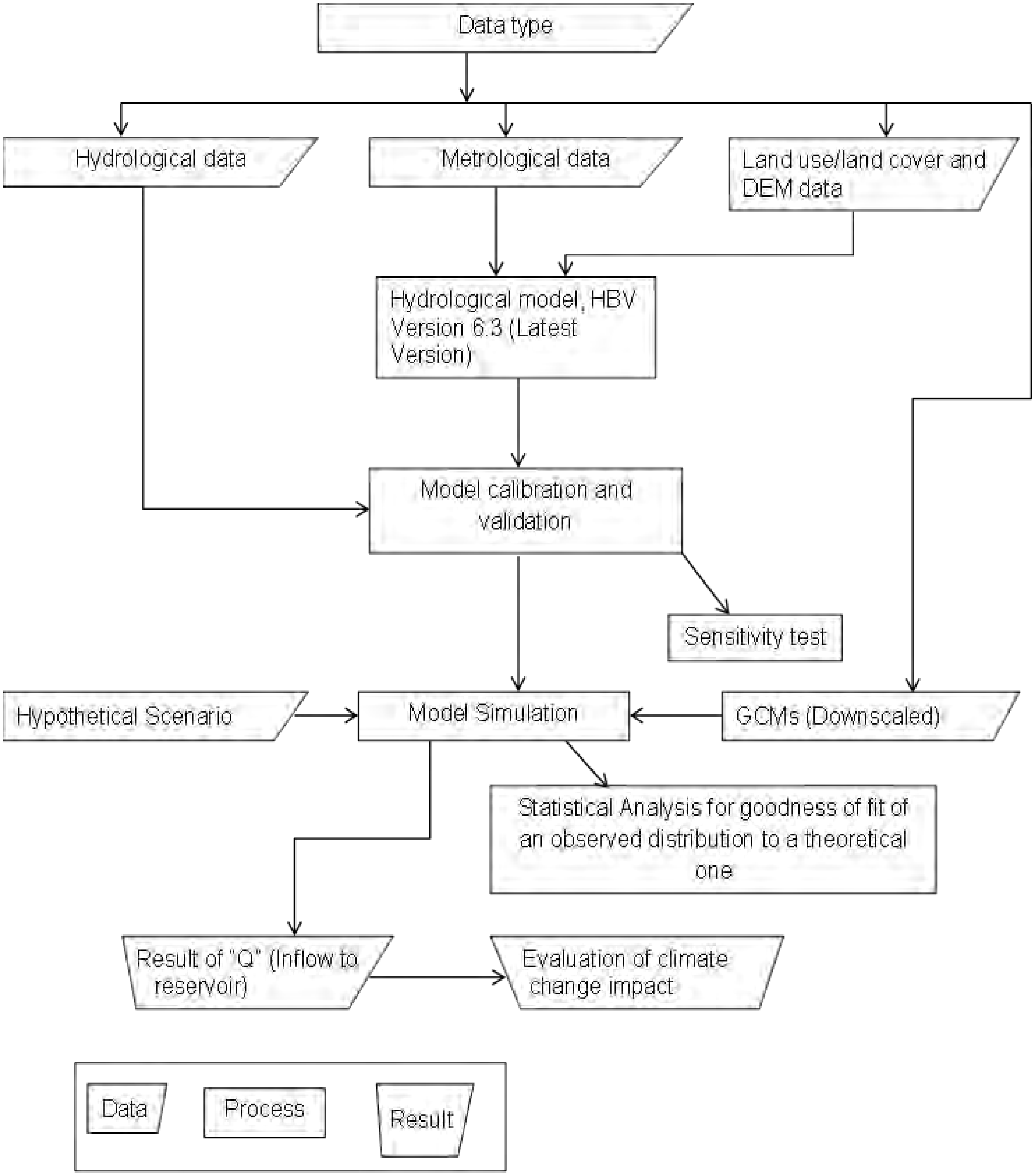


Figure 3-2: ***Conceptual framework for climate change study***

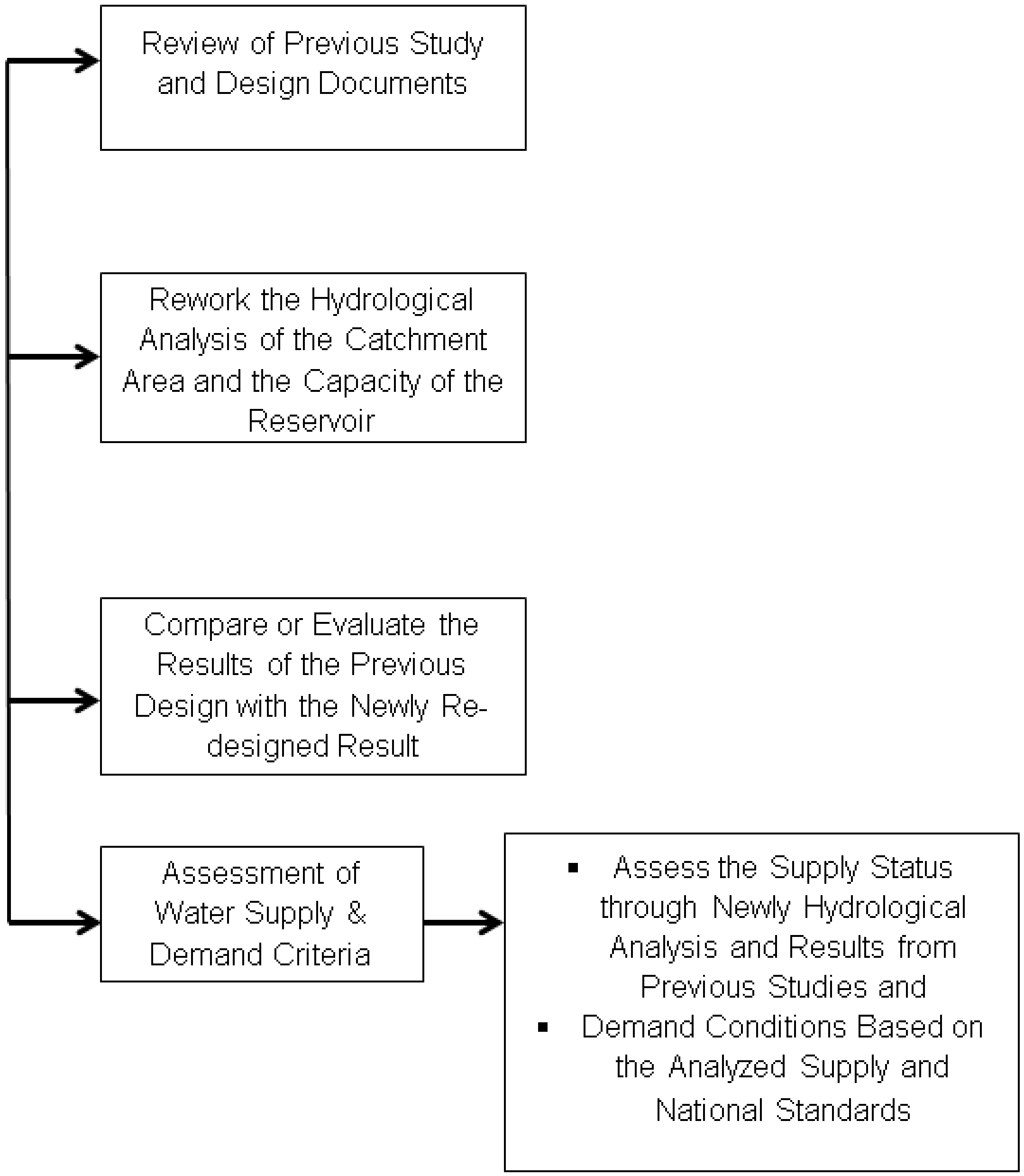


Figure 3-3: Conceptual framework for the assessment of reservoir capacity and supply and demand criteria

In general, the research methods for this study followed the following steps, which have reviewed as earlier:

- The development and use of general circulation models (GCMs) to provide future global climate scenarios under the effect of increasing green-house gases,

- The development and use of downscaling techniques (both nested regional climate models, RCMs, and statistical methods) for "downscaling" the GCM output to the scales compatible with hydrological models,
- The development and use of hydrological models (HBV model) to simulate the effects of climate change on hydrological regimes at various scales, and
- Hydrological data analysis for the evaluation of the reservoir capacity and evaluation of demand and supply criteria.

3.4.1 Hydrological Data Analysis

The goal of the hydrological data analysis is for the estimation of water availability and its reliability.

The water resources estimation by hydrological analogy at Dire Dam has been applied for this study. Accordingly, a good correlation was found between the Beke hydro-meteorological station, which intercepts a catchment area of 50 km², and the discharge at Dire Dam site.

The flow data at Dire Dam used for the correlation analysis are of two kinds:

- Gauged data at the dam site before the dam construction in 1993-1994,
- Inflow discharges estimated by water balance analysis for the periods in which there is no spill water and the quantity corresponding to abstractions for water supply is well known.

The data was checked for internal and external consistency using double mass curve techniques. Detection and correction of systematic errors was done through residual analysis techniques, homogeneity tests depending on the error. Infilling of missing data was also done using Time Series Reconstruction techniques that are based on the number of data gaps in the record.

3.4.1.1 Filling of Missing Hydrological Data

During periods of recession when the flow is dependent on surface and sub-surface storage rather than rainfall, the flow exhibits a pattern of exponential decay giving a curved trace on a simple plot of Discharge versus Time, but a straight line on a logarithmic plot. During long recession periods, interpolation between the logarithmically transformed points before and after the gap will result in a more realistic recession than simple linear interpolation. It is possible to make this interpolation as stage rather than as discharge but, as the principle is based on depletion of a storage volume, it is conceptually simpler to apply the interpolation to discharge rather than to stage. Based on SWDP (http://www.cwc.gov.in) explanation, the following equations were used to fill the missed hydrological data.

The slope of the logarithmically transformed flow recession α (also called a reaction factor), from the last value before the gap Q_{t0} at time t_0 to the first value after the gap Q_{t1} at time t_1 as is:

$$\alpha = \frac{lnQt_o - lnQt_1}{t_1 - t_0} - - - - - - - - - - - - 3.1$$

and $k = \frac{1}{a}$, where k is a reservoir coefficient

Hence at time t within the gap, Q_t is:

$$Q_t = Q_{t_o}\, exp\left(-\frac{t - t_o}{k}\right) - - - - - - - - - - - 3.2$$

3.4.2 Climatological Data Analysis

Climatic data for the study area such as temperature, relative humidity, sunshine hours, wind speed and rainfall data were collected and reviewed. Consistency tests, data rectification and other adjustment works were performed as necessary. A reference base period for the meteorological parameters was also considered and data gaps have been filled using interpolation and correlation methods as appropriate.

In order to check the homogeneity of the selected gauging station in the Legedadi watershed and the nearby stations, monthly rainfall records were non–dimensionalized and plotted to compare the stations with each other.

The non-dimensionalizing of the monthly values was carried out as R.K Linsley, L.H, (1983):

$$P_i = \frac{\overline{P_\imath}}{\overline{P}} * 100\% - - - - - - - - - - - - 3.3$$

Where P_i= non-dimensional value of precipitation for the month i

$\overline{pi}$ =Over years averaged monthly precipitation for the station i

$\overline{p}$ =The over years averaged yearly precipitation of the station

In addition to this, checking for consistency of rainfall records for the selected watershed was done by the method of double mass curve analysis.

3.4.2.1 Filling of Missing Meteorological Data

Sometimes, the rainfall amount at a certain rain gauge station for a certain day(s) may be missing due to the absence of some observer or instrumental failure. In such cases, it might be needed to estimate the missing rainfall amount by approximating the value from the data of the nearby rain gauge stations. The following methods were generally adopted for computing the missing rainfall data.

Three rain gauge stations as close to and as evenly spaced around the station with the missing record (i.e. station X) as possible, are, first, chosen. The rainfall data for these three stations (i.e. 1, 2, and 3) on the day for which the data at the station X is missing are now collected. The average annual rainfall values at all the four stations should also be known. Now, if the average annual rainfall at each of these three index stations differs within 10% of the average annual rainfall of the station X (i.e. the station with missing data), then a simple arithmetic average of the precipitations (corresponding to the missing precipitation) at the three index stations will give us the estimated quantity. Thus, if N_1, N_2, N_3 and N_x represent the average annual rainfalls at stations 1, 2, 3 and X respectively; and P_1, P_2, P_3 and P_x represent their respective precipitation data of the day for which the data is missing at station X; then we have

$Px = \frac{\mathrm{P1+P2+P3}}{3} ------3.4$ [Provided N_1, N_2 and N_3 differ within 10% of N_x]

However, when the average annual precipitation at any of the three stations differs from that at the station in question by more than 10%, the normal ratio method is used. In this method, the amounts at the three index stations are weighted by the ratios of their average annual precipitation values. Hence, the missing precipitation data P_x , in such a case, will be given by

$Px = \frac{1}{3}\left[P1\frac{Nx}{N1} + P2\frac{Nx}{N2} + P3\frac{Nx}{N3}\right] - - - - - - - - 3.5$ [Provided any of N_1, N_2 andN_3 differs from N_x by more than 10%](Santosh Kumar Garg, 2005).

Based on mentioned above, the normal ratio method, it was conducted to fill missing climatic variables of the study area.

3.4.3 General Circulation Models (GCMs)

The development and use of general circulation models (GCMs) to provide future global climate scenarios under the effect of increasing greenhouse gases was carried out using different climate scenarios. As the evaluation of climate change impacts on hydrology required the climate information at finer scale, the GCMs data was downscaled at station level climatic variables with the help of Statistical Downscaling Model (SDSM).The reason why the Statistical Downscaling Model is selected for this study is because the model is used for local-scale applications.

3.4.3.1 Statistical Down Scaling Methods (SDSM)

SDSM, which is designed to downscale climate information from coarse-resolution of GCMs to local or site level, is applied here to downscale the precipitation, maximum and minimum temperatures for the study area. SDSM uses linear regression techniques between predictor and pridictand to produce multiple realizations (ensembles) of synthetic daily weather sequences. The predictor variables provide daily information about large-scale atmosphere condition, while the pridictand described the condition at the site level.

It is appropriate to use this software when the impact assessments is require at small-scale or regional level, provided that quality observational data and large scale daily GCMs climate variables are available. Additionally, the model can also produces a range of statistical parameters such as variances, frequencies of extremes and spell lengths for the downscaled climatic parameters (R.L. Wilby and C.W.Dawson, 2007).

The main reasons to apply the SDSM model for the study are:

- It is widely applied in many regions of the world over a range of different climatic condition.
- It can be run on PC-based systems and has been tested on Windows98/NT/2000/XP.
- The availability of the software (i.e. new users can register and download freely the software package at (https://co-public.lboor.ac.uk/cocwd/SDSM/)
- Compared to other downscaling methods, the knowledge of atmospheric chemistry required by the SDSM is less.
- The required time for simulating the surface weather parameter is low.
- The ability of the model to permit risk/uncertainty analyses by using the generated ensembles.

Limitations related SDSM

The limitation related to SDSM model can be summarized as follows:

- The relationship between the predictor and predictand is achieved by only considering the data statistical condition, i.e. the model does not take in to consideration the physical nature of the catchments (such as land use/land cover data) (major drawback).
- It requires high quality data for model calibration.
- The model is highly sensitive to the choice of predictor variables and empirical transfer scheme.

For the SDSM 30 years, historic data of maximum and minimum daily temperature and rainfall of the two stations (Addis Ababa Bole Airport and Intoto) were used.

3.4.3.2 Station Selection for Statistical Down Scaling Method

Since, SDSM is Windows-based decision support tools that used for the rapid development of single-site ensemble and scenarios generation under different regional climate forcing, the correlation coefficient between the selected stations is carried out in order to find a single station for downscaling purpose which has high correlation with most of the other neighboring stations. In additional to the correlation coefficient the quality and the available length of period of record also take into consideration during selection of stations for downscaling.

Table 3-4: Precipitation correlation coefficient of the two metrological stations (1988-2013) based on daily data

	Addis Ababa	Intoto
Addis Ababa	1	0.53
Intoto	0.44	1

As per the above-mentioned criteria the two stations were not correlated hence, average of the two stations was chosen for downscaling the climate parameters for Dire catchment. For this study because of the limited time available and difficulties related to downscaling of all climate parameters, only the daily precipitation and daily maximum and minimum temperature were downscaled for the study area.

3.4.3.3 Statistical Downscaling Model (SDSM) Set Up

I. Predictor Files

The large scale predictors which are used for SDSM model input was downloaded from the website of Canadian Institute for Climate Studies for model output of HadCM3 (http://www.cics.uvic.ca/scenarios/sdsm/select.cgi)or(http://www.cccsn.ec.gc.ca/?page=scen-viz). The predictors are found in grid basis for different regions in the world, so after selecting the African window the predictors that include the Dire catchment was downloaded. This predictor was found in zip file format. When the zip file was opened, the following climatic parameters were found:

NCEP_1961-2001: this directory contains 41 years of daily-observed predictors‟ data, derived from the NCEP (National Center for Environmental Prediction) reanalysis, and normalized (with respect to the mean and standard deviation) over the complete 1961-1990 period. These data were interpolated to the same grid as HadCM3 (2.5^o latitude x 3.75^o longitude) before the normalization was implemented.

H3A2a_1961-2099: this directory contains 139 years of daily GCM predictors data, derived from the HadCM3 A2(a) experiment, and normalized over the 1961-1990 period.

H3B2a_1961-2099: this directory contains 139 year of daily GCM predictor data, derived from the HadCM3 B2(a) experiment, and normalized over the 1961-1990 period.

NCEP data, which were re-analysis, sets from the National Center for Environmental Prediction was, re-girded to match with the grid system of HadCM3. These data were used for model calibration. Both NCEP and HadCM3 data have daily predictors. There exist 26 predictors variables in both NCEP and HadCM3 which used for analysis (as shown in Table 3-5).

The GCM data were collected from the IPCC Data Distribution Center (DDC) which however, because the daily fields are only available directly from the respective modeling centers, the climatic data used for SDSM were collected from the Canadian Institute for climate studies website for model output of HadCM3. The predictor variables were supplied on a grid basis of size 2.5° latitude by 3.75° longitude so that the data were downloaded from the nearest grid box to the study area. The nearest grid box for the HadCM3 used for the study area is 9.13N 38.91E to 9.17N 38.95E.

Table 3-5: The predictor variables, which are available for both NCEP and HadCM3

S/N	Type of predictor variable	Symbol/Code
1	mean sea level pressure	mslpaf
2	surface air flow strength	p-faf
3	surface zonal velocity	p-uaf
4	surface meridional velocity	p-vaf
5	surface vorticity	p-zaf
6	surface wind direction	p-thaf
7	surface divergence	p-zhaf
8	500hpa air flow strength	p5-faf
9	500hpa zonal velocity	p5-uaf
10	500hpa meridional velocity	p5-vaf
11	500hpa vorticity	p5-zaf
12	500hpa geopotential height	p500af
13	500hpa wind direction	p5thaf
14	500hpa divergence	p5zhaf
15	850hpa air flow strength	p8-faf
16	850hpa zonal velocity	p8-uaf
17	850hpa meridional velocity	p8-vaf
18	850hpa vorticity	p8-zaf
19	850hpa geopotential height	p850af
20	850hpa wind direction	p8thaf
21	850hpa divergence	p8zhaf

22	relative humidity at 500hpa	pr500af
23	relative humidity at 850hpa	pr850af
24	near surface relative humidity	rhumaf
25	surface specific humidity	shumaf
26	mean temperature at 2m	tempaf

II. Setting of Model Parameter File

Year Length: The default "Calendar (366)" allows 29 days in February every fourth year (i.e., leap years) and should be used with observed data whereas the alternative model years consisting of 360 days used for HadCM3.

Event Threshold: For some variables it is necessary to specify an event threshold. As a Dawson and Wilby (2007) explanation for instance, when calibrating daily precipitation models, the parameter might be set to 0.3 mm/day to treat trace rain days as dry days. Similarly, the threshold for sunny versus cloudy days, might be set at 1.0 hours/day to discriminate between overcast and sunny conditions. Therefore, 1.0 was set for temperature and 0.095 mm/day for precipitation to get an optimum predictive power of the model for the corresponding study area.

Model Transformation: Specifies the transformation applied to the predictand in conditional models. The default (None) is used whenever the predictand is normally distributed (as is often the case for daily temperature) whereas Fourth root transformation was used whenever data are skewed (as in the case of daily precipitation).

Variance Inflation: Controls the magnitude of variance inflation in downscaled daily weather variables. This parameter changes the variance by adding/reducing the amount of "white noise" applied to model estimates of the local process. The default value (i.e. 12) produces approximately normal variance inflation in the case of unconditional processes for maximum & minimum temperature while the value was adjusted to 18 for conditional processes (i.e. Precipitation).

Bias Correction: Compensates for any tendency to over–or under–estimate the mean of conditional processes by the downscaling model (e.g., mean daily rainfall totals). The default value 1.0, indicating no bias correction (Dawson and Wilby, 2007). Therefore, the default value 1.0 was taken for temperature variables whereas for that of precipitation the value was adjusted to 0.90.

III. Screening of Potential Downscaling Variables

Screening of the potential predictors for the selected pridctand (i.e. observed precipitation, minimum and maximum temperature) is the most crucial and decisive part in statistical downscaling model. Identifying an appropriate large scale girded predictor result in good correlation between observed and downscaled climate variables during model calibration and scenario generation. The recommended methods for screening the potential predictors is starting the processes by selecting seven or eight predictor at a time and analyze their explained variance, then select those predictor which has higher explained variance and drop the rest. For the selected predictor analysis or calculation of their correlation matrix with the observed predictand is made. This statistics identify the amount of explanatory power of the predictor to explain the pedictand and finally the scatter plot is carried out in order identify the nature of the association (linear, non–linear, etc.), whether or not data transformation(s) may be needed, and the importance of outliers. This procedure is repeated by holding those predictors which passé the above criteria and add new predictors from the reset of available predictors.

Because precipitation is conditional process i.e. there is an intermediate processes between regional forcing and local weather, downscaling of precipitation at site level is more challenging than downscaling of maximum and minimum temperature.

The screened potential predictors for Dire catchment are shown in the following Table 3-6.

Table 3-6: Large-scale predictor variables selected for analysis

Predictand	Predictor	Symbol
Minimum Temperature	Mean temperature at 2m nceptemp	nceptemp
	Surface specific humidity ncepshum	ncepshum
	Surface meridional velocity ncepp_v	ncepp_v
	500 hpa geopotential height	ncepp500
Maximum Temperature	Surface Zonal Velocity ncepp_u	ncepp_u
	Surface divergences ncepp_zh	ncepp_zh
	Mean Temperature at 2m nceptemp	nceptemp
Precipitation	Surface meridional velocity	ncepp_v
	Surface divergence ncepp_zh	ncepp_zh
	Relative humidity at 500 hpa	ncepr500

IV. SDSM Model Calibration, Validation and Scenario Generation

The model calibration operation takes a selected predictand along with a set of predictor variables, and computes the parameters of multiple regression equations via an optimization algorithm (either dual simplex of ordinary least squares). There are options in either SDSM model structure to perform calibration process monthly, seasonally or annual time scale. Selecting one of these model type decide how the regression parameters are developed (for example if a monthly model type is selected, then the model develops one regression equation for the whole months and if annul model type is selected again one regression equation is developed for the whole one year and so on). For this particular study among the total period length of 1983-2002, 20 years of daily data was used for model calibration and the rest 11 years (from the year 2003-2013) daily data for model validation using a monthly model type.

