RESERVOIR SIMULATION OF THE MULTIPURPOSE PROJECT UNDER CHANGING CLIMATE: A CASE STUDY OF KANKAI MULTIPURPOSE PROJECT, NEPAL

A DISSERTATION

Submitted in partial fulfillment of the requirement

for the award of the degree

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WATER RESOURCES DEVELOPMENT

by

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CANDIDATE'S DECLARATION

I hereby declare that the work presented in the dissertation entitled, "**RESERVOIR SIMULATION OF THE MULTIPURPOSE PROJECT UNDER CHANGING CLIMATE: A CASE STUDY OF KANKAI MULTIPURPOSE PROJECT, NEPAL**", in partial fulfillment of the requirement for the award of the degree of **Master of Technology in Water Resources Development**, submitted in the Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee is an authentic record of my own work carried out during the period from July 2018 to May 2019 under the supervision of **Dr. Deepak Khare, Professor and Er. R.D. Singh, Visiting Professor,** Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee, India.

Date: May20, 2019

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CERTIFICATE

This is to certify that the above declaration made by candidate is correct to the best of our knowledge.

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ABSTRACT

Climate Change has stood as a burning issue since last two decades because of its potential impacts on the environment. Its impact has been observed predominantly in the hydrological cycle in global, regional as well as local scale. As water has stood as one of the major commodity for sustaining a life, its spatial and temporal variation can be a major hindrance in almost all aspects of natural life ecosystem and can have a severe impact on it. In order to develop the resilience against climate change, there stands a challenge to minimize the temporal and spatial variation of water resources. Reservoir system is an artificial system composed of several physical infrastructures which serves single or multiple purposes by regulating the natural flow of water as per the demand downstream and hence to cope up with the temporal variation of water resources.

This study has been carried out in order to predict the impact of climate change in the reservoir operation for Kankai Multipurpose Project (KMP), Nepal. Kankai Basin is one of the five medium River Basins in Nepal originating in the Mahabharata range and draining towards south in Mahananda River Basin in India. The catchment of Kankai River at the dam axis of KMP is 1164 sq. km. To carry out this study, four specific objectives have been set.

The first specific objectives was the analysis of trend of temperature and precipitation of the stations in/ around Kankai Basin and analysis of trend of Kankai stream flow using Mann Kendall and Sen's Slope Estimate. It has been observed that annual maximum mean temperature of two of the stations are in rising trend whereas annual minimum mean temperature for one of the stations is in falling trend. There was no significant trend observed for the other stations. Even though there is not much significant trend observed in precipitation, there has been observed significant increasing trend for stream flow.

After having the preliminary idea about the trend of climatic parameters, the next objective was the hydrological modeling of the Basin using Soil and Water Assessment Tool (SWAT). Window of nine years for climatic data (1990-1998) along with the other required input parameters were prepared for the model run (3 yrs warm-up, 4 years calibration period and 2 years validation period). SWAT- CUP has been used for calibrating the model for the daily data. 15 parameters were identified to be sensitive from global and one at time sensitivity analysis. The values of NS coefficient and the Coefficient of determination for the calibration period were 0.6 and 0.64 respectively and for the validation period, the values were 0.69 and 0.70 respectively.

The third objective of simulating the reservoir using the historical data has been accomplished by the use of HEC Res Sim software using the observed time series of 2004-2011. The simulation has been carried out, prioritizing the environmental release and the Irrigation water demand in each alternatives/ scenarios formulated for the simulation. 14 scenarios (S1-S14) scenarios have been formulated for the simulation using historical time series. Simulations has been carried out in daily time step of various installed capacity from 60MW to 130 MW and then in hourly time step for 60, 90 and 120 MW with various operation patterns. The result of these simulations with reference to the energy generated, uncontrolled spill and power duration curves suggested 90 MW installed capacity would be the best option among all. This came up with 309.6 GWHr annual energy generation with the average annual uncontrolled spill of 15.6 cumec and 30 MW of energy generation at 75% exceedence.

Next objective was the simulation of the reservoir for the predicted future flows. For this the CNRM-CM5 model data were extracted for temperature and precipitation from CMIP5 database for the mid century (2061-2070) for two scenarios RCP 4.5 and RCP 8.5. Extracted data were bias corrected using the linear bias correction technique. The flows for both the scenarios have been generated using the calibrated SWAT model. The flows generated for future, for both the scenarios, were compared to the historical observed as well as the historical SWAT simulated flows. It was found that the future flow had been deviated considerably from the observed flow, but had maintained the agreement with the SWAT simulated flow. 3 scenarios (S15-S17) were formulated to see the impact of climate change in reservoir simulation. Two of them corresponded to the future flow (RCP 4.5 and RCP 8.5) and next one corresponded to the SWAT simulated flow. On comparing the reservoir simulation result with the SWAT simulated historical flow, the energy generated is expected to increase by 13.8% and 28.9% for RCP 4.5 and RCP 8.5 respectively. The uncontrolled spill showed no definite pattern of change.

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LIST OF ABBREVIATIONS

95PPU	95 Percent Prediction Uncertainty
amsl	Above Mean Sea Level
AOGCM	Atmosphere-Ocean General Circulation Models
AR	Assessment Report
CCS	Carbon capture and storage
CFSR	Climate Forecast System Reanalysis
CMIP	Coupled Model Inter-comparison Project
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
DOED	Department of Electricity Development
DoI	Department of Irrigation
DSS	Decision Support System
ED	Electricity Department
EDF	Electricite De France
EIA	Environmental Impact Assessment
ESM	Earth System Models
ESMIC	Earth System Models of Intermediate Complexity
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization
FCOP	Flood Control Operating Plan
GCAM	Global Change Assessment Model
GCM	General Circulation Model /Global Climate Model
GDP	Gross Domestic Product
GHG	Green House Gas
GIS	Geographical Information system
GoN	Government of Nepal
GUI	Graphical User's Interface
HBV	Hydrologiska Byrans Vattenavdelning
HEC	Hydrologic Engineering Corps
HEC DSS	Hydrologic Engineering Center Data Storage System
HEC HMS	Hydrologic Engineering Center Hydrologic Modelling System
HEC ResSim	Hydrologic Engineering Center Reservoir Simulation
HMS	Hydrological Modeling System
HRU	Hydrological Response Units
HSG	Hydrologic Soil Group
IAM	Integrated Assessment Model
ICIMOD	International Centre for Integrated Mountain Development
ICWU	Irrigation Consumption water use
IPCC	International Panel on Climate Change
IWWU	Irrigation Withdrawal water use
KIP	Kankai Irrigation Project
KMP	Kankai Multipurpose Project
LU/LC	Land Use / Land Cover

MK	Man Kendall
MoI	Ministry of Irrigation
NEA	Nepal Electricity Authority
NSE	Nash-Sutcliffe Efficiency
NWP	National Water Plan
OAT	One at a time
OP	Operation Pattern
PBIAS	Percentage Bias
QPMF	Probable Maximum Flood Discharge
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
ResSim	Reservoir Simulation
S1	Scenario 1
SCS CN	Soil Conservation Service Curve Number
SHE	Systeme Hydrologique European
SRES	Special Report on Emissions and Scenarios
SUFI	Sequential Uncertainty Fitting
SWAT	Soil and Water Assessment Tool
SWAT CUP	SWAT Calibration and Uncertainty Procedures
TWL	Tail Water Level
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
VIC	Variable Infiltration Capacity
WECS	Water and Energy Commission Secretariat
WMO	World Meteorological Organization

CHAPTER ONE
INTRODUCTION

1.1. Background

Wise use of water resources in integrated and sustainable manner is the prime objective targeted across the globe. This is supposed to address the issues related to the availability, demand and distribution of the water resources. Among the total water available in the world, only 2.5% is the fresh water and out of which 70% is in the form of ice caps. It leaves only 0.7% of the world's water for humans' use. Comprehensive assessment of water management reveals that 1 in 3 people are already facing water shortages (IPCC 2007).

Climate Change, on the other hand, has stood as a burning issue since last two decades because of its potential impacts on environment and ecosystem. After the fifth Assessment Report (AR) of International Panel on Climate Change (IPCC) has evidently presented the fact of increment of 0.85^0C in the global mean temperature during the duration between 1880 and 2012 (IPCC 2013b), the issue has been taken more seriously among all stakeholders. The variation in global temperature has been accompanied by several aspects (Feng et al. 2014). Change in climate is expected to have a strong impact on the hydrological regimes in local as well as the regional scale (Dibike and Coulibaly 2005). Precipitation being the most important component in the hydrological cycle contributing to the availability of the water in different forms, its variability has been more predominant, mostly because of climate change. Global runoff has been extensively affected by the shrinkage of the glacier and thawing of the permafrost. The impact of climate change in the hydrological regime has been observed mostly along with the frequent occurrence of flood (Min, Zhang, and Zwiers 2008) and drought (Dai 2011).

Nepal is one of the countries in Hindu Kush Himalayan region which is also known as the third pole of the world. The altitudinal variation in the country is from approximately 60m above mean sea level in the South to the Mount Everest (8848m) in the North. Rapid changes in altitude and aspect, creates a wide range of climatic conditions in Nepal, subtropical to alpine. It has been estimated that out of 225 BCM water available in the country, only 15 BCM per annum is in use. Water use for agriculture accounts 95.9%, domestic water use accounts for 3.8% and for industrial use accounts for 0.3%. It is observed that around 78% of the average flow of the country is available in the first category river basins (Koshi, Gandaki, Karnali and Mahakali), 9 % in the second category basins (Kankai, Kamala, Bagmati, West Rapti and Babai) and 13 % in the numerous small southern rivers of the Terai. Studies have shown that the first Category Rivers have surplus flow but the second category rivers have deficit flow in the dry season (WECS 2011). The temporal variation of water resources is predominant in Nepal, and especially more unfavorably, in these second category river basins because of predominating monsoon rain.

Nepal's economy is largely based on agriculture which is however, mainly rain fed and agriculture production in both rain fed as well as irrigated areas are being adversely affected due to droughts, flooding, erratic rainfall, and other extreme weather events. Nepal was self sufficient in food grain production until 1990. Due to drought condition in 2005/06, production fell short by 21553 metric tonnes and by 179910 metric tonnes in 2006/07 due to drought and natural calamities (WECS 2005).

Linking the impact of climate change in the water availability in the developing nations like Nepal, it is much more difficult to create a balance between the demand and supply of the water resources because of uncontrolled demand caused by haphazard population growth whereas at the same time, the lack of appropriate infrastructure to avail water from the potential sources. The impact of climate change is expected to be more adverse in developing countries and even more in terms of hydrological cycle and its components. The final impact will be in the alteration of available water resources in time and space. One degree rise in temperature would have a huge loss in agricultural production, causing to decrease the value addition by Rs. 542 million (Acharya and Bhatta 2013).

Absence of strong initiative for the solution will certainly degrade the situation more in the developing countries as the negative impact of climate change is most predominant for these areas. One of the ways of addressing the impact of climate change by the means of adaptation is water storage (IPCC 2013a). Bartlett et al. (2010) has suggested the Expansion and refurbishment of irrigation and water storage infrastructure. This urges the establishment of mechanism and development of climate resilient physical infrastructures like the reservoir system.

Reservoir system is the combination of physical infrastructures along with the predefined operational characteristics to meet the demand of water for single to multiple uses of water. The reservoir is considered as the regulator of the natural flow of the river, wherein the surplus flow of the stream network is stored and which is used to supplement the dry season when there is flow deficit. In this regard, the reservoir also serves the purpose of attenuation of the hydrograph and hence the regulated and safe flow is achieved downstream of the reservoir. Therefore it is expected that the reservoir projects for multipurpose use can withstand the alteration of water availability in the days to come

1.2. Need of the Study

From different studies, it has been established that the developing countries are the ones which will be hit hard by the impact of climate change causing the spatial and temporal variation of water resources that will have negative impact on people and livelihood (IPCC, 2013). On the other hand, the role of the reservoir projects in context of addressing the temporal variation is very promising. Hence, as the topographical variation of the Nepal has created the tremendous opportunity by providing numerous natural locations for the development of Storage Water Resource Projects (Hydropower/ Irrigation/ Multipurpose Projects), the study in this area has much scope. However, due to various issues and constraints, the study as well as the implementation is not yet up to the expectation and more particularly in the considered geographical area (Kankai Watershed).

Also, there are very few literatures/ research papers available for Kankai Basin. Therefore Research over this particular topic for the considered geographical area is considered to be of much need and scope and has been chosen as a research area for current study.

1.3. Objectives

The study seeks to develop the hydrological model and the reservoir operation policies as overall objectives of the study. Specifically they are objectified as

1. To analyze the trend of temperature, precipitation and stream flow using Mann Kendall and Sen's Slope estimate
2. To calibrate and validate the hydrological model of the basin using SWAT for the simulation of discharge.
3. To simulate the reservoir operation using historical data and develop the Reservoir Operation Policies.
4. To simulate the reservoir operation scenarios under the changing climate to examine the reliability of the reservoir and study its impact on Reservoir Operation Policies.

1.4. Organization of the Dissertation

Apart from Introduction and Conclusion chapters, there are five major chapters in this dissertation report. First chapter is a brief introduction of the research background containing the need and objectives of the study. Second chapter describes the study area and the study methodology along with the overall framework of the study. This chapter gives the glance of all the tools and software along with the overall methodology adopted to achieve the pre-defined objectives.

From this chapter onwards, each chapter deals with an objective/ part of an objective consisting the specific information, theoretical background, applications of the tools/ software used, specific methodology adopted to achieve the objectives, results and discussion and concluding each chapter with summary.

Third chapter correspond to the first objective, where in trend analysis description along with results are summarized. Fourth chapter explains about the hydrological modeling and its theoretical consideration along with the results obtained. Fifth chapter forms the basis of carrying out a last objective/ sixth chapter, wherein it has been discussed the methodology and results of future flow prediction. Sixth Chapter describes the Reservoir simulation process and the software employed to achieve the result in detail. The final chapter is conclusions and recommendations. It summarizes the outcomes of the study along with the remarks. Conclusions are followed by limitations of the study and thereafter by the Recommendations.

CHAPTER TWO

STUDY AREA AND METHODOLOGY

2.1. Study Area

2.1.1. Location and Geography

Kankai River basin is situated in the south east part of Nepal, in Province no. 1, lying in Jhapa and Ilam districts with their east and south boundaries bordering with India. It is situated between 26.46° to 27.10° north and 87.819° to 88.00° east. The catchment area of Kankai River basin at Nepal-India border is 1285 km^2.

The major land cover of the basin constitutes of forest and cropland. There is a huge variation in the topography of the basin as the upper part is the steep hilly terrain while the lower part is narrowed and lies in the flat pains. Clay is predominant in the soil of this basin. The upper Kankai basin is dominated by sandy loam whereas the lower basin has variety in the land form with sand, clay and clay loam as major soil type.

2.1.2. Climate and Hydrology

Nepal has a predominant monsoon climate; hence similar kind of climatic condition is expected in the Kankai basin. However, the marked difference between the altitudes of the watershed causes two distinct climatic condition, hilly upper region has temperate climate whereas the lower flat plains has sub-tropical climate. According to the data of station no 1407, the average maximum and minimum temperature for the basin during the observation period 1990-1998 is 22.6^0C and 15.7^0C respectively, however the maximum/ minimum temperature recorded is 31^0C in April and 4^0C in January respectively.

Kankai River is a trans-boundary rain fed Perennial River originating from Mahabharat range at the elevation of 1820 amsl in Ilam district that flows from north to south and drains into Mahananda river basin of India. It has four major tributaries, Jog Mai, Mai, Puwa and Deu Mai. The river is said to be Kankai Mai after the Mainachuli gauging station. This is one of the five medium river basins in Nepal, which is also known as second category river basin and thus is water deficit during the dry seasons. There is no precipitation in the form of snow in Kankai basin and is characterized by the wide seasonal fluctuation in the flow. The four major seasons, on the basis of monsoon characteristic, are pre-monsoon (Mar-May), monsoon (Jun-Sep), post monsoon (Oct- Nov) and winter (Dec-Feb). The monsoon is characterized by the heavy rainfall which accounts about 70-80% of the total annual rainfall. According to the data observed in Mainachuli Gauging station during the observation period 1990-1998, the highest flow recorded in the basin is 4540 cumec on August 12, 1990 and the lowest flow recorded is 4.5 cumec on April 15, 1994.

As the present study is about with Kankai Multipurpose project and the proposed dam axis of the project nearly coincides with the Mainachuli gauging station site, the watershed is considered up to Mainachuli gauging site. The location of basin in the Map of Nepal, outline of the Districts, outline of Kankai catchment and stream network upto Indo-Nepal Border, Hydrological and meteorological stations used for the study and the DEM of the core study area has been shown in the Figure 2.1.

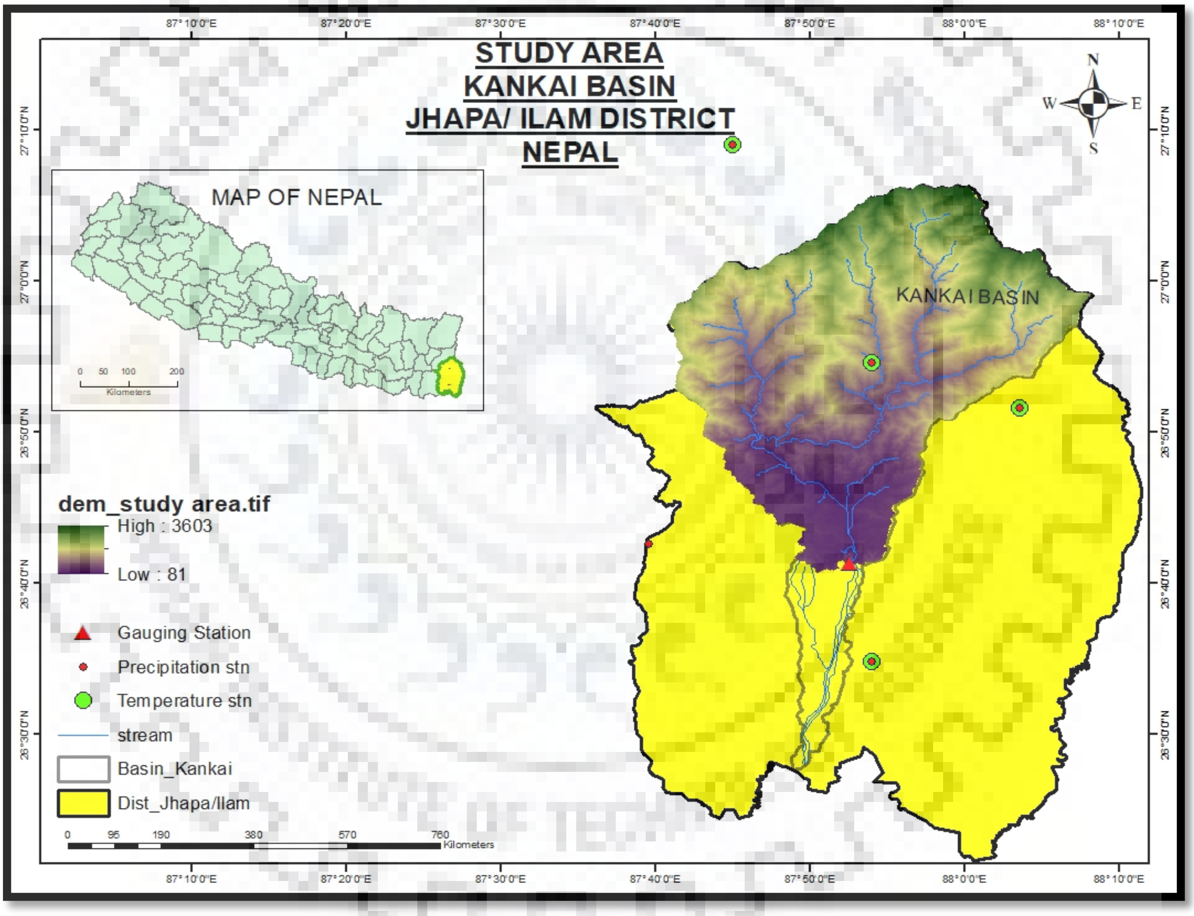

Figure 2.1 Location Map of the Study area

2.2. Previous Studies in Kankai Basin

2.2.1. Previous Research

Kankai River carries a significant importance in fulfilling the major water demand for Jhapa and Morang districts such as irrigation water use, rural, municipal and industrial water use and hydropower use. Similarly, frequent and extreme flood events have been reported which has made the livelihood vulnerable. Both of these situations demand extensive research for the Kankai Basin. But, although being one of the five medium river basins in Nepal, not many research papers are found to be focused in this geographical area. However few studies carried out focusing the flood hazard are found.

Khadka and Bhaukajee (2018) carried out a study in Kankai basin. HEC- HMS and HEC-RAS models have been used for the flood inundation analysis. The analysis has been done for 100 years return flood and the depth of flooding has been categorized spatially as less than 2 m, 2to 4 m, 4 to 6 m, 6 to 8 m and more than 8 m using the DEM of 30m resolution. The analysis also concluded that the area under inundation are mostly in the left bank of the basin and consists of the settlement areas and the agricultural areas.

With the objective of flood risk mapping, flood simulation model has been prepared with the help of remotely sensed data, topographic and social data using the GIS interface for the Kankai River basin Nepal. The results obtained were verified by social approach using vulnerability assessment. Flood frequency analysis was done with different available methods and the flood hazard map for 25 yr return period and 50 yr return period was prepared. The vulnerable areas form the 25 yrs return flood are the agricultural areas whereas the settlement areas also comes into picture for the flood hazard map of 50 yrs return period (Karki et al. 2011).