The Weather Generator operation generates ensembles (up to a maximum of 100) of synthetic daily weather series given observed (or NCEP re–analysis) atmospheric predictor variables. The procedure enables the verification of calibrated models (using independent data) and the synthesis of artificial time series for present climate conditions.

The Scenario Generator operation produces ensembles of synthetic daily weather series from the starting of the baseline period to the end of the next century (1961-2100) for a given daily atmospheric predictor variables supplied by a GCM (either under present or future greenhouse gas forcing). This function is identical to that of the Weather Generator operation in all respects except that it may be necessary to specify a different convention for model dates and source directory for predictor variables.

3.4.4 HBV Hydrological Models

For this study, the development and use of HBV hydrological models to simulate the effects of climate change on hydrological regimes at various scales was carried out. A hydrological model, HBV (the latest version 6.3) was utilized for runoff simulation and hydrological forecasting. The model requires minimal input of meteorological data (temperature and precipitation) to generate hydrographs.

The main reasons to apply the HBV model for this study were depicted as follows:

- it is a conceptual model for runoff simulation,
- it has a simple structure,
- it is semi-distributed, i.e., allows to divide the catchment into subbasins, elevation and vegetation zones,

- it is easy to understand, learn and apply,
- it provided good results in most applications,
- it needs a moderate amount of input data,
- it can be run on a PC (286 or better),
- it is (partly) used in other models.

The main drawback related to HBV model is that, the model is usually calibrated (optimized) manually by trial and error (Bergstrom, 1992). Therefore, the problem of subjectivity has to be considered when judging calibration results. Usually a user will start from parameter values that gave good results in a similar catchment and try to keep them within certain ranges during calibration.

3.4.4.1 Model Setup

As it is indicated in Figure 3-4, the model involves four routine called Snow, Soil moisture, Response function and Routing routines. Except snow routine, which was skipped due to the absence of snow in the study area, the remained three routines were applied to simulate the runoff.

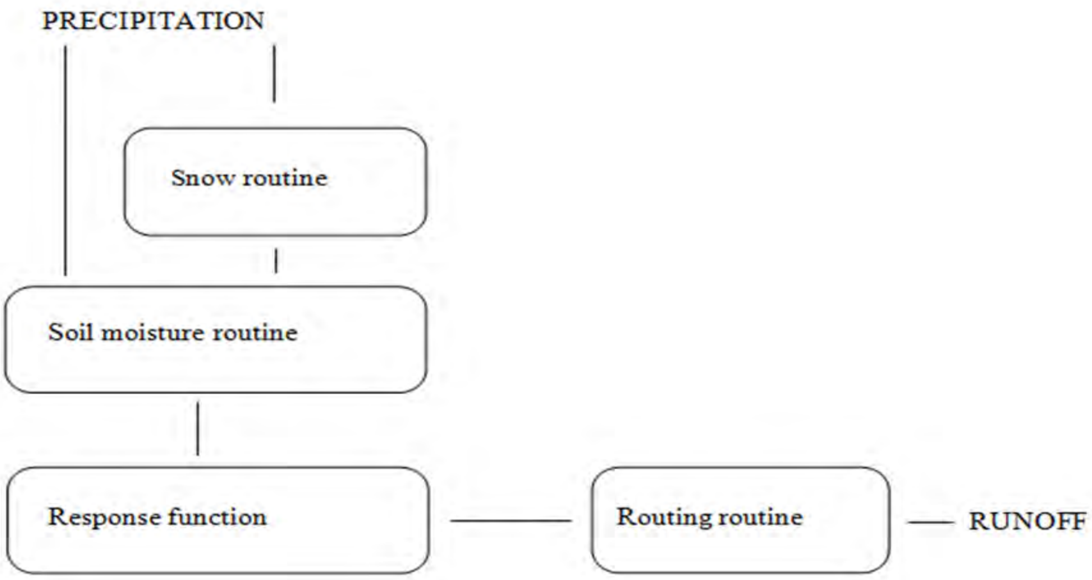
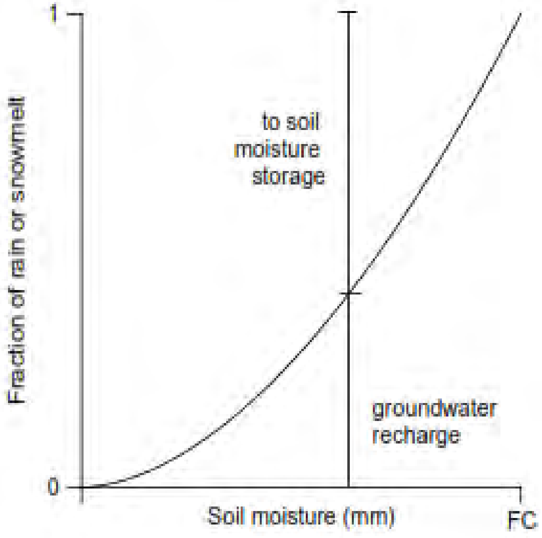


Figure 3-4: Schematic structure of the HBV model setup routine (Seibert, 2005)

I. Soil moisture routine

FC = maximum soil moisture storage (mm)

LP = soil moisture value above which ETact reaches ETpot (mm)



$$\frac{\text{recharge}}{\text{P}} = \left(\frac{S_{sm}}{FC}\right)^{BETA}$$

Figure 3-5: Contributions from rainfall or snowmelt to the soil moisture storage and to the upper groundwater zone (Seibert, 2005)

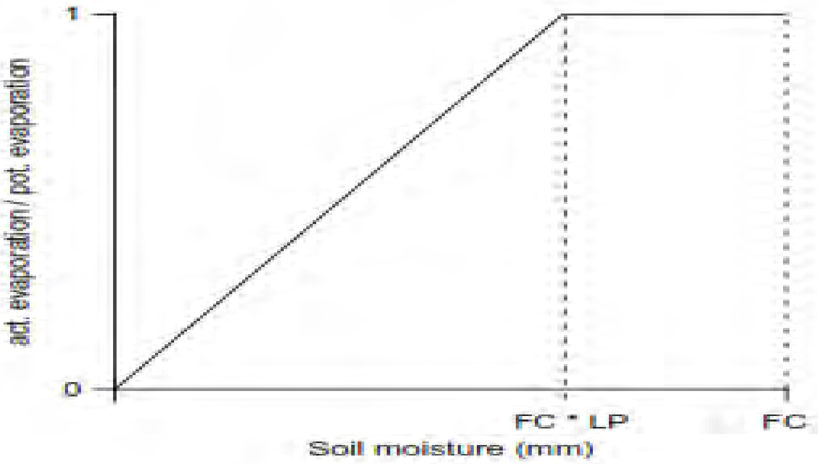


Figure 3-6: Reduction of potential evaporation depending on soil moisture storage (Seibert, 2005)

Here FC is a model parameter and not necessarily equal to measured values of „field capacity"

II. Response Function

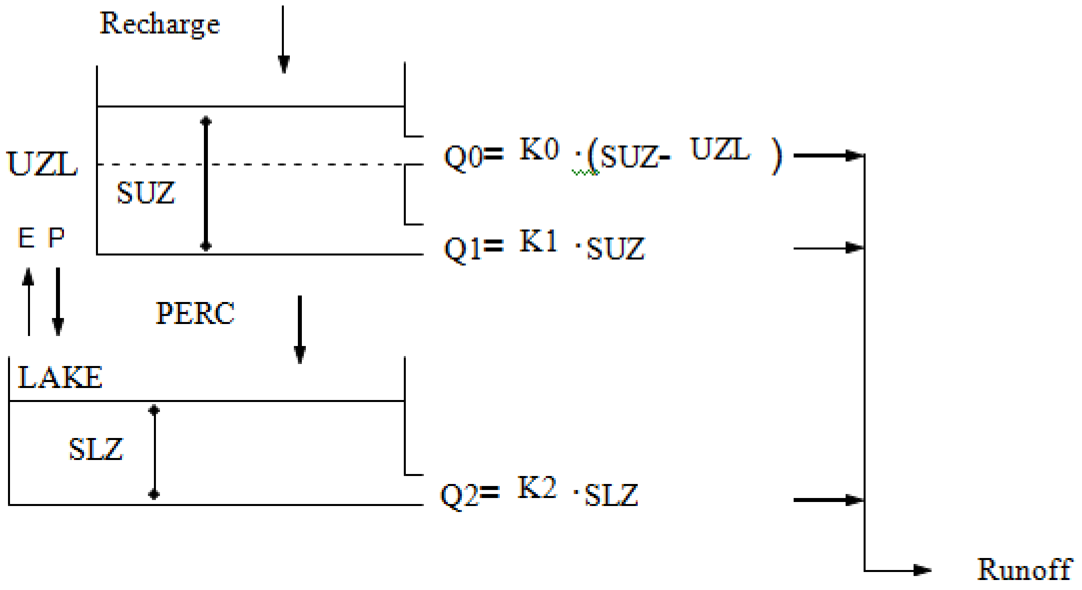


Figure 3-7: Response function (Seibert, 2005)

Recharge = input from soil routine (mm day^{-1})

SUZ = storage in upper zone (mm)

SLZ = storage in lower zone (mm)

UZL = threshold parameter (mm)

PERC = maximum percolation to lower zone (mm day^{-1})

Ki = recession coefficient (day^{-1})

Qi = runoff component (mm day^{-1})

❖ Recession Analysis

If lnQ is plotted against time during a dry period, the slopes of the hydrograph at different runoff values provide good first estimates of the response-function parameter.

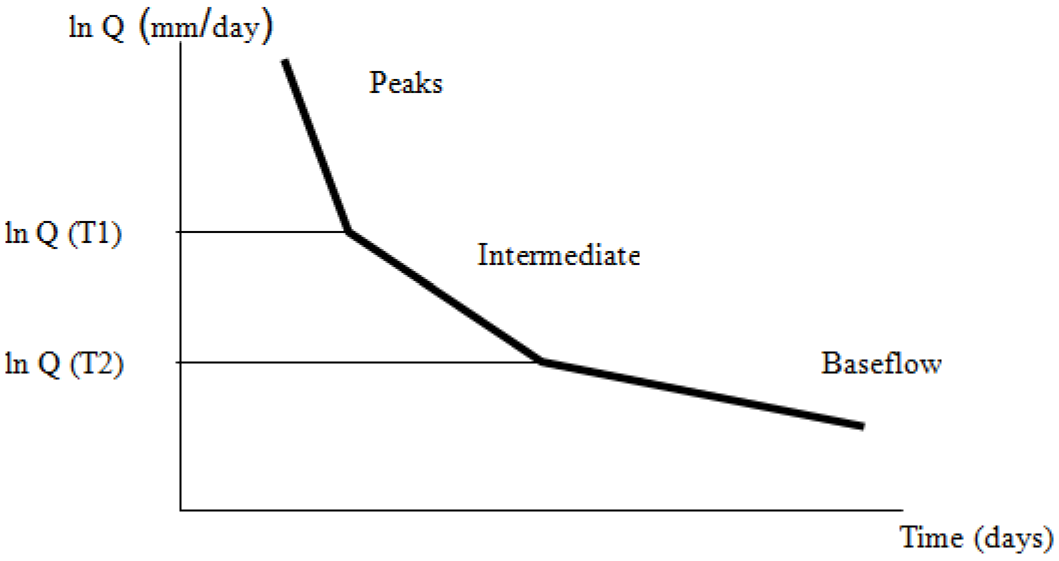


Figure 3-8: Schematic shape of recession in relation to the different parameter (Seibert, 2005)

Slope of the recession:

- Peaks = $K_0+K_1+K_2$
- Intermediate = K_1+K_2
- Base flow = K_2

Thresholds:

- Q (T1) = PERC+K_1UZL
- Q (T2) = PERC

III. Routing Routine

The generated runoff of one time step is distributed on the following days using one free parameter, MAXBAS, which determines the base in an equilateral triangular weighting function.

3.4.4.2 HBV-Model Input Data

The conceptual semi-distributed HBV model computes, runoff from observed daily rainfall, daily temperature, long-term monthly potential evapo-transpiration, catchment characteristics and runoff data for calibration.

I. Precipitation

The Thiessen polygon method, which is one way of calculating areal precipitation, was used for this study. This method gives weight to station data in proportion to the space between the stations (IHMS, 2012). The daily areal rainfall was calculated from the daily point measurement of rainfall in and around the catchments by Thiessen polygon method. Accordingly, two meteorological stations data from Addis Ababa and Intoto have been taken to conduct this study.

$$\bar{P} = \frac{1}{A}\sum_{s}^{s=n}(A_s * P_s) -----------------3.6$$

Where, $\bar{P}$: Areal average rainfall, P_s : Rainfall measured at sub-region, A_s : Area of sub-region and A : total area of sub regions.

II. Temperature

Weighted mean of stations temperature in and around the catchment was used for the study. When different elevation zones were used temperature was corrected for elevation above sea level with usually -0.6ºC per 100 m (parameter TCALT).

III. Flow Data

HBV hydrologic model needs daily flow data to simulate hydrology of the river catchment. Therefore, the data of Legedadi River for the period 1986-2013 had taken for simulation.

IV. Catchment Data

Due to its semi-distributed nature, HBV model needs sub-division of the basin in to different elevation. Each elevation zone is also divided in to different vegetation cover (forested and non-forested areas, IHMS, 2012). The Dire catchment also processed and divided in to different elevations and vegetation zone based on the information gathered from the previous studies for the land use/land cover data of the study area.

Table 3-7: Extent of land use /land cover in the Dire Catchment Area

Type	Area (ha)	% of catchment area	General occurrence in the catchment area
Moderately cultivated	3,143	40.5	All over the catchment area
Intensive cultivated land	274	3.5	South-eastern part of the catchment
Eucalyptus woodland	1,587	20.4	North-east and south-west of the catchment area
Eucalyptus, grass land and natural vegetation	908	11.7	Along the rivers
Shrub land	181	2.3	Generally at high elevations
Grassland	1406	18.1	All over the catchment area
Bare soil	255	3.3	Scattered throughout the catchment area
Built-up area (paved road, dam, concrete buildings)	16	0.2	South of Dire
Total	**7,770**	**100**	

(Source: TAHEL, 2000)

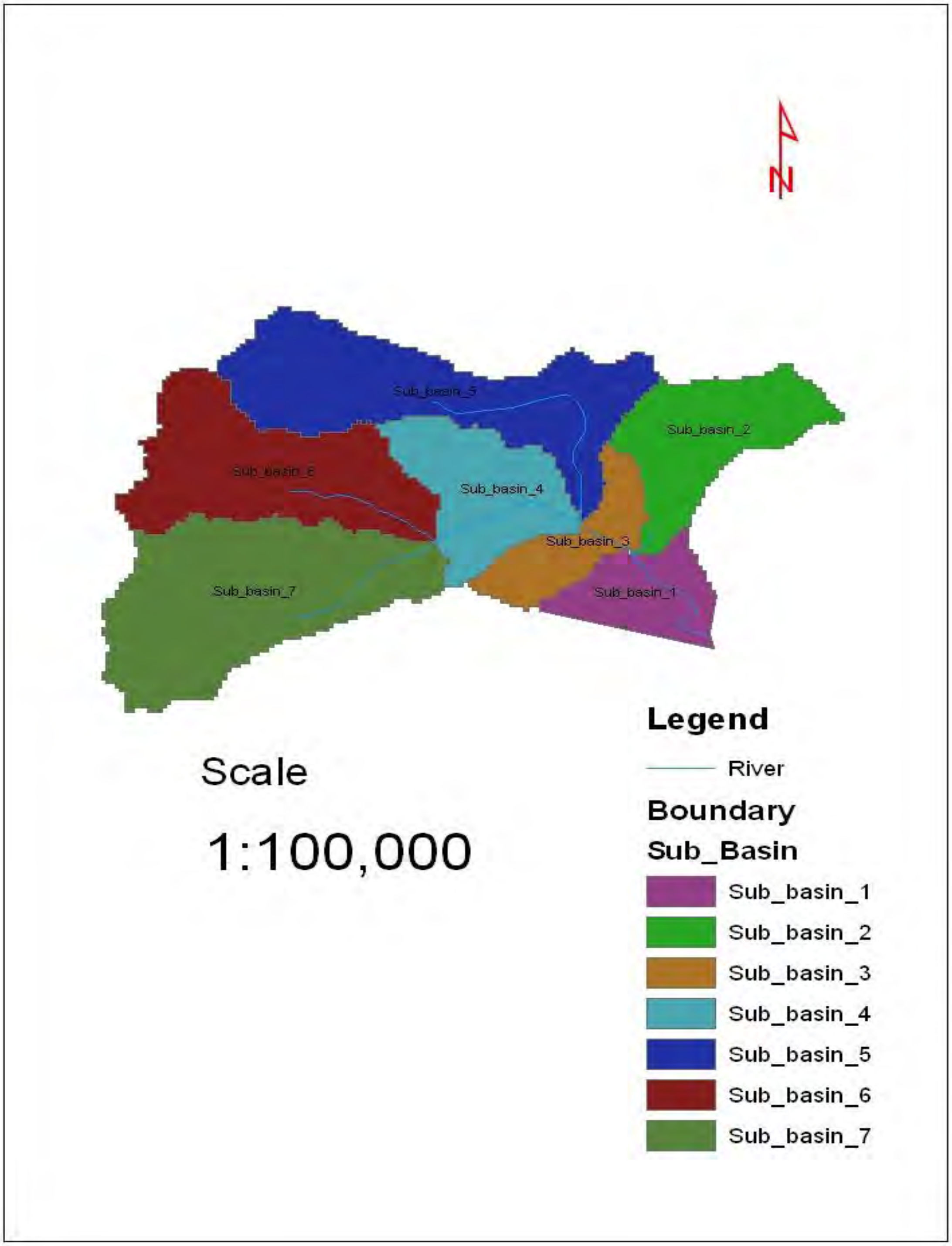


Figure 3-9: Sub-basins of Dire catchment

V. Potential Evapo-Transpiration for Model Calibration and Validation

Long-term mean values were used as estimates of potential of evapo-transpiration at a certain time of the year. It is thus assumed that the inter-annual variation in actual evapo-transpiration is much more dependent on the soil moisture conditions than on the inter-annual variation in potential evaporation. For a smaller region, it is enough with one station to compute the potential evaporation (IHMS, 2012). For this specific study Penman-Monteith (CROPWAT-8.0), method was adopted to calculate the daily potential evaporation during model calibration and validation. The average potential evapo-transpiration from Addis Ababa station was used for model input.

Table 3-8: Long-term average monthly potential evapo-transpiration (mm/month) from Addis Ababa station

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
99.51	105.27	118.42	113.7	118.73	97.8	87.42	86.8	93.9	102.3	96.3	95.17	99.51

VI. Potential Evapo-Transpiration for Future Runoff Generation

The potential evapo -transpiration would have different value for the three time horizons (i.e. 2020s, 2050s and 2080s) compared to the present potential evaporation that was calculated using Penman-Monteith method. Since the existing data were the downscaled precipitation and minimum and maximum temperature, the potential evapo-transpiration for future time horizon was calculated by using Hargreaves method. To be compatible with the method adopted during model calibration and validation, a regression equation was developed to estimate the Penman potential evaporation from Hargreaves potential evapo-transpiration.

According to Allen et al (1998) explanation, when solar radiation data, relative humidity data and or/ wind speed data are missing, ETo can be estimated using the Hargreaves ETo equation where:

$$ET_o = 0.0023\,(T_{mean} + 17.8)(T_{max} - T_{mean})^{0.5} R_a --------- 3.7$$

Where,

ETo is the potential evapotranspiration (mm d^{-1});

T_{max} is maximum air temperature (°C)

T_{min} is minimum air temperature (°C)

T_{mean} is average air temperature (°C)

Ra is the water equivalent of the radiation (MJ m^2 d^{-1})

Due to the models requirement of potential evapotranspiration data, it was derived by using Hargreaves equation for the period 1989-2013(Average of Addis Ababa & Intoto stations) based on the existing climatic variables. Hargreaves equation conducted for this study due to its limited climatic variables requirement for instance, temperature and extraterrestrial radiation (Ra) variables.

3.4.5 HBV-Model Parameters

IHMS HBV model parameters can be grouped into volume controlling (FC, LP and Beta) that influence the total volume and shape controlling parameters (K4, Perc, KHQ, HQ and Alfa) that distribute the calculated discharge in time and inflaming the shape of hydrograph. The parameter maxbas, which control the smoothness of the hydrograph, also calibrated for this study. HQ is the high flow level at which the recession rate KHQ is assumed to hold, normally the parameter HQ is not calibrated, it is calculated from the mean of observed discharge over the whole period and the mean of annual peak flows.

$$HQ = \frac{\sqrt{(MQ * MHQ)}}{A} * 86.4 ---------- 3.8$$

Where: MQ: the mean of observed discharge over the whole period, MHQ: is the mean of annual peak flow and A: area of catchment in Km^2.

For this specific study, HQ was calculated and it was found with a value of 2.5 mm/day. The predominant type of soils for the study area is Vertisols (Hydrology-Detail Design Report, 2009). Based on the identified soil type, the estimated maximum soil storage capacity is in the range of 320 – 400mm/m (FAO-56). For this study, 320mm/m has been adapted.

The quick flow was calibrated by KHQ and Alfa. KHQ results in higher peaks and dynamic response in hydrograph. Alfa was used in order to fit the higher peaks in to the hydrograph, the higher the Alfa the higher the peaks and the quicker the recession (IHMS, 2012). Base flow was adjusted with PERC and K_4. The level of the base flow was adjusted with PERC as a lower value of PERC result in low base flow. K_4 describes the recession of base flow. The following table shows recommended start values and range of parameters used for new basin/ sub-basin to be calibrated.

Table 3-9: Model parameters and their range values (IHMS, 2012)

Parameters	Starting Values	Approximate Interval	Comment
FC	Use a value for the region	100 – 1500	Maximum soil moisture storage [mm]
Lp	1	<=1	Limit for potential evaporation
Beta	1	1 - 4	Exponent in the equation for discharge from the zone of soil water
K_4	0.01	0.001 – 0.1	Recession coefficient for lower response box
PERC	0.5	0.01 - 6	Percolation from upper to the lower response box [mm]
KHQ	0.09	0.005 – 0.2	Recession coefficient for upper response box
Alfa	0.9	0.5 – 1.1	Measure of non-linearity to the response of upper reservoir

The model calibration was done manually by trial and error method. The approach of calibration have two steps, first the model was calibrated by volume controlling parameters FC, LP and Beta, that is followed by calibration of shape governing parameters KHQ and Alfa for the quick flow and K_4 and PERC for the base flow.

3.4.6 HBV-Model Calibration and Validation

The calibration of the model was made by manual try and error technique (Bergström, 2012). Different criteria were used to assess the fit of simulated runoff to observed runoff:

- visual inspection of plots with Q_{Sim} and $Q_{Obs,}$
- accumulated difference and,
- statistical criteria.

The coefficient of efficiency (Reff) is normally used for assessment of simulations by the HBV model.

$$\text{Efficiency (Reff)} = 1 - \frac{\sum(Q_{Obs} - Q_{sim})^2}{\sum(Q_{obs} - \overline{Q_{obs}}\ )^2} -----------3.9$$

The coefficient of efficiency (Reff) was used for assessment of simulations by the HBV model.

3.4.7 Evaporation and Seepage from Reservoir

Because reservoir/lake evaporation cannot be measured directly, it should be determined indirectly by one or more of several methods, such as water balance, energy balance, Penman–Monteith's formula, pan evaporation technique and so on(F.Bautista et al., 2009).

For this study, the Penman–Monteith method was selected to determine the monthly evaporation rates.

Open water evaporation was calculated by using the FAO CROPWAT Version 8.0 program, which uses the Penman-Monteith method and then applies an aridity correction factor. The CROPWAT program was developed to estimate potential evapotranspiration (PET) or ETo which is also defined as reference evapotranspiration (FAO, 1998). According to FAO Irrigation and Drainage Paper 56, page 114, the conversion of ETo to evaporation of open water, with depth higher than 5 m, clear of turbidity, in temperate climate, would be varied between 0.65 and1.25. The lower values "correspond to the period when the water body is gaining thermal energy", and the higher to the period "during the fall and the winter when heat is released from the water body". For Ethiopia, the aridity correction factor was estimated to be 1.2 (source-Hydrology-Detail Design Report, 1995).

Since, Intoto and Addis Ababa are closest to the dam site area; they were selected to represent the Dire reservoir evaporation rates. The open water evaporation for future time period was found by multiplying the evapo-transpiration found in Table 4-3 and Table 4-4 by aridity correction factor of 1.2. The monthly seepage from Dire reservoir was estimated as 25% of monthly evaporation (Detail Design Report, 1995).

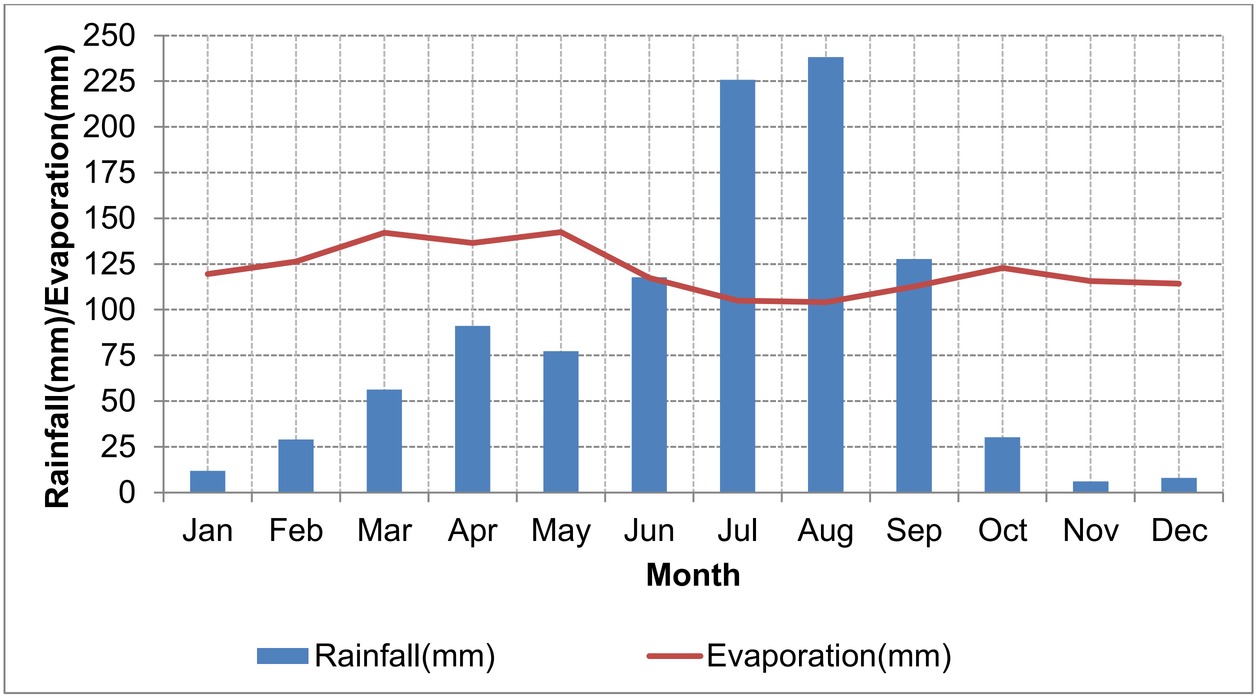


Figure 3-10: Current (1983-2013) mean monthly evaporation and rainfall (mm) for Dire reservoir

3.4.8 Water Balance Prediction of the Catchment for Future Periods

The water balance of a catchment can be summarized by the basic water balance equation as Woods *et al*. (2006) explanation with inflow equal to outflow plus a gain or loss due to storage:

$$P = AE + Q + \Delta S ---------3.10$$

In this equation, P is the precipitation, AE is the actual evapotranspiration, Q is the runoff and ∆S is the change in storage in the seasonal snow, glaciers, channels and lakes, and biological, soil moisture and groundwater storage. However, when the water balance is considered over long time periods (i.e., tens of years or more), changes in catchment water storage can be considered to be negligible. Consequently, omitting ∆S and rearranging the terms now provides the following simple equation for runoff:

$$Q = P - AE ---------- 3.11$$

Wang *et al.* (2008) also discussed that, the annual runoff was estimated with precipitation (P) minus actual ET, Q = P -ET

According to Lu (1998) description, ET=PET, if Pr + Rs ≥ PET and

$$Q = P - PET -----------3.12$$

Where, ET =Actual evapotranspiration in mm/day

Pr=Precipitation as rainfall in mm/day

Rs=Snowmelt recharge in mm/day

PET=Potential evapotranspiration in mm/day

Based on equation (3.12), the water balance of the Dire catchment for the future period was predicted by using downscaled potential evapotranspiration and areal precipitation.

3.4.9 Reservoir Capacity

The analysis of the reservoir capacity was carried out by:

- Reviewing of both design documents of the Dam,
- Understanding why the re-designing works was needed,
- Study the supply part from the catchment(hydrological analysis),
- Assess the capacity of the reservoir by undertaking new hydrological analysis of the catchment and using contour map of the reservoir area,
- Compare or evaluate the previous design with the results obtained from the newly hydrological analysis result.

Input data used to undertake the reservoir capacity includes, design documents, river flow data, and contour map of the reservoir area.

3.4.10 Water Demand and Supply Criteria

The criteria used for supply and demand analysis performed by SEURECA-BRLi-TROPICS and their strength and limitations were discussed. The demand evaluation was carried out using the national standards for water supply.

While, the supply part was addressed using the results obtained from hydrological analysis, which further compares with the data used for the design purpose.

4. RESULT AND DISCUSSION

Under this topic, the methods undertaken for data screening, filling of missing data and results obtained by the analysis are discussed in detail.

4.1 Meteorological Data Screening

The selected rainfall stations were non-dimensionalized and plotted together to analyze their homogeneity. As shown in figure 4-1, one can see the homogeneous nature of the stations for the study since they have *similar climatic and rainfall pattern*, the maximum rainfall falls between June to September.

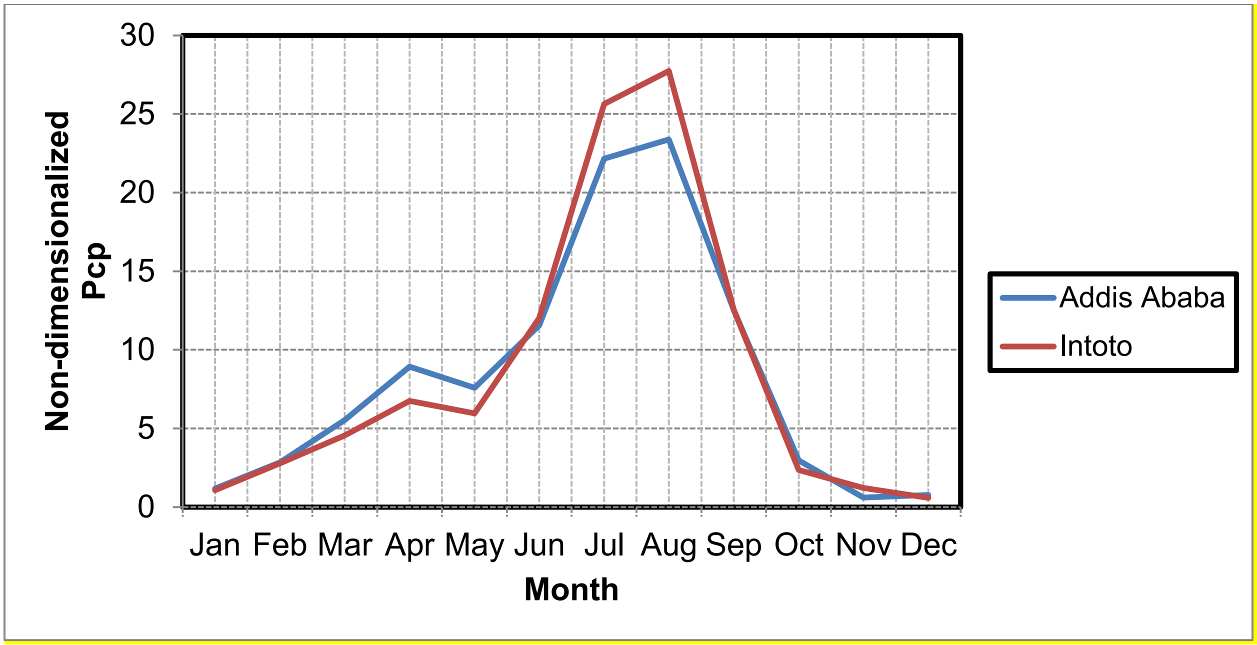


Figure 4-1: Non- dimensionalized for the selected stations

Graphical comparison and visual examination of the rainfall data was done by plotting the time series monthly rainfall data .The selected stations show similar periodic pattern of records (Figure 4-2). Comparison of data of one station with the other station using tabular and graphical approach didn‟t show other suspicious values.

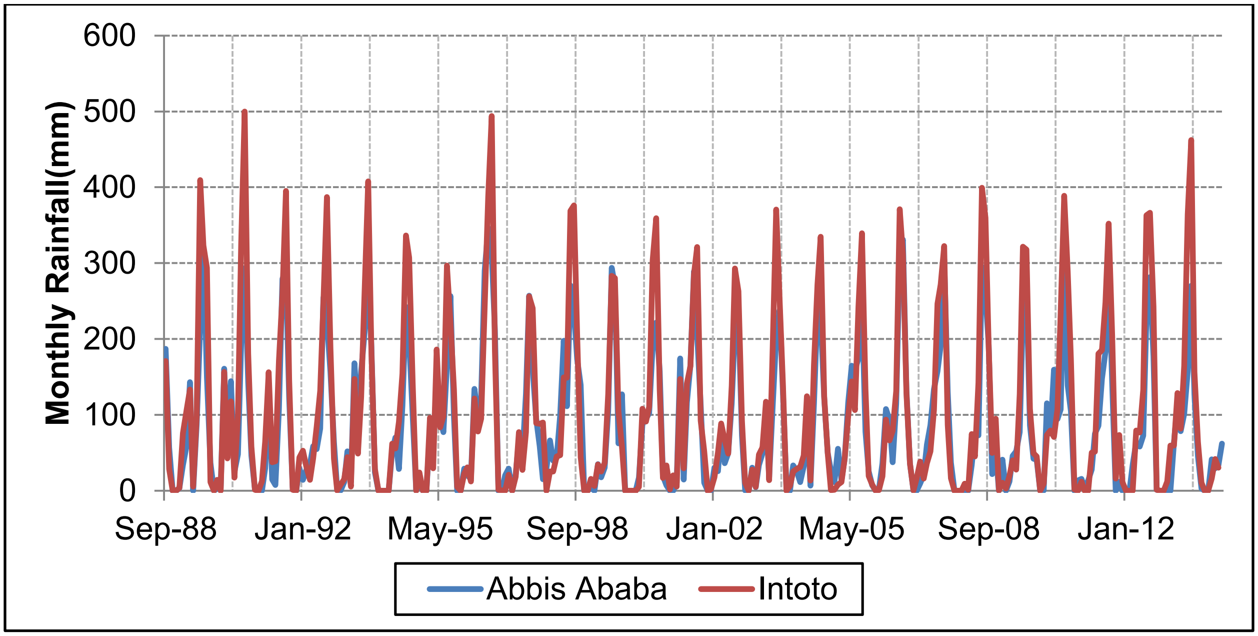


Figure 4-2: Monthly rainfalls of selected stations [mm/month]

A time series observational data is relatively consistent and homogeneous if the periodic data are proportional to an appropriate simultaneous period. This proportionality can be tested by double mass analysis in which accumulated rainfall/hydrological data is plotted against the mean value of all neighborhood stations.

Accordingly, the consistency of the rainfall data was checked by employing the double mass curve. The results of the double mass curve are plotted in Figure 4-3.

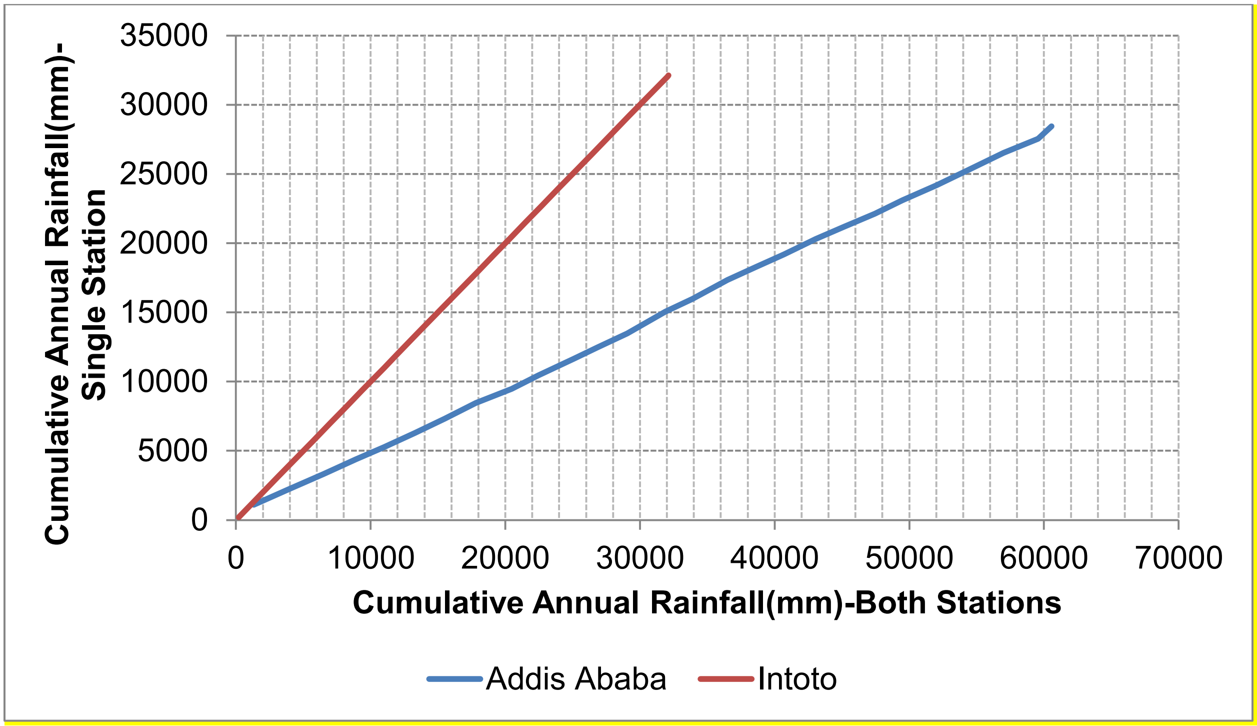


Figure 4-3: Double mass curve for the selected metrological stations

Both of them follow a straight-line trend. Hence, none of the stations show inconsistency. The data could be used for analysis.

4.2 Missing Data Filling

Missing data‟s of precipitation and other climatic variables of the downscaling station of Intoto and its neighboring station of Addis Ababa was filled by the technique of normal ratio method as their normal annual value differed more than 10%.

4.3 Climate Projection

4.3.1 Correlation of Predictor with Predictand

As discussed in the previous section downscaling was carried out for precipitation, maximum and minimum temperature. The selected predictors (as shown in the Table 3-6) resulted in good correlation with their respective predictand in all months. Precipitation showed stronger correlation with nceppr500 and ncepp_zh from the month of April to October and necpp_v also exhibits a better correlation for the month of

January and December. The maximum temperature showed remarkably very good correlations for all months with the selected predictors. It shows high correlation with *nceptem* for the month of January, February, March, June and July. The correlations of observed minimum temperature with the selected predictor resulted in great correlation with *ncepp500* for all months except for the month of November.

4.3.2 Calibration and Validation

The SDSM model was calibrated with 20 years of daily data (1983-2002) and validated with the rest of 11 years daily data (from the year 2003-2013). The coefficient of variation R^2 values for observed and downscaled maximum and minimum temperature and precipitation revealed that they have good relations (Table 4-1).

Table 4-1: R^2 value for the observed and downscaled climate variables

Predictand Variable	Calibration				Validation			
	HadCM3 A2a		HadCM3 B2a		HadCM3 A2a		HadCM3 B2a	
	R^2	SE	R^2	SE	R^2	SE	R^2	SE
Minimum temperature	0.97	0.29	0.98	0.29	0.98	0.29	0.97	0.29
Maximum temperature	0.81	1.01	0.78	1.12	0.60	1.45	0.58	1.46
Precipitation	0.73	1.14	0.73	1.17	0.64	1.38	0.65	1.37

4.3.3 Maximum Temperature

As shown in Figure 4-4, the downscaled monthly average maximum temperature revealed good agreement with the observed temperature for the baseline period of both A2a and B2a emission scenarios.

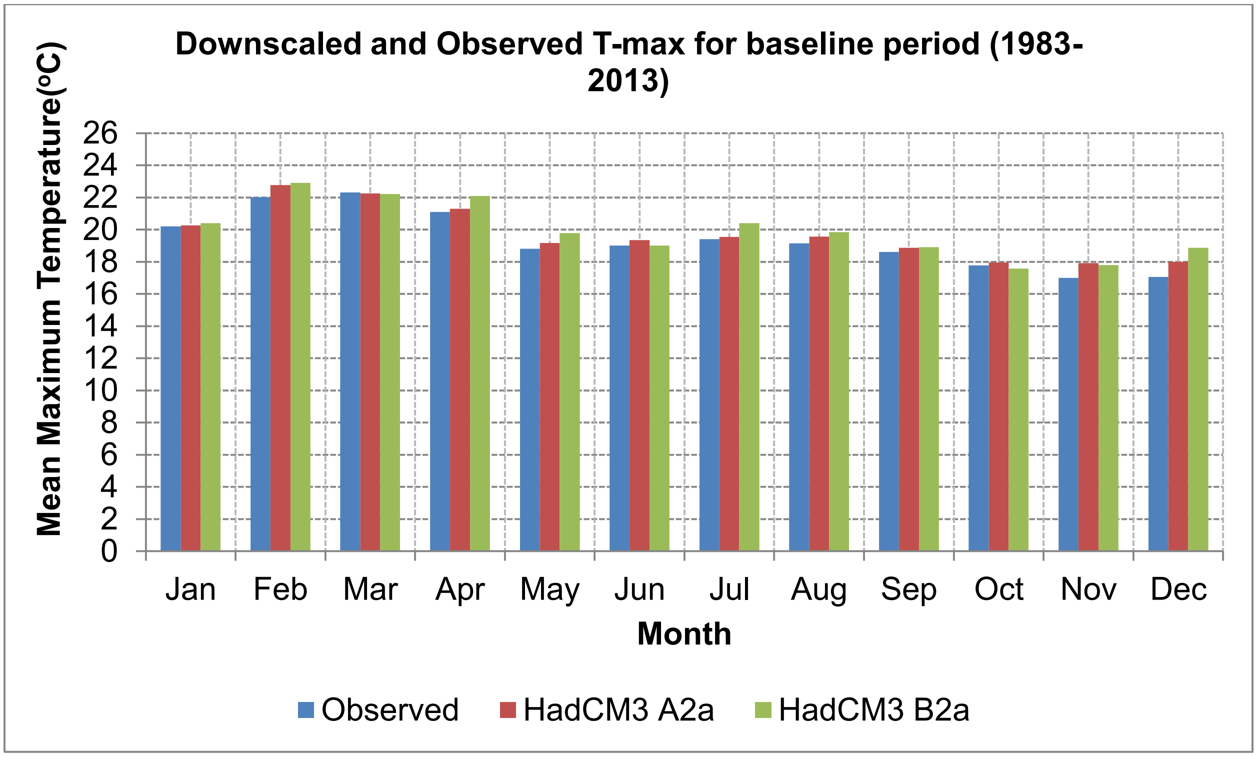


Figure 4-4: Downscaled and Observed mean monthly maximum temperature (1989-2013)

The monthly absolute model error of the downscaled maximum temperature for the baseline period shows almost similar result for both A2a and B2a emission scenarios. Though the magnitude is small, the model underestimates the maximum temperature for both A2a and B2a emission scenario. Here the minimum model error has been observed in the month of May, which was about -0.26 for HadCM3 A2a and 0.00 for HadCM3 B2a while the maximum monthly model error had seen in January with 1.04 and 1.0 for HadCM3 A2a and HadCM3 B2a respectively.

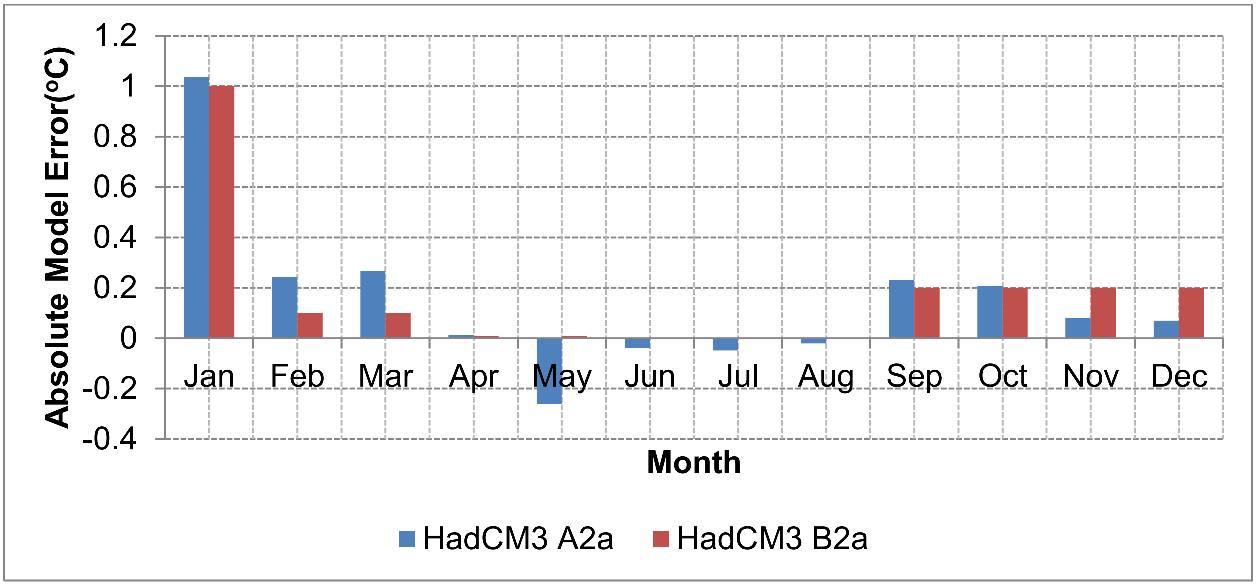


Figure 4-5: Absolute model error for each month of downscaled maximum temperature (1989-2013)

4.3.4 Minimum Temperature

Similarly, the downscaled minimum temperature showed a good agreement with the observed minimum temperature for all months both under A2a and B2a emission scenarios.