2.2.2. Kankai Multipurpose Project

Kankai Multipurpose Project (KMP) with the purposes of power generation, Irrigation and flood control had drawn interest of Government or Nepal since a long time. The then Electricity Department (ED) and Department of Irrigation (DOI) conducted a preliminary studies on Kankai river Separately. Asian Development Bank (ADB) showed a keen interest on Irrigation scheme of this project and provided fund for carrying out the feasibility study of the Kankai Irrigation Project (KIP). After the completion of feasibility study, implementation of KIP took place, the construction work of which was completed in 1981.

Similarly, Kankai dam and power project has been investigated and studied separately by ED. The project report (not in feasibility study level) produced in June 1972 suggested 75 m high dam on Kankai river at about 5 Km upstream from the East-West Highway to generate 33 MW of Power and a supply of year round irrigation water to 36000 ha in Jhapa district.

With the cooperation of Government of Federal Republic of Germany, Salzgitter Consultant conducted the feasibility study of KMP. This feasibility study identified 85 m high dam at about 4.5 Km far from East-West Highway to generate 38 MW electricity and to supply water to irrigate 67450 ha of land on the eastern and western side of Kankai River.

Later on, Electricite De France (EDF) studied further KMP and produced "Further Feasibility Study" report in August 1985. The Further Feasibility Study Report suggested the 85 m high sand-gravel type dam (same in the feasibility report 1978). The EDF report also suggested increasing power from 38 MW to 60 MW and year round irrigation water to 67450 ha.

In 1999, a consultant prepared Feasibility Study Level Analysis (Updating Parameter) of Kankai Multipurpose Project for Water and Energy Commission Secretariat (WECS).

In addition to the above studies, Nepal Electricity Authority, in 2003, conducted a feasibility review with recommendation of 90 m high dam and a re-regulating reservoir (design discharge 178 m3 /s, total storage 925 MCM and live storage 525 MCM, annual energy 247 GWH) and prepared a scoping document for EIA Study.

2.2.3. Project Description

The existing documents of the project, which have been referred to extract the data and information required for the current study are:

1. Kankai Multipurpose Project Feasibility Study, **Main Report Volume IV**, Salzgiter Consult GMBH, Salzgiter, July 1978 (Salzgiter Consult GMBH 1978)
2. Feasibility Study Level Analysis (Updating Parameter) of Kankai Multipurpose Project, **Final Report**, Water and Energy Commission Secretariat (WECS), Ministry of Water Resources, July 1999 (WECS/GON 1999)
3. Kankai Multipurpose Project, further Study, Nepal Electricity authority, 2003(NEA 2003)
4. Feasibility Study and environment impact Assessment of Kankai Multipurpose Project, Jhapa and Ilam District, **Inception Report**, Department of Electricity Development, July 2017 (DOED 2017)

The said documents have been reviewed and the required data and information for the study have been acquired. In case of conflict of data, the data and information have primarily been accessed from second reference. The data and information which are missing in this particular reference has been subsequently referred and adopted from the rest of the documents.

The salient feature of the Kankai multipurpose project has been presented in the Table 2.1, and irrigation water diversion requirement has been presented in Table 2.2. The required physical data of the project components in the various stages of study are acquired from these tables.

Table 2.1 Salient feature of Kankai Multipurpose Project

Description		Unit
Type of dam	Gravel and sand fill dam	
Height of Dam (m)	85	m
Crest Elevation of the dam	205	amsl, m
Flood control Zone	202.5	amsl, m
Maximum reservoir normal operating level	195	amsl, m
Minimum Operating Level	173.5	EL, m
Intake elevation	165	amsl, m
Height of flood storage	7.5	m
Free board	2.5	m
Crest elevation of the spillway	195	EL, m
Length of spillway	18	m
Design Spillway Flood (QPMF)	825	m^3/s
Tail Water Level (TWL)	121.5	amsl, m
Irrigation command area	67450	ha
Design Discharge	113	m^3/s
Installed Capacity in MW	60	MW
Number of turbine units	2	units
Flood control storage at 202.5 amsl	1680	MCM
Active storage at 173.5 amsl	1370	MCM
Dead storage at 165.0 amsl	400	MCM
Sediment volume in 50 yrs	275	MCM
Sediment volume in 100 yrs	550	MCM
Life of Reservoir	73	yrs

Table 2.2 Irrigation Water Diversion requirement

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
m3/s	16.3	12.4	21.9	41.8	34	4	0.7	0.7	4.7	24.4	28.3	21.2

2.3. Study Methodology

The overall methodology has been presented in the following sections. The specific methodologies for each objective are discussed in details in the corresponding chapters.

2.3.1. Tools and Softwares

Various tools and softwares that are used in different stages of work are

1. Makensen's sheet
2. Geographic Information System (GIS)
3. Soil and Water Assessment tool (SWAT)
4. SWAT-CUP
5. HEC- Res Sim

2.3.2. Work Flow

The overall workflow has been progressed in the given chronological order

1. Trend analysis of Precipitation, Temperature and Stream flow
2. Preparation of required maps and layers using GIS interface
3. SWAT model set up using the acquired soil map, land use land cover map, Digital Elevation Model (DEM) and meteorological data
4. Calibration and validation of SWAT model using SWAT CUP
5. Extracting Projected data for Temperature and Precipitation from selected GCM
6. Bias Correction of the projected data
7. SWAT model set up using the calibrated parameters for the bias corrected projected data for the simulation of future flow
8. Simulation of Reservoir operation for historic data
9. Simulation of Reservoir operation for the future data
10. Comparison of the results
11. Conclusion

2.3.3. Action Plan

The overall methodology of the work in the form of action plan is presented in Figure 2.2

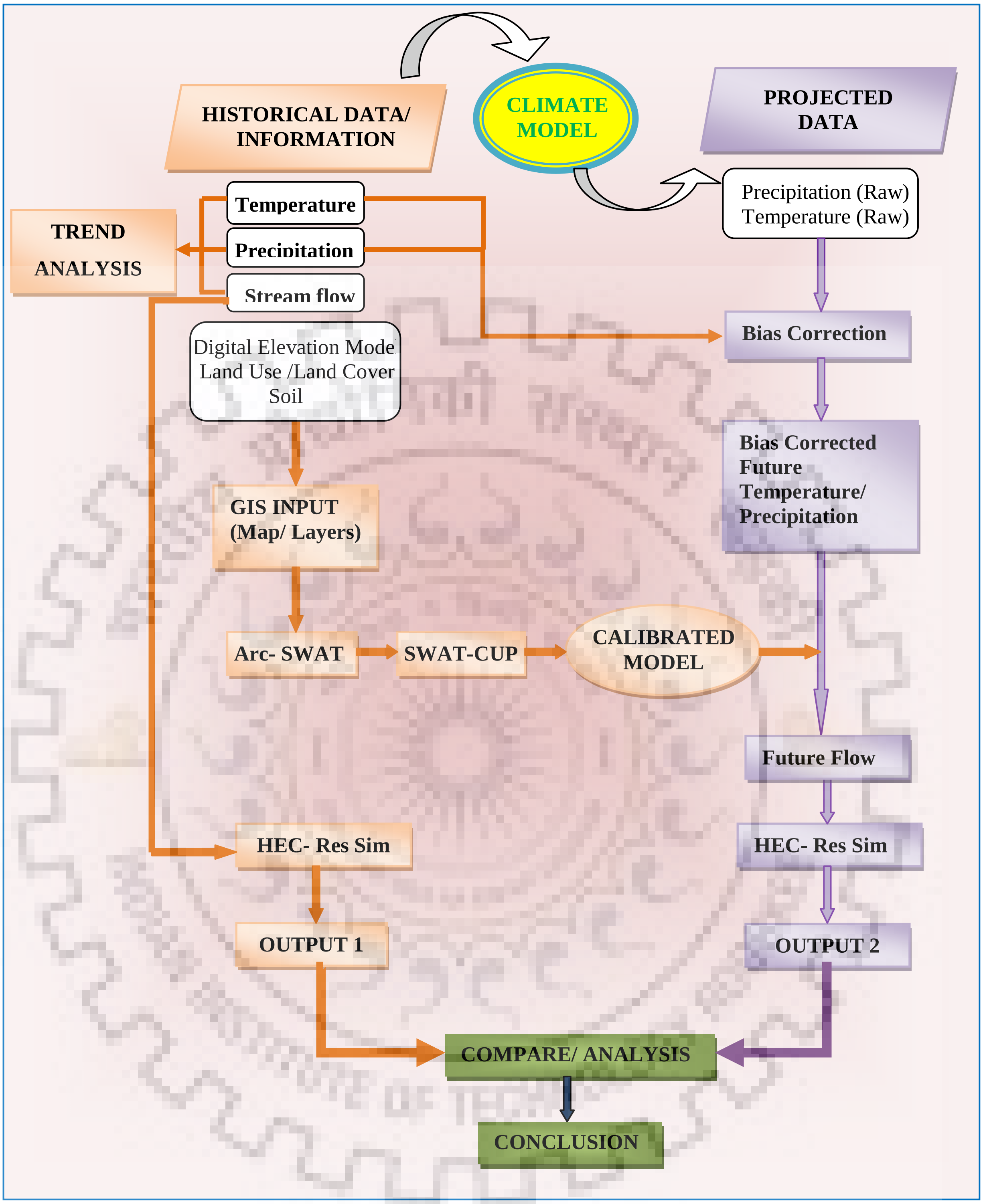

Figure 2.2 Overall Study Methodology

CHAPTER THREE
TREND ANALYSIS

This chapter corresponds to the first objective of the research. The trend has been analyzed for the temperature, precipitation and the stream flow for the historical data of various hydro-meteorological stations. The details associated with the work are described in the subsequent sections.

3.1. Prelude

Temperature, Precipitation and stream flow are among those climatic parameters which are of prime importance in the hydrological cycle. The detection of trend of these climatic parameters is always of the prime concern for the design as well as the operation and management of hydraulic structures and the basin management. This leads the better understanding of the temporal variability of the water availability which ultimately helps in basin planning.

In order to detect the trend of temperature, precipitation and stream flow in Kankai Basin and stream flow in Kankai River, Man-Kendall and Sen's Slope estimate has been used.

3.2. Mann Kendall test and Sen's Slope Estimate

Mann Kendall (MK) Test is a non-parametric test which is reported to be as strong as a parametric test with the advantage of allowing the outliers and extreme values in the dataset.

The dataset need not to be in any specific proportion to be tested under MK Test. This test examines whether there is a trend persisting in the dataset (in terms of -1, 0, +1 respectively for negative trend, no trend or the positive trend)

According to this test, there is null hypothesis: H_0, which assumes there is no significant trend in the data. Against to it, there is an alternative Hypothesis: H_1 which assumes there is significant trend in the dataset.

So the trend will be established only upon the rejection of the null hypothesis H_0 .The test statistic S is given as (Partal and Kahya 2006)

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_k) \qquad 3.1$$

Where, x_j and x_k are the annual values in years j and k and j>k n is the number of signum function. i.e.

$$\operatorname{sgn}(\theta) = \begin{cases} -1 & \text{for} \quad \theta < 1 \\ 0 & \text{for} \quad \theta = 0 \\ +1 & \text{for} \quad \theta > 1 \end{cases}$$

Whenever the sample size n is greater than 10, the data is assumed to be asymptotically normal, with the mean E(s) =0 and variance given as;

$$\operatorname{Var}(S) = \frac{1}{18}[n(n-1)(2n+5)] \qquad 3.2$$

And for the data set having the tied pair of the values, variance is given by,

$$\operatorname{Var}(S) = \frac{1}{18}\sum[n(n-1)(2n+5)] - \frac{1}{18}\sum_{p=1}^{q}\left[t_p\left(t_p-1\right)\left(2t_p+5\right)\right] \qquad 3.3$$

Where, q is the number of tied groups and t_p is the number of data values in the p^{th} group

The values of S and Var (S) are used to compute the test statistic Z_{mk} as follows

$$Z_{mk} = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{Var}(s)}} & for \quad s > 1 \\ 0 & \text{for} \quad s = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{Var}(s)}} & \text{for} \quad s < 1 \end{cases} \qquad 3.4$$

The positive (or negative) value of Z_{mk} embarks upward or downward trend and is statistical significance is measured by comparing its value with $Z_{1-\alpha/2}$. H_0 is rejected if modulus of Z> $Z_{1-\alpha/2,}$. where α is the level of significance. The test statistic Z_{mk} has normal distribution and $Z_{1-\alpha/2}$ is obtained from the normal cumulative distribution table.

The Sen’s method uses a linear model to estimate the slope of the trend. The magnitude of the trend of the data set is given by the Sen’s slope, estimate which is the median of the individual slope Q_i of all pairs of data (x_j and x_k) where j > k

$$Q_i = \frac{x_j - x_k}{j-k} \qquad 3.5$$

3.3. Methodology

The nonparametric Mann–Kendall criterion has been chosen to test trend because this procedure has the merit of not assuming any special form for the data distribution function, while having the power nearly as high as their parametric competitors. For these reasons, it has been highly recommended by the World Meteorological Organization (WMO). The

Mann–Kendall statistical test has been frequently used to quantify the significance of trends in hydro-meteorological time series.

In this study, the macro enabled excel sheet published by Finnish Meteorological Institute, popularly known as MAKENSEN has been used to detect the trend of the precipitation, temperature and the stream flow, based on observed historical data of the study area.

To see the trend, the monthly mean data of the hydrological/ meteorological stations in the chronological order of time were given as input to the MAKENSEN sheet (Salmi et al. 2002). Some missing data in the observations were encountered but as the sheet has been developed to allow the missing data, the result was expected not to be distorted from what it should be. The monthly dataset were prepared for the stations as shown below.

Table 3.1 Station Details for Trend Analysis

SN	Station No.	Station Name	No of dataset (n)	Range of Available	Missing data set
Precipitation					
1	1407	Ilam Tea Estate	48-53	1956-2010	Upto 5
2	1408	Damak	45-47	1963-2009	Upto 2
3	1416	Kanyam Tea Estate	37-38	1972-2010	Upto 1
4	1419	Phidim	32-33	1978-2010	Upto 1
5	1421	Gaide	32-33	1984-2016	Upto 1
Temperature					
1	1407	Ilam Tea Estate	38		
2	1416	Kanyam Tea Estate	38	1972-2009	-
3	1419	Phidim	20-21	1989-2009	Upto 1
4	1421	Gaide	26	1984-2009	-
Discharge					
1	795	Mainachuli	40	1972-2011	-

For the precipitation, trend detection has been done using the monthly mean values and has covered the trend of precipitation for

a. Each month
b. Pre-monsoon (Mar-May)
c. Monsoon (Jun- Sep)
d. Post-monsoon (Oct-Nov)
e. Winter (Dec-Feb)
f. Annual

For the Temperature, trend detection has been done using the monthly mean values and has covered the trend of

a. Maximum annual mean temperature trend
b. Minimum annual mean temperature trend

For the discharge, trend detection has been done using the monthly mean values and has covered the trend of flow for

a. Each month
b. Pre-monsoon (Mar-May)
c. Monsoon (Jun- Sep)
d. Post-monsoon (Oct-Nov)
e. Winter (Dec-Feb)
f. Annual

3.4. Result and Discussion

The values of Var(S) are used to compute the test statistic Z_{mk} for all the series of temperature, precipitation and discharge as given in equation 3.4,

$$Z_{mk} = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var(s)}}} & for \quad s > 1 \\ 0 & \text{for} \quad s = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var(s)}}} & \text{for} \quad s < 1 \end{cases}$$

The positive (or negative) value of Z_{mk} embarks upward or downward trend. Magnitude of the linear slope has been given by sen's estimate.

H_0 is rejected and the trend is said to exist if modulus of $Z_{mk} > Z_{1-\alpha/2}$., and is statistical significance is measured by comparing its value with $Z_{1-\alpha/2}$ at different level of significance, α, as given below with the symbol used along with it in Table 3.2.

Table 3.2 Value of normal variate Z for different level of Significance (α)

symbol	Level of significance (α)	$Z_{1-\alpha/2}$
***	α=0.001	3.29
**	α=0.01	2.575
*	α=0.05	1.96
+	α=0.1	1.645
	α>0.1	<1.645

3.4.1. Temperature Trend

The annual maximum mean and annual minimum mean trend for temperature is presented in Table 3.3.

Table 3.3 Trend of temperature for various stations

	TEMP_1407				**TEMP _1416**				**TEMP _1419**				**TEMP** _1421			
Time series	**n**	**Test Z**	α	**Q**	**n**	**Test Z**	α	**Q**	**n**	**Test Z**	α	**Q**	n	Test Z	α	Q
Max. Temp	38	1.38		0.023	38	3.57	***	0.047	21	1.48		0.036	26	3.84	***	0.06
Min. Temp	38	-1.79	+	-0.022	38	-1.61		-0.015	20	-0.68		-0.021	26	0.18		0.007

- The trend of annual maximum mean temperature is in the rising phase for two station (1416 and 1421) at α=0.001, whereas the trend for other two stations are not much significant.
- The trend of annual minimum mean temperature is falling phase for one station (1407) at α=0.1, whereas the trend for other three stations are not much significant.

3.4.2. Precipitation Trend

- The trend of pre monsoon mean precipitation is in rising phase for one station (1408) at α=0.05, whereas the trend for other stations is not much significant.
- The trend of monsoon mean precipitation is falling for two stations (1408 and 1421) at α=0.05, whereas the trend for other stations is not much significant.
- The trend of post monsoon mean precipitation is falling for one station (1421) at α=0.1, whereas the trend for other stations is not much significant.
- The trend of Winter mean precipitation is in rising phase for one station (1407) at α=0.05, falling for two stations (1416 and 1421) at α=0.1
- The impact of rising or falling trend of precipitation in all seasons are viewed via the trend of annual mean precipitation, which is falling for one station (1421) at α=0. 1, whereas the trend for other stations is not much significant.

The trend for monthly mean, seasonal mean and annual mean precipitation is presented in the Table 3.4.

Table 3.4 Trend of precipitation for various stations.

	PPT_1407				**PPT_1408**				**PPT_1416**				**PPT_1419**				**PPT_1421**			
Time series	**n**	**Test Z**	α	**Q**	**n**	**Test Z**	α	**Q**	**n**	**Test Z**	α	**Q**	**n**	**Test Z**	α	**Q**	**n**	**Test Z**	**α**	**Q**
Annual	48	1.15		0.136	47	-1.39		-0.271	38	-1.61		-0.392	33	0.33		0.065	32	-1.897	+	-20.3
Pre Monsoon	53	0.10		0.004	47	2.31	*	0.084	37	-0.27		-0.021	32	-0.92		-0.034	33	0.155		0.405
Monsoon	50	0.87		0.095	47	-2.07	*	-0.344	38	-1.41		-0.370	32	0.18		0.019	33	-1.999	*	-19.7
Post Monsoon	50	0.21		0.004	47	-0.09		-0.001	38	-0.83		-0.040	33	1.12		0.029	33	-1.937	+	-3.13
Winter	49	1.91	+	0.018	47	0.90		0.009	38	-2.07	*	-0.033	33	-0.90		-0.020	33	-2.466	*	-1
Jan	51	0.18		0.000	45	0.50		0.000	37	-1.44		-0.007	32	-0.45		0.000	32	-0.15		0
Feb	52	1.22		0.002	46	0.74		0.002	37	-1.27		-0.013	32	-0.75		-0.006	32	-1.758	+	-0.27
Mar	53	0.59		0.001	47	0.91		0.004	37	-0.13		-0.002	32	-0.02		-0.001	33	-1.132		-0.41
Apr	53	-0.59		-0.006	47	1.17		0.021	37	-0.12		-0.004	32	-0.96		-0.026	33	0.2324		0.192
May	53	-0.32		-0.008	47	1.34		0.038	38	-0.23		-0.019	32	-0.31		-0.022	33	0.3564		0.527
Jun	52	0.11		0.005	47	0.09		0.005	37	0.75		0.085	32	0.18		0.010	33	0.3874		1.232
Jul	53	-0.12		-0.007	47	-1.65	+	-0.155	37	-0.75		-0.103	33	-0.91		-0.053	33	-1.069		-6.28
Aug	52	1.71	+	0.075	47	-1.05		-0.109	37	0.25		0.032	33	2.03	*	0.106	33	-0.976		-4.72
Sep	51	-0.78		-0.029	47	-0.61		-0.046	38	-1.79	+	-0.156	33	-1.47		-0.067	33	-1.131		-4.55
Oct	50	-0.34		-0.005	47	-0.04		0.000	38	-0.73		-0.030	33	1.55		0.037	33	-1.751	+	-2.71
Nov	51	0.78		0.000	47	-0.47		0.000	38	-1.76	+	0.000	33	-0.97		0.000	33	-0.995		0
Dec	51	2.69	**	0.000	47	2.77	**	0.000	38	-0.64		0.000	33	-1.01		0.000	33	-2.886	**	0

3.4.3. Flow Trend

The trend for monthly mean, seasonal mean and annual mean stream flow of Mainachuli gauging station is presented in the Table 3.5.

Table 3.5 Trend of discharge at station Mainachuli (Station no.795)

Time series	First year	Last Year	n	Test Z	Signific. α	Q
Annual	1972	2011	40	2.71	**	10.440
Pre Monsoon	1972	2011	40	1.62		0.314
Monsoon	1972	2011	40	2.67	**	8.777
Post Monsoon	1972	2011	40	2.46	*	1.368
Winter	1972	2011	40	-0.29		-0.036
Jan	1972	2011	40	0.22		0.006
Feb	1972	2011	40	1.20		0.039
Mar	1972	2011	40	1.36		0.036
Apr	1972	2011	40	1.11		0.043
May	1972	2011	40	1.48		0.170
Jun	1972	2011	40	0.59		0.214
Jul	1972	2011	40	0.94		1.674
Aug	1972	2011	40	2.16	*	3.027
Sep	1972	2011	40	2.09	*	1.703
Oct	1972	2011	40	2.78	**	1.245
Nov	1972	2011	40	1.34		0.140
Dec	1972	2011	40	-0.45		-0.038

- The trend of winter mean flow is falling, which in not even statistically significant, whereas all other season trend of flow is in rising trend.
- The trend of annual mean flow, pre monsoon mean flow and post monsoon mean flow are observed to be statistically significant at α=0.01, α=0.01, α=0.05 respectively, which shows that the annul mean flow in the river is in the rising trend. The linear slope estimate given by Sen's slope estimator is also very high for monsoon mean and hence for annual mean time series, when viewed in the frame of 40 years (1972-2011).

3.5. Summary

The trends of temperature, precipitation and stream flow have been analyzed using Mann Kendall test and Sen’s slope estimate. MAKENSEN sheet has been used for analyzing the trend at different level of significance.

Annual maximum mean temperature and annual minimum mean temperature ranging from 20-38 yrs time frame for four stations has been taken into consideration for trend analysis of temperature. It has been observed that, fort two stations, annual maximum mean temperature is showing the rising trend at α=0.001 and The annual minimum mean temperature is showing falling trend for one of the stations at α=0.1, whereas, for remaining three stations, no significant trend has been observed.

Monthly mean, seasonal mean and annual mean precipitation for the time frame ranging from 32-53 yrs for five stations have been considered for trend analysis of precipitation. It has been observed that, the pre monsoon mean precipitation is showing rising trend for one of the stations at α=0.05, while other stations are not showing any statistically significant trend. monsoon mean precipitation is showing falling trend for two stations at α=0.05 whereas remaining stations are not showing any significant trend. Post monsoon mean precipitation is showing falling trend for one of the stations at α=0.1, whereas others are not showing any significant trend. Winter mean precipitation is showing rising trend for one of the stations at α=0.05, falling for two stations at α=0.1. On observing the trend of annual mean precipitation, the falling trend has been noticed for one station at α=0.1, whereas the trend for other stations is not much significant.

Monthly mean, seasonal mean and annual mean flow for the time frame of 40 yrs for Mainachuli gauging stations have been used for analysis. It has been observed that, winter mean flow is not showing any statistically significant falling trend at α>0.10 whereas the annual mean, pre monsoon mean and post monsoon mean flow are showing rising trend at α=0.01, α=0.01, α=0.05 respectively. It shows that the overall flow in the river is showing the rising trend. The linear slope estimate given by Sen’s slope estimator is also very high for monsoon mean flow and hence for annual mean time series, when viewed in the time frame of 40 years.

CHAPTER FOUR
HYDROLOGICAL MODELLING

4.1. Hydrological Model

Hydrology refers the earth water, its occurrence, circulation and distribution as well as the chemical/ physical properties of water and its reaction with the environment and its components (Ray 1975). The hydrologic components include precipitation, evaporation, snowmelt, infiltration, runoff and other processes in the hydrologic cycle. In the due course of time, the change in the land use/ land cover, water availability and water use is inevitable which leads to the various changes in the hydrologic system. In order to find these variations, various hydrological models are developed around the world, which are supposed to be capable of prediction of impact of climate and soil properties on hydrology and the water system.

A hydrological model is the replica of the real world water system (in a certain scale) in the simplified form representing its processes and the components. A model consists of several parameters that define the characteristic of the model. Depending upon the theoretical background, physical principle and the structure of the model, it may require different set of inputs; however two most important inputs required for any surface water hydrological model are rainfall data and the drainage area. Others are the watershed characteristics such as land use and vegetation cover, topography, soil characteristics, ground water condition etc.

4.1.1. Classification of Hydrological Model

Surface water modeling are classified based on the extent of physical principles assumed for structuring the model, input and the parameters required/ contained by the model. There are various approaches of hydrological modeling.

4.1.1.1. Lumped, Distributed and Semi Distributed Model

This classification is based on spatial variation incorporated in the watershed. Lumped model ignores the spatial variability in the hydrological system formulation so that a homogenous condition prevails in all part of the watershed assuming it to be a single entity for computation of the parameters. The parameters' values are averaged over this single entity. This model is also called black box model. SCS-CN model is one of the popularly used models of this category.

Distributed models are those wherein the parameters and the processes are allowed to vary spatially as per the users' choice. The model considers various land use/ soil/ topography and catchment is divided into small units, usually square or the triangulated irregular network, where the input, output as well as the parameters can vary spatially (Dwarakish and Ganasri 2015).

Semi Distributed (quasi-distributed) models are the ones which contains the feature of both the distributed as well as lumped model, wherein the parameters are allowed to vary partially in spatial scale dividing the watershed into sub watersheds (Moradkhani and Sorooshian 2008).

4.1.1.2. Deterministic and Stochastic model:

Deterministic model gives the same set of output for a certain input values, whereas, different set of output values are produced by the same set of input in the case of stochastic models.

4.1.1.3. Static and Dynamic model:

This classification is based on the time factor. Static model ignores the time whereas dynamic model takes into account the time factor.

4.1.1.4. Event based and Continuous:

This classification is based on the runoff process within a watershed. Event based models take into account a single rainfall event (few hours to days) and are used for flood forecasting and inundation mapping, whereas the continuous model accounts for a certain period of time and keeps account of the surface and groundwater conditions of the watershed (Devi, Ganasri, and Dwarakish 2015).

4.1.1.5. Empirical, Conceptual and Physically based Model:

Empirical models are data driven models which are established on the basis of observation and thus requires only the existing data without considering the processes of the hydrological system. It involves the equations derived from the concurrent input and output time series and not from the physical process involved in the watershed. These models are valid only within the boundaries. Example- unit hydrograph

Conceptual model also known as parametric model describes the components of the hydrological processes. It generates numerous interconnected reservoirs which represent the physical elements in a watershed, which are recharged and emptied by several hydrological processes such as rainfall, percolation and infiltration and evaporation, runoff and drainage. Semi empirical equations are used in this method and the parameters are assessed from field data as well as through calibration. The conceptual models developed are of various complexities. Stanford Watershed model (SWM IV) is the first major conceptual model developed.

Physically based model is the mathematically idealized representation of real phenomenon occurring in a watershed. It makes use of the state variables which are the function of time and space and are measurable. The hydrological processes of water movement are represented by the finite difference equations. Physically based model requires the huge amount of input data i.e. topography, topology, dimension of river network, soil moisture content, initial water depth etc. This model can overcome the shortcomings because of use of parameters having physical interpretation. The information it provides is valid even outside the boundary and can be applied for the wide range of situations. SHE/ MIKE-SHE is an example of this model (Abbott et al. 1986).

The classification of the hydrological model is presented in Figure 4.1

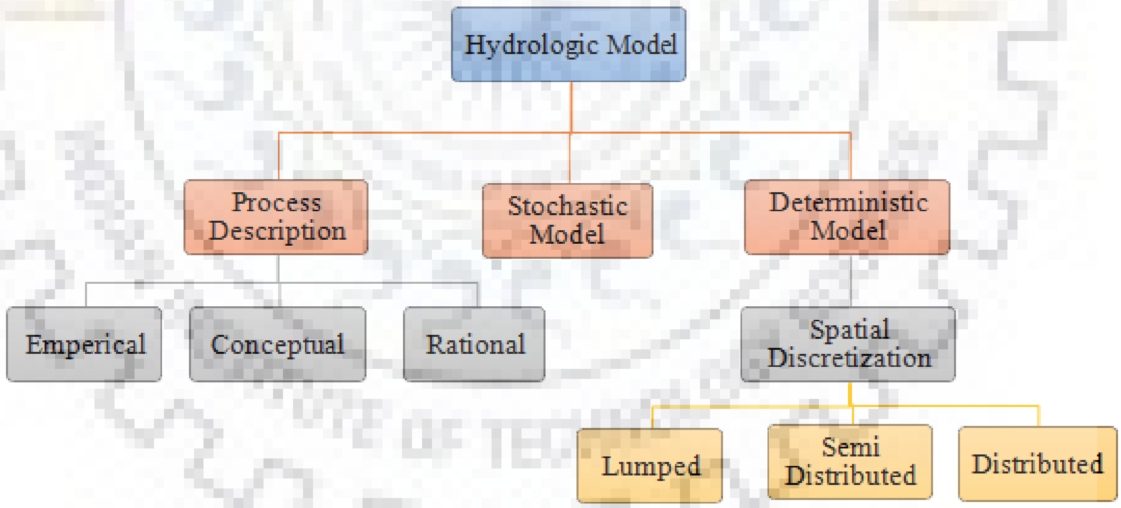

Figure 4.1Classificaiton of Hydrological Models

4.1.2. Popular Hydrological Models:

Herein discussed are some of the hydrological models which are popularly in use.

4.1.2.1. MIKE SHE Model (Systeme Hydrologique European)

It is a physically based model requiring wide-ranging physical parameters and considers numerous processes and mechanisms in a hydrological cycle like precipitation, evapo-transpiration, interception, saturated ground water flow, unsaturated ground water flow, river flow etc. With the help of this software one can replicate surface and subsurface water movement, their interaction, sediment, nutrient and pesticide transport within the mock-up region. It can also be used in solving problems of various water quality issues even for large water basins. It was developed by Abbott et al. (1986) in cooperation with the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH (France). One of the major characteristic of this software is that it uses the Saint Venant's equations to calculate the various parameters like overland flow, runoff, water depth etc. The software has been examined by various researchers for its applicability globally.

4.1.2.2. TOPMODEL

TOPMODEL is software that takes into account the topographic information associated to runoff generation due to which it is considered as a semi distributed conceptual rainfall runoff model. However it does have the characteristics of a physically based model since the parameters used can be theoretically measurable. The model can be used in the calculation of the hydrological behaviour of watersheds. It can be utilized in hydrological prediction of watersheds through single and multiple sub basins using gridded elevation data of the basin. The catchments topography and soil transmissivity are the major parameters considered by the software. Calculating the storage deficit or water table at a given location is intended as a main mechanism. The storage deficit is taken as function of topographic index($a/\tan\beta$) (Beven 1986), where a is drained area per unit contour length and $\tan\beta$ is the slope of the ground surface at the given location. The model uses the exponential Green-Ampt method of Beven(1984) for estimating the runoff discharge . In this model the best results are anticipated when the number of parameters are reduced. The outcome takes the form of map or simulated hydrographs.

4.1.2.3. HBV Model (Hydrologiska Byrans Vattenavdelning Model)

In this model the basin is divided in sub basins which are further divided into different elevation and vegetation zones. The model is a type of semi distributed conceptual model. The model uses lesser input data viz. daily and monthly rainfall data, temperature and evaporation for processing. The temperature data are used for the estimation of the snow accumulation. The general water balance equation

$$P-E-Q=d/dt\ (SP+SM+UZ+LZ+lakes) \quad 4.1$$

In this P is precipitation, E is evaporation, Q is runoff , SP is the snow pack, SM is the soil moisture, UZ and LZ are the upper and lower ground water zone and lakes represent the volume of lake. There are various versions of the model available and are used based on the specific climatic conditions of the regions of use. The method utilized by the model is the Degree day method and is used to simulate the snow accumulation and the snow melt. The model divides the basin into various sub basins on the basis of elevation, lake area and vegetation cover. The newer version called HBV-light also has the added feature of simulating warm up period so that the variables will get its suitable values according to the meteorological data and parameter values.

4.1.2.4. VIC (Variable Infiltration Capacity)

This model uses both energy and water balance equations and is a grid based large-scale model. The VIC model is found to be more effective for the moist conditions due to which they are desirable for managing water efficiently in agricultural fields. The major inputs in the model are the precipitation, minimum and maximum temperatures, wind speeds and land use types. The hydrologic processes are based on different empirical relations. The runoff is created by infiltration excess runoff also known as Hortonian flow and the saturation excess runoff known as Dunne flow. Soil heterogeneity and precipitation is considered while simulating the saturation excess runoff. The model uses three soil layers in which the top layer permits rapid soil evaporation, middle layer characterize dynamic response of soil while the lowest one represents the soil moisture. Newer version of the model has included both the parameters taking into account the variability of soil heterogeneity on runoff characteristics. Nowadays, the model has been extensively used climate change impact and land use pattern change in various basins.

4.1.2.5. HEC- HMS

HEC-HMS, an open source software, developed by the US Army Corps of Engineers Hydrologic Engineering Centre, is widely used in simulations of the hydrological processes in a basin. The program incorporates mathematical models for all the components that theoretically represent basin behaviour. Separate models are used by the model to characterize each element of the runoff process like model to figure runoff volume, model to figure out direct runoff, base flow, channel flow. It also takes into account alternative models to incorporate the cumulative losses. Finally the runoff volume is estimated by deducting the losses from the precipitation.

The software has now been upgraded to solve diverse range of problems which included water supply, flood hydrographs small urban or natural watershed runoff. HEC-HMS can be used in the case where limited data in a selected basin is available. It is also used in combination with ArcGIS which makes the users easy in creation of basin models. HEC- Geo HMS is the ArcGIS extension program which is used to generate basin and meteorological models for use with the program.

4.2. SWAT Model

Soil and water assessment tool (the SWAT Model), presently a widely accepted interdisciplinary watershed model, was developed by United States, Dept. of Agriculture to study the impact of land management practices on water, sediment and agriculture in the complex watershed over a long time, having different land use, topography, soil texture and watershed management practices (Neitsch et al. 2011).

In SWAT model, any study area watershed is divided in to sub watershed and sub watershed divided further in to hydrological response units (HRUs). These HRUs are the areas of same type of land use, land slope and soil properties and it is the percentage of watershed area which is not spatially identified at the time of swat simulation (Gassman et al. 2007b).

Whatever be the area of study, water balance is the key to every process occurring within watershed. To exactly simulate the different ongoing phenomena with in a watershed, watershed hydrological cycle can be divided in to two phases viz. land phase and routing phase.

4.2.1. Land Phase of Hydrological Cycle.

The different inputs and processes involved in land phase of the hydrologic cycle are summarized in the following sections.

4.2.1.1. Weather

The climatic information of a watershed is utilized to get the moisture and energy inputs which control the water balance and help to decide the relative significance of various features of hydrology. The climate parameters utilized are daily maximum and minimum temperature, daily precipitation or rainfall, solar radiation, relative humidity and wind speed. The model has capability of reading these inputs directly from the input file or it will take average monthly data of number of years, do analysis and generate the daily values of weather parameter. SWAT uses WGEN weather generator model to generate climate data or to fill gaps in the measured records if any (Worku, Khare, and Tripathi 2017).

4.2.1.2. Hydrology

SWAT model simulates hydrological process based on following water balance equation.

$$SW_t = SW + \sum(R_{day} - Q_{surf} - E_a - W_{seep} - QR_i) \quad 4.2$$

Where,

SW_t = final soil water content (mm H2O),

SW_o = initial soil water content (mm H2O),

t = time in days,

R_{day} = amount of precipitation on day i (mm H2O),

Q_{surf} = amount of surface runoff on day i (mm H2O),

E_a = amount of evapotranspiration on day i (mm H2O),

W_{seep}= amount of percolation and bypass exiting the soil on day i (mm H2O),

Q_{gw} = amount of return flow on day i (mm H2O).

4.2.1.3. Evaporation

Evaporation is the process by which water in solid or liquid gets converted to vapors. Potential soil water evaporation is estimated as a function of potential evapotranspiration (PET) and leaf area index. PET is the rate at which evapotranspiration will occur when unlimited amount of water is supplied to the large area covered uniformly with growing vegetation. In SWAT model three options are available for estimation of PET i.e. Priestley-Taylor, Hargreaves, and Penman-Monteith.

4.2.1.4. Percolation

Percolation is calculated for each soil layer in the profile. Water can percolate if water content exceeds the field capacity for that layer. The flow rate is governed by the saturated conductivity of the soil layer.

4.2.1.5. Lateral Sub-surface Flow

Lateral subsurface flow is the contribution of stream flow originating below the surface and above the zone where rocks are saturated with water. SWAT model uses a kinematic storage model to estimate the lateral flow in each soil layer and kinematic storage model takes in to account of variation in soil conductivity, slope and soil water content.

4.2.1.6. Groundwater Flow

SWAT divides the groundwater in to two aquifer systems. One is Shallow-unconfined aquifer which contributes return flow to streams with in watershed and another is a deep-confined aquifer system which contributes return flow to stream outside the watershed. Water balance for each aquifer is calculated separately.

4.2.1.7. Transmission loss

Transmission losses occur by leakage from the bed of flow channels when ground water table is below the bed of channels. Transmission losses decrease surface runoff and SWAT makes use of Lane's method described in USDA SCS Hydrology Handbook to find the losses during transmission.

4.2.2. Key Processes in SWAT Simulation

There are various processes and phenomena simulated in the SWAT model which are occurring in watershed. Among them, the key process/ phenomena like canopy storage and infiltration are discussed in the following sections.

4.2.2.1. Canopy Storage

Water captured by vegetative layers, where it falls and evaporates is called canopy storage. When we use SCS-CN method for runoff calculation, canopy storage is taken in to account, but if Green and Ampt method is used for infiltration and runoff calculation canopy storage should be modeled separately. We can give the value of maximum canopy storage and Leaf area index for land cover as input in SWAT model and based on these we can compute maximum storage and hence evaporation. When computing evaporation, water is first removed from canopy storage.

4.2.2.2. Infiltration and Runoff

Infiltration is the process of downward movement of water in to the soil profile. As infiltration time goes on increasing, soil becomes wet and infiltration rate decreases and attains a constant or steady value. There are two options available in SWAT model for calculation of runoff. One is Modified SCS curve number method and another is Green & Ampt Infiltration equation.

The curve number method requires daily rainfall data and is unable to model infiltration directly. The quantity of water that entering to the soil layers is obtained from the difference between rainfall and surface runoff. On the other hand, the Green & Ampt method uses rainfall data of smaller interval than daily and computes infiltration as a function of wetting front metric potential and effective hydraulic conductivity.

The SCS Curve number equation used by SWAT is given below.

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad 4.3$$

Where Q = runoff depth in (mm), P = effective depth of precipitation in (mm), I_a = initial abstraction of water in (mm), S = maximum potential retention. The initial abstraction of water (Ia) is the function of maximum potential retention S and can be expressed as I=λS, where λ = a constant value usually taken as 0.2 or 20%. Therefore, I_a=0.2S. Hence by combining above equations we have,

$$Q = \frac{(P - 0.2S)^2}{(P - 0.2S) + S} \qquad 4.4$$

The runoff process starts when P = 0.2 S. Depending on soil types, topography and slope of the catchment, and land use practices, maximum potential retention varies and the maximum potential retention 'S' has been correlated with dimensionless parameter curve number expressed in the following equation.

$$S = \frac{25400}{CN} - 254 \qquad 4.5$$

Where, maximum potential retention is in mm. The curve number decreases as the soil attains the wilting point and increases to near 100 as the soil reaches to saturation.

Modified rational method is used for calculation of peak runoff rate. Rational method assumes that that if a rainfall of intensity i falls continuously for time period more than the time of concentration tc, runoff will increase until tc when maximum runoff occurs and all of the area of sub-basin contributes to flow at the outlet. In the modified rational formula, the peak runoff rate is given by:

$$q_{peak} = \frac{\alpha_{tc} Q_{Sur} A}{3.6 t_c} \quad 4.6$$

Where, q_{peak} is the peak runoff rate (m^3/s); α_{tc} is the part of daily rainfall occurring during the time of concentration; A is the sub-basin area (km^2); and tc is the concentration time for a sub-basin (hr).

The concentration time for sub basin is obtained by adding time for overland flow and time for channel flow.

$$Qt_c = t_{ov} + t_{ch} \quad 4.7$$

Where, t_c is the time of concentration for a sub-basin (hr.), t_{ov} and t_{ch} are the time of concentration for overland flow and channel flow (in hour) respectively.

The overland flow time of concentration, t_{ov}, is computed using the equation.

$$t_{ov} = \frac{{l_{slp}}^{0.6} n^{0.6}}{slp} \quad 4.8$$

Where, l_{slp} is the sub-basin slope length (m), n is the Manning's roughness coefficient and slp is the average slope in the sub-basin (mm^{-1}).

The channel flow time of concentration, tch is computed using the equation.

$$t_{ch} = \frac{0.62 \mathrm{ln}^{0.6}}{\mathrm{Area}^{0.125}\, {\mathrm{Slp}_{ch}}^{0.375}} \quad 4.9$$

Where, t_{ch} is the time of concentration for channel flow (hr.), L is the channel length from the most distant point to the sub-basin outlet (km), n is the Manning's roughness coefficient for the channel, Area is the sub-basin area (km^2) and Slp_{ch} is the channel slope (mm^{-1}).

4.2.3. Routing Phase of Hydrological Cycle.

Once the amount of water, sediment, nutrients and pesticides to the main channel are determined using SWAT model, these are routed through the stream network within the watershed. Routing process takes place in main channel and reservoir. As our study is concerned with flow routing, flood routing is discussed here.

SWAT model uses variable coefficient method developed by Williams or Muskingum routing method to route the flow through main channel. It is necessary to define the depth and width of the flow channel along with the length, slope and Manning's 'n' value of the channel by the user itself. Manning's equation for uniform flow in a channel is used to calculate the rate and velocity of flow in a reach segment for a given time step.