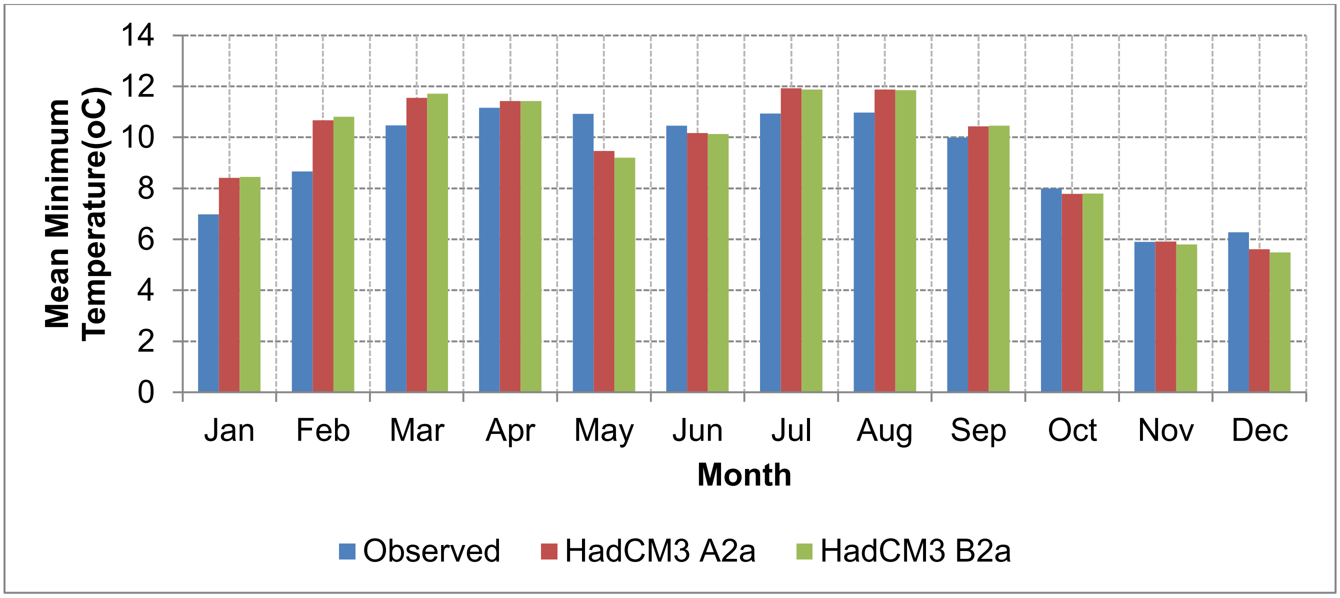


Figure 4-6: Downscaled and observed mean monthly minimum temperature (1989-2013)

The absolute model error (i.e. the difference which was seen between the A2a and B2a emission scenarios) for minimum temperature, also explained similar magnitude. For both of them the maximum model error was observed in the month of February, which is -2.0 and -2.1°C for A2a and B2a respectively.

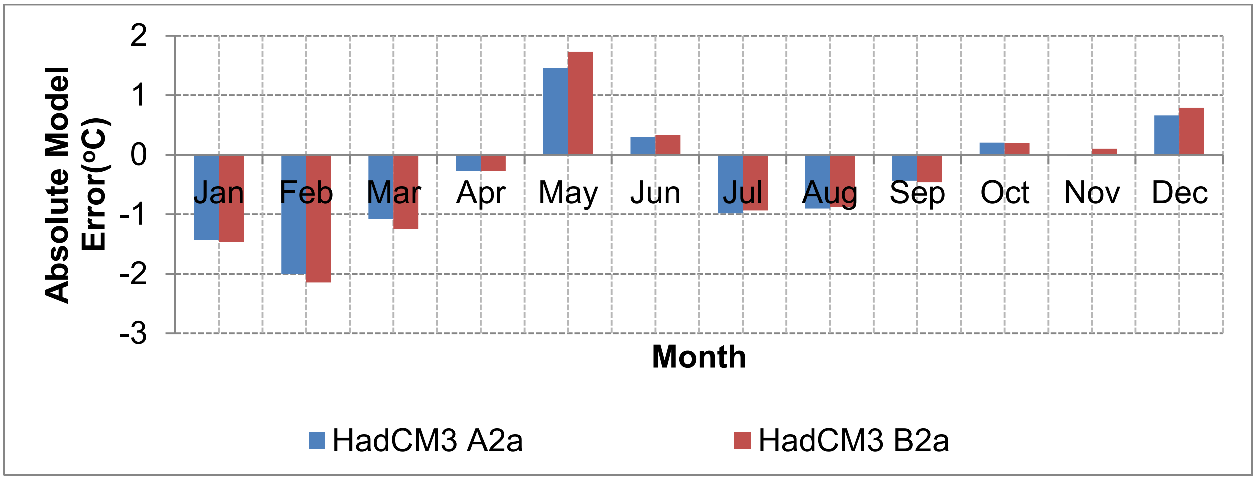


Figure 4-7: Absolute model error for each month of downscaled minimum temperature (1989-2013)

4.3.5 Precipitation

In the short rainy season (Belg) that runs from February to May, there was an increasing trend of rainfall, which helps to generate additional water from the reservoir. While in the main rainy season (Kiremt), July and August it was observed that, there is a decreasing trend of rainfall.

Relative to the minimum and maximum temperature the precipitation could not be able to replicate the historical (observed) data. This is due to complicated nature of precipitation processes and its distribution in space and time. Climate model simulation of precipitation has improved over time but is still a problematic (Bates et al., 2008).

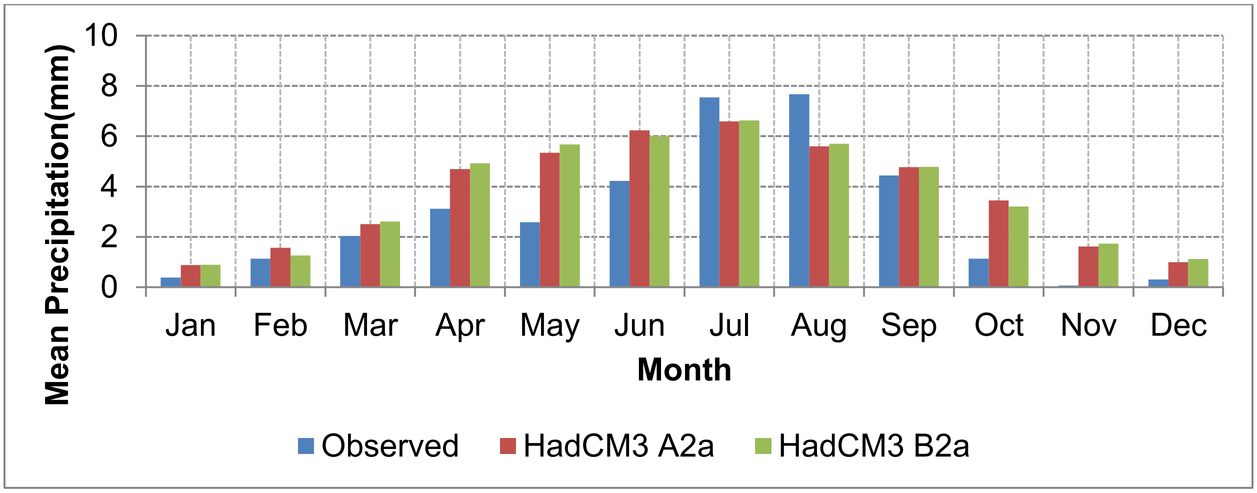


Figure 4-8: Downscaled and observed mean monthly precipitation (1989-2013)

Relative similarity had been observed by considering the model error between the HadCM3A2a and HadCM3B2a emission scenarios during the precipitation downscaling of the study area (Figure 4-9). The maximum model error was -2.0mm for A2a and -1.8mm for B2a scenarios in the month of May.

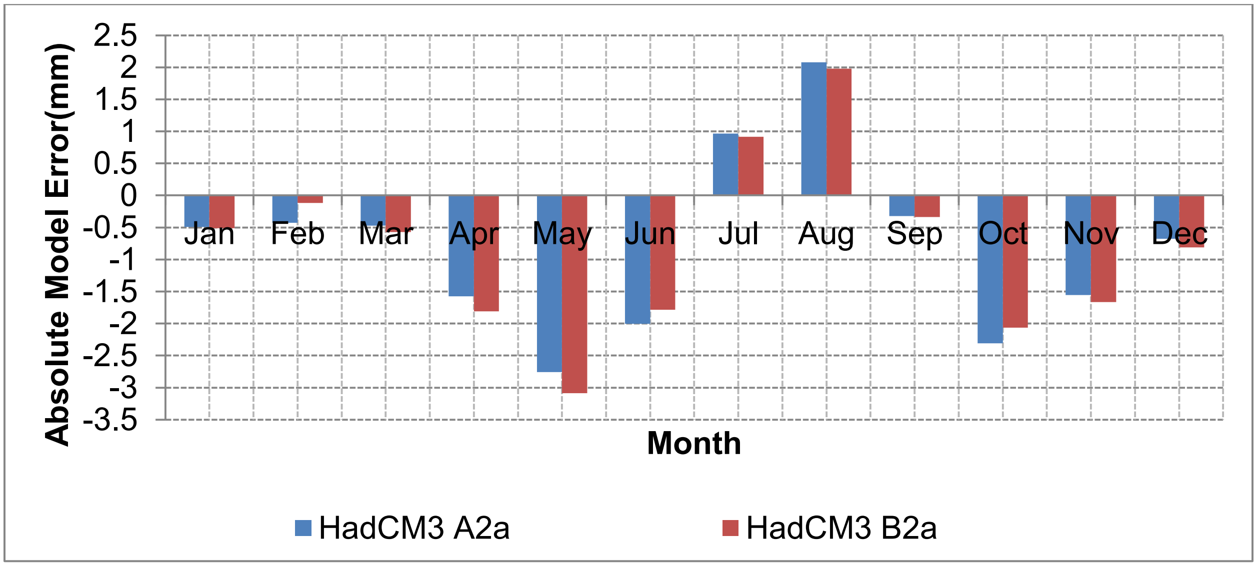


Figure 4-9: Absolute model error for the downscaled precipitation (1989-2013)

4.3.6 Potential Evapotranspiration

A good agreement was also observed in between observed and downscaled mean monthly potential evapotranspiration as shown in Figure 4-10.

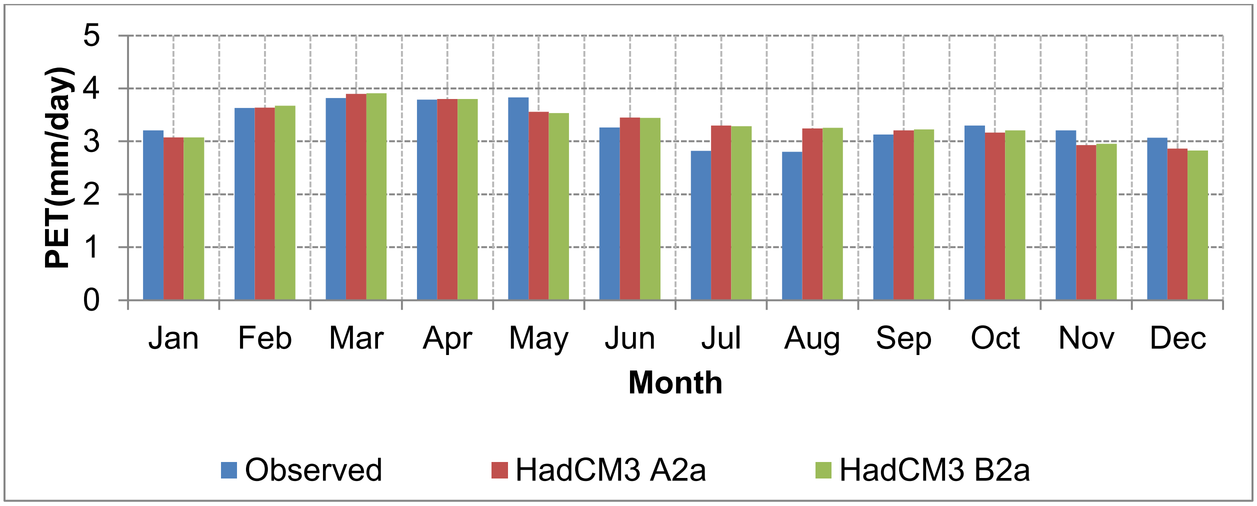


Figure 4-10: Downscaled and observed mean monthly PET (1989-2013)

Similarity had seen regarding the existence model error between HadCM3A2a and HadCM3B2a emission scenarios that indicated in Figure 4-11 for the potential evapotranspiration. The maximum model error obtained were 0.28 for A2a and 0.26 for B2a. On the other hand the resulted minimum model errors were -0.48 for A2a and -0.47 for B2a scenarios.

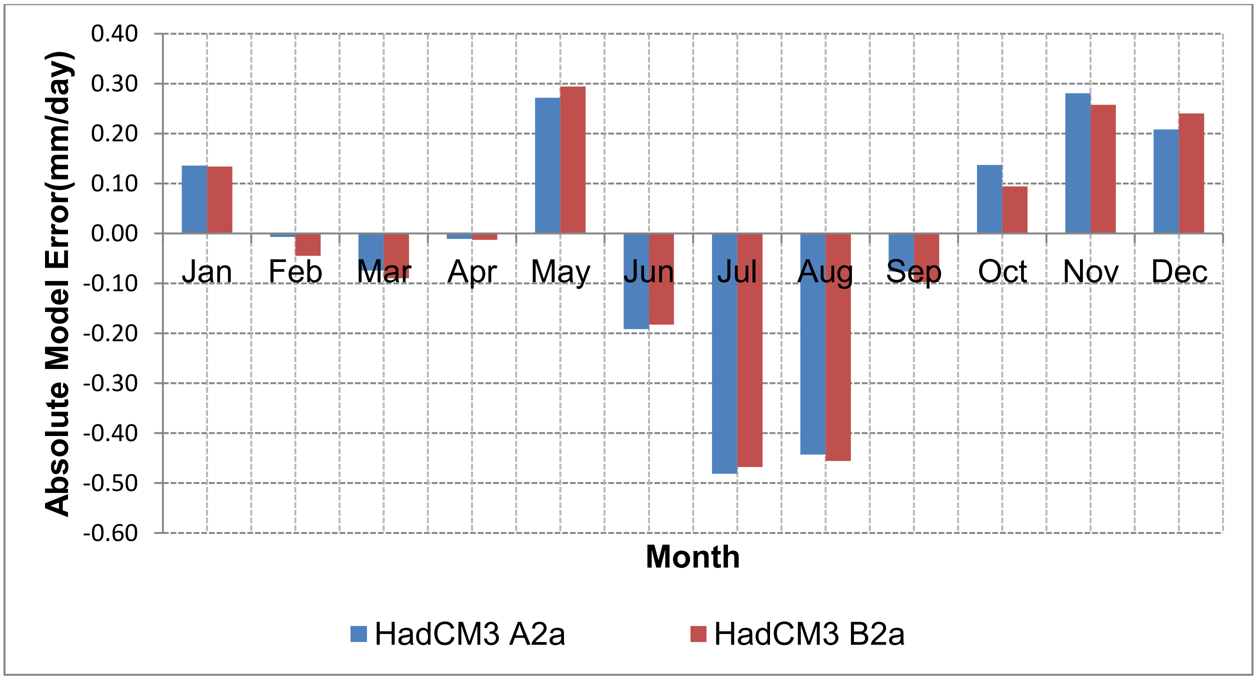


Figure 4-11: Absolute model error for the downscaled PET (1989-2013)

4.3.7 Monthly Total Time Serious Rainfall

6.4.7.1 Main Rainy Season (Kiremt)

In the main rainy season (Kiremt), from June to September there was reliable rainfall throughout the whole years, which have been taken for analysis as shown in Figure 4-12. This indicates that there is enough inflow to the reservoir. In all months of the specified years, the total amount of rainfall in the month of August is greater than 200mm.

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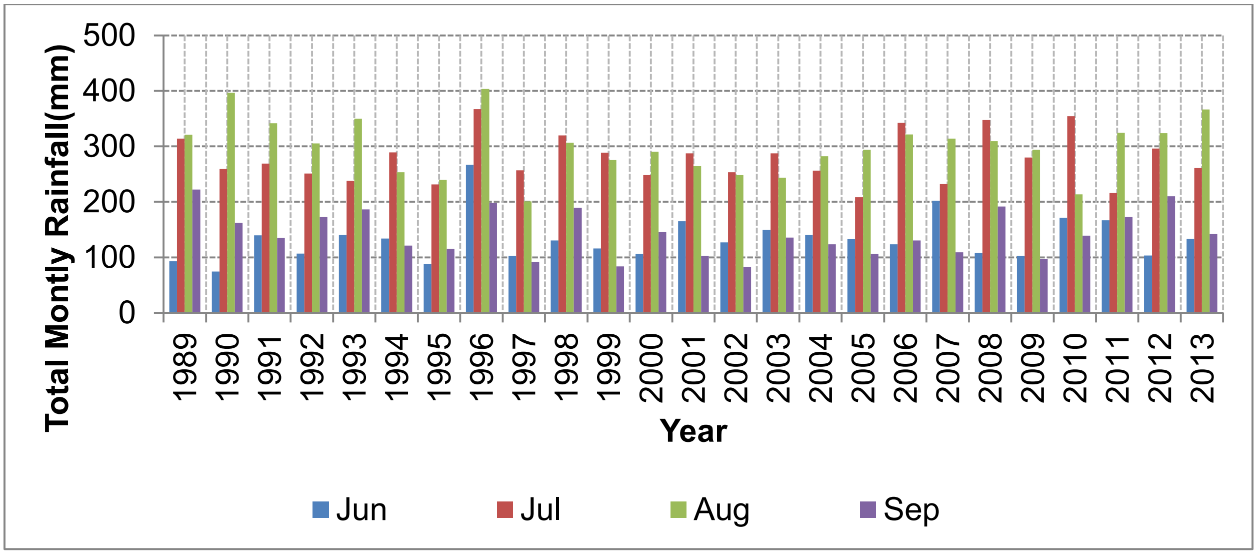

Figure 4-12: Total monthly rainfall (June, July, August and September) for the period of 1989 to 2013

6.4.7.2 Short Rainy Season (Belg)

In the short rainy season (Belg) that runs from February to May, there is no significant variation of rainfall among the selected years as show in Figure 4-13 which helps for additional inflow to the reservoir to suffix the required demand.

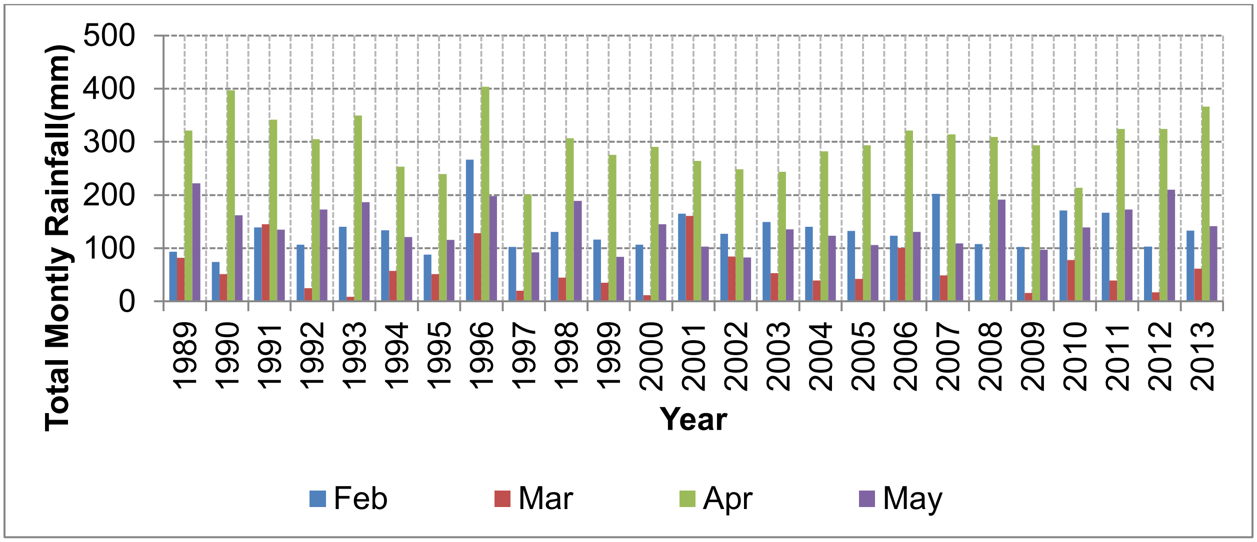

Figure 4-13: Total monthly rainfall (February, March, April and May) for the period of 1989 to 2013

4.3.8 Projected Future Climate Variables (Scenario Generation)

The future climate scenarios was developed from GCM predictor variables for the corresponding A2 and B2 scenarios for the classified a twenty six and two thirty years period called 2020 (2014-2039), 2050 (2040-2069), and 2080 (2070-2099) respectively. The results obtained for minimum temperature, maximum temperature, precipitation and potential evapotranspiration indicated in Figures 4-14 to 4-19.

4.3.8.1 Maximum Temperature

As shown in the Figures 4-14 and 4-15 the maximum temperature has an increasing trend for all future time. The mean annual maximum temperature increases from the base period by 0.1, 1.22, 1.98°C for 2020s, 2050s, and 2080s respectively for HadCM3A2a climate respectively. Similarly for HadCM3B2a climate scenario‟s it increases by 0.085, 0.419, 1.69ºC for 2020s, 2050s and 2080s respectively.

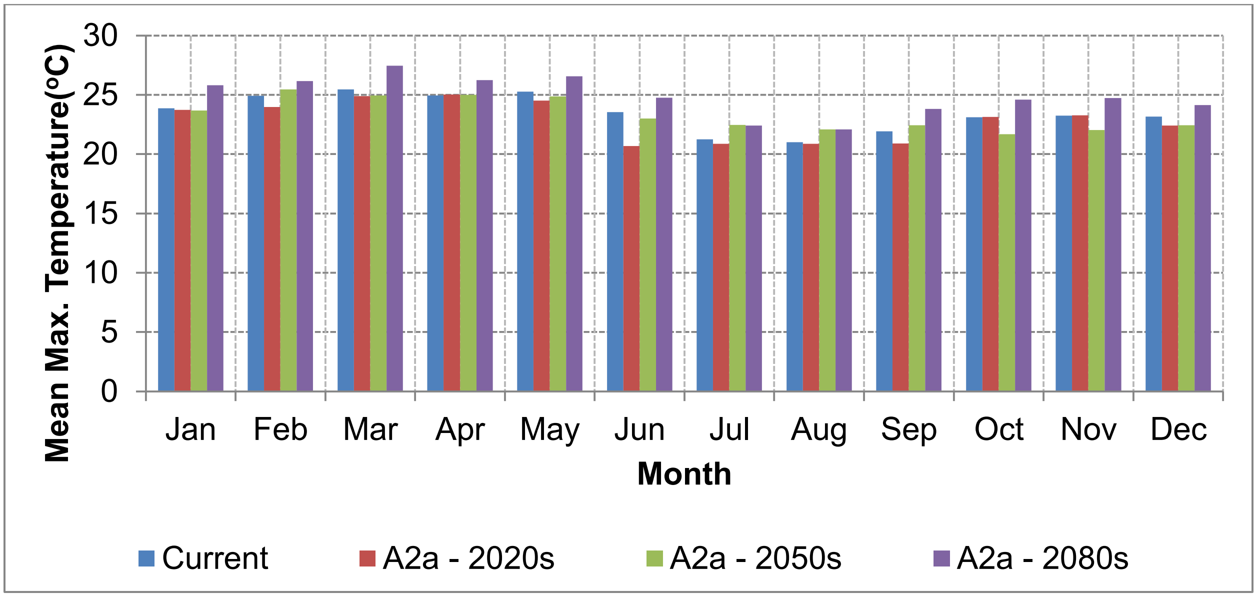

Figure 4-14: Monthly mean maximum temperature for the baseline period and HadCM3 A2a scenario

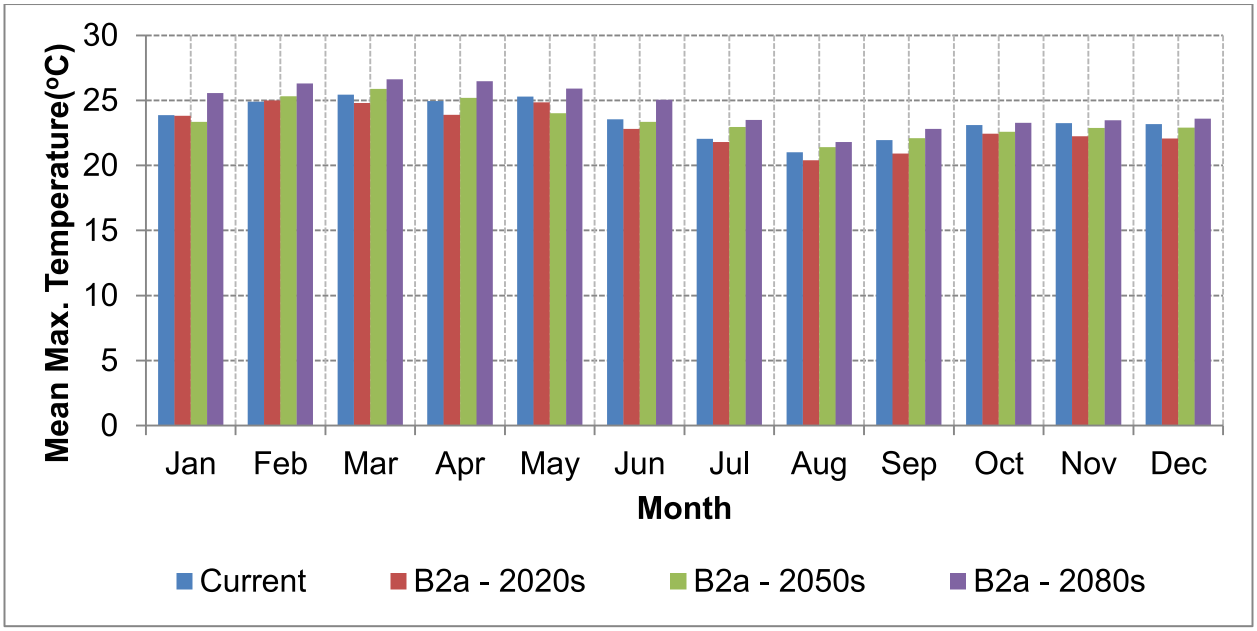

Figure 4-15: Monthly mean maximum temperature for the baseline period and HadCM3 B2a scenario

4.3.8.2 Minimum Temperature

The results for minimum temperature revealed an increasing trend for both future scenarios. The mean annual minimum temperature reaches, 1.37, 1.5, 1.8ºC for 2020s, 2050s, and 2080s for HadCM3A2a scenario respectively. While for HadCM3B2a scenarios it reaches 1.03, 1.55, 1.78°C for the aforementioned time periods.

According to IPCC (Boko, et al., 2007), in eastern Africa observed temperatures especially since the 1960s have indicated a greater warming. The warming of eastern Africa in the 20th century has occurred at a rate of about 0.5°C per decade, and the rate of warming increased in the last three decades of the century (Hulme, et al., 2001).

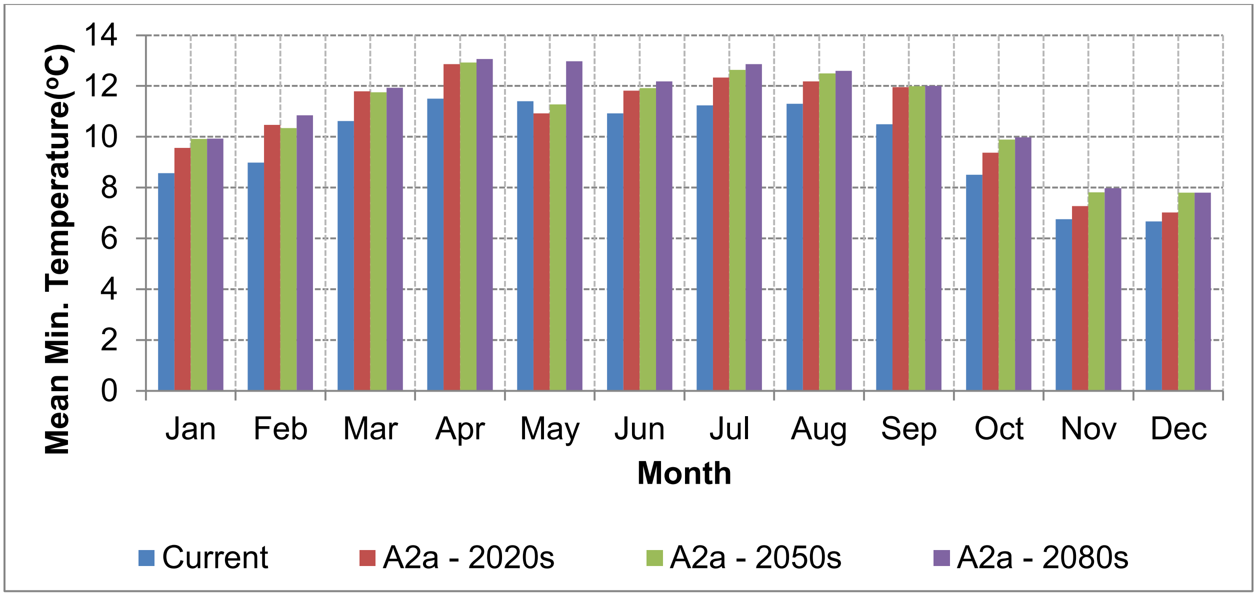

Figure 4-16: Monthly mean minimum temperature for the baseline period and HadCM3 A2a scenario

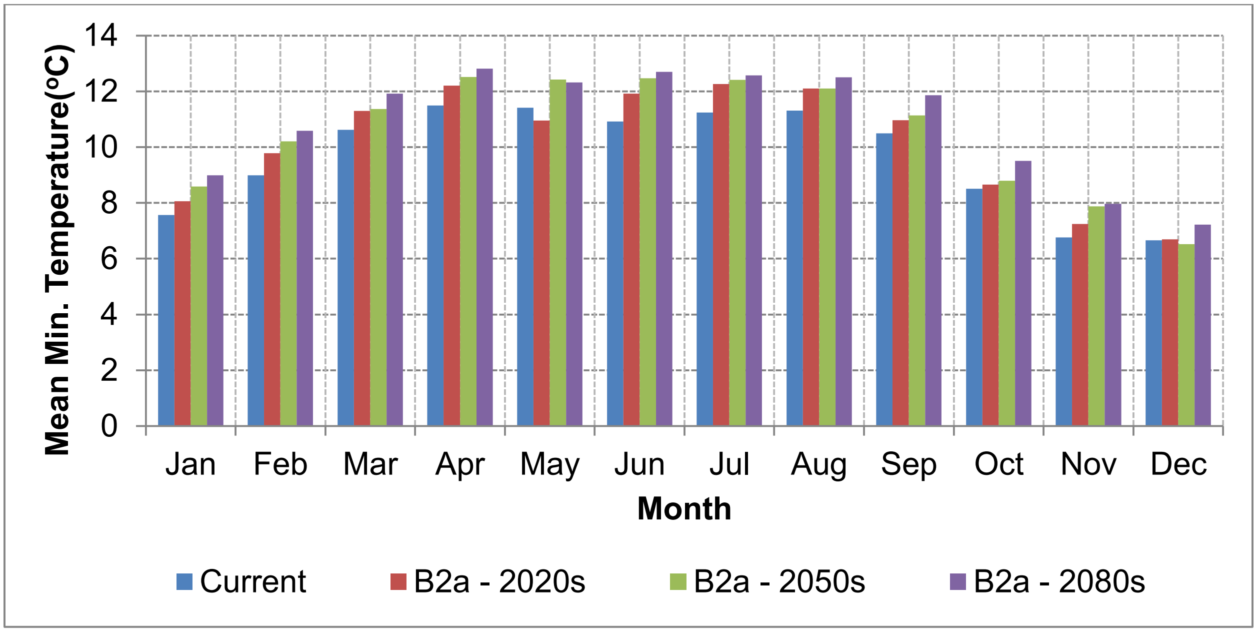

Figure 4-17: Monthly mean minimum temperature for the baseline period and HadCM3 B2a scenario.

4.3.8.3 Precipitation

Downscaling precipitation for future period in A2a scenario had shown an increasing trend for mean annual by 4.25%, 12.7% and 17.2% for the corresponding 2020s, 2050s, and 2080s time period. However, its monthly mean had both decreasing and increasing trends as observed in the Figure 4-18.

The resulted downscaling for B2a scenario had varying trends for the mean annual values. The mean annual precipitation shows a various trends by 5.2%, 10.25% and 0.1% increment for 2020s, 2050s and 2080s time period respectively. Regarding the mean monthly trends, it had both decreasing and increasing manner (Figure 4-19). This fluctuation of precipitation will result in the increase and decrease in surface water potential, which influences inflow to the reservoir.

According to Dr. Mekuria Argaw, the main impacts of climate change are reduced water in reservoirs and increased conflict over water resource use and its main indicators are extreme weather events (increased frequency of floods and droughts) and increased variability in rainfall (in amount, spatial and temporal distribution).

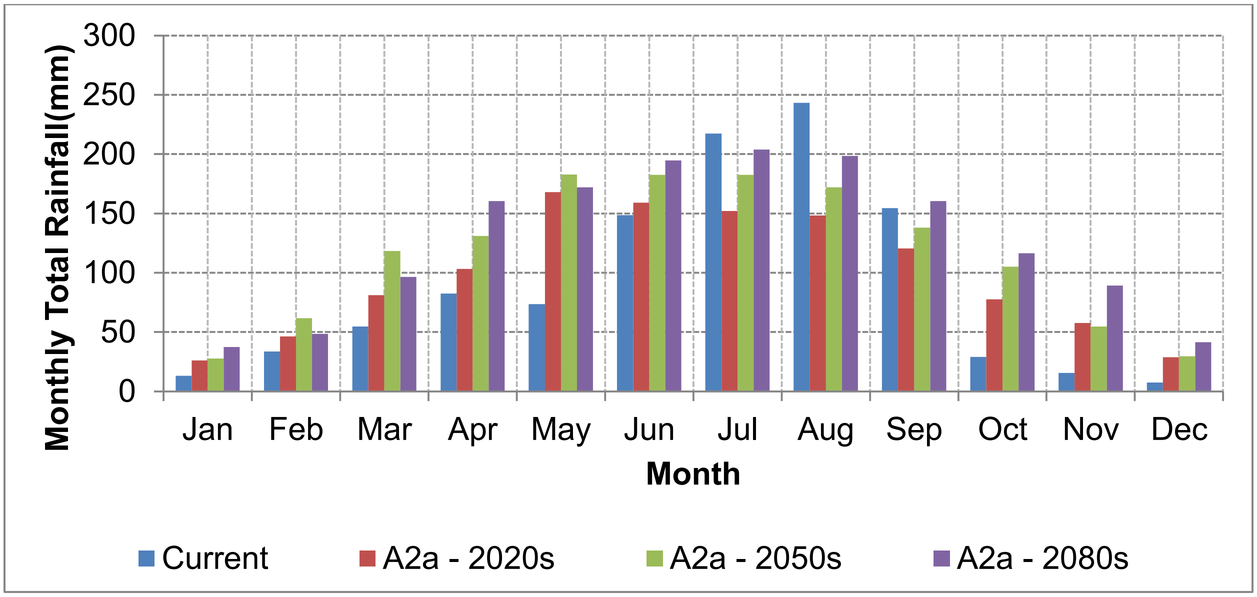

Figure 4-18: Monthly Total Precipitation from HadCM3 A2a

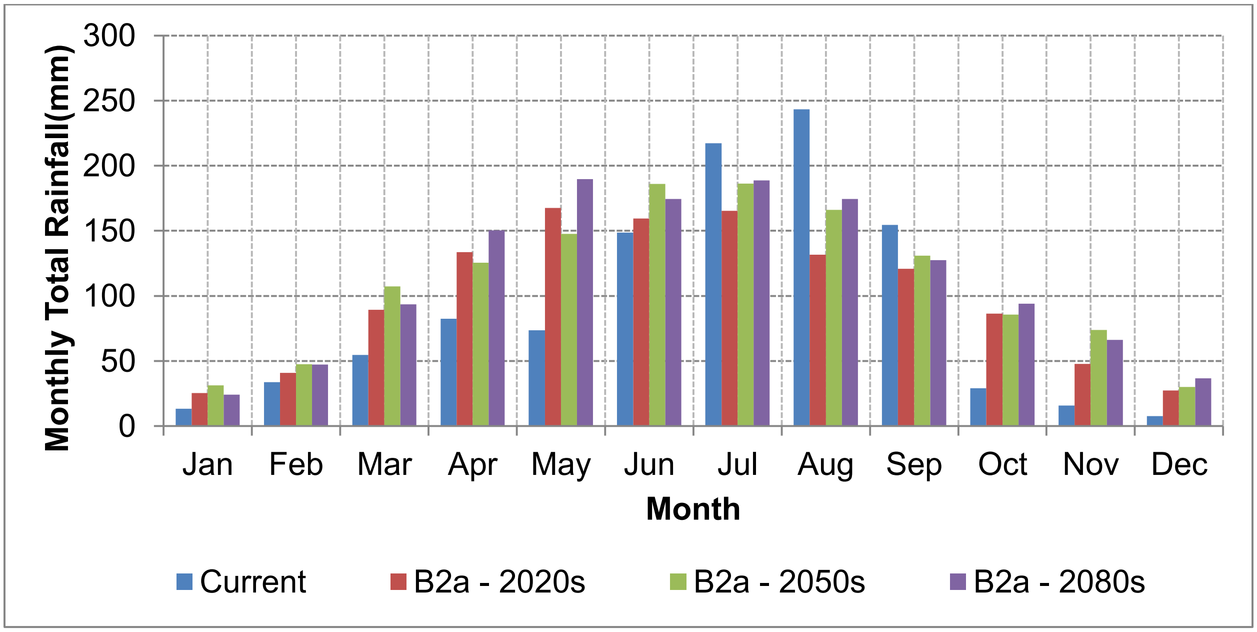

Figure 4-19: Monthly Total Precipitation from HadCM3 B2a

4.3.8.4 Evaporation from the Reservoir

The projected future Potential Evapotranspiration (PET) value of the Dire reservoir was computed from downscaled maximum and minimum average temperature of the catchment by Hargreaves‟s method to make the water balance of the reservoir with the corresponding areal precipitation.

As it was explained in section 3.4.7, the open water evaporation was calculated by multiplying the respective potential evaporation by the aridity correction factor of 1.2. The average annual open water evaporation shows an increasing trend by 2.4% in 2020s; 4.1% in 2050s and 11.2% for the projected period in 2080s under the A2a emission scenario. In the case B2a scenario the evaporation is expected to increase by 3.1 % in 2020s and by 4.94% in 2050s and 10.71% by 2080s under B2a scenario.

As it was indicated in the above analysis, both minimum and maximum temperature shows an increasing trends. Stored water evaporates from open reservoir when the air is dry and the climate is fairly hot; significant water quantities could be lost and evaporation should therefore be taken in account. According to a report from United Nations Environment Programme (UNEP, 2000) called “Climate Change and Dams”, reservoirs/dams are affected by climate change. Increased temperature increases the evaporation/evapotranspiration and increased rainfall intensity will increase the sediment transport to dams. Both of these impacts reduce the capacity of the dam.

Table 4-2: Monthly Conversion equations from PET (Hargreaves) to PET (Penman Monteith)

Equation	r^2
$ET_{O\_Penman} = 1.2648 * ET_{o\_Hargreaves} - 0.7585$	0.9373

Table 4-3: Projected PET at different time horizon in mm/month for HadCM3 A2a

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2020s	99.07	99.99	122.68	113.02	111.99	105.84	101.89	103.45	100.80	100.98	91.83	88.16
2050s	97.46	116.78	121.30	113.83	115.80	107.64	104.69	105.39	104.50	96.08	100.32	96.25
2080s	112.59	127.33	145.05	136.26	131.31	126.41	124.14	122.09	121.23	126.38	111.32	94.68

Table 4-4: Projected PET at different time horizon in mm/month for HadCM3 B2a

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2020s	100.17	107.48	125.27	124.71	109.11	100.28	100.90	100.68	97.23	100.99	95.10	95.18
2050s	109.11	112.56	127.96	123.22	120.71	112.13	105.81	103.94	98.59	97.26	91.91	100.47
2080s	115.79	128.05	139.55	131.48	133.52	125.35	120.48	115.71	115.84	122.60	105.50	110.26

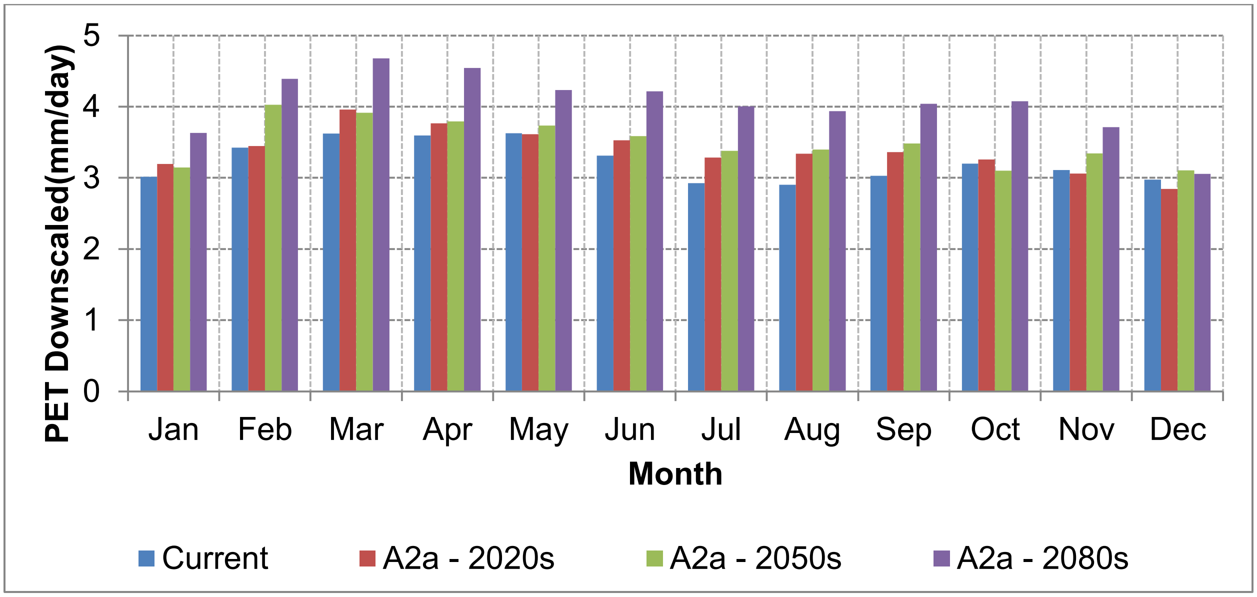

Figure 4-20: Projected monthly potential evapotranspiration for open water from HadCM3 A2a

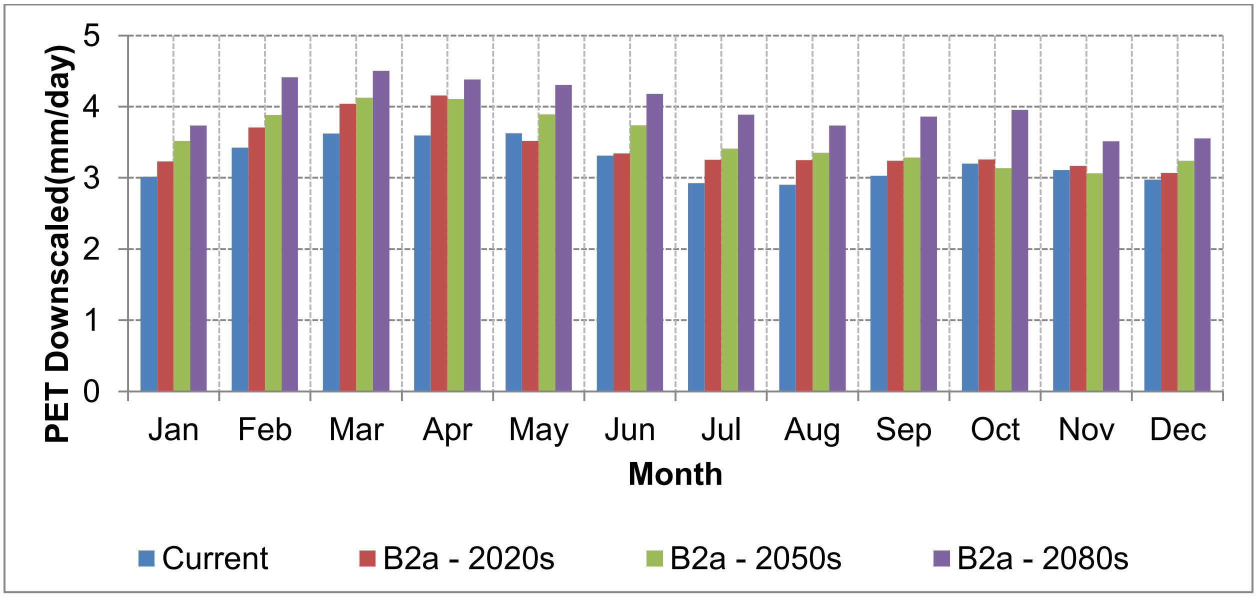

Figure 4-21: Projected monthly potential evapotranspiration for open water from HadCM3 B2a

4.4 Hydrologic Model

4.4.1 Calibration and Validation

The HBV-model was calibrated and validated for the observed period of ten year (2004-2013) and the best-fit parameters sets are selected. Calibration aimed at the water balance and over all shape agreement of the observed discharge using RV_E (relative volume error) and R^2 (Nash and Sutcliffe coefficient). In simulation of the runoff the observed period was divided in to three zones, the first is for warm up the model (2004), the second is to calibrate (2005-2010), and the last is for validation (2011-2013). The calibration and validation was carried out for both daily and monthly time steps. It is observed that the model is capable to simulate the observed flow for both low flow and high flow period with $RV_E < 5\%$(which is -4.69%) and R^2= 0.78 (Figure 4-22). In general, the efficiency of the model was good for both calibration and validation periods for which the coefficient of determination (R^2) obtained were about 0.78 and 0.69 respectively, though there exists, differences in the years 1996 and 2012. This may occurs due to the FC parameter, which is the most sensitive parameter for this study.