4.3. SWAT CUP

SWAT CUP is the standalone software developed for the calibration, validation, sensitivity analysis and uncertainty analysis of the SWAT model. The process and the algorithm used in SWAT- CUP are discussed in the sections below.

4.3.1. Calibration /Validation and Uncertainty Analysis

Calibration trains the model with respect to selected hydrological conditions which are those resembled by the observed data. Calibration through optimization of model performances is a trial and error method for which initial guess of model parameter is done, the model is run and comparison of simulated values with observed values is made. If the values are different then simulation is assumed to be not satisfactory and the parameter values are again changed and model is run again. The simulation is repeated until a satisfactory value is obtained.

After calibration of any model it is recommended that the developed model, before using it in practice, is to be check for its performances and the test process is called validation.

In this study, for uncertainty analysis using SWAT CUP, based on available literature, some of the model sensitive parameters were initially selected and Latin hypercube once at a time sensitive analysis was carried out. Sensitive parameters were identified, and calibration and validation were carried out. The SUFI-2 accounts for all the sources of uncertainties and quantifies them in terms of p-factor and r-factor. The p- factor is the percentage of observed data captured within 95% Prediction Uncertainty (95PPU) and r-factor indicates the average thickness of the 95 PPU band divided by the standard deviation of the observed data.

The theoretical value of p-factor ranges from 0 to 100 % and that of r-factor ranges from 0 to ∞. The p-factor of 1 and r-factor of zero is the ideal condition of simulation i.e. exact matching of simulated data with observed ones. While calibration and validation of model our concern is always getting reasonable values of these two factors. We try to capture most of the observations in 95 PPU band (p-factor near to 1) and at the same time we want smaller envelope (smaller r-factor). So, a balance between p-factor and r-factor is required to judge the strength of calibration (Abbaspour, 2015).

4.3.2. Sensitivity Analysis

SWAT CUP has two options for sensitivity analysis and they are global and one at a time (OAT) sensitivity analysis. OAT sensitivity analysis is performed taking one parameter at a time keeping other parameter's value constant to identify the parameters sensitive to the model and global sensitivity analysis is performed after an iteration to get the rank of sensitivity of all the selected sensitive parameters from OAT sensitivity analysis. Global sensitivity analysis is determined on the basis of t-stat and p- value. Higher the absolute t-stat value and smaller p-value, the parameters are assumed to be more sensitive (Abbaspour, 2015).

4.3.3. Model Performance Evaluation

An objective function is defined as a numerical measure of the difference between the model output and the observed/measured output (Schaefli and Gupta 2007). There are several objective functions for the evaluation of the model performance. In this study, evaluation of model performance or the measure of degree of fit has been done taking two objective functions in SWAT CUP. The objective functions were Nash-Sutcliffe efficiency (NSE) and Coefficient of Determination (R^2). The coefficient of determination (R^2) is given by the relation,

$$R^2 = \frac{\left[\sum_i (Q_{m,i} - \bar{Q}_m)(Q_{s,i} - \bar{Q}_s)\right]^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2 \sum_i (Q_{s,i} - \bar{Q}_s)^2} \quad 4.10$$

Nash Sutcliffe efficiency criterion (NSE) has stood as a popular objective function in the available hydrological literatures. This gives the proportion of the variance of the data explained by the model(Nash and Sutcliffe 1970). NS is given by the relation,

$$NS = 1 - \frac{\sum_i (Q_m - Q_s)_i{}^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2} \quad 4.11$$

Where Q is the variable and 'm' stand for measured and's' stands for simulated values, bar stands for average and i is the i^{th} measured or simulated variable. R^2 value ranges from 0 to 1, value near to 1 indicating strong linear relation between measured and simulated values. NSE value varies from - ∞ to 1 showing how strongly the simulated results and measured data fit the 1:1 line. The NSE value less than or near to zero indicates poor model performance and near to 1 indicates best results from the model (Moriasi et al. 2007).

4.4. SWAT Applications for Flow Simulation

SWAT has been used in a study in Kaligandaki basin, Nepal to assess the water availability and compare the future water availability to detect the impact of climate change in the basin and an existing ROR hydropower project. Window of 10 years has been considered for the SWAT simulation where the warm up/ calibration and validation periods are 1998-1999, 2000-2004 and 1995-1999 respectively. Four GCMs under CMIP 5 has been used to predict the climate change impacts based on RCP 4.5 and 8.5. Under RCP 8.5, model revealed 26% increase in the average annual precipitation (major contribution being from the snow) and leads to significant change in basins hydrological regime affecting the water balance of the basin. This leads increment in the dry season flow reach up to 35% and 50% increase in the average annual discharge at the outlet of the basin. The climate change seems to have no adverse impacts on the existing Kaligandaki hydropower project (144MW), in fact the positive effect is been expected by the future flows by increasing the dry season flow regarding the operation of the hydropower project and hence the annual energy generation from the power plant is expected to increase considerably along with the dry season energy (Bajracharya et al. 2018).

A study has been conducted by Manjan and Aggarwal (2014) in the Bagmati Basin, Nepal, using the SWAT with the purpose of hydrological simulation of runoff. The performance of the SWAT for the basin has been evaluated in the lights of the correlation of the simulated data with the observed data as explained by NS efficiency and the coefficient of determination. In the study the required soil data has been extracted from the lab test from the undisturbed soil samples from 78 locations from different depth using the core cutter, whereas the landuse map has been prepares using the hybrid algorithm of classification from the landsat image of 2001. The SWAT model was calibrated/ validated for 6 yrs/2 yrs time period respectively. The meteorological data were taken representing upper, middle and lower basin. The parameters were adjusted manually on physical catchment understanding and sensitivity analysis. The performance of the model on the monthly time step was very good regarding the NS efficiency and R^2. The study resulted with the relationship of the evapo-transpiration, total water yield and surface runoff in terms of the total precipitation occurring in the basin. Evapo-transpiration and total water yield accounted for 71% and 23% of precipitation respectively. Average annual surface runoff accounted for 40% and 43% for calibration and validation period.

Government of Nepal has undertaken the interbasin water transfer project and is now in the implementation phase, wherein the water from Bheri River will be transferred to the Babai River so as to supplement he irrigation water requirement in the Babai basin. A study has been carried out by Mishra et al. (2018), with the objective of analyzing the stream flow under different climate change scenarios (RCP 4.5, RCP 8.5) for various future time periods, using the SWAT model. The study has been carried out using the projected data from three GCMs individually as well as ensembling them altogether. The purpose of the study has been states to help in the formulation of water management studies. The model has been set up for daily time step. Total simulation period was 1986-2013, out of which warm up/ calibration and validation periods were 5,16,7 years respectively. The result obtained from the ensemble of GCMs predict increase in temperature, precipitation and ultimately in the river flow at the outlet of the basin. The model performance accorded to the “good” range as suggested by Moriasi et al. (2007). The model has been focused to match the baseflow, but the peaks were underestimated and hence suggested that the model may not be used for the flood forecasting but can be used for assessing the stream flow volume. The prediction highlighted that the annual rainfall is expected to increase by 6.8-15.2% and annual flow by 6-12.5% as compared to the baseline data, however, the model simulated the reduced flow for the month of July and August by 20% whereas increased flow for dry periods by 70%. This will be a quite favorable change for the water users of Bheri as well as Babai basin. This predicts that Bheri could be a donor river and the inter basin water transfer as the sustainable project as well in the long run and.

A study using the SWAT model in Kasillian River basin, Iran was performed to simulate the discharge value at the outlet of the basin and verified by the observed discharge from the existing hydrometric station. The model was further used to investigate the impact of input data types and combination on the water flow computed. The model performance was evaluated in the monthly time step for the duration of 12 years (1978-1989) and was found to fulfil the accuracy and scaling expectancy. The model was set up to simulate the discharge for the various values of two parameters such as curve number and the overland roughness coefficient. The model output revealed that the flow was sensitive for both the parameters. 13.4% increment in the value of CN reduced the error value by 2.5% and increment of roughness coefficient reduced the error value only by 0.01%. Also, the model was set up to simulate the discharge at outlet for the different combinations of the input meteorological data sets i.e. precipitation, temperature, wind, relative humidity, solar radiation. 21 different combinations were tabulated ranging from different single meteorological dataset input up to all five meteorological dataset input. Observing the error values tabulated for each input combination, for the mentioned basin, maximum error value reported were (95%-82%) for the combinations: 1.temperature-radiation-wind, 2.radiation-wind, 3.radiation, 4.Precipitation-radiation-wind-RH, 5.Temperature-radiation-wind-RH) and the minimum error value reported were (3.2%-14.3%) for the combinations: 1.RH, 2.Precipitation-temperature-RH-radiation, 3.Precipitation-temperature-Radiation-Wind-RH. Hence it was concluded by the author that precipitation, relative humidity and temperature had greater positive impact on the calculated discharge compared to solar radiation.(Ghane et al. 2017)

A study was carried out in Skunk Creek watershed in South Dakota using the SWAT model to simulate the stream flow for the period of 21 years from 1980-2000, on daily and monthly time step using 24 parameters using SWAT- CUP, SUFi-2 algorithm. The model revealed a good correlation between the observed and the simulated flow. For daily time step, NSE and R^2 were 0.56 and 0.7 for calibration and 0.55 and 0.44 for validation. Similarly, For monthly time step, NSE and R^2 were 0.84 and 0.84 for calibration and 0.76 and 0.77 for validation. The most sensitive parameter was found to be SOL_AWC during calibration.(Mehan, Neupane, and Kumar 2017).

The study was conducted for the evaluation of applicability of SWAT model in the Shaya watershed of Ethiopia. It analyzed the influence of the hydrological parameters on the river flow and yield estimation. The performance was good with value 0.71 for both R2 and ENS for calibration and 0.76 and 0.75 respectively for validation for monthly time step. The model captured the flow series trend quite well conforming the appropriateness of the model application.(Shawul, Alamirew, and Dinka 2013)

A study carried out by Pechlivanidis et al. (2011) about the model evaluation and uncertainties associated in the model explained that the uncertainty inherent to the model needs to be quantified into basically four sources. The first is the natural uncertainties, second is data uncertainties, third is model parameters uncertainties, and fourth is the uncertainties associated with the model. The author also claimed that the modeler is unable to extract or measure everything the model needs to acquire as model input because of the heterogeneity of the watershed and the limitation in the measurement techniques. This is the reason the calibration should be associated with the quantification of the uncertainty, arising from the mentioned four sources.

A research has been carried out to calibrate a hydrological model using SWAT for integrated Europe for monthly time step, wherein different components are simulated. Within the research, a detailed calibration protocol has also been discussed along with the uncertainty analysis and the rules for the regionalization of the parameters. The regionalization has been illustrated for various probable conditions which the simulation can attain, such as base flow/ peak flow too high/ too low, discharge shift, evapo-transpiration too high. The paper also discussed about the model uncertainties which may be due to various reasons including conceptual simplification of model processes included in the model or occurring in the watershed and the input data quality. The difficulty faced in the given study which has been highlighted included the limited and unevenly distributed stations. The study was overall aimed to present the insights into freshwater availability and quality of water.(Abbaspour et al. 2015)

In Karnali basin, Nepal, the model SWAT as well as one more hydrologic simulation model (snowmelt Runoff Model) has been used to test the applicability of the model in the assessment of the water balance of the basin and determine contribution of the snowmelt for the stream discharge. The model performance for the said basin came out to be quite good both for calibration as well as validation. The evapotranspiration accounted for 25% of annual precipitation whereas the runoff was about 12%. The study also concluded the appropriateness of the SWAT model use for the mountain watershed in Nepal (Dhami et al. 2018).

An extensive review paper has been published by incorporating 250 peer reviewed published research papers based on various application of SWAT model. The papers can be categorized under applications field such as stream flow, sediment, hydrological analyses, climate impact on hydrology, pollutants analysis, sensitivity, calibration and validation and uncertainty analysis, comparison of hydrological models. The paper has also focused on the strength and weaknesses and recommendations for the improvement of the model. The papers wherein simulation had been carried out on the monthly and annual time step had shown the good conformity, whereas some had shown the inadequate performance when it came for the simulation on daily time step. The author had recommended the continued testing of the model including more uncertainty analysis, when the comparison is to be made in daily time step.(Gassman et al. 2007a)

4.5. Working Methodology for SWAT MODEL

The model used in the study is Arc–SWAT, which is an extension added to Arc-GIS 10.2. This is capable of interpreting data (soil data, land use/ land cover), map preparation and analysis and creation of watershed boundary and river system using Digital Elevation Model and showing spatial distribution of hydrological and meteorological station and information related to these stations. The detailed working methodology is described below.

4.5.1. Data Acquisition and Processing

4.5.1.1. Topographic Data:

The model input for topographic data for the study area was given in the form of Digital elevation model, which was downloaded from the website of United States Geological Survey (USGS) https://earthexplorer.usgs.gov/ as well as from Bhuvan Indian Geo-platform of Indian Space Research Organization https://bhuvan.nrsc.gov.in/bhuvan_links.php. The downloaded DEM was of spatial resolution of 30 m (i.e. grid size30m*30m). The DEM downloaded were freely available. The values in DEM represent the spot height. The required four number of DEM covering the area of study were downloaded and processed using Arc GIS 10.2. The DEM filled after creating a mosaic and was then used as an input raster after projecting it to WGS 1984 UTM zone 45. The Projected map was used in the watershed delineation in Arc SWAT. The processed DEM map of study area is as shown in Figure 4.2 and indicates the highest elevation of the watershed to be 3608 masl and lowest elevation is 81 masl.

4.5.1.2. Soil Data:

Soil Data has as also a very significant impact, like DEM for the modeling of stream flow in SWAT. SWAT model requires several soil properties such as soil texture, water content, hydraulic conductivity, bulk density etc of each soil type. In this study, soil data was obtained from Food and Agriculture organization (FAO) at the spatial resolution of 10 km, which is freely available. The scale of the map is very low and when clipped by the SWAT model to the required watershed area, it assigned two soil types for the entire watershed, out of which one was almost entirely covering the watershed. Thus low resolution data might have adversely affected the simulation result. The soil distribution in the watershed is tabulated in the Table 4.1

Table 4.1 Soil Distribution

SN	Soil Name	Soil code	Area (sq.km)	Percent (%)	No. of layers	Hydgrp	texture
1	Humic Acrisol	Ah12-2bc-3639	1137.04	97.65	2	c	loam
3	Lithosol	I-Bh-U-c-3717	27.36	2.35	3	c	loam
Total			1164.4	100			

4.5.1.3. Land Use Data:

The detail analysis and mapping of land use / land cover data is the next significant input for the hydrological modeling in SWAT model.

For this study, land use land cover data was obtained from the website of ICIMOD Nepal, (http://apps.geoportal.icimod.org/ArcGIS/rest/services/Nepal/Landcover2010/MapServer/0), which has been published in official webpage of ICIMOD Nepal This is freely available resources in the website for the academic purpose. The land use land cover map extracted using the basin boundary consists of different percentage of distribution, presented in Table 4.2.

Table 4.2 Land use Distribution

SN	Land use type	Land use code	Area (sq. km)	Percentage (%)
1	Forest-Mixed	FRST	712.60	61.22
2	Range-Grasses	RNGE	2.68	0.23
3	Pasture	PAST	60.53	5.2
4	Agricultural Land	AGRL	377.72	32.45
5	Barren	BARR	3.72	0.32
6	Water	WATR	6.52	0.56
7	Residential	URBN	0.12	0.01
Total			1164	100

4.5.1.4. Land Slope Data:

Slope plays a vital role in the hydrological modeling process as it governs the overall flow of the flow. SWAT allows the use to choose among the options of slope class or the multiple slope classes. The number of classes of slope in the study is according to the terrain of the watershed. The watershed was chosen to be categorized under 5 different classes as presented in the Table 4.3. It is evident from the table that most of the watershed is a high slope terrain.

Table 4.3 Classification of Slope

SN	Land slope(%)	Area (sq. km)	Percentage (%)
1	0-10	60.30	5.18
2	10-20	134.33	11.54
3	20-30	204.51	17.57
4	30-40	233.38	20.05
5	>40	531.48	45.66
Total		1164	100

4.5.1.5. Weather Data:

For hydrological modeling at daily time step, SWAT requires the same time window of climate data recorded at daily time step in the form of precipitation, maximum and minimum air temperature, wind speed, solar radiation and relative humidity.

The data for temperature and precipitation have been taken from the Department of Hydrology and Meteorology (DHM), Nepal. All other remaining database was generated by the model itself with reference to the weather generator database, CFSR database as W-Gen.

In this study, the meteorological stations to be used and the window of data to be used was determined from the procedure as follows:

1. Meteorological stations of the eastern Nepal were mapped along with the watershed.
2. Thiessen polygon was prepared to find out the appropriate stations to be considered, and the most important meteorological station was noted. For this watershed, most important station was considered to be Ilam tea estate , station no 1407
3. The data available (1980-2010) for all the meteorological stations were extracted in excel.
4. Missing data was analyzed in term of percentage and data availability was categorized in several classes corresponding to the year, viz. missing a, missing up to 75%, missing up to 50%, missing up to 25%, missing up to 10% and missing below 10%.
5. The stations and the window were finalized so as to get the clean data for the station 1407 and reduce the missing data for other station in the frame.
6. Data of the Since most of those stations were lacking the observed data (temperature or precipitation or both) in bulk for several years, the time window of 9 years from 1990 to 1998 was finally selected the considering that fair data available for the meteorological stations for temperature and precipitation.

The list of meteorological stations considered for the study are listed in the Table 4.4 and graphically represented in Figure 4.3 and the missing data details are presented in Table 4.5

Table 4.4 Hydrological meteorological stations details

SN	Station Name	Station No	Station Type	Lat(^{O})	Long (^{O})	Elevation (m)	Data Type
Meteorological Station							
1	Ilam Tea Estate	1407	Climate	26.91	87.9	1300	P & T
2	Damak	1408	Precipitation	26.71	87.66	163	P
3	Kanyam Tea Estate	1416	Climate	26.86	88.06	1687	P & T
4	Phidim	1419	Climate	27.15	87.75	1205	P & T
5	Gaide	1421	Climate	26.58	87.9	143	P & T
Hydrological Station							
6	Mainachuli	795	Gauging	26 41 12	87 52 44	1000	Q
P= Precipitation, T= Temperature, Q= Discharge							

Table 4.5 Missing data details

variables	Station no	Percentage of data missing in the stated year									Total % for station
		1990	1991	1992	1993	1994	1995	1996	1997	1998	
precipitation	1407	0	0	0	0	0	0	0	0	0	0
	1408	0	0	0	0	0	0	0	12.9	0	1.43
	1416	0	0	0	0	0	0	0	0	0	0.00
	1419	4.1	3.6	5.8	6.6	6.8	4.7	4.4	7	4.4	5.27
	1421	0	0	0	0.3	0	0	0	0	0	0.03
Total % for year		0.8	0.7	1.2	1.4	1.4	0.9	0.9	4.0	0.9	1.35
Temperature	1407	0.4	0.3	0	0.4	0.7	2.6	0	0.4	0.4	0.58
	1416	1.4	0.5	0	0.3	1.2	0.4	0.8	0.5	0.4	0.62
	1419	2.5	58.6	17.8	32.5	2.2	0.1	0.1	0.7	1.8	12.92
	1421	0	0	3.8	0.3	0.3	0	0	4.9	4.8	1.57
Total % for year		1.1	14.9	5.4	8.4	1.1	0.8	0.2	1.6	1.8	

4.5.2. Missing Data Handling

4.5.2.1. Precipitation

As described, the stations and window has been selected in such a way so that the percentage of missing data for precipitation is very small. So the arithmetic mean method of estimation for missing data has been adopted as the missing data ranges within 10%.

4.5.2.2. Temperature

For temperature, the missing data has been estimated by

- Linear interpolation (if up to 4 consecutive data are missing)

- Correlation and Multiple Regression method (if more than 4 consecutive data are missing)
- Correlation between the T max and T min of same year and same station
- Correlation between the T max or T min of different year and same station
- Correlation between the T max or T min of same year and different stations
- Verification by linear interpolation and visual inspection

4.5.2.3. Stream Discharge

SWAT model is simulates the runoff from the weather data as described above, which needs to be calibrated with the daily river flow data from the observed values of flow in the existing gauging site. For this purpose, the daily flow data of the same window as of weather database i.e. 1990- 1998 from the gauging station number 795, Mainachuli has been used. This data has been acquired from the Department of Hydrology and Meteorology (DHM), Nepal. The location of the gauging site is mapped in the Figure 4.3.

4.5.3. SWAT Modelling

4.5.3.1. Model Setup

SWAT model was set up in various specific stages. These includes data preparation, watershed discretization, HRU definition, weather data input, set up of the model and run, sensitivity analysis and finally calibration, and validation.

The mosaic DEM, Land use/ Land cover map and soil map of the area covering the study area were prepared in Arc GIS and were projected to UTM zone 45N.. The watershed area was delineated after selecting the 5 sub-watershed outlet which resulted 5 sub-watersheds and total area of the watershed being 1164.4 sqkms. Land use/ Land cover was reclassified according to the SWAT land cover classification. So a look up table was prepared assigning the proper codes and was supplemented. For soil data, the user soil lookup was chosen and proceded. The land slope of the study was classified in 5 classes as described and overlaid with the land use and soil map to divide the watershed into hydrologic responsive units (HRUs).

HRU is the smallest spatial unit, which consists of similar land use soil and slope class. Any area under same HRU will exhibit the same hydrologic response under similar circumstance. So in the definition process, the intended sub-basins are further classified into numerous HRUs. The division of the sub basin into further smaller units (HRUs) help to study the variation in the evapotranspiration and other hydrological components. ARC SWAT manual suggests 20% land use, 10% soil and 20% slope value as sufficient threshold, but model run with these values in this study resulted very few numbers of HRUs. Hence the threshold value was reduced to 0% land use, 0% soil, and 0% slope which defined 168 numbers of HRUs from 5 sub watersheds. The DEM, Hydro-met stations map, LULC Map, Soil Map, Slope Map and HRU/ Sub basin Maps are presented in Figure 4.2 to Figure 4.7

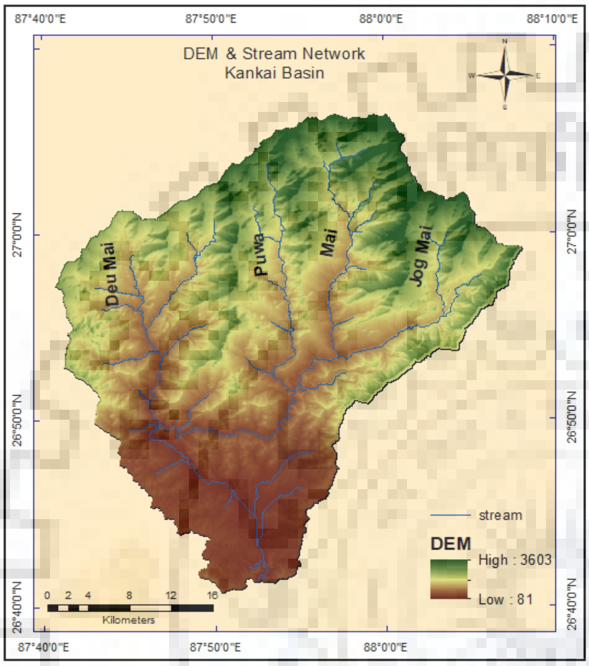

Figure 4.2 Digital Elevation Model

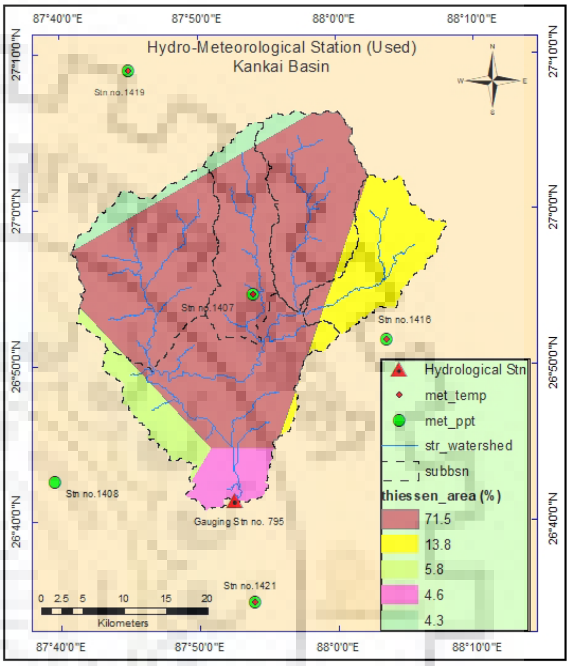

Figure 4.3 Hydro-Meteorological stations and Thiessen polygon

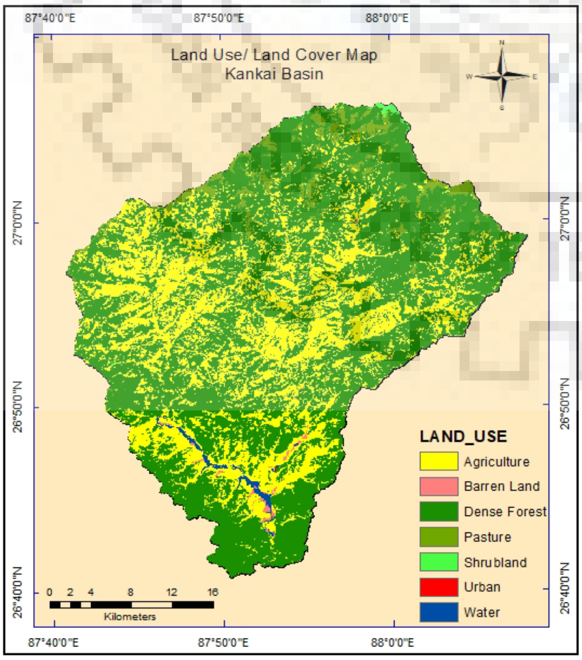

Figure 4.4 Land Use Land Cover Map

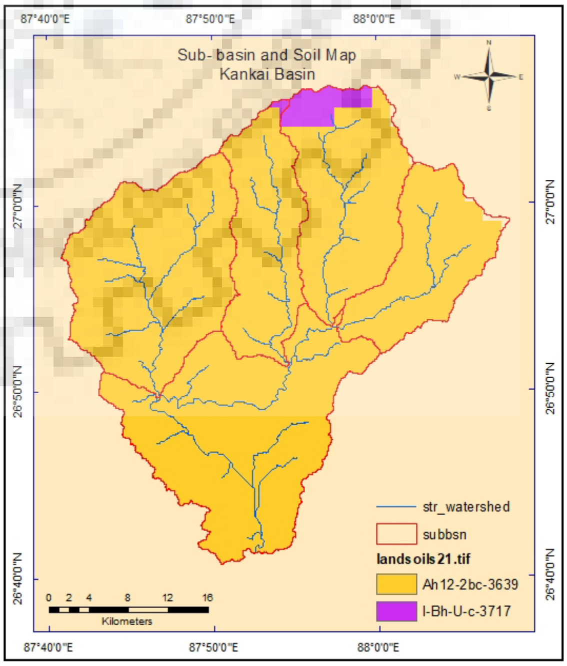

Figure 4.5 Soil Map

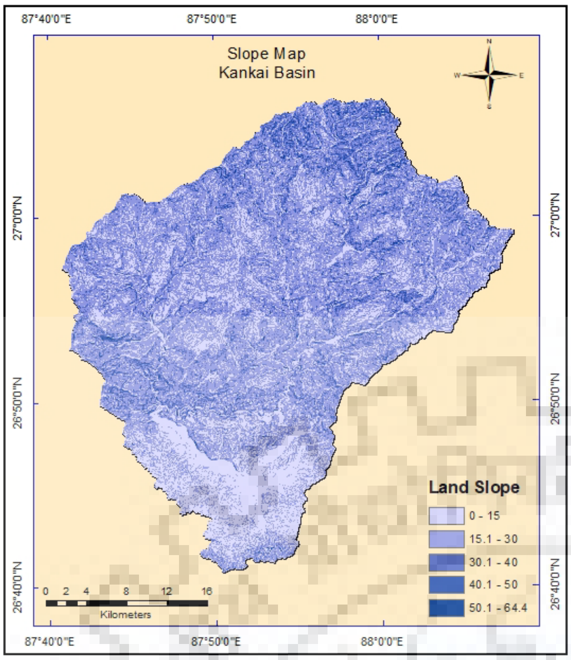

Figure 4.6 Slope Map

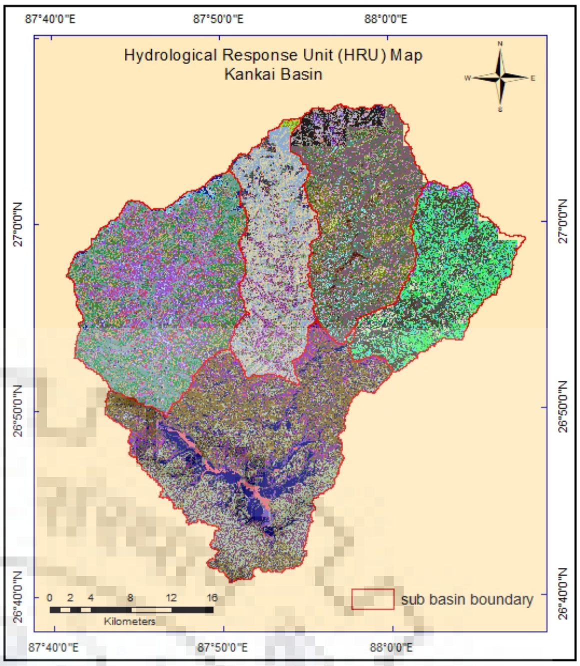

Figure 4.7 HRU and Sub basin

The process followed with importing the weather data in the SWAT model for the purpose of hydrological simulation. The weather data (precipitation and temperature) are formatted in the *.txt file type. All other remaining database was generated in the model itself with reference to the weather generator database.

The model was run considering the following methods of calculation for various hydrological processes; Hargreaves method for potential evaporation process, SCS Curve number for surface runoff, initial curve number estimation using soil moisture method, Muskingum method for channel routing.

The model was run for 1990 to 1998 including three years of warm up period from 1990 to 1992.

The work flow method is presented in the Figure 4.8

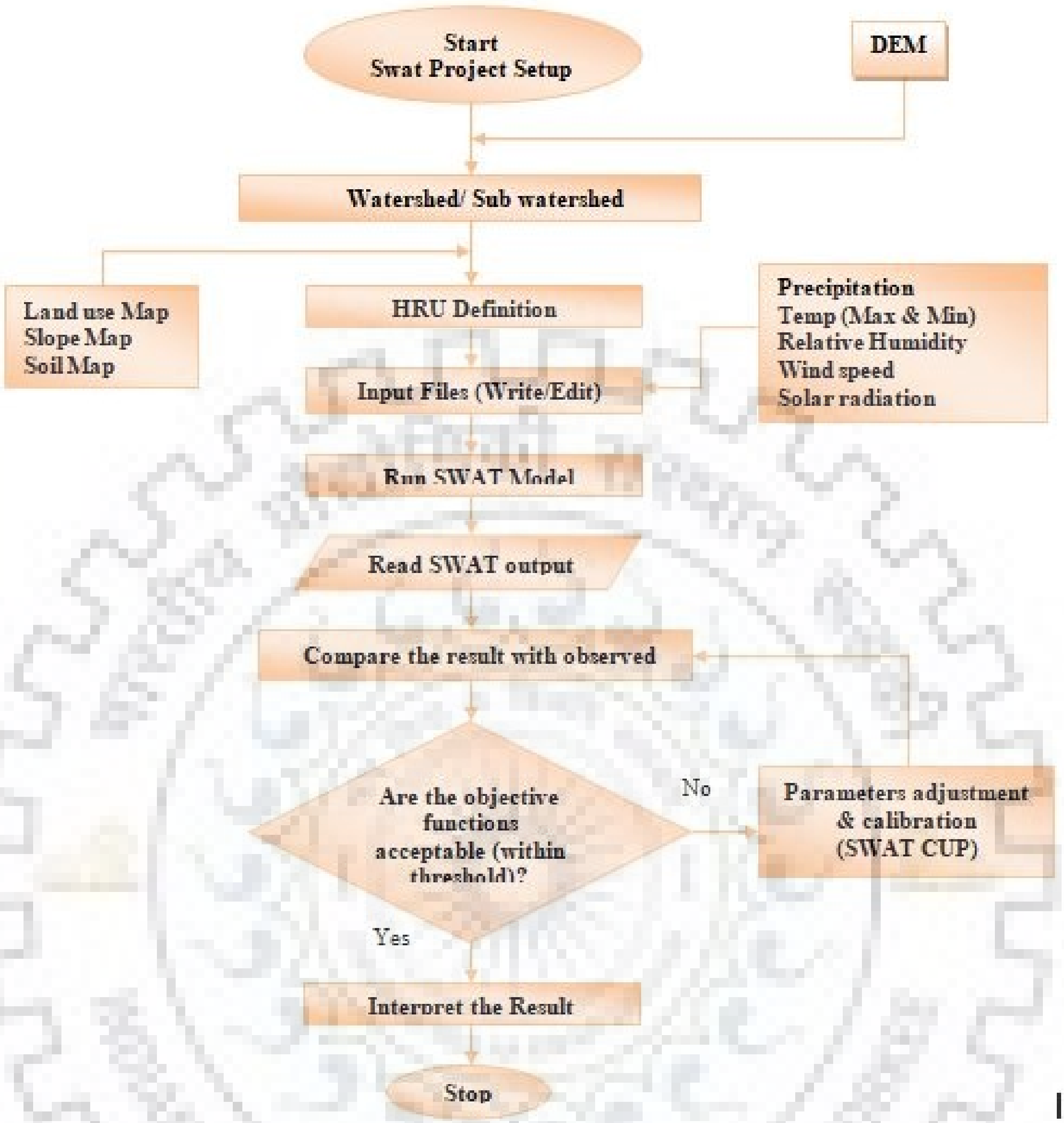

Figure 4.8 Model setup and work flow of SWAT

4.5.3.2. Sensitivity Analysis

The review of several research papers led to the identification of the relevant sensitive parameters to be considered for the simulation of the flow. The relevance of those parameters in the river basin under study was checked. One at time sensitivity Analysis (OAT) was performed to find out the parameters which were sensitive to the objective function. This was carried out in the auto calibration software SWAT-CUP using SUFI-2 Algorithm.

The second step carried out was the global sensitivity analysis, which shows the relative sensitivity of the parameters considered for the study area.

4.5.3.3. Calibration and Validation

Based on the parameters considered, the auto calibration software, SWAT CUP was used for the calibration and validation of the model by taking the objective function as Coefficient of Determination (R^2) and Nash Sutcliff (NS). The p-factor and r- factor were also considered for the observing the model performance.

4.6. Result and Discussion

4.6.1. Sensitivity Analysis

Considering the database for the calibration period (1993-1996), the sensitivity analysis was done for the flow in two steps: a. OAT sensitivity analysis and b. Global Sensitivity analysis. Some of the parameters which much more sensitive to OAT were less sensitive to Global Sensitivity analysis whereas, some parameters which were less sensitive in the Global sensitivity analysis were more sensitive when performed in OAT. Hence sensitive parameters from both the analyses were merged to form a set of 15 parameters for calibration purpose.

The selected 15 parameters and their performance in the global sensitivity are shown in Figure 4.9 along with the corresponding p- value and t-stat.

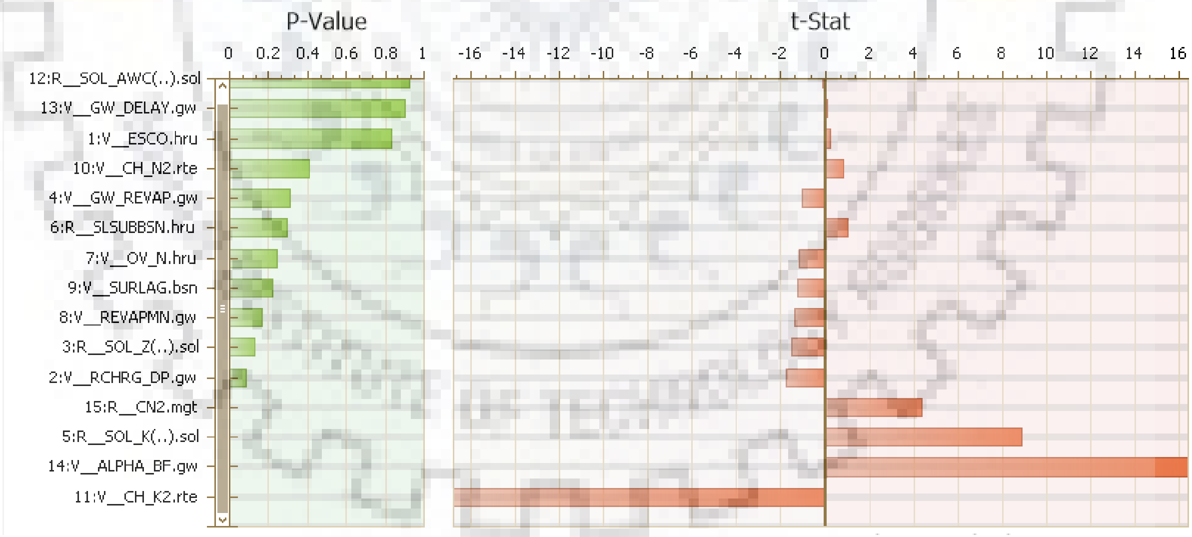

Figure 4.9 Global sensitivity analysis chart

4.6.2. Model Calibration and Validation

As stated earlier the database used for the calibration period is from 1993 to 1996. The simulated flow obtained by using the parameters identified was plotted along with observed flow. The plot thus obtained revealed the problem in the simulated flow: a. base flow too low

b. Peak too high. Several iterations were run by altering the values of the parameters based on the following.

a. Address for the problem "base flow too low"

- lower the value of deep percolation loss(lowering the threshold depth of water in the shallow aquifer required for the baseflow to occur), GWQMN
- lower the value of ground water revap coefficient, GWREVAP
- Raise the value of threshold depth of water in shallow aquifer for revap to occur, REVAPMN

b. Address for the problem "Peak too high"

- Lower the value of curve number, CN2
- Raise the value of available soil water content, SOL_AWC
- Raise the value of soil evaporation compensation factor, ESCO

For this, firstly, the values attained by the model for these parameters were accessed and then according to the protocol the values of the parameters were adjusted. Making balance between the value of the parameters within the absolute range and improvement of the objective function was a big challenge.

Several iterations were run by adjusting the parameters as said. Final adjusted value and their maximum and minimum value are tabulated in the Table 4.6

Table 4.6 Final calibrated parameter with the Maximum and Minimum range

SN	Parameter_Name	Fitted_Value	Min_value	Max_value
1	V__ESCO.hru	0.95465	0.93	0.98
2	V__RCHRG_DP.gw	0.68782	0.34	1
3	R__SOL_Z(..).sol	-0.1454	-0.2	0
4	V__GW_REVAP.gw	0.06375	0.05	0.1
5	R__SOL_K(..).sol	4.441	2.6	9.6
6	R__SLSUBBSN.hru	-0.11498	-0.2	0.06
7	V__OV_N.hru	0.25406	0.01	0.53
8	V__REVAPMN.gw	435.335297	416.7	473
9	V__SURLAG.bsn	11.481	4.5	17.5
10	V__CH_N2.rte	0.46065	0.33	0.98
11	V__CH_K2.rte	32.482098	0	94. 7
12	R__SOL_AWC(..).sol	0.12685	-0.02	0.13
13	V__GW_DELAY.gw	47.172001	30	242
14	V__ALPHA_BF.gw	0.12814	0.01	0.67
15	R__CN2.mgt	-0.04945	-0.12	0.05
Note: V_:Altering the value of the parameter by replacing R_:Altering the value of the parameter by multiplying the initial value by (1+ initial value)				

Moriasi et al. (2007) have related the performance of the model with reference to the values of the objective function for the simulation for the monthly time step, the summary of which relevant to the objective function considered in this study is tabulated in the Table 4.7

Table 4.7Model Performance evaluation (Moriasi et al. 2007)

Model performance	NS	R^2
very good	$0.75<NSE\leq1$	>0.5
good	$0.65<NSE\leq0.75$	
satisfactory	$0.5<NSE\leq0.65$	
unsatisfactory	$NSE<0.5$	<0.5

The result for the calibration and the validation period is tabulated in the Table 4.8 and depicted graphically in the Figure 4.10 and Figure 4.11.