Table 4-5: Calibrated model parameters for Dire catchment with their recommended range of values

Parameters	α	β	FC	KHQ	K_4	Lp	Perc
Range	0.5 -1.1	1-4	100-1500	0.005-0.2	0.001-0.1	<=1	0.01-6
Calibrated value	0.5	1	320	0.09	0.05	0.98	0.02

- Alfa (α) is a measure of non-linearity of the upper reservoir to transfer excess water from the soil zone as quick flow, it is used in equation Q=K.UZ (1+alfa).
- Beta (β) is the exponent in the equation for discharge from the zone of soil water.
- FC is the maximum soil moisture storage capacity in the model [mm] which is related to soil properties.
- KHQ is the recession coefficient for the upper response box when the discharge is HQ.
- K4 is the recession coefficient for lower response box, describes the recession of the base flow.
- Perc describes the percolation from the upper to lower response box [mm/day].

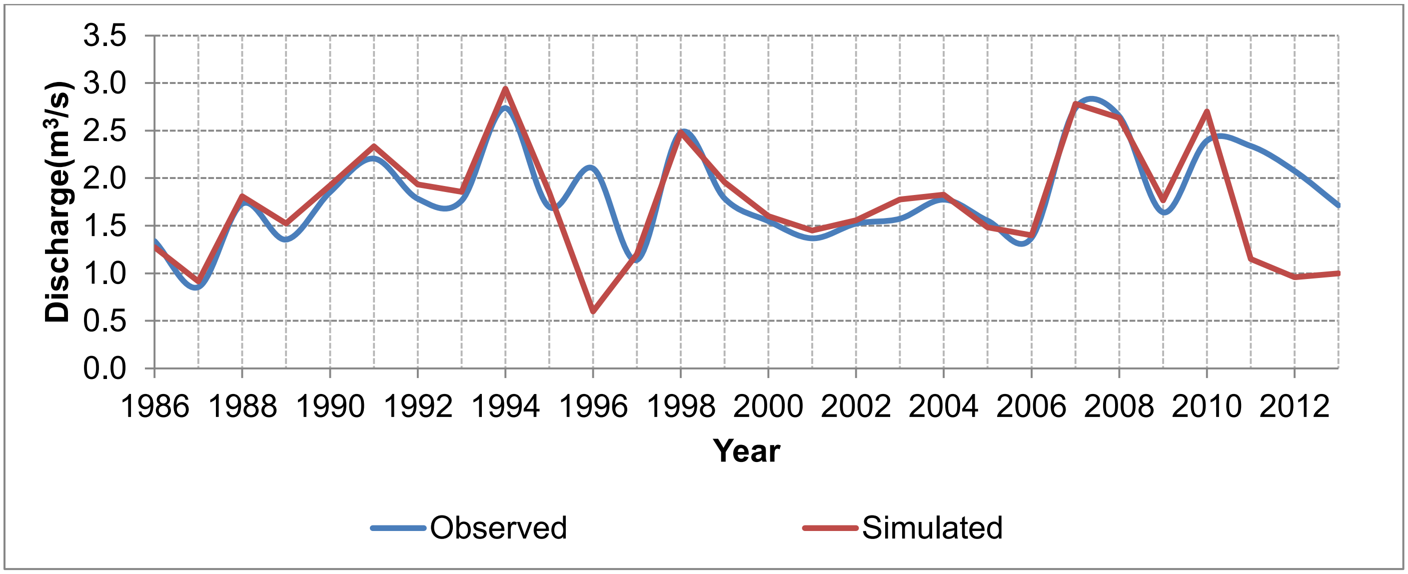

Figure 4-22: Observed and simulated discharge of Legedadi river for the period 1986-2013

4.5 Hydrological Impact of Future Climate Change Scenario

The overall objective of relating downscaled climate scenario data with hydrology was to determine the circumstances to be occurred in the long future run time processes of the hydrologic cycle. The discharge situation for the future time was determined by simulating the downscaled climate variables of temperature, precipitation and potential evapotranspiration to generate the runoff. The potential evapotranspiration was derived from the downscaled minimum and maximum temperature and finally the water balance was made based on the catchment‟s average areal precipitation and potential evapotranspiration. As a result, the runoffs for the three future time period of HadCM3A2a and HadCM3B2a scenarios of 2020s, 2050s and 2080s were generated and shown in Figures 4-23 and 4-24.

For HadCM3A2a scenario, the mean annual runoff was increased by 21.1%, 21.8% and 19.1% for 2020s, 2050s and 2080s respectively. Moreover, the seasonal percentage changes were increased by 47.98%, 46.65% and 42.81% for 2020s, 2050s and 2080s respectively for the month of June.

The results for HadCM3B2a scenario with mean annual runoff indicates an increment by 25.6%, 11.0% and 8.5% for the time period for2020s, 2050s and 2080s respectively. Regarding to seasonal change, the percentage changes were increased by 50.79%, 46.0% and 28.45% for 2020s, 2050s and 2080s respectively for the month of June.

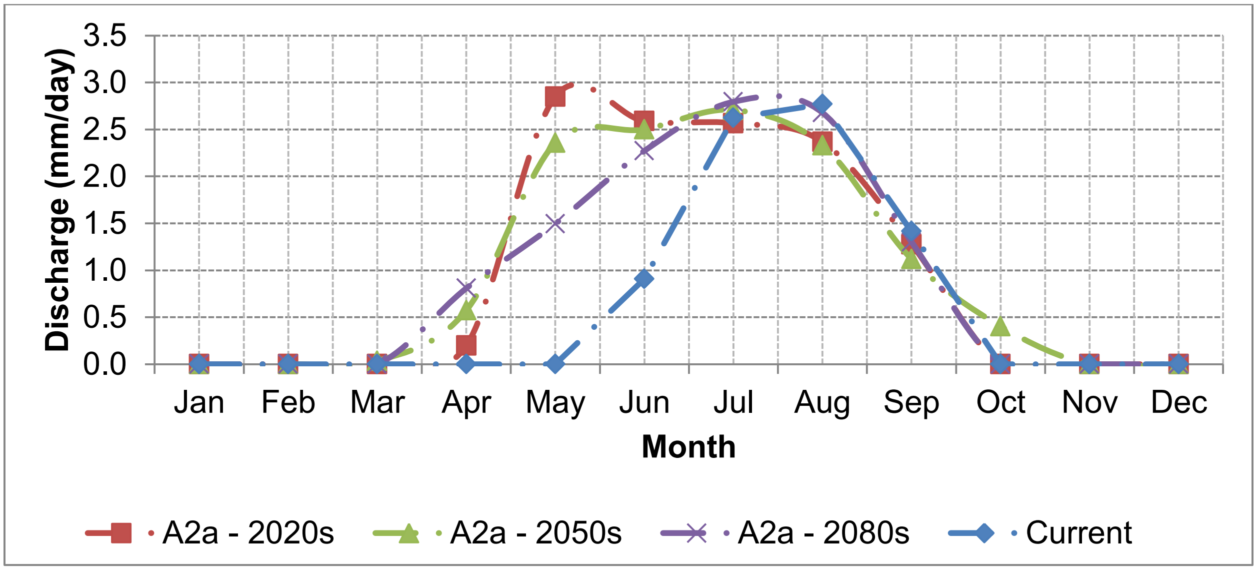

Figure 4-23: Mean monthly flow of Legedadi river catchment for A2a Scenarios

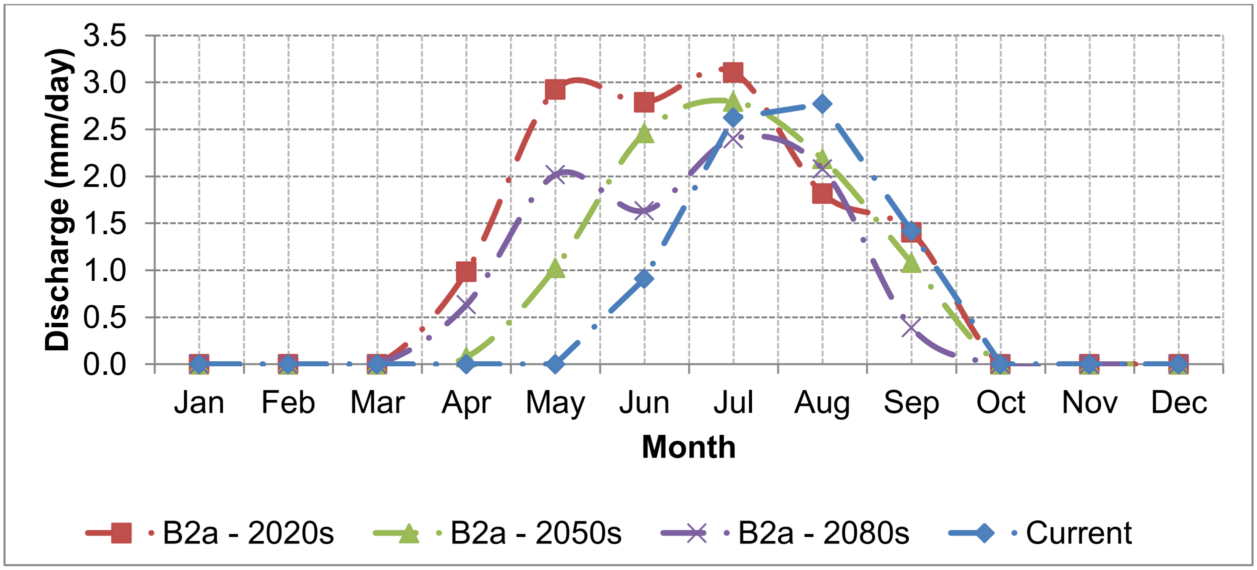

Figure 4-24: Mean monthly flow of Legedadi River catchment for B2a Scenarios

The runoff increasing trend followed similarity with the corresponding precipitation increasing trends. From this, it has been observed that the impacts on climatic variables results with the variability of the hydrologic cycle, the discharge flow in particular.

Current studies carried out by the Ministry of Water, Irrigation and Energy (2013); on the impact of climate change on the extreme flow hydrology and water availability of Akaki Basin using different emission scenarios shows that:

- There will be an increase in flow volumes and flooding,
- There will be a 13% increase in the annual flow volume of Akaki Basin in the 2030s and a 15% increase in the 2090s, and
- The extreme floods will likely increase by 37% in the 2030s and by 15% in the 2090s.

In addition to these, studies on evaluation of the impact of climate change on the water supply reservoir of Dire dam, and other future water supply sources to Addis Ababa also shows, inflows to, and storage in the reservoir is likely to increase significantly (inflow to Dire increases by 9 and 3% for 2030 and 2090, respectively, whilst the storage increase in the in the reservoir is 21 and 19%, respectively).

4.6 Hydrological Analysis

During the preparation of detail design study (1995), it has been found that no hydro-meteorological stations were established within the watershed prior to the commencement of the study. After the initiation of the Dam design project, the need for gauging stations below the confluence of Yeso and Hurufa streams (both streams are tributaries of Legedadi river) has got due attention. Since August 1993, a gauging station with staff gauge has been installed near the dam site, which was believed to be ideal, proposed as Dam site. As a result, proper relationships regarding rainfall and runoff could not be evolved using nearby rain gauge station (Sendafa). However, staff-gauging station was established in the middle of August near the Dam site and measurements are being taken starting from August 1993 for about a year.

As per the Hydrological design report carried out in the year 1995, the recorded data and the rating curve of the Legedadi River for the duration of 13th August 1993 up to 26th May 1994 depicts a total flow of 27Mm^3. The main drawbacks of the recorded data were:

- Short duration of 287 days and even does not cover the whole of the rainy season in the year.
- High flow data collection by the help of staff gauge requires extraordinary alertness. Therefore, there was strong reservation in tracing out the peak flows and in the estimation of potential water resources.

Due to the absence of recorded data, they were forced to resort to other deterministic approaches (regionalization approach and SCS model) to generate monthly flow series. Considering the reliability of the flow magnitude which was based on the consistency of the method used, the regionalization approach sounds acceptable and hence the surface water resources estimated was 30.5Mm^3.

Certain losses from storage facility were also considered in the detail design to account for the possible water requirements. Hence, annually a total loss of 0.9Mm^3 of water was conservatively taken as a provision for seepage loss through the embankment and foundation while 0.64Mm^3 of water was taken as evaporation loss from the reservoir surface.

Detail design report (in the year 2009) carried out for raising of the spillway and Dam height also indicates that, the estimated surface water potential of the study area is 47.75Mm^3. Seepage and evaporation losses were estimated to be 0.8 and 1.35Mm^3 while environmental release remains constant with the previous study (1.54Mm^3).

When it comes to the current study, the hydrological analysis was undertaken based on data obtained from correlation analysis with a nearby hydro-meteorological station (Beke Station), which has a long time flow series (1986-2013). The correlation is entirely satisfactory as shown in the Figure 4-25.

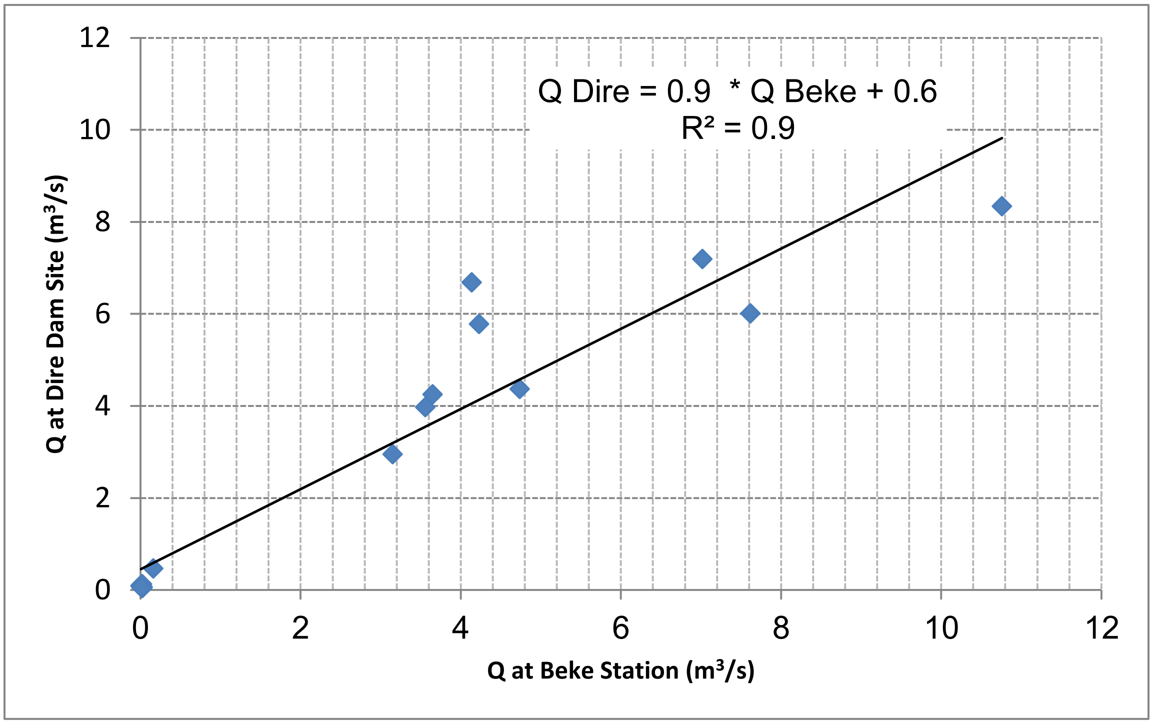

Figure 4-25: Ccorrelation of Dire and Beke inflow data

Further analysis has been carried out in order to apply different correlation formulas for rainy season (July – September) and dry season. Finally, the following formula was proposed:

$$Q\ Dire = 0.9 * Q\ Beke + 0.6 - - - - - - - - - - 4.1$$

Using the above correlation formula, a time series was constituted for daily discharge at Dire Dam from 1986 to 2013; the monthly summary is presented in the Annex 10 below.

As per the time serious analysis, it was found that the mean annual flow is 1.82 m^3/s, which is greater than previous estimations results derived for the feasibility study, detail design study and study results carried out for dam raising (1995 and 2009), 1.32 and 1.52m^3/s respectively.

As per the current estimation, the surface water potential of Legedadi River is 57.54 Mm^3 per annum. This indicates that the surface water resource potentials estimated in the previous reports were underestimated as 41.63 $*10^6$ m^3 and 47.75 $*$ 10^6 m^3 respectively.

4.7 Evaluation of Reservoir Capacity and Demand/Supply Criteria

4.7.1 Reservoir Capacity

In the previous design reports, the physical reservoir capacity and yield for the reservoir planning was estimated using three different approaches; mass curve diagram approach, sequent peak algorithm approach and conventional reservoir simulation method. Accordingly, the estimated reservoir capacity was 17.014, 17.034 and 17.034Mm^3 respectively (Detail Design Report, 1995).

Results obtained from the Detail Design Reports (in the year 2009) carried out for the raising of the Dam and spillway is presented in the Table 4-6.

Table 4-6: Previously proposed Dire Dam operation simulations

Parameter	Existing situation before raising	Raising Spillway by 2.5m
Normal water level(m.a.s.l.)	2554.5	2557
Normal storage(mcm)	19.54	23.5
Live storage(mcm)	17.54	21.5
Water surface at NWL(km^2)	1.52	1.66
Estimated inflow(mcm)	41.63	47.75
Net loss by evaporation(mcm)	0.64	0.8
Release for e-flow(mcm)	1.54	1.54

Source: Hydrology reports by SEURECA-BRLi-TROPICS, 2009.

As per the current computation carried out using mass curve diagram and sequent peak algorithm approaches to determine the capacity of the reservoir, it has been found that the reservoir capacity and yield is 19.62 and 19.67Mm^3 respectively. However, using the elevation-area-capacity relationship based on the existing topographic map of the area, the storage capacity of Dire reservoir is 17.62 Mm^3. This indicates that the storage capacity of the reservoir is used only to store the live storage part, excluding the estimated dead storage. This indicates that the storage capacity of the reservoir was overestimated which cannot practically accommodate the estimated storage required.

4.7.2 Demand and Supply Criteria

Domestic water consumption varies according to the mode of services, climatic conditions, socio-economic condition and other related factors. After reviewing previous design criteria in the country, the Ministry of Water, Irrigation and Energy have established the following per capita water consumption criteria. Accordingly, House Connection (HC) in the year 2014 is 120 l/c/day, in 2020 is 150 l/c/day while in year 2030 is estimated to be 150 l/c/day (NICHOLAS O‟DWYER, June 2014). In the design reports carried out in the year 1995 and 2009, there was no any statement, which indicates the number of proposed users and their projections.

In order to increase the capacity of the reservoir, two configurations had been simulated:

- Existing situation
- Re-raising the dam crest by 14m

Setting environmental flow (e-flow): at least 0.15m^3/s or natural inflow discharge, dead Storage: 2 Mm^3 and hydrological year from July to June the following results were obtained:

Table 4-7: Anticipated Dire Dam Operation Simulations

Parameter	Existing situation before raising	Raising Spillway by 2.5m	Anticipated raise of the Dam by 14m
Normal water level(m.a.s.l.)	2554.5	2557	2571
Normal storage(mcm)	19.54	23.5	57.54
Live storage(mcm)	17.54	21.5	55.54
Dead storage(mcm)	2.0	2.0	2.0
Water surface at NWL(km^2)	1.52	1.66	4.81
Estimated inflow(mcm)	41.63	47.75	57.54
Net abstraction(mcm)			41.57
Net loss by evaporation(mcm)	0.64	0.8	7.39
Release for e-flow(mcm)	1.54	1.54	4.73
Seepage loss through embankment and foundation(mcm)	0.9	0.9	1.85*

*Seepage losses have been taken 25% of evaporation losses based on the previous design reports.

Source: Hydrology reports by SEURECA-BRLi-TROPICS, 2009.

The anticipated domestic water demand based on the national standard is depicted in the Table 4-8.

Table 4-8: Anticipated domestic water demand

Scenarios	Net water abstraction(l/day)	Number of Population to be Served		
		Year 2014 (120 l/c/day)	Year 2020 (150 l/c/day)	Year 2030 (150 l/c/day)
Anticipated	113,890,411	949,087	759,269	759,269
Spillway raised by 2.5m	72,712,329	605,936	484,749	484,749
Existing before raising	64,191,781	534,932	427,945	427,945

Source: NICHOLAS O"DWYER, June 2014.

4.8 Uncertainties Related to the Study

There may exists various sources of uncertainties related to this study staring from the quality of the data, uncertainty related to model assumptions itself and uncertainties arise from the level of understanding of the atmospheric chemistry.

Only single out-put of the GCM (HadCM3) and two emission scenarios (A2a and B2a) were used for this study, though other output of GCM and emission scenarios are also existed which can be used for climate change impact studies which is another source of uncertainty. On the other hand, the coarser resolutions of GCMs outputs are not used directly for climate change impact studies. “Downscaling” is a solution towards narrowing the temporal and spatial resolution disparity and hence the SDSM techniques involved in this study were the source of uncertainty because of its difficulties to find good predictors-predictand correlation which is important part in the downscaling process.

The climate change impact on the Dire reservoir is evaluated only by considering the change in precipitation, maximum and minimum temperature. However, in real situation other climatic variables, land use/land cover and sediment inflow to the reservoir will also be changed. Such and other similar characteristics will certainly reduce the reliability of the result.

It has also be noted that, in this study the reservoir capacity was assessed taking only the hydrology of the catchment area under consideration and the criteria set for the demand and supply. It does not address other hydraulic parameters like spillway, dam and its appurtenant structures, etc. due to time constraint.

5. CONCLUSION AND RECOMMENDATION

Generally, from this specific study, the following conclusions and recommendations are forwarded.

5.1 Conclusion

The objective of this study is to assess the climate change impact of Dire Dam Water Supply. In Downscaling of large-scale climate variables from GCM out puts to local scale is very essential in order to investigate the impact of future climate change scenarios on the reservoir. For proper climatic change impact assessment the General Circulation Model (GCM) data was downscaled to station level data by Statistical Downscaling Model (SDSM) based on the observed meteorological variables and generating scenarios for future climate forcing was made. In addition to this, assessing the reservoir capacity and its demand and supply criteria is also very essential to investigate the current status of the reservoir and forward the necessary information‟s to the decision makers. Lastly, by caring out detail hydrological analysis and by integrating the climatic information with the hydrologic model, the impact of climate change and the reservoir capacity were evaluated and the following conclusions had drawn.

The result of climate projection reveals that the SDSM model had very good ability to replicate the historical maximum and minimum temperature for the observed period; but less for the observed precipitation with the simulated precipitation due to its conditional nature and high variability in space.

As it was indicated, both minimum and maximum temperature had increasing trends from the present situation to a twenty-six and two 30 years future periods respectively. The mean annual minimum temperature increases as 1.37, 1.5, 1.8ºC for 2020s, 2050s, and 2080s for HadCM3 A2a scenario. While for HadCM3 B2a scenarios it reaches 1.03, 1.55, 1.78°C for the aforementioned time period. The mean annual maximum temperature increases from the base period by 0.1, 1.22, 1.98°C for 2020s, 2050s, and 2080s respectively for HadCM3 A2a climate scenario. Similarly for HadCM3 B2a climate scenario‟s it increases by 0.085, 0.419, 1.69ºC for 2020s, 2050s and 2080s respectively. According to IPCC report, mean annual global surface temperature has increased by about 0.3-0.6^{O}C since the last 19th century and anticipated to further increase by 1-3.5 ^{O}C over the next 100 years. Such changes in climate will have significant impact on local and regional hydrological regimes, which will in turn affect ecological, social and economic systems.