Table 4.8 Calibration and Validation Result

Time step	Daily		Monthly	
Objective function	Calibration	Validation	Calibration	Validation
p- factor	0.65	0.81	0.46	0.54
r- factor	0.35	0.52	0.30	0.42
R^2	0.64	0.70	0.87	0.75
NS	0.60	0.69	0.83	0.75
PBIAS	20.6	6.4	15.9	1.0

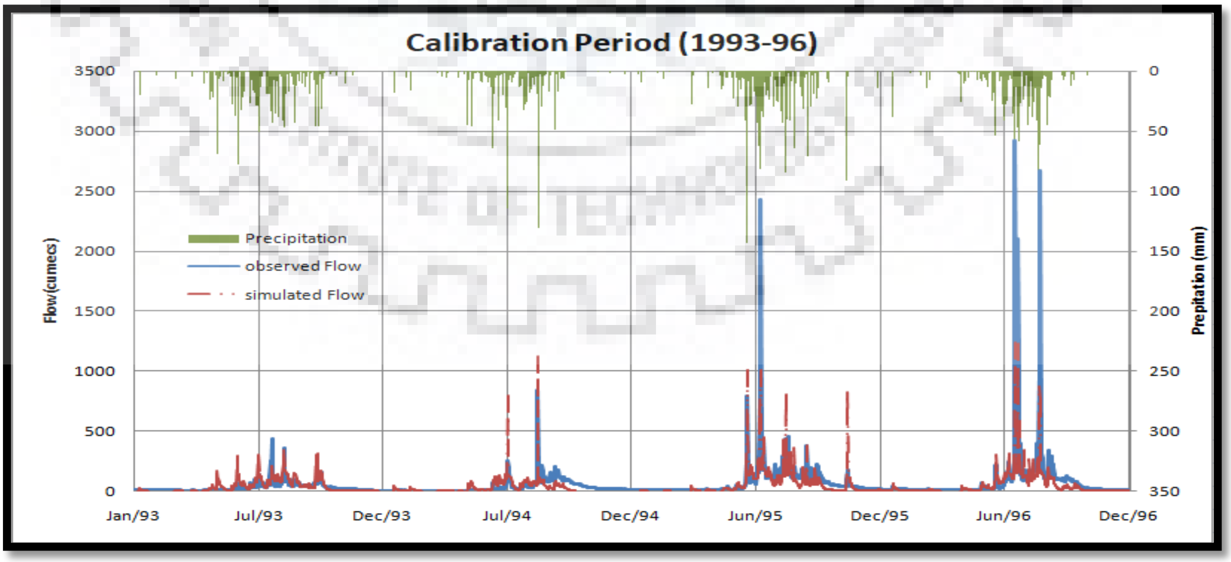

Figure 4.10 Daily Calibration of Flow of (1993-96)

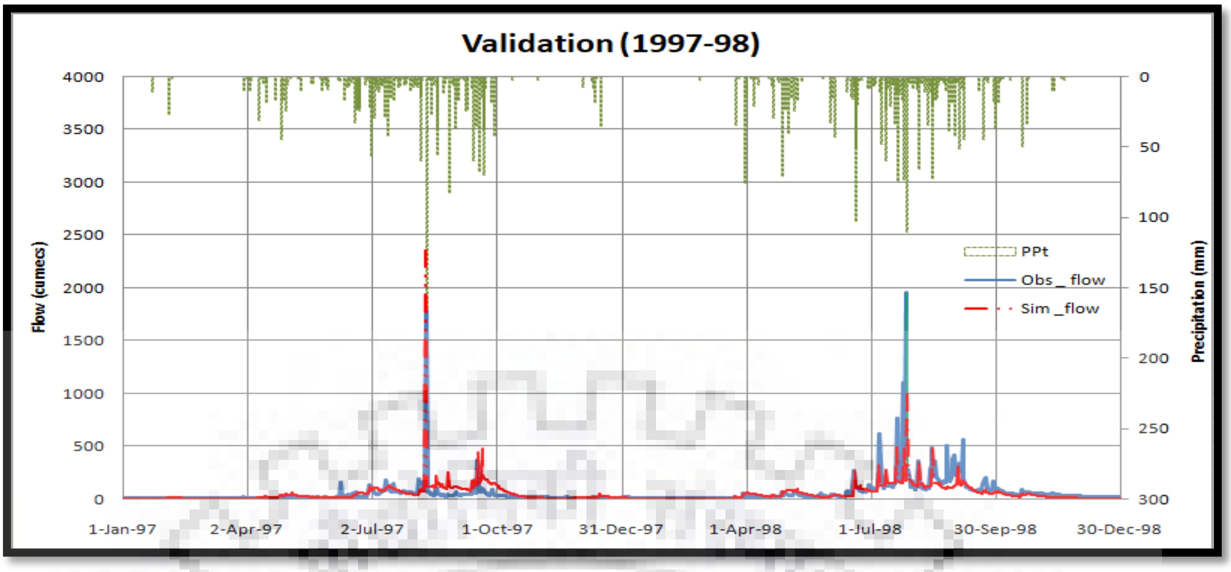

Figure 4.11 Daily Validation of Flow of (1997-98)

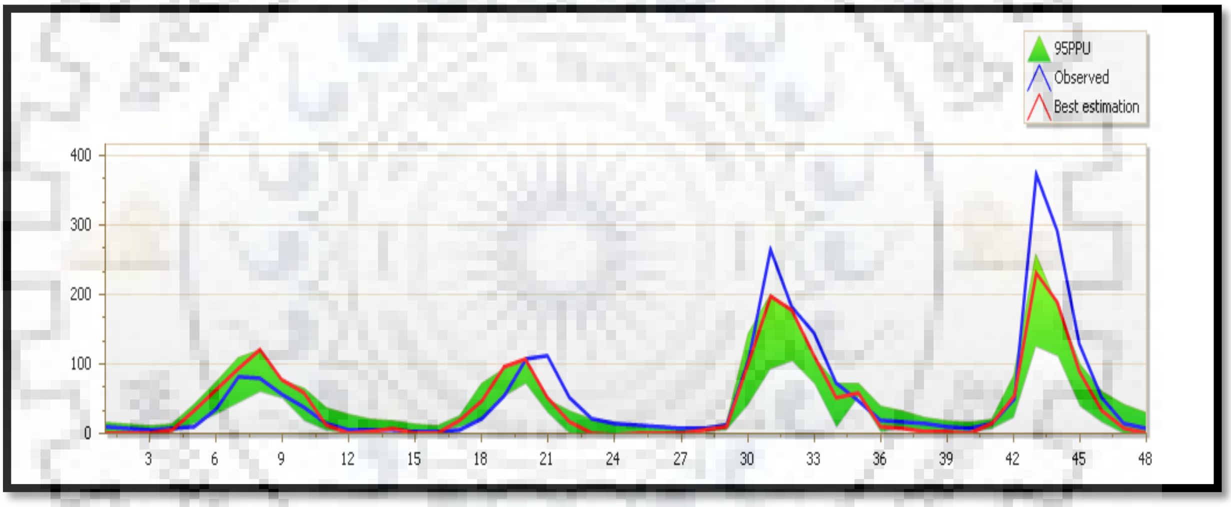

Figure 4.12 Monthly Calibration of Flow of (1993-96)

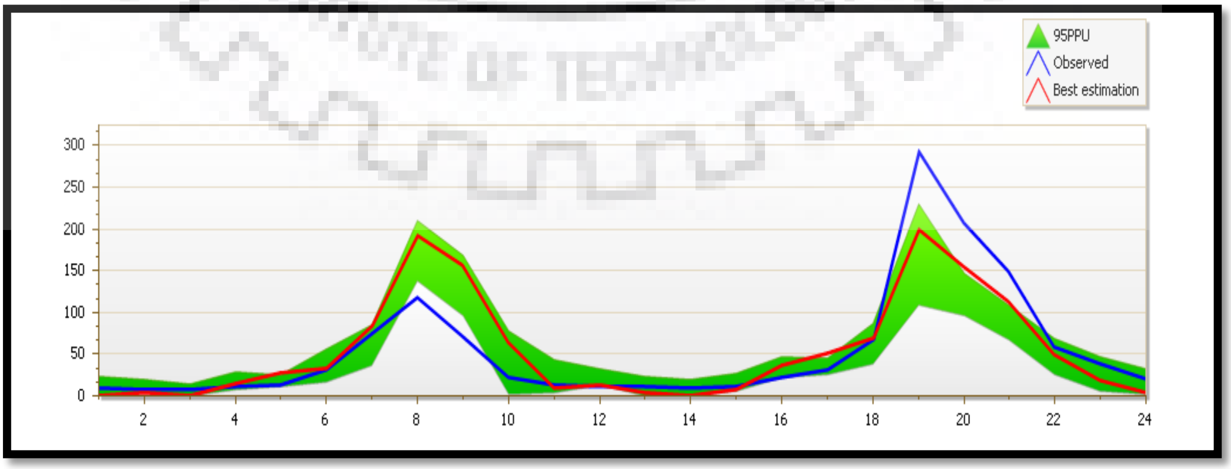

Figure 4.13 Monthly Validation of Flow of (1997-98)

From Table 4.8, Figure 4.10 and Figure 4.11 it is evident that the model had performed somewhat better for the validation period in comparison to the calibration period as the NS efficiency and the coefficient of determination for the calibration period is 0.6 and 0.70 respectively whereas for validation period, it is 0.69 and 0.70 respectively.

4.7. Summary

Hydrological model of the basin has been established using the SWAT model. Daily database from 5 precipitation stations and 4 temperature stations have been prepared for the nine years window (1990-1998). The window was selected so as to have least number of missing data. Similarly, same daily flow database for same window was prepared for the calibration and validation purpose. The weather database along with DEM, LULC and Slope Map were used as input to set up the model. Allocating initial 3 years as warm-up period, the model was calibrated using 4 years database and validated with 2 years database. SWAT CUP has been employed for calibration of the model, wherein 15 sensitive parameters were identified from one at a time sensitivity analysis and global sensitivity analysis.

NS efficiency and the coefficient of determination for the calibration period is 0.6 and 0.70 respectively whereas for validation period, it is 0.69 and 0.70 respectively for daily flow. The model had performed somewhat better for the validation period in comparison to the calibration period based on NS efficiency criteria.

CHAPTER FIVE
FUTURE CLIMATE PREDICTION

5.1. Climate Change

Climate is considered as the average weather condition mostly including temperature, precipitation, wind, humidity, solar radiation of a particular area over a specific length of time. Climate change, in broad sense, hence can be defined as the change in these climatic conditions in addition to the natural climatic variability due to anthropogenic interventions over a comparable period of time (United Nations 1992). However, climate change has been defined by IPCC as the long-term significasnt shift in weather conditions, indicated by precipitation, temperature, wind etc which persist usually for decades or even longer. The major cause of the climate variability is attributed firstly to green house gas emission due to the anthropogenic activities, which alters the atmospheric composition; and next natural climatic variability observed over a comparable time period. (IPCC 2013a).

Almost the entire globe has been experiencing surface warming and the evidence for this warming comes from multiple climate system indicators from atmosphere to the oceans such as change in temperature of oceans, atmosphere and surface, change in glacier, snow cover, sea ice, sea level and water vapor (Hartmann et al. 2013).

The green house gases production varies due to various factors such as population size, economic activities, land use pattern, energy consumption and technological advancement. Four different 21st century pathways; Representative concentration pathways (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5) are adopted by IPCC in its fifth Assessment Report, which are used for making projection of climatic condition depending upon the various assumptions of these factors.

5.2. Impact of Climate Change in Hydrological Components

It has been reported from all over the world through various research and studies that the change in the climate is impacting the global economy. Along with the influence in the spatial distribution and availability of natural resources, ecosystems and human economy, the alteration is profoundly observed in the availability of water resources, due to the impacts of climate change. The impact can be seen on several hydrological components as depicted in the Figure 5.1,

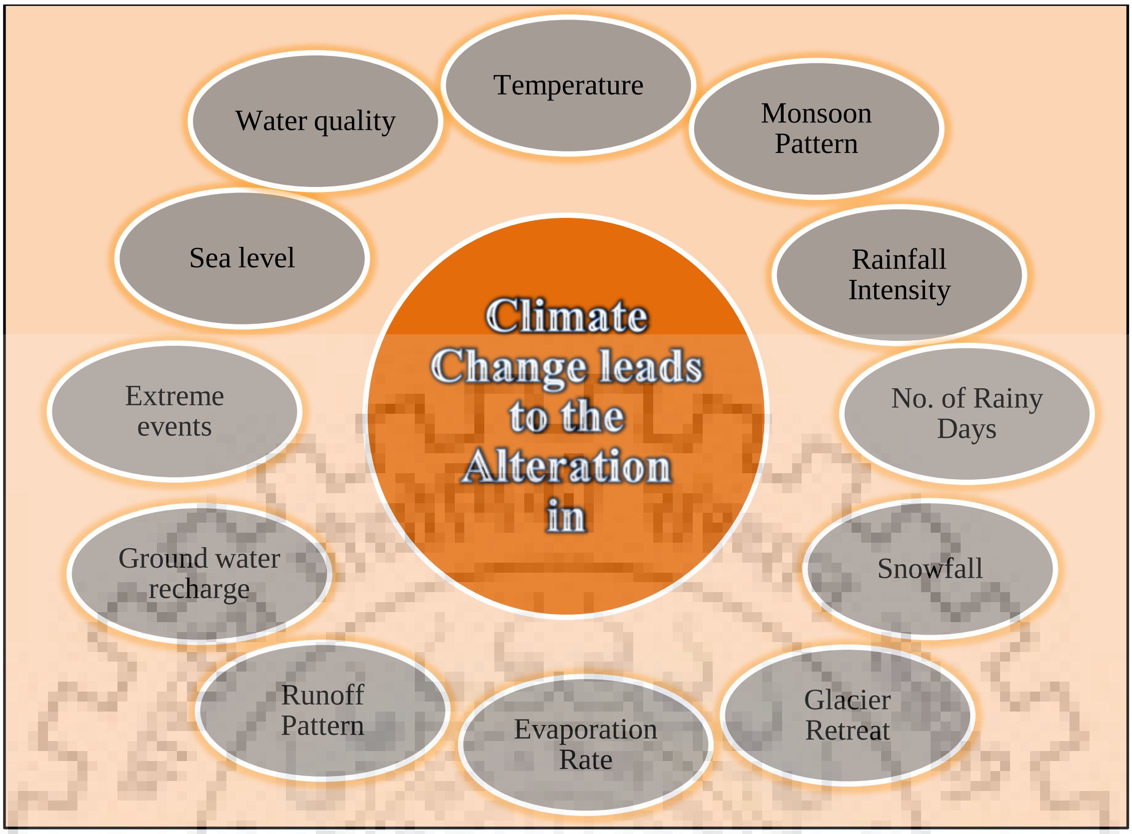

Figure 5.1 Different impacts of climate change in water resources

5.3. Climate Models and Their Characteristics

The response and extent of climate in terms of time and space are predicted with the help of several tools and allows the projection of the future climate over various time scales. These primary tools developed for the investigation of the climate change for different forcings are known as the climate models.

Models are categorized under several types as listed below, which are evaluated in AR5;

a. Atmosphere-Ocean General Circulation Models (AOGCM)
b. Earth System Models (ESM)
c. Earth System Models of intermediate complexity (ESMIC)
d. Regional Climate Model (RCM)

AOGCMs were the standard climate models evaluated in the fourth AR. Their main purpose is to recognize the dynamics of the physical working of the climate system, and for projecting climate based on future GHG and aerosol forcing.

ESM models provide the most comprehensive tools available for simulating pre and post responses of the climate to external forcing, in which biogeochemical response has a significant impact.

EMICs try to contain the significant parameters of ESM, but generally at lower resolution.

RCMs are limited-area models which represents climate processes similar to those in the components of AOGCMs. RCMs are often used to dynamically 'downscale' global model simulations and generate detailed information.

5.3.1. Global Climate Model

The General Circulation Model also known as Global Climate Model (GCM) is a complex mathematical model which represents physical processes in the atmosphere, cryosphere, ocean and land surface (IPCC 2013b). The GCMs were initially developed in 1956 to simulate average, synoptic-scale, atmospheric circulation patterns but since then various GCMs were designed and developed to use for weather forecasting, understanding the climate and predicting future change in climate (Lupo et al. 2013). There are two major GCMs viz., atmospheric GCMs and Oceanic GCMs. The combined form of these two GCMs is then called as atmosphere-ocean coupled general circulation model (AOGCM).

The GCMs divide the globe into 3 dimensional grid of cells to depict the climate, with horizontal resolution between 250 to 600 km, 10 to 20 vertical layers in the atmosphere and up to 30 layers in the oceans (IPCC-TGICA 2007). This resolution is quite coarse and therefore the processes that occur at smaller scales cannot be properly modeled. Till few years back, GCMs only included atmosphere, land surface components, and sometime oceanic component. However, these are not the only components to define the climate; there are biological and chemical processes as well which impacts on climate. Considering these, GCMs recently started incorporating sophisticated models of sea ice, carbon cycle, ice-sheet and even atmospheric chemistry (Goosse et al. 2015). Currently, all these processes are included in a new climate model called Earth System Model (ESM) (Heavens, Ward, and Mahowald 2013).

5.3.2. Future Climate Scenarios

Over time, different scenarios have been used in climate research in IPCC's first assessment report to Special Report on Emissions and Scenarios (SRES) used in third and fourth assessment report. And recently, the new scenarios called Representative Concentration

Pathways were developed and used for preparing fifth assessment report. The RCPs were developed by combined effort of the researchers involved in climate research. The total of four pathways RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 were developed. They were named based on the radiative forcing target levels of 2.6, 4.5, 6 and 8.5 W/m2, by the end of 21st century. The estimation of radiative forcing is based on the forcing of GHGs and other agents. All these four pathways were considered to be the representative of all the literature pertinent to change in climate (Wayne 2013).

5.3.2.1. RCP 2.6

RCP 2.6 is the mitigative scenarios which targets to limit the increase of global mean temperature to 2^0C. This pathway is also referred as RCP3-PD in which PD stands for peak and decline. This pathway indicates that radiative forcing will reach around 3 W/m2 in the mid-century and decline afterward to 2.6 W/m2 by the end of 21^{st} century. In order to achieve this, emission would need to be significantly reduced. CO_2 emissions need to be reduced by more than 100 % by 2100. This can be achieved only by replacing use of fossil fuel by renewable energy, nuclear power, increased use of bioenergy and use of carbon capture and storage (CCS). The underlying assumption for this pathway is that new energy efficient technologies can be rapidly transferred to all over the world and implement immediately (Van Vuuren et al. 2011).

5.3.2.2. RCP 4.5

RCP 4.5 is the scenario of stabilization wherein the stabilization of the radiative forcing takes place at 4.5 W/m^2 (approx. 650 ppm CO2-equivalent) in 2100 without ever exceeding that value (Thomson et al. 2011). The underlying assumptions involved is that the global population reaches a maximum of more than 9 billion by 2065 and then declines to 8.7 billion in 2100, global GDP grows by an order of magnitude, declines in energy consumption, increase in fossil fuel consumption, substantial increase in renewable energy and nuclear energy use, and large increase in forest area as a mitigation strategy (Wayne 2013).

5.3.2.3. RCP 6

It is also stabilization scenario like RCP 4.5 but here radiative forcing stabilizes at 6.0 W/m2 in the year 2100 without exceeding that value in prior years. It is climate policy intervention scenario in which climate policies are implemented to restrain radiative forcing not to exceed

6.0 W/m2. In this scenario, the GHG emissions will be the highest in 2060 and then decline thereafter. The primary assumptions of this RCP are increase in energy demand, shift from coal based to gas based technologies, increase in use of non-fossil fuel energy type and increasing use of CCS technology, increase in population and economic growth in urban area, expansion of cropland and forest area, and decrease in grassland (Masui et al. 2011).

5.3.2.4. RCP 8.5

RCP 8.5 is a high emission scenario characterized by increasing GHG emission over time. It is consistent with future with no change in climate policy to reduce emissions. The GHG emissions increase significantly over time leading to 8.5 W/m2 of radiative forcing by the end of 21st century. The underlying assumptions for this case are the increment of global population upto 12 billion by 2100, low income growth with modest rates of technological progress, high energy demand, coal intensive technologies and high emission in the absence of climate change policies (Riahi et al. 2011).

The summary of these RCPs are presented in Table 5.1 and graphically represented in Figure 5.2

Table 5.1 Summary of RCPs

RCPs	Radiative forcing	Concentration (ppm)	Pathway
RCP 2.6	Peaks at 3 W/m^2 before, then declines	Peaks at 490 CO_2 Equivalent before 2100, then declines	Peaks and declines
RCP 4.5	4.5 W/m^2 stabilized after 2100	650 CO_2 Equivalent at stabilization after 2100	Stabilize without overshooting
RCP 6	6 W/m^2 stabilized after 2100	850 CO_2 Equivalent at stabilization after 2100	Stabilize without overshooting
RCP 8.5	Greater than 8.5 W/m^2 in 2100	Greater than 1370 CO_2 Equivalent 2100	Rise

Source:(Moss et al. 2010)

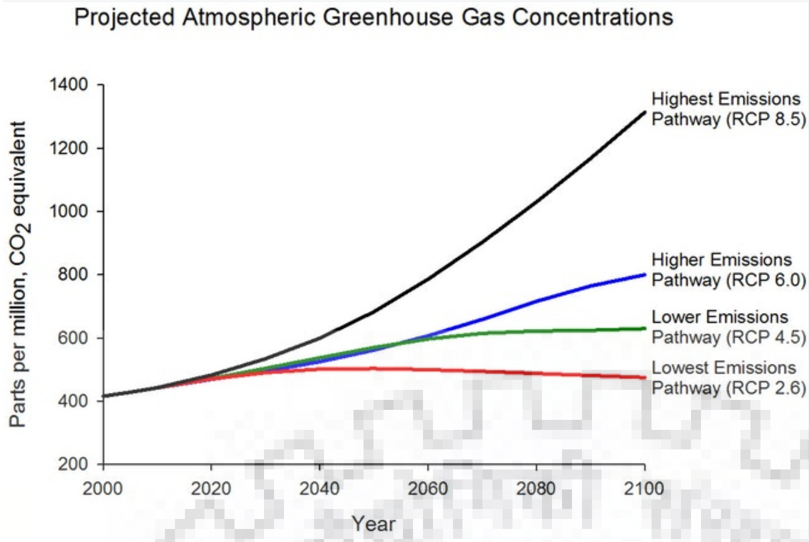

Figure 5.2 Projection of Greenhouse gas concentration
Source: (United States Environmental Protection Agency 2017)

5.3.3. Downscaling

GCM simulates the weather in different layers of atmosphere resulting the coarse output, 2-3 degrees. Due to this, it is required to convert GCM output at least at the scale of watershed/ region scale before using for further studies. The process of extracting the data and information known at a larger scale to make the predictions of the same at lower/ local scale is known as downscaling. There are basically two methods of downscaling the climatic information; dynamic downscaling and statistical downscaling.

Dynamical downscaling involves nesting a regional climate model (RCM) into a GCM. A specific location is defined and high-resolution model basically regional climate model (RCM) driven by boundary conditions from a GCM is used to derive finer spatial scale information (Schmidli et al. 2007). Instead of using mathematical equations, dynamical downscaling uses numerical meteorological modeling to bring global-scale projection down to the regional scale which is computationally intensive (Lenart 2008).

Statistical downscaling primarily involves two step processes. The first is to develop statistical relationship between local climate variables (predictand) and large-scale atmospheric variables (predictor variables) and next is to apply the established relationship to the output of GCM to simulate future climatic data (Hoar and Nychka 2008). This method is computationally cheaper and can be applied to provide site specific information. There are three techniques of statistical downscaling: Weather generators, Transfer functions and Weather typing scheme.