The projected precipitation shows that mean annual precipitation may have an increasing trend by 4.25%, 12.7% and 17.2% for the corresponding 2020s, 2050s, and 2080s respectively in A2a scenario. In case of B2a scenario, the mean annual precipitation shows varying trends by 5.2%, 10.25% and 0.1% increment for 2020s, 2050s and 2080s time period respectively.

The HBV-6.3 Latest hydrologic model calibration and validation results indicated that the model could simulate historical daily discharge with an acceptable accuracy. The efficiency of the model was good for both calibration and validation periods for which the coefficient of determination (R^2) obtained were about 0.78 and 0.69 respectively.

The hydrological impact of future period scenarios indicated that there would be both an increasing runoff trends for HadCM3A2a and HadCM3B2a climate forcing scenarios. For HadCM3 A2a scenario, the mean annual runoff shows an increasing trend by 21.1%, 21.8% and 19.1% for 2020s, 2050s and 2080s respectively.

In addition, the seasonal percentage changes were increased by 47.98%, 46.65% and 42.81% for 2020s, 2050s and 2080s respectively for the month of June. The results for HadCM3 B2a scenario with mean annual runoff indicates a varying increment by 25.6%, 11.0% and 8.5% for the time period of 2020s, 2050s and 2080s respectively. Regarding to seasonal change, the percentage changes show various trends which were increased by 50.79%, 46.0% and 28.45% for 2020s, 2050s and 2080s respectively for the month of June.

Therefore, there was high variability of runoff as a result of the occurring precipitation variability. As both climatic and hydrologic parameters has strong interacting relations to proceed their cycle, the occurring variability among one of them has significant impact on their sustainability. While the precipitation shows an increasing trend, there exists an increasing runoff and water resources potential too.

The capacity of the reservoir and the surface water potential of the area were under estimated in the previous design reports; mainly due to the limitation of hydrological and meteorological data. This study confirmed that, there is excess surface water potential for Dire catchment (57.54 Mm^3) than previously estimated for the detail design purpose (47.75Mm^3). As per this study, the anticipated populations to be served from this source were estimated at 949,087, 759,269 and 759,269 in the years 2014, 2020 and 2030 respectively, based on the national standard criterion.

5.2 Recommendation

- The results of this study are based on the outputs of a single GCM and only two emission scenarios. However, it is recommended to use different GCM outputs and emission scenarios to compare the results of different models and explore a wide range of climate change scenarios that would result different hydrological impacts. Meanwhile, the GCM was downscaled to a catchment level only using statistical downscaling model which is a regression based model, even though other methods exists which are used for climate change impact assessment. Thus, this study should be extended in the future considering other downscaling methods.

- To bring the global climatic information into finer scale, the statistical downscaling model was applied under this study. Other downscaling techniques for instance dynamical downscaling technique should be practiced additional to test comparability.

- This study focused mainly on climatic variables, for instance temperature, precipitation and evapotranspiration to arrive at the point of climate forcing on the hydrologic cycle of the catchment. Further study should be undertaken on other related parameters like land use-land cover.

- The results obtained from this study addressed that the catchments exist under the climate change impacts and was sensitive for this impacts. Therefore, the decision makers, planners and other stakeholders should design strategies to ensure the sustainability of the catchment hydrology for the sake of protecting the yield of the reservoir and every development activities for instance agricultural and other related activities within the catchment and also downstream of the projects.

- There is excess surface water potential for the catchments under caption. This is a clue to the decision makers to understand the issue and design strategies to use this additional water for the city.

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7. APPENDIXES

Appendix 1: Calculated potential evapo-transpiration of the study area using Penman Monteith method (using CROWAT-8.0)

Month	Min Temp	Max Temp	Humidity	Wind	Sunshine	Radiation	ETo	Days	ETo
	°C	°C	%	m/s	hours	MJ/m²/day	mm/day		mm/Month
January	8.8	23.9	58	0.6	9.4	21.3	3.21	31	99.51
February	9.7	24.9	56	0.8	9.2	22.3	3.63	29	105.27
March	10.6	25.8	57	0.6	8.3	22.1	3.82	31	118.42
April	12	25.4	64	0.6	7.1	20.4	3.79	30	113.7
May	12.2	24.9	61	0.7	7.5	20.5	3.83	31	118.73
June	11.6	22.9	70	0.3	5.7	17.6	3.26	30	97.8
July	11.7	21	79	0.3	3.6	14.6	2.82	31	87.42
August	11.8	20.6	80	0.2	3.8	15.1	2.8	31	86.8
September	11.3	21.6	74	0.4	5.4	17.6	3.13	30	93.9
October	9.5	23.4	60	0.6	8.7	21.7	3.3	31	102.3
November	7.8	22.9	60	0.7	9.3	21.3	3.21	30	96.3
December	6.7	22.8	58	0.6	9.1	20.4	3.07	31	95.17
Average	**10.3**	**23.3**	**65**	**0.5**	**7.2**	**19.6**	**3.32**		**101.28**

Appendix 2: Daily average maximum temperature in °C for Addis Ababa station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1983	22.97	24.04	24.61	24.18	23.97	23.69	22.76	20.61	21.57	22.11	22.68	22.18
1984	23.17	24.41	25.63	26.75	24.29	22.08	20.38	21.66	21.39	22.97	23.20	22.51
1985	23.44	23.95	24.96	22.90	23.54	23.34	20.12	20.04	21.42	22.20	23.00	22.89
1986	23.54	24.13	24.07	22.47	24.17	21.79	21.14	21.30	21.64	22.67	23.10	23.10
1987	22.89	24.36	23.22	23.65	23.85	22.68	22.01	21.85	23.10	23.79	24.03	24.30
1988	24.73	25.03	27.38	25.11	25.83	23.47	20.93	21.10	21.16	21.93	22.46	22.84
1989	22.69	23.15	24.42	22.95	24.85	23.61	20.70	21.20	21.59	22.78	23.09	22.82
1990	23.99	23.24	23.88	23.56	25.26	23.54	21.39	21.35	21.93	23.05	23.47	23.58
1991	24.99	24.80	25.57	25.61	25.85	24.37	21.29	21.05	21.99	23.09	22.73	22.89
1992	22.45	23.53	25.72	25.77	26.23	23.88	21.01	19.67	20.97	21.91	22.11	23.06
1993	23.44	23.31	26.38	23.96	23.81	22.66	20.93	21.12	21.17	22.88	22.96	23.52
1994	24.43	25.73	25.91	26.08	26.72	23.13	21.17	20.80	21.96	23.32	23.47	23.48
1995	24.20	25.44	25.09	23.82	25.16	24.49	20.88	21.53	22.38	23.83	23.96	23.92
1996	23.58	26.38	24.90	24.70	24.37	21.09	20.87	21.43	22.11	23.62	23.26	23.05
1997	23.40	25.16	26.02	24.54	26.90	24.93	21.74	21.90	23.27	23.10	23.26	24.19

1998	24.31	25.01	25.40	26.59	25.20	24.71	22.26	21.87	21.91	22.25	22.75	23.20
1999	24.66	26.74	25.47	27.61	26.86	24.69	20.53	20.63	22.10	21.85	22.65	22.72
2000	24.66	25.47	27.33	25.68	25.39	23.07	21.46	20.55	21.07	22.55	22.91	23.76
2001	23.53	25.15	23.98	25.55	24.35	22.47	21.47	20.98	22.93	24.66	24.23	24.17
2002	24.17	26.22	25.69	26.73	27.00	24.86	23.02	21.75	22.41	24.34	24.28	23.75
2003	24.39	26.19	26.33	25.05	26.78	24.45	21.16	20.77	21.87	23.69	23.60	23.34
2004	25.07	25.12	25.43	23.86	26.80	24.46	21.49	21.52	22.23	22.30	23.70	24.05
2005	24.08	26.55	26.42	25.94	24.07	23.42	21.09	22.15	22.39	23.64	22.88	22.96
2006	23.80	24.97	24.51	24.30	25.06	23.11	20.76	20.08	21.85	24.18	23.54	22.84
2007	23.61	24.67	25.93	24.38	25.01	22.39	20.75	20.19	20.96	22.36	22.93	22.56
2008	24.14	24.29	26.35	25.89	25.51	22.84	21.15	20.72	21.91	23.40	22.20	22.88
2009	23.16	25.20	27.04	25.87	26.37	26.03	20.91	20.81	22.56	22.55	23.23	22.00
2010	23.39	23.67	23.65	24.43	24.08	23.29	20.89	20.93	21.89	24.11	22.87	22.77
2011	23.68	25.43	24.65	24.43	24.93	23.73	21.79	20.73	21.48	24.20	23.48	22.75
2012	24.53	25.52	26.73	24.67	26.48	24.04	21.20	20.67	22.00	23.91	24.43	22.75
2013	24.53	26.26	26.30	26.00	25.11	23.27	21.33	20.84	22.70	23.24	23.90	23.37

Appendix 3: Daily average minimum temperature in °C for Addis Ababa station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1983	6.60	10.40	11.70	11.41	11.30	10.36	10.20	11.37	10.67	8.56	6.60	5.36
1984	4.75	4.44	9.82	10.42	11.97	11.05	10.70	10.27	9.54	6.03	6.15	5.21
1985	5.17	9.53	10.48	12.04	11.10	10.22	11.37	11.50	10.05	8.31	6.28	7.85
1986	4.39	9.80	9.25	11.45	10.29	9.57	7.99	7.55	6.47	3.68	5.14	6.32
1987	5.99	8.59	11.26	10.31	10.84	10.16	10.99	11.14	10.46	8.37	5.81	5.76
1988	7.44	10.85	9.57	11.51	10.16	10.35	11.65	11.20	10.36	8.11	3.80	4.68
1989	5.49	8.16	9.86	10.69	9.34	9.75	10.77	10.62	9.78	8.43	5.76	8.35
1990	6.06	10.88	9.91	10.62	9.89	9.77	10.81	10.95	10.49	7.55	6.60	4.70
1991	8.10	9.59	11.23	11.04	10.77	10.77	11.54	11.15	10.29	7.20	5.37	6.11
1992	8.62	10.03	10.75	10.68	10.52	9.79	10.49	11.63	9.72	8.15	6.23	7.47
1993	8.32	9.28	8.67	11.37	10.80	10.35	11.05	10.80	10.13	8.28	5.46	4.77
1994	4.97	7.34	10.65	10.85	10.93	10.87	11.59	11.18	9.62	6.96	6.66	4.95
1995	5.17	9.53	10.48	12.03	11.10	10.22	11.37	11.50	10.05	8.37	6.26	7.85
1996	8.86	7.74	11.06	10.49	11.08	11.34	11.11	10.98	9.81	7.08	6.29	5.72
1997	9.30	6.06	10.31	11.15	11.11	11.69	11.35	11.54	10.61	10.04	6.29	6.57
1998	9.77	11.66	12.03	12.07	12.60	11.19	11.75	12.29	11.01	9.09	4.65	3.37
1999	6.67	7.28	10.29	10.40	10.53	10.30	10.53	10.40	9.88	9.20	5.41	5.59
2000	6.67	5.84	10.24	12.14	11.09	10.14	11.05	10.79	10.63	8.86	6.83	8.89
2001	6.79	7.78	10.83	10.94	11.28	10.45	11.13	11.63	9.82	8.61	5.90	6.44
2002	7.66	8.50	10.85	11.44	11.79	10.76	11.22	10.90	10.50	8.92	6.51	9.55
2003	8.49	9.91	10.30	11.83	11.44	10.91	11.45	11.88	11.43	8.16	7.44	6.09

2004	9.89	8.67	10.26	11.92	11.06	11.21	11.39	11.50	10.92	8.28	7.08	7.82
2005	8.49	8.63	11.18	11.69	12.11	11.05	11.52	11.84	11.54	8.68	7.39	5.82
2006	9.10	10.99	11.17	12.20	11.88	11.76	11.86	11.93	11.05	10.33	8.67	8.57
2007	9.44	10.68	10.99	12.01	12.36	11.83	12.14	11.82	11.80	9.32	7.58	5.60
2008	8.04	8.44	9.13	12.02	12.36	11.78	11.35	11.48	10.98	9.81	7.77	6.81
2009	8.96	9.73	11.44	11.83	12.37	12.12	11.96	11.98	11.48	9.83	7.68	10.11
2010	8.91	11.63	11.73	12.63	13.19	12.01	11.88	12.46	11.50	10.08	8.36	8.07
2011	9.27	9.00	10.96	12.63	12.76	12.31	12.04	12.29	11.89	9.28	10.52	7.30
2012	8.02	8.50	10.71	12.21	12.68	12.23	12.12	11.88	11.72	9.90	9.47	7.30
2013	9.28387	10.4321	13.0226	13.22	12.8452	12.1433	11.9129	11.9839	11.3552	10.5094	9.76333	7.90323

Appendix 4: Daily average minimum temperature in °C for Intoto station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1989	6.62	7.86	9.05	8.61	9.80	8.52	8.01	7.84	8.61	7.65	7.50	7.33
1990	7.20	9.05	8.78	9.51	10.16	8.54	7.86	8.10	8.50	8.26	8.35	7.39
1991	8.63	8.84	9.03	9.95	10.13	9.44	8.72	8.36	8.65	8.22	7.29	7.66
1992	7.38	7.79	7.69	7.58	9.70	8.54	8.19	7.55	5.96	5.62	5.58	6.16
1993	8.37	9.49	9.68	9.85	11.15	9.13	8.63	8.96	9.00	8.68	7.85	7.28
1994	8.36	8.54	9.57	9.96	10.27	8.84	8.74	8.69	9.00	8.41	7.79	7.47
1995	8.22	9.26	9.55	9.75	10.30	10.08	8.72	8.90	9.13	8.47	8.13	8.22
1996	8.05	9.00	9.23	9.79	9.98	8.78	8.16	8.45	8.93	8.24	7.90	7.71
1997	8.53	7.97	10.02	9.50	9.81	9.57	8.69	8.70	9.55	9.06	8.46	7.85
1998	9.18	10.00	10.77	11.04	10.98	9.76	8.91	8.95	9.12	8.87	8.00	7.39
1999	7.88	9.63	9.25	9.69	10.11	9.03	7.56	8.13	8.87	8.58	7.06	7.22
2000	8.02	8.64	9.07	9.26	9.77	8.78	8.05	8.23	8.86	8.25	7.73	7.63
2001	7.44	8.59	8.75	9.73	9.71	8.54	8.15	9.00	9.13	8.67	7.48	7.86
2002	7.53	9.42	9.43	9.54	10.31	8.96	8.71	8.35	8.99	8.83	8.10	8.57
2003	8.37	9.49	9.68	9.85	11.15	9.13	8.63	8.96	9.00	8.68	7.85	7.26
2004	8.99	8.33	8.91	9.64	10.41	9.13	8.25	8.77	8.84	8.06	7.59	7.68
2005	7.91	9.39	9.69	9.80	9.53	8.96	8.88	8.89	8.87	8.05	7.26	7.20
2006	7.99	9.02	9.06	9.51	10.07	8.69	8.99	8.71	8.95	8.55	8.05	7.42
2007	7.71	8.84	9.59	9.89	9.99	8.85	8.60	8.24	8.96	7.97	7.26	6.84
2008	7.77	7.59	8.99	9.30	9.63	8.92	8.12	8.32	8.98	8.29	7.28	6.88
2009	8.05	8.74	9.46	9.60	10.25	9.52	8.32	8.96	9.00	8.68	7.85	7.25
2010	8.03	9.04	9.26	9.12	9.53	9.11	8.41	8.78	8.91	8.58	8.03	7.41
2011	7.84	8.20	8.96	9.77	10.06	9.50	8.13	8.54	9.15	8.30	8.60	8.52
2012	8.92	8.07	9.56	8.77	10.14	9.66	7.86	8.15	8.58	7.97	7.26	6.85
2013	8.70	9.99	9.91	10.04	10.10	8.77	6.87	7.12	8.56	9.08	8.05	8.58

Appendix 5: Daily average maximum temperature in °C for Intoto station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1989	18.30	18.23	19.26	17.16	19.84	17.47	15.57	16.56	17.46	18.06	19.28	17.08
1990	19.68	18.53	19.53	19.56	20.89	18.59	16.67	16.24	17.32	16.35	18.84	19.34
1991	19.90	19.49	19.32	19.89	20.55	19.07	15.96	16.29	17.28	18.95	18.96	18.86
1992	19.25	19.13	20.21	19.42	19.19	18.21	15.56	14.50	15.81	16.89	16.94	17.87
1993	17.83	17.85	20.50	17.51	17.96	16.56	15.56	15.23	15.15	17.10	17.76	18.28
1994	19.16	20.30	19.53	19.70	20.15	17.09	15.34	15.36	16.34	18.17	17.90	18.42
1995	19.35	19.53	19.67	17.79	19.34	18.84	15.53	15.63	16.50	18.38	18.96	18.50
1996	17.55	20.78	19.18	18.93	18.55	16.24	15.97	15.27	16.24	17.84	17.67	18.04
1997	18.19	19.79	20.59	18.78	20.71	18.76	15.97	16.37	17.71	17.89	17.23	18.76
1998	19.05	20.06	20.07	21.10	19.53	18.57	15.93	15.95	16.39	16.95	18.13	18.22
1999	18.90	21.03	19.78	20.87	20.44	18.80	15.71	15.91	16.51	16.35	17.74	18.29
2000	19.20	21.10	19.80	20.85	21.45	19.21	17.70	16.48	17.71	19.51	20.39	18.98
2001	19.55	21.31	18.36	20.26	19.57	17.14	16.61	16.74	18.15	18.71	19.40	19.82
2002	19.20	21.06	19.80	20.85	21.45	19.21	17.70	16.48	17.71	19.51	20.39	18.98
2003	19.89	21.66	20.85	20.02	21.97	18.96	15.96	16.58	16.68	19.42	19.86	19.53
2004	20.33	20.59	21.57	19.29	21.46	18.22	16.60	16.66	17.35	17.86	19.98	20.25
2005	20.21	23.01	21.94	21.70	19.15	18.69	15.97	17.32	17.75	19.60	20.17	20.47
2006	21.07	21.87	20.76	19.26	20.22	18.21	16.35	16.46	17.17	19.35	20.29	20.04
2007	21.07	21.33	22.50	20.42	20.84	18.16	16.21	16.22	16.75	19.20	20.31	20.38
2008	16.41	18.96	17.87	17.35	16.24	15.38	14.35	14.47	15.21	16.51	15.48	15.74
2009	15.48	17.26	17.34	16.22	19.61	18.69	15.07	16.48	17.71	19.51	20.39	18.98
2010	16.77	16.94	17.26	17.19	17.62	16.11	14.28	14.17	14.98	17.77	17.44	17.06
2011	18.21	19.09	18.98	20.28	18.86	17.38	16.15	14.77	16.47	18.79	16.78	16.05
2012	18.97	20.59	21.32	17.87	18.19	17.58	14.68	14.35	14.05	18.38	18.96	18.50
2013	18.70	20.39	20.32	19.29	19.13	17.57	15.00	13.47	17.23	16.15	18.21	19.03

Appendix 6: Daily total precipitation in mm for Addis Ababa station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1983	12.4	41.2	28.9	113.7	186.9	56.1	217.9	213.7	202.2	35.9	0	1.5
1984	0	0.4	11.6	11.6	135	334.2	317.9	180.4	98.8	0	0	7
1985	35.1	0	49.1	132.3	92.8	110.9	209.8	260.8	168.6	29.8	0	35.1
1986	0	37.6	56.2	216.6	37.7	175.2	167.9	222.3	107.4	31.6	0	2.5
1987	0	49.1	180.1	85.7	154.6	71.9	155.9	98.1	57	16.6	0	0
1988	4.7	33.4	6.7	157.9	34.7	93.2	181.4	265.3	187.3	57.3	0	0
1989	3.4	33.7	58.4	143.3	0	88.1	218.1	318.6	150	36.8	0	3.2
1990	3.2	161.1	60.4	144.5	25.2	48.3	194.2	293.6	143	46.1	2.1	3.2
1991	0.2	29.6	134.1	15	7.7	107.5	279.4	287.9	123.1	4.4	0.2	29.6

1992	14.5	28	35	58.6	55	82.2	254.8	223.3	157	64.4	2.2	0.4
1993	11.7	52.1	11.6	168.3	91.5	157.2	209.5	291.7	190.1	24.1	0	0
1994	0	0	52.9	70	29	112.4	242.3	199.3	99.4	0.5	11	0
1995	0	81.3	73.1	133.3	95.9	77.4	165.5	256.9	97	0	0	29.3
1996	20.5	15.8	134.4	96	124.6	290.2	346.3	312.7	211.4	0.2	0.4	20.5
1997	29.1	0	22.1	66.8	44.8	128	257	160.7	94.7	58.6	15.3	29.1
1998	66.6	40	43.8	99.8	197.7	111.6	270.7	236.8	173.4	139.4	0	0
1999	4.4	0	35	17.8	30.5	104.6	294	270.5	62.8	127.1	0	0
2000	0	0	17.6	87.8	95.2	102.1	192.9	221.9	157.5	19.6	7.5	0
2001	0	10.3	174.3	14.8	116.7	166	289.4	207.3	113.3	10.6	0	0
2002	30.6	25.9	79.4	36.6	49.6	115.5	213.9	233.6	72.6	0.5	0	30.6
2003	4.8	34.1	48.9	111.5	18	111	204.3	238.4	130.2	4.6	0	33.3
2004	26.1	11.7	32.4	108.027	7	114.5	240.6	230.1	122.1	50	26.1	11.7
2005	55.4	14.1	41.8	116.2	164.6	159.1	174.3	248	77.6	25.8	7.2	0
2006	2	36.6	107.8	93.9	37.8	115.1	313.2	331.1	132.5	35.9	0	0
2007	9.9	21.3	61.1	86.8	134	157.6	191.3	305.4	130.9	37.2	0.1	0
2008	0	0	0	34	75.3	73.1	295.1	259.1	192.7	22.2	53.1	0
2009	40.9	0	12.4	46.1	52	77.5	238.2	269.5	86.1	42.4	40.9	0
2010	0.4	115.2	75.6	159.5	94.7	107.2	320.2	138.8	105	0	13.8	15.7
2011	3.4	13.6	27.9	75.1	86	148	183.1	296.5	141.3	0	11.9	0
2012	0	0	34.5	63.8659	58.5	72.8	228.8	281.6	176.9	1.2	0	0.2
2013	0	0	63.5	114.4	78.5	101.4	157.6	270.2	126.7	45.3	3.2	0