5.4. Literature review

5.4.1. Global Assessments of Climate Change

The research performed by (Miralles-wilhelm et al. 2017) is based on the application of an Integrated Assessment Model to quantify the impacts for a wide range of scenarios of socioeconomic development that offer a mix of possible futures for the availability, use, and management of water resources. The Global Change Assessment Model (GCAM) has been used. This is an Integrated Assessment Model for exploring consequences and responses to global change. For this study, three different Global Climate Models (GCMs) were selected; *CCSM*, The Community Climate System Model, *GISS*, The Goddard Institute for Space Studies and *FIO-ESM*, The FIO Earth System Model (First Institute of Oceanography).The study determined the Water Scarcity Index (WSI) for a given GCAM simulated scenario and global runoff change estimation.

Study made by (Siebert and Döll 2007) focused on the spatial distribution of irrigation on the globe as well as on quantitative estimates of historic and possible future developments of both irrigated areas and irrigation water use. According to the study, by applying the global water model WaterGAP, average annual global Irrigation Withdrawal water use (IWWU) was determined to be 2942 km^3/yr (78% of total withdrawal water use) and Irrigation Consumption water use (ICWU) was 1287 km^3/year (91% of total consumptive water use), respectively.

Change in climate is expected to have an influence for changing the location as well as the extent of irrigation. Also, irrigation water use efficiency is also expected to make an influence on IWWU. All these variants are uncertain in the future. The specific impact of climate change on irrigation water use was assessed with the WaterGAP model. Irrigated areas were kept constant, and results of two GCMs (ECHAM4 and HadCM3 and) for the same emissions scenario (IS92a) were applied. It was found that global ICWU would increase by 3% to 5% until the 2020s and by 5% to 8% until the 2070s (as compared to the climate normal 1961–1990). At the regional level, large climate driven increases of ICWU were computed for Canada (21% -38% for the 2070s, South Asia (12% to 15%). A large climate driven decrease of ICWU was computed for Northern Africa (-16% to -13%). (Siebert & Doll, 2007)

5.4.2. Climate Trends and Projection Studies Review (Basin scale) in Nepal

A. Bheri River Basin

The study was conducted to explore the impact of climate change using SWAT model for the Bheri using three GCMs, wherein there was observed the increasing trend of temperature 0.025 and 0.071 the RCPs 4.5 and 8.5 respectively. Annual rainfall has also been expected to increase by 6.8-15.2%. Similarly, projected annual streamflow is increased by 6-12.5%, when compared to the historical data. Nevertheless, the projection is expected to be favourable as the flow in the wet season is expected to decrease by 20% and increase upto 70% in the dry period (Xu, Chen, and Li 2004).

B. Koshi River Basin

The study was conducted to explore the impact of climate change using SWAT model for the Koshi River Basin to generate the projection for 2030s and 2015s under IPCC A2 and B1 scenarios. The result concluded to increase the flow during the monsoon and post monsoon but decrease during pre-monsoon and winter season.The authors also suggested for the provision of some storage infrastructures so as to address the demand during the water deficit seasons (Bharati et al. 2014).

Another study on the same basin for assessing the impact of climate change on river hydrology under IPCC SRES A1B scenario did not find much threat in overall. However, the temporal variation is expected. The lean season flow is supposed to decrease by 30% whereas the flow will increase for the high flow season by 25% compared to the baseline values. The shift in peak from August to July was also forecasted by ECHAM05.The design flood estimation was also covered under this study wherein, it was found that due to the said impact in the river hydrology, the design flood values were found to be higher in compared to the baseline values. The case specific study revealed, the design flood of more **than 1000 yr** return period (47,445 m^3/s) in the baseline would be equivalent to a **100-year** design flood flow (57,900 m^3/s) in order to account for the impact of climate change and furthermore the 10,000 yr return flood may come as a 500 yr return flood due to the impact of climate change. This obviously necessitates the revision of the design of the in the hydraulic structures, to accommodate the impact of climate change (Devkota and Gyawali 2015).

C. Gandaki River Basin

The result of analysis of precipitation for the Gandaki Basin using Mann-Kendall estimate showed that rainfall is increasing for the monsoon season whereas decreasing for all other seasons. Even the later departure of monsoon was depicted, indicating the increase in the monsoon duration. The same basin under climate change study using PRECIS regional model further showed that the drier seasons are expected to get drier whereas the wet seasons will continue to get wetter (Kirat, Dahal, and Small 2015).

D. Karnali River Basin

The result of analysis of precipitation for the Karnali Basin using Mann-Kendall estimate showed that rainfall is increasing significantly for the monsoon season whereas in overall decreasing by 4.36 mm/ yr.

The peak discharge was observed to be on August which is a month later than the peak precipitation which was in the month of July (Katiwada 2012).

E. Bagmati River Basin

The study has shown a significant upward trend of the annual rainfall, with a rate as high as 2.2 mm/year during the monsoon season (June and July). However, there were no significant results in the other months of the year. The rising trend of monsoon precipitation might lead to severe flooding in future (R. M. Shrestha and Sthapit 2015).

F. Kamala River Basin

The temperature and precipitation trend for the Kamala Basin for different seasons had shown increasing trends but statistically insignificant.(Neupane and Dhakal 2017)

5.5. Methodology

5.5.1. Model Selection

The selection of the climate model is generally based on the capability of the model to simulate the past and near present data, this approach of selecting the model is called the past performance approach (Biemans et al. 2013). Based on the performance for South Asia, the three models that has been suggested by a study (Talchabhadel, Nakagawa, and Kawaike 2018) are CNRM CM5, GFDL- ESM 2G and GFDL- ESM 2M. Because of several constraints, all the models suggested could not be incorporated in model, hence models selected for the present study is CNRM CM5.

The details of the GCM such as the grid size (The European Network for Earth System Modelling 2011) and the modeling centre/ institution (CMIP5 WCRP n.d.), are presented in the Table 5.2.

Table 5.2 Description of model CNRM CM5

Model	Modelling Center	Institution	Atmospheric Grid	
			Latitude	Longitude
CNRM CM5	CNRM-CERFACS	Centre National de Recherches Meteorologiques/ Centre European de Recherches et Formation Avancees en Calcul Scientifique	1.4008	1.40625

CNRM-CM5 is an Earth system model designed to run climate simulations. It consists of several existing models designed independently and coupled through the OASIS software developed at CERFACS. This model is able to simulate present climate and its variability on timescales ranging from months to centuries. In particular, this model is used to perform experiments in the framework of the Coupled Model Intercomparison Project (CMIP5), which serves as a base of IPCC AR5 (National Centre for Meteorological Research 2014).

5.5.2. Downscaling and Bias Correction

Downscaling takes into account of the average difference of the monthly observed historical time series and the hind cast time series of GCM/ RCM over the same period of time. This average difference is then employed to generate the bias corrected data out of the forecast climatic time series. Additive correction is preferable for temperature whereas multiplicative correction is preferable to variables like precipitation, vapor pressure, solar radiation etc. (S. Shrestha, Shrestha, and Babel 2015)

Weather data from 5 precipitation stations and 4 temperature stations, similar to those used in SWAT model has been used. Since the available observed daily data set window is 1990-1998, same duration of historical data set was downscaled from the Climate model for the comparison/ bias correction purpose. To predict the flow, the projected data set for mid future (2061-2070) for two different scenarios RCP 4.5 and RCP 8.5 were extracted from the model. For this, Multi-dimension tool in Arc-GIS has been used.

The data obtained from the model for the precipitation was in the term of Flux and the Degree Kelvin for the Temperature. The suitable conversion factors were applied to the obtained data to convert them into the conventional units of precipitation (mm) and temperature (Degree Centigrade)

Bias correction is a technique applied to correct the mean and standard deviation of the projected time series using a correction factor so that the projected model time series closely matches to the observed time series. Here, in this study, linear bias correction technique has been used for the downscaled future time series on daily time scale. This is the simplest form of bias correction. The difference between the monthly observed mean and the model data mean is applied to the future climate data. The Linear Scaling bias correction V.1.0 has been used for the study. (M. Shrestha 2015)

5.5.3. Future Flow

The model extracted data for the 5 precipitation stations and 4 temperature stations, after converting into the conventional units, has been used to generate the predicted future flows. The bias corrected future precipitation and temperature (maximum and minimum) data base for two different scenarios, RCP 4.5 and RCP 8.5 were formatted in the text file type as the weather input for the SWAT Model. For generating the future flow for both scenarios, the calibrated SWAT model along with the fitted parameters as concluded in the previous chapter has been used.

5.6. Result and Discussion

5.6.1. Projection of Temperature

The Figure 5.3 and Figure 5.4 show the maximum and minimum temperature (^{0}C) pattern over the years for the raw/ model and the bias corrected data for different stations for the scenarios RCP 4.5 and RCP 8.5 respectively.

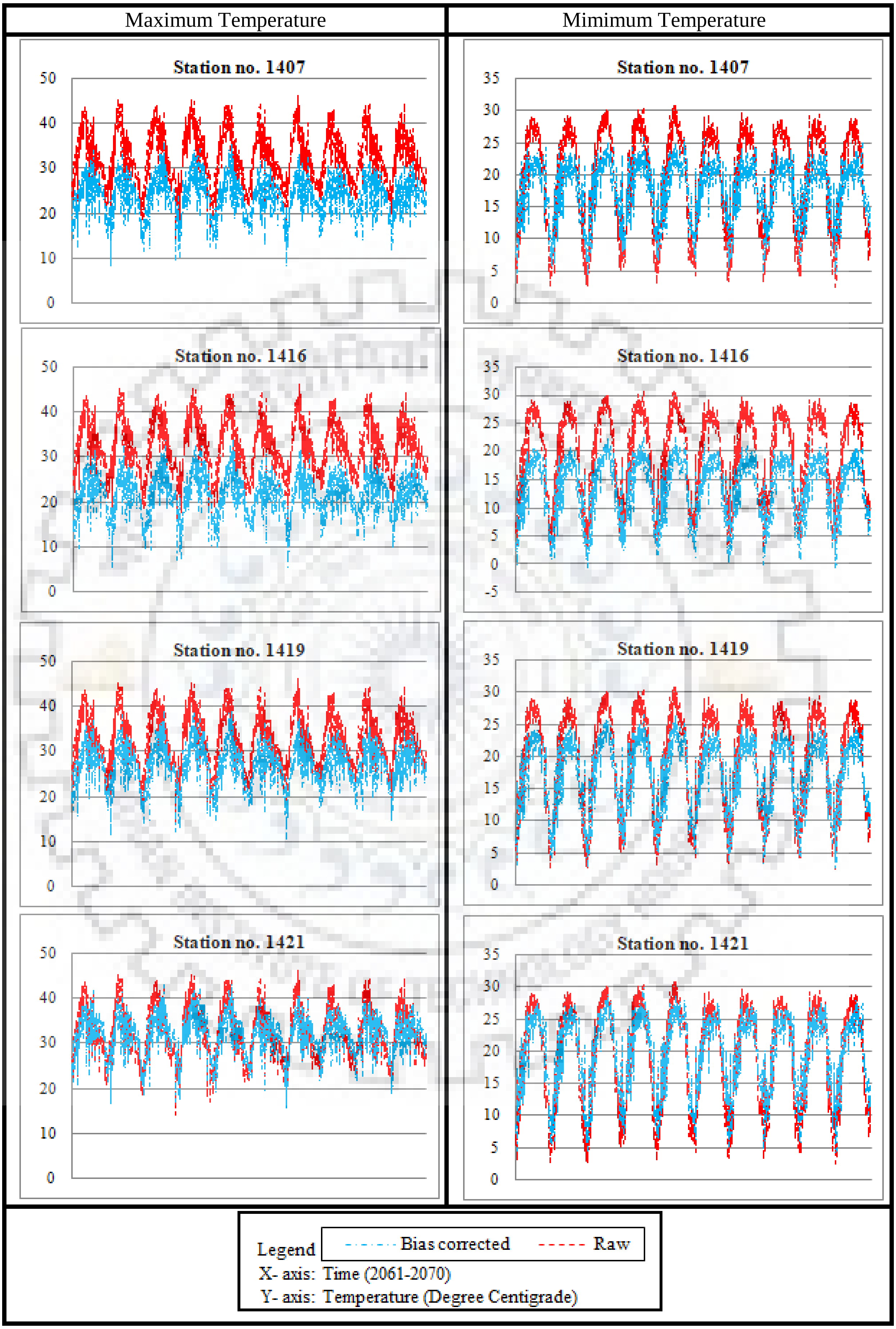

Figure 5.3 Raw and bias corrected temperature (Max/ Min) for 2061-70 for **RCP 4.5**

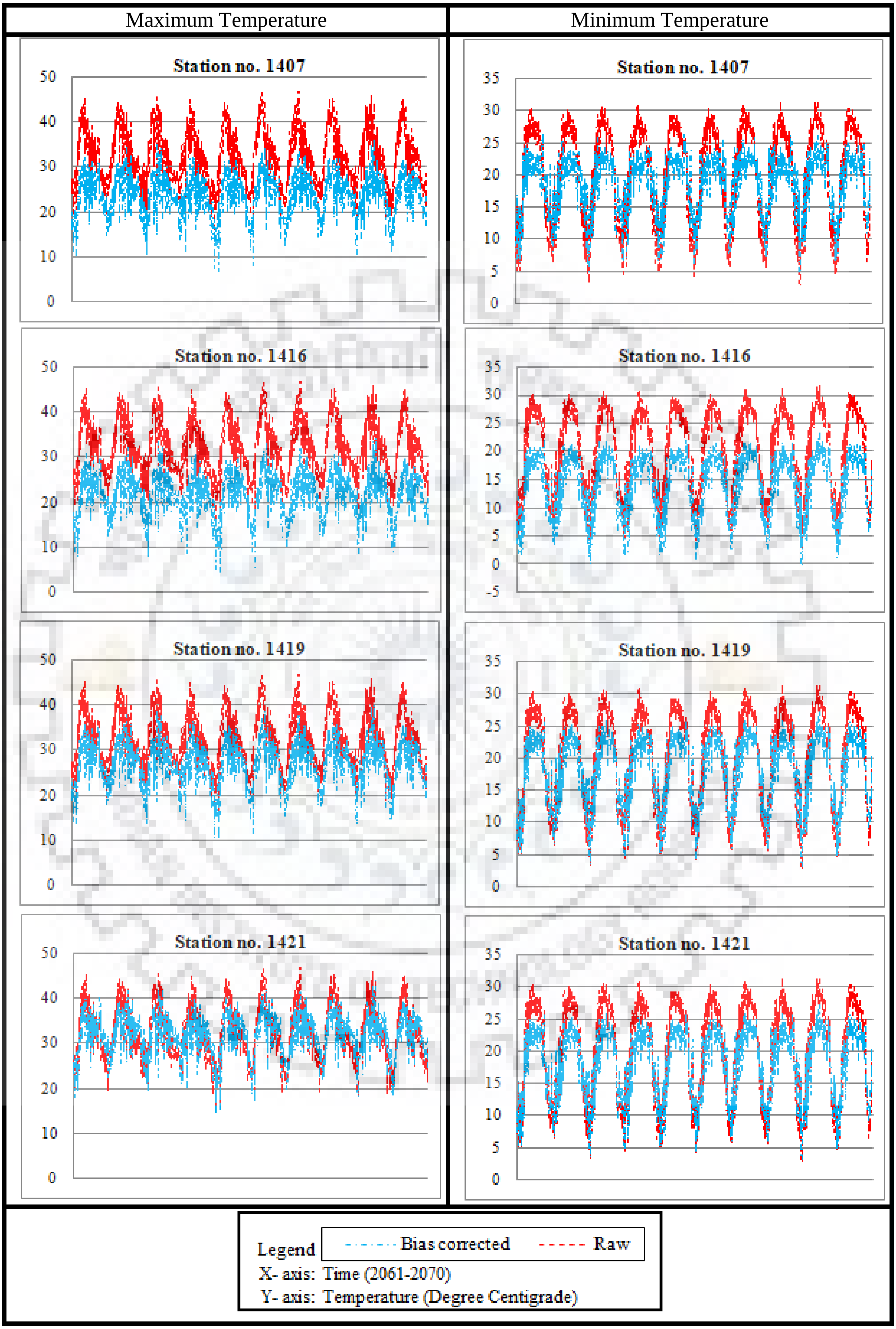

Figure 5.4 Raw and bias corrected temperature (Max/ Min) for 2061-70 for **RCP 8.5**

5.6.2. Projection of Precipitation

The Figure 5.5 and Figure 5.6 show the rainfall (mm) pattern over the years for the raw/ model and the bias corrected data for different stations for the scenarios RCP 4.5 and RCP 8.5.

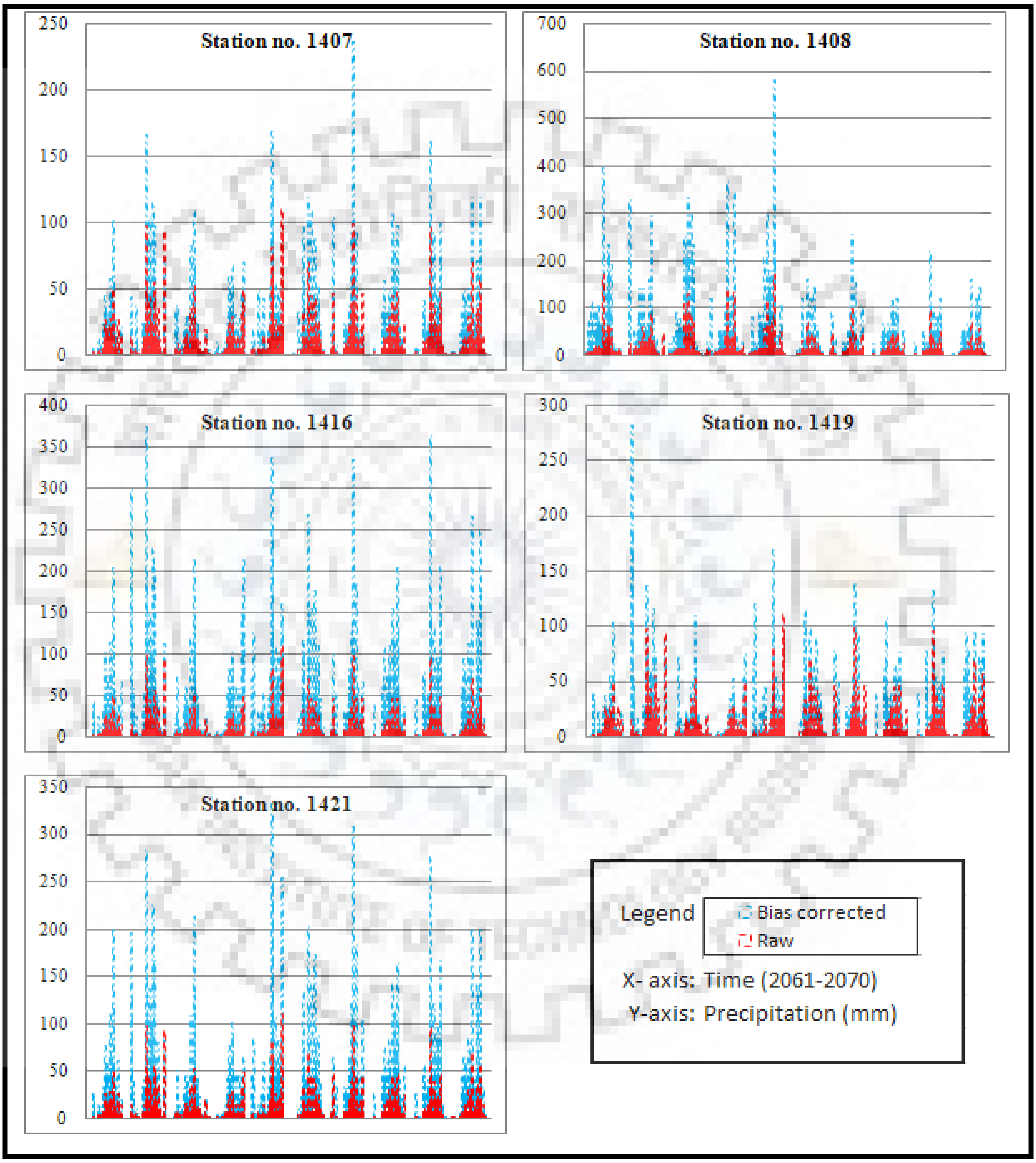

Figure 5.5 Raw and bias corrected precipitation for 2061-70 for RCP 4.5

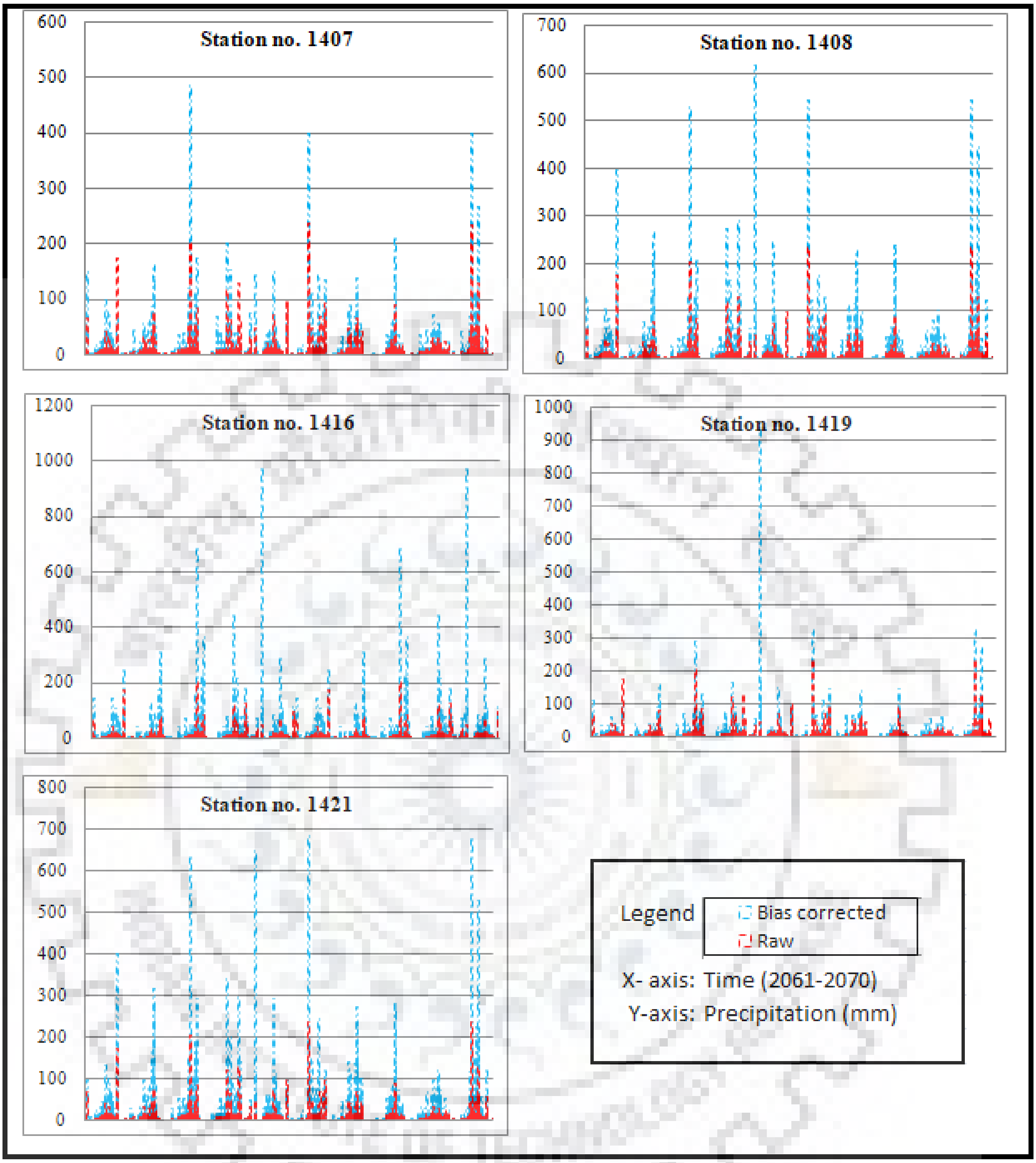

Figure 5.6 Raw and bias corrected precipitation for 2061-70 for RCP 8.5

Since the histogram chart prepared for the precipitation is not able to compare the precipitation for the different flow scenarios, the graph has been plotted for the cumulative precipitation over time for the most representative precipitation station; station no 1407. The cumulative chart has been presented in the Figure 5.7