Appendix 7: Daily total precipitation in mm for Intoto station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1989	4	76	105.4	133.3	5.8	98.2	409.5	323.4	293.9	11.7	0	14.5
1990	0	156.6	42.8	117.9	17.6	100.5	324.5	499.7	180.8	58.524	1.5	0
1991	12.8	64.9	156.2	37.5	39	171.2	258.5	395.2	146.7	1.4	0	44.2
1992	52.7	31.5	14.6	42.7	84.6	131.6	247.8	387	188.4	42.4	0.7	8.1
1993	15.3	44.6	5.7	147.5	49	123.3	266.1	407.6	183.2	28.7	0	0
1994	0	0	62.2	56	91	154.8	336.3	307.2	142.5	0.3	24.4	0
1995	0	96.3	29.7	186.1	83.7	98	297	222.1	133.7	5	0.2	22.7
1996	31.1	12.2	121.6	78.3	95.2	242.7	387.2	493.9	184.7	1.2	0.6	0
1997	21.2	0	18.6	77.3	27.4	77.2	256.3	240.8	89.3	88.3	90	0.2
1998	25.3	25.3	45.2	47	149.5	149.2	369	376.3	204.8	44.5	0	0
1999	15.8	6.3	34.9	25.4	37	127.7	283.1	280.3	105	58	0.2	0
2000	0	0	5.2	108	91.4	110.7	303.8	359.1	132.8	17.2	33.5	1.7
2001	20.6	5.5	147.5	29.8	141.7	164.3	285.6	321.4	92.5	52.4	0	1.8
2002	17.9	50.4	88.8	67.4	49.2	138.7	293.1	262.9	92.1	10.7	0	28
2003	5.2	47.7	57.1	117.3	13.9	188	370.8	248.9	141.1	0	6.3	25.6

2004	28.8	31.3	46.7	124.6	13.8	166	271.9	334.7	124.8	49.7	1.1	1.6
2005	8.3	11.4	42.8	98.6	143.9	106.4	241.8	339.3	134.4	19.6	8.2	0
2006	0.9	19.1	93.8	66.5	79.1	131.5	371.1	311.5	128.7	36.1	0.6	16.5
2007	38.6	16.2	36.4	52.1	106.4	246.7	272.1	322.6	87	16.4	0	0
2008	0	9.3	1.5	74.8	45.3	142.5	399.3	359.5	190.6	50.1	95.1	0.5
2009	10.9	3.3	19.9	40.1	28.2	127.7	321.7	317.87	108.171	49.6	45.4	0
2010	9.5	73.4	79.4	71.2	107.9	235.2	388.8	288.6	173.2	1.8	0	11.9
2011	0	0	50.3	51.7	180.8	185.5	248.71	352.18	203.7	16	73.5	11.6
2012	0	0	0	79.5	77.1	133.2	363	366.3	242.7	1.6	0	0.24
2013	12.2	59.8	59.8	128.8	82.1	164.6	364.3	462.2	156.8	64.3	10.7	0.2

Appendix 8: Mutincha daily average discharge value in (cumecs) at Beke Station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1986	0.012	0.018	0.053	0.317	0.069	0.339	2.905	4.065	1.89	0.107	0.035	0.026
1987	0.023	0.021	0.095	0.058	0.18	0.22	0.885	1.683	0.182	0.043	0.01	0.01
1988	0.007	0.013	0.003	0.016	0.008	0.013	3.373	8.024	3.434	0.155	0.026	0.016
1989	0.016	0.014	0.01	0.131	0.012	0.007	0.949	7.145	1.65	0.09	0.019	0.017
1990	0.011	0.058	0.015	0.055	0.019	0.021	0.895	14.439	1.057	0.107	0.018	0.009
1991	0.006	0.006	0.015	0.002	0	0.527	5.445	12.717	2.621	0.046	0.019	0.013
1992	0.017	0.108	0.007	0.012	0.058	0.089	1.294	8.871	4.842	0.413	0.053	0.029
1993	0.024	0.041	0.012	0.034	0.026	0.036	4.671	5.732	4.739	0.163	0.015	0.004
1994	0.032	0.023	0.026	0.022	0.016	0.043	7.548	18.594	2.052	0.099	0.017	0.011
1995	0.004	0.006	0.04	0.022	0.008	0.007	2.488	10.926	1.022	0.057	0.03	0.024
1996	0.04	0.012	0.029	0.016	0.035	0.12	7.407	10.625	1.557	0.119	0.049	0.019
1997	0.028	0.01	0.01	0.022	0.004	0.098	3.841	2.968	0.168	0.029	0.02	0.008
1998	0.015	0.011	0.005	0	0.024	0.079	7.831	13.709	2.677	0.559	0.093	0.053
1999	0.045	0.033	0.04	0.015	0.015	0.046	4.912	8.36	2.062	0.205	0.059	0.037
2000	0.058	0.072	0.14	0.563	0.171	0.516	3.296	4.858	2.533	0.236	0.109	0.092
2001	0.025	0.021	0.052	0.04	0.1	0.102	4.728	4.415	0.634	0.066	0.033	0.023
2002	0.028	0.018	0.031	0.018	0.015	0.031	3.649	6.379	1.725	0.186	0.103	0.113
2003	0.197	0.083	0.038	0.579	0.029	0.403	4.228	5.179	2.009	0.096	0.041	0.102
2004	0.036	0.033	0.028	0.070	0.020	0.090	3.149	9.574	2.096	0.332	0.138	0.095
2005	0.101	0.067	0.122	0.113	1.207	0.42	3.56	5.601	1.271	0.133	0.057	0.056
2006	0.03	0.033	0.033	0.197	0.031	0.122	3.133	5.22	1.441	0.048	0.006	0.002
2007	0.027	0.020	0.037	0.013	0.247	0.150	9.743	12.663	5.360	0.163	0.027	0.012
2008	0.038	0.026	0.018	0.178	0.031	0.433	6.679	15.926	3.867	0.152	0.002	0.015
2009	0.032	0.099	0.016	0.129	0.019	0.130	2.043	9.459	1.774	0.048	0.074	0.059
2010	0.008	0.002	0.017	0.153	0.165	0.120	4.442	16.288	2.507	0.194	0.003	0.012
2011	0.044	0.036	0.076	0.416	0.138	0.415	3.083	16.416	2.176	0.313	0.056	0.012
2012	0.014	0.029	0.051	0.147	0.031	0.356	7.260	11.076	0.353	0.189	0.082	0.088

2013	0.074	0.029	0.049	0.195	0.139	0.484	6.519	6.080	0.950	0.222	0.061	0.059
Mean	0.036	0.033	0.038	0.110	0.097	0.159	3.818	8.052	1.984	0.157	0.045	0.036
SD	0.043	0.028	0.037	0.171	0.259	0.173	2.053	4.247	1.233	0.134	0.037	0.035

Appendix 9: Flow data used for correlation analysis

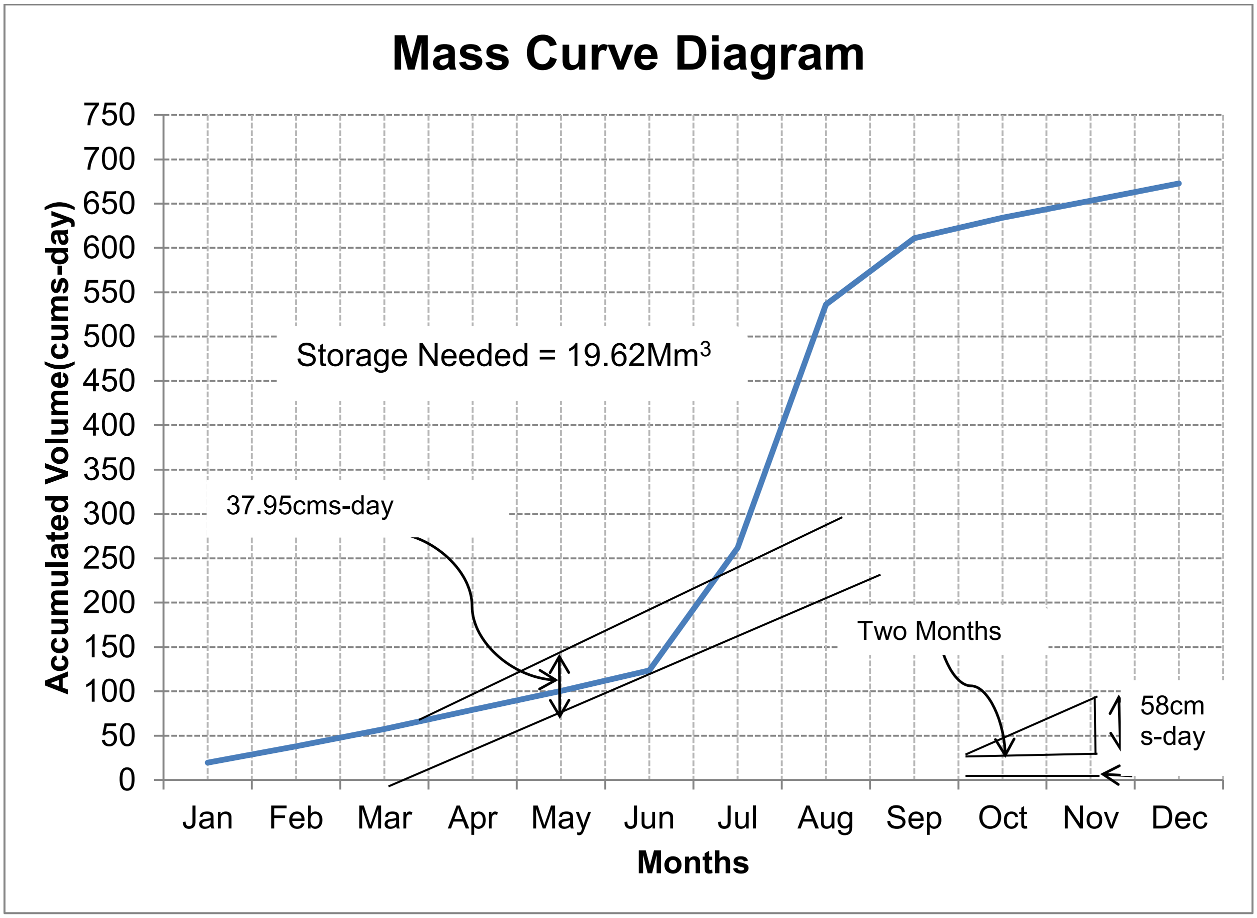
	Q Beke	Q Dire	Remark
13-31 Aug 1993	7.02	7.19	Q Dire: gauged at Dam site before dam construction
Sept-93	4.739	4.368	
Oct-93	0.163	0.466	
Nov-93	0.015	0.089	
Dec 1993	0.004	0.088	
Jan-94	0.032	0.0586	
Feb 1994	0.023	0.042	
mars-94	0.026	0.043	
Apr 1994	0.022	0.122	
May-94	0.016	0.051	
July 2002	3.65	4.25	Q Dire: estimated from water balance at Dire dam
1-14 Aug 2002	7.62	6.01	
July 2003	4.23	5.78	
July 2004	3.15	2.95	
1-15 Aug 2004	10.76	8.34	
July 2005	3.56	3.97	
July 2006	4.14	6.68	
Average	**2.89**	**2.97**	

Appendix 10: Inflow discharge at Dire Dam estimated from hydrometric data at Beke station

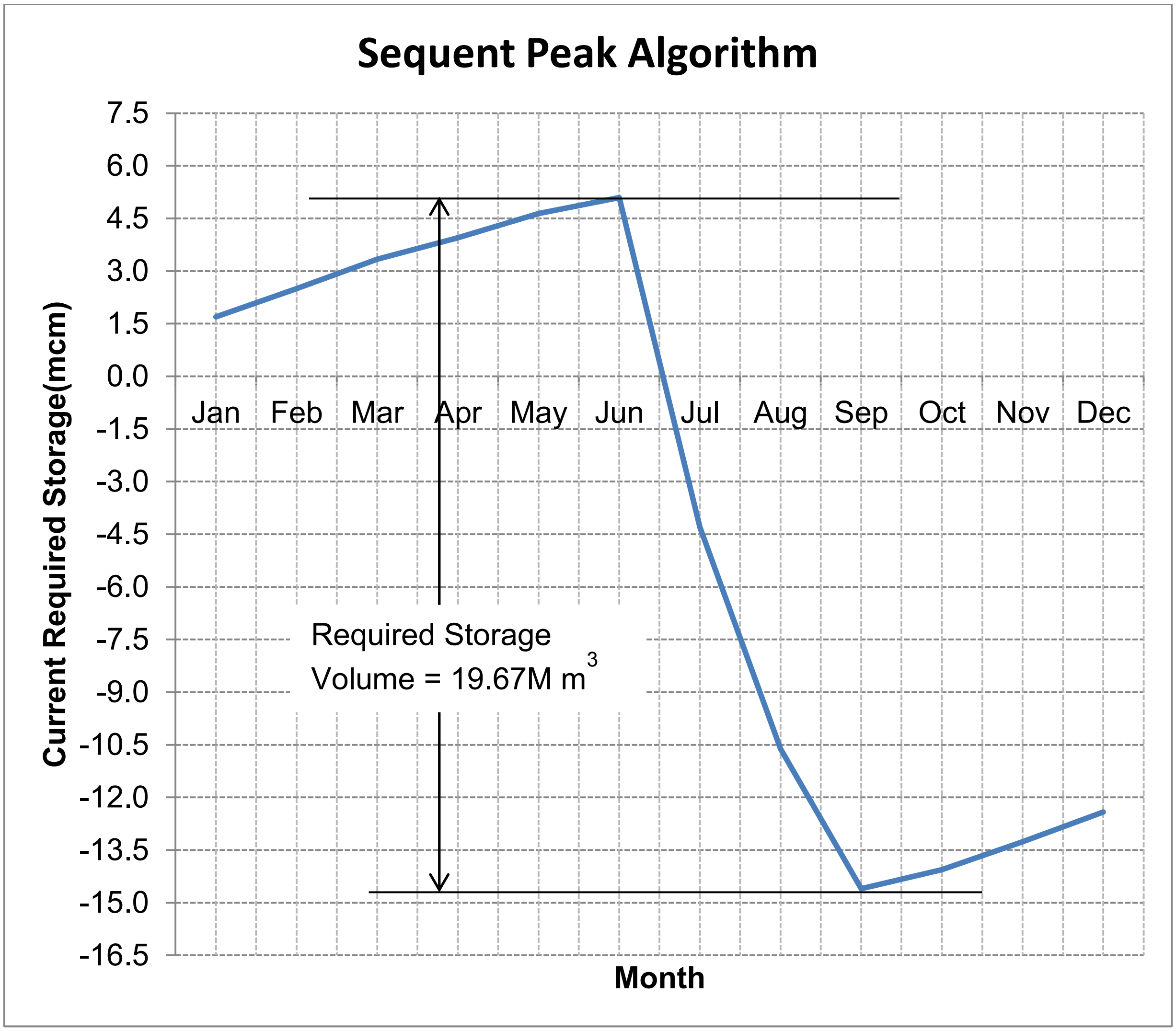
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
1986	0.61	0.62	0.65	0.89	0.66	0.91	3.21	4.26	2.30	0.70	0.63	0.62	**1.34**
1987	0.62	0.62	0.69	0.65	0.76	0.80	1.40	2.11	0.76	0.64	0.61	0.61	**0.86**
1988	0.61	0.61	0.60	0.61	0.61	0.61	3.64	7.82	3.69	0.74	0.62	0.61	**1.73**
1989	0.61	0.61	0.61	0.72	0.61	0.61	1.45	7.03	2.09	0.68	0.62	0.62	**1.35**
1990	0.61	0.65	0.61	0.65	0.62	0.62	1.41	13.60	1.55	0.70	0.62	0.61	**1.85**
1991	0.61	0.61	0.61	0.60	0.60	1.07	5.50	12.05	2.96	0.64	0.62	0.61	**2.21**
1992	0.62	0.70	0.61	0.61	0.65	0.68	1.76	8.58	4.96	0.97	0.65	0.63	**1.78**
1993	0.62	0.64	0.61	0.63	0.62	0.63	4.80	5.76	4.87	0.75	0.61	0.60	**1.76**
1994	0.63	0.62	0.62	0.62	0.61	0.64	7.39	17.33	2.45	0.69	0.62	0.61	**2.74**
1995	0.60	0.61	0.64	0.62	0.61	0.61	2.84	10.43	1.52	0.65	0.63	0.62	**1.70**

1996	0.64	0.61	0.63	0.61	0.63	0.71	7.27	10.16	2.00	0.71	0.64	0.62	**2.10**
1997	0.63	0.61	0.61	0.62	0.60	0.69	4.06	3.27	0.75	0.63	0.62	0.61	**1.14**
1998	0.61	0.61	0.60	0.60	0.62	0.67	7.65	12.94	3.01	1.10	0.68	0.65	**2.48**
1999	0.64	0.63	0.64	0.61	0.61	0.64	5.02	8.12	2.46	0.78	0.65	0.63	**1.79**
2000	0.65	0.66	0.73	1.11	0.75	1.06	3.57	4.97	2.88	0.81	0.70	0.68	**1.55**
2001	0.62	0.62	0.65	0.64	0.69	0.69	4.86	4.57	1.17	0.66	0.63	0.62	**1.37**
2002	0.63	0.62	0.63	0.62	0.61	0.63	3.88	6.34	2.15	0.77	0.69	0.70	**1.52**
2003	0.78	0.67	0.63	1.12	0.63	0.96	4.41	5.26	2.41	0.69	0.64	0.69	**1.57**
2004	0.63	0.63	0.63	0.66	0.62	0.68	3.43	9.22	2.49	0.90	0.72	0.69	**1.77**
2005	0.69	0.66	0.71	0.70	1.69	0.98	3.80	5.64	1.74	0.72	0.65	0.65	**1.55**
2006	0.63	0.63	0.63	0.78	0.63	0.71	3.42	5.30	1.90	0.64	0.61	0.60	**1.37**
2007	0.62	0.62	0.63	0.61	0.82	0.73	9.37	12.00	5.42	0.75	0.62	0.61	**2.73**
2008	0.63	0.62	0.62	0.76	0.63	0.99	6.61	14.93	4.08	0.74	0.60	0.61	**2.65**
2009	0.63	0.69	0.61	0.72	0.62	0.72	2.44	9.11	2.20	0.64	0.67	0.65	**1.64**
2010	0.61	0.60	0.61	0.74	0.75	0.71	4.60	15.26	2.86	0.78	0.60	0.61	**2.39**
2011	0.64	0.63	0.67	0.97	0.72	0.97	3.37	15.37	2.56	0.88	0.65	0.61	**2.34**
2012	0.61	0.63	0.65	0.73	0.63	0.92	7.13	10.57	0.92	0.77	0.67	0.68	**2.08**
2013	0.67	0.63	0.64	0.78	0.72	1.04	6.47	6.07	1.45	0.80	0.65	0.65	**1.71**
Mean	**0.63**	**0.63**	**0.63**	**0.71**	**0.69**	**0.77**	**4.46**	**8.86**	**2.49**	**0.75**	**0.64**	**0.63**	**1.82**

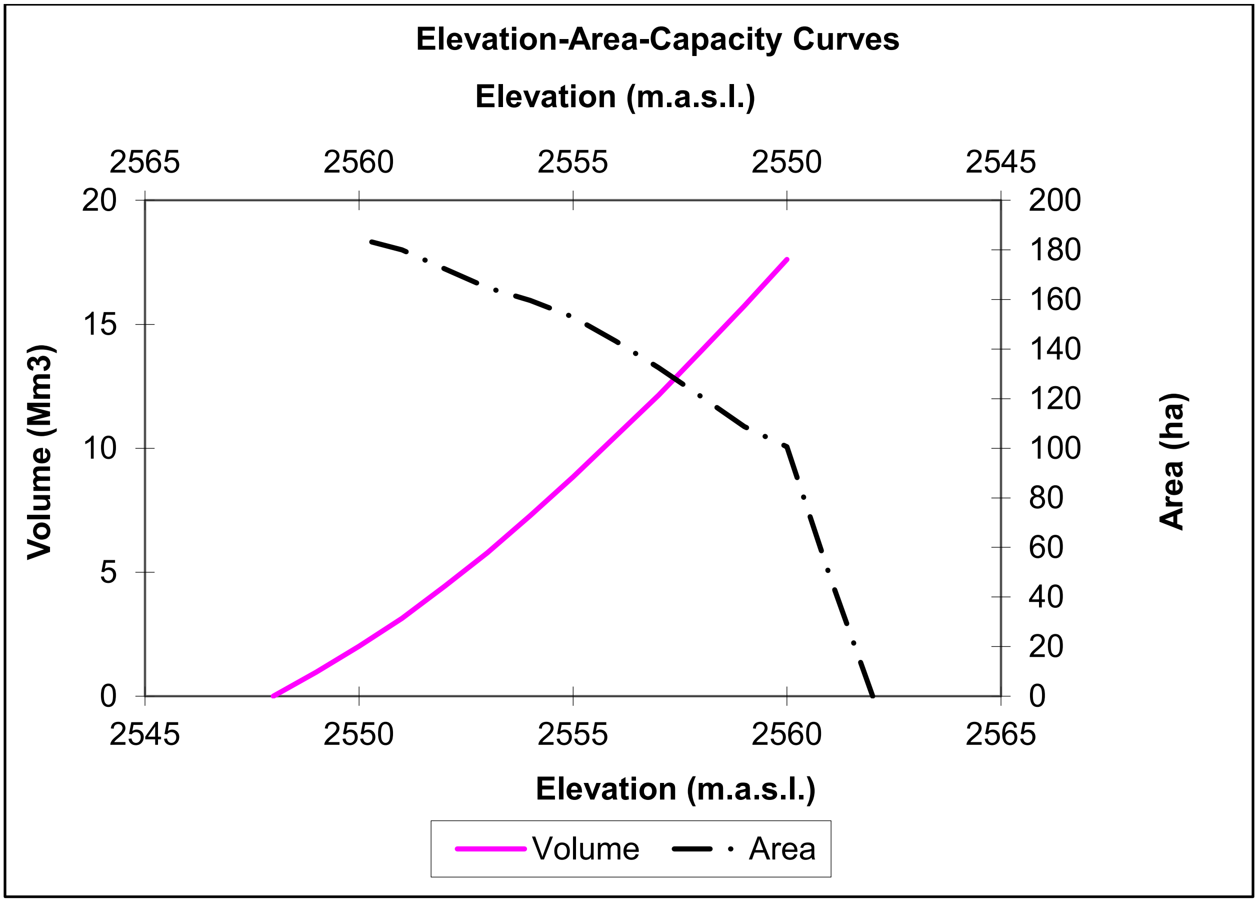
Appendix 11: Reservoir mass curve analysis, sequent peak algorithm diagrams & elevation-area-capacity curve



Mass curve diagram approach



Sequent peak algorithm approach



Elevation-Area-Capacity curve

Appendix 12: Temperature analyzed from daily records of Intoto station for the period 1988-2013

Month	**Min. T° (°C)**	**Max. T° (°C)**	**Mean (°C)**
Jan	8.11	18.87	13.48
Feb	8.90	20.00	14.45
Mar	9.37	19.87	14.62
Apr	9.66	19.33	14.48
May	10.12	19.72	14.92
Jun	9.07	17.95	13.51
Jul	8.32	15.86	12.09
Aug	8.47	15.76	12.11
Sep	8.74	16.68	12.71
Oct	8.31	18.08	13.19
Nov	7.67	18.68	13.16
Dec	7.22	18.60	13.01

Appendix 13: Computed potential evapotranspiration by Hargreaves method

Month	ETo(mm/day)	Days	ETo(mm/month)
Jan	3.01	31	93.43
Feb	3.43	29	99.35
Mar	3.62	31	112.31
Apr	3.59	30	107.80
May	3.63	31	112.47
Jun	3.31	30	99.34
Jul	2.92	31	90.64
Aug	2.90	31	89.93
Sep	3.03	30	90.85
Oct	3.20	31	99.26
Nov	3.11	30	93.34
Dec	2.97	31	92.20

Appendix 14: Photos from field visit

Newly constructed spillway (2.5m height from the crest of the existing spillway)

Existing spillway about 200m downstream of the new spillway

Current feature of Dire reservoir