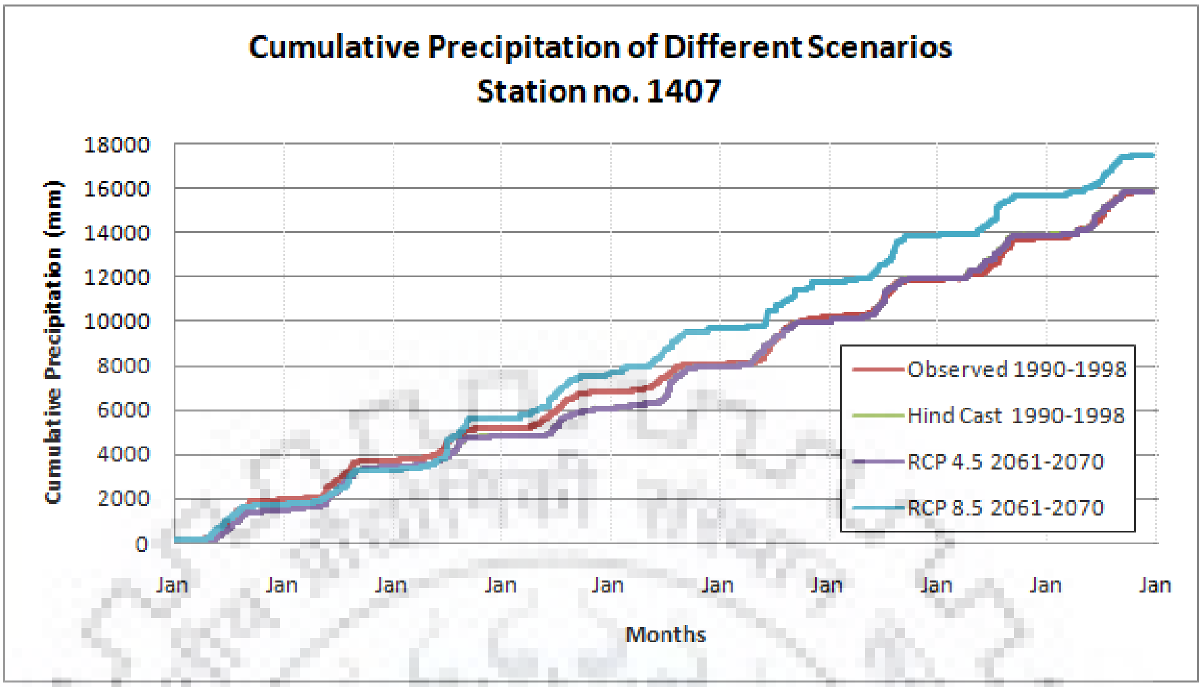

Figure 5.7 Cumulative precipitation for different scenarios for stations no 1407

5.6.3. Projection of Flow

The SWAT output as the future flow (cumecs) for the mid century (2064-2070) for the gauging station no 795, Mainachuli for two scenarios, RCP 4.5 and RCP 8.5 has been presented in the Figure 5.8.

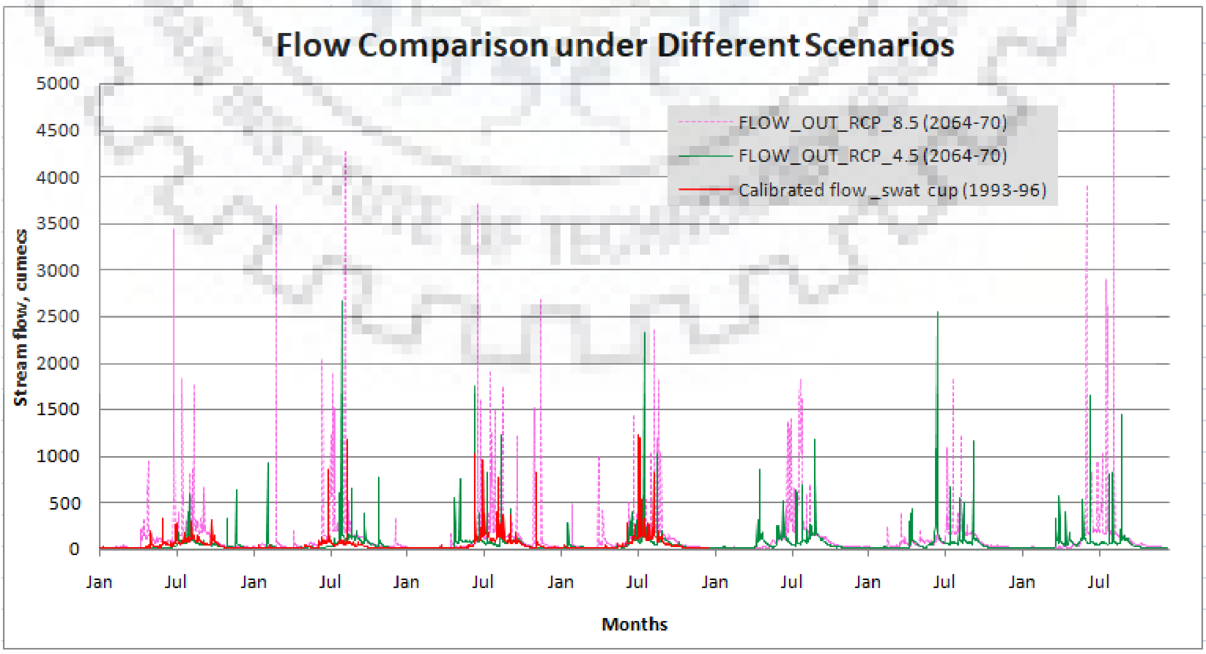

Figure 5.8 Flow comparison under different scenarios

Since the time series of the flow for the various scenarios presented in Figure 5.8 is not able to compare the flows for different flow scenarios, the graph has been plotted for the cumulative flow volume over time. The cumulative chart has been presented in the Figure 5.9.

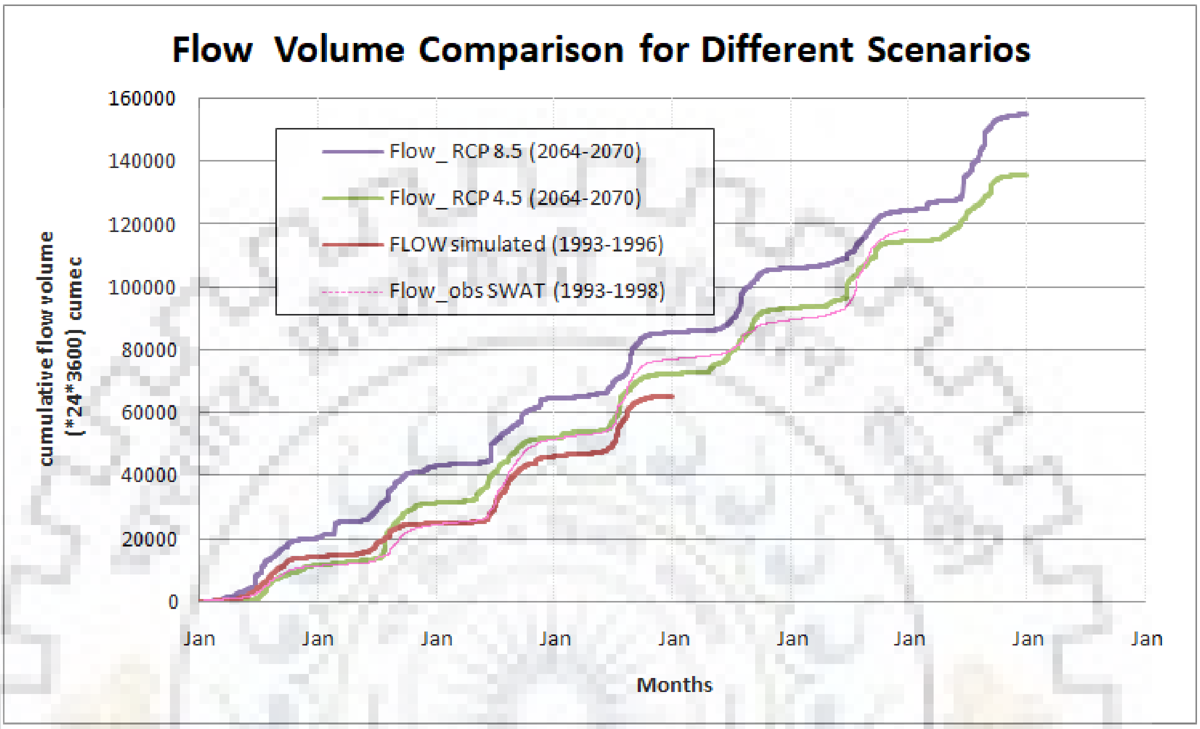

Figure 5.9 Comparison of observed, simulated and future cumulative flows flow volume

The flow characteristic in terms of minimum, maximum and the average flow from the figure has been summarized in the Table 5.3.

Table 5.3 Flow characteristic for different scenarios

Scenarios	Flow_obs (cumec)	Flow_calibrated (cumec)	Flow RCP 4.5 (cumec)	Flow RCP 8.5 (cumec)
Period	1993-1998	1993-1996	2064-2070	2064-2070
Average flow(cumec)	54.02	44.87	53.14	60.76
Min. Flow (cumec)	4.59	1.334	1.536	2.265
Max. Flow (cumec)	1960	1233	2959	4146

If the future data are to be analyzed with respect to observed data set, shows the disagreement of the flow data in terms of minimum, maximum and the average flows, since there is much difference in between the respective flow values. But if the future data are to be analyzed with respect to the calibrated set, the table shows the agreement of the flow data in terms of minimum, maximum and the average flows.

5.7. Summary

To predict the impact of climate change in reservoir simulation, the prediction of future flow was necessary. So for that purpose temperature and precipitation data in daily basis have been extracted from CNRM-CM5 global climate model for the mid-century (2061-2070). The raw temperature and precipitation data have been extracted for two RCP scenarios, RCP 4.5 and RCP 8.5. Hind cast data were also extracted from the model for the period of 1990-1998. Based on observed historical data base (1990-1998) and hind cast Model data (1990-1998), the linear bias correction technique was used to get the bias corrected future data for 2061-2070. Using the pre- calibrated model developed as discussed in the preceding chapter, the predicted future flows for the period of 2064-2070 have been generated for both scenarios, RCP 4.5 and RCP 8.5.

CHAPTER SIX
RESERVOIR SIMULATION

6.1. Prelude

Reservoir serves as the key component of any water resources development system. They regulate natural stream-flow which modifies the temporal and spatial availability of water as needed (CWC 2005). Reservoir are constructed and operated for single or multiple purposes. There are various demands to be meet by the operation of the reservoir such as flood control, domestic water supply, irrigation, power generation, recreational use of the reservoir pool, environmental release to the downstream and ultimately the safety and the structural stability of the dam itself.

Reservoir simulation undergoes the mathematical simulation of river networks with reservoirs. The simulation models involve the mass balance of inflow, outflow and storage fluctuations. These models can supply with an economic evaluation of floods damage, irrigation benefit, hydropower generation etc. Simulation models provide a realistic and detailed representation of reservoir operations. The parameters that have the influence on availability and requirement of the flow to or from the reservoir (system) are hydrologic condition, climatic condition and the simultaneous operation of the reservoirs in the system.

The major components of any reservoir simulation model include firstly the inputs, which include reservoir inflow, evaporation rate, irrigation and power water demands, etc secondly the physical relationships and constraints, which includes defining the associations among the physical variables of the system involve reservoir storage-elevation-area relationship and finally the operating rules and outputs which characterize the maneuver of the system. The outputs are actually the system responses resulting from operating the system that are guided by specified rules and restraints (Kumar 2011).

6.1.1. Models for Reservoir Simulation

Varieties of the simulation and optimization algorithms have been. Simulation modeling provides the user with the useful framework to assess the specific possibilities for cooperatively operating the reservoirs. Some of the commonly adopted reservoir operation models are:

6.1.1.1. HEC-5

This includes iterative search algorithms which makes multiple-reservoir discharge choice for each time interval for the duration of the replication of any flood event. Program has elective economic analysis ability for calculating the anticipated annual flood damages for different operating policies. HEC-5 also has the potential for simulate reservoir maneuver for conservation purposes.

6.1.1.2. WEAP (Water Evaluation and Planning system)

This is computer software which works as a decision support system for integrated water resources management. Program was created by Stockholm Environmental Institute in Boston, Massachusetts. It is used to model replication of various water demands, power demand, ground water and the water quality in a reservoir system. The user can create various models by the help of script editor in the software.

6.1.1.3. MIKE-BASIN

It is versatile software to replicate the integrated river basin development. This program can analyze, store and portray temporal data in GIS. MIKE BASIN was developed by a research and consulting organization known as DHI Water & Environment.

6.1.1.4. MODSIM

This is a software tool that can be used for the integrated analysis of water segment components and optimization of resources by assigning limited water resources in the river basin. It was developed at Colorado State University in 1978, making it the longest continuously maintained river basin management software available. Earlier, MODSIM was among the handful river reservoir modeling instrument that was capable of simulating water allocation based on prioritized water rights. So, most water allocation models were developed using MODSIM, mostly in the Western United States in association with the Bureau of Reclamation. The software utilizes a optimization solver which routes water on the basis of network costs.

6.1.1.5. Hydrologic Engineering Center Reservoir Simulation (HEC ResSim) Model

ResSim is the descendant of HEC-5. ResSim consists of a graphical user interface, software program to replicate reservoir operation, data organization potential, and graphical and reporting qualities. Multi-purpose, multi-reservoir systems are also replicated using algorithms developed particularly for the model rather than recognized numerical programming techniques. The model can also be used in the planning works. The full variety of multi-purpose reservoir system maneuvers can be modeled. In particular, complete facility is availed for modeling flood control function. Besides, the software replicates reservoir function for flood risk management, low flow adaptation and water supply for planning works. The software also has the capability to work as decision support tool that can help analysts in reservoir project studies while meeting the requirement of reservoir regulators in real time events. For the present study, HEC Res Sim has been chosen to simulate the reservoir operation (Klipsch and Marilyn 2011).

6.2. HEC Res Sim Model

HEC Res Sim has three sets of functions called modules that provide access to specific types of data within a watershed as shown in Figure 6.1. These modules are watershed setup, reservoir network, and simulation.

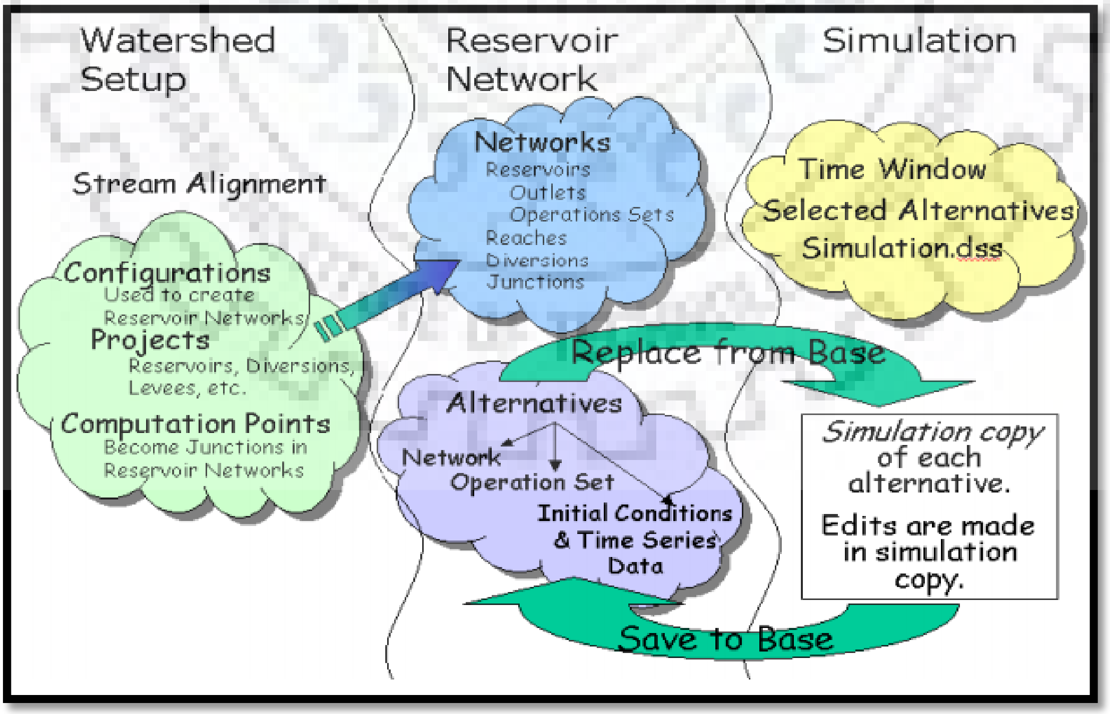

Figure 6.1 Modules in HEC Res Sim

The watershed setup module provides a common framework for watershed creation and definition among different modeling applications. It includes streams, projects, computation point, impact areas, time series location etc which when configured gives a watershed framework of the system. The reservoir network module permits the analyst to create a river schematic, illustrate the physical and operational components of the reservoir system, and create alternatives to be considered for analysis. The network components of the module are junction, routing reach, diversion and reservoir. This is the core part of the software as it embeds the complete physical and operational data required for the reservoir simulation. The simulation module is then utilized to organize and execute a simulation and analyze the outcomes (Klipsch and Marilyn 2011).

6.2.1. Theoretical development of Reservoir Network

The major idea of theoretical development consists of two parts. Physical part includes different components of the dam and the reservoir viz. spillways, power station, tail water etc. The data related to dam structure and their correct definition very important in the sense that results within acceptable limits cannot be anticipated without it and even minor amendments can significantly change the system performance.

Next is the operation rule, which functions as the main component of the model. Defining it is a really complicated job. It needs a lot of data and computation is done with the use of hydraulics and hydrological analysis. Operating rules portray the logic used in making decisions on accumulating or discharging of water. Dam operation on the other hand involves choice to be made about the scale and timing of water discharges.

6.2.2. Guide Curve Operation

A reservoir in HEC-ResSim must have a target elevation. The target elevation, depicted to as a time function, is known to be its Guide Curve. This elevation is the separating line between the upper zone known as the flood-control and the lower zone known as the conservation pool. Guide curve operation controls the releases to sustain that storage elevation. The general rule is firstly to discharge water as rapidly as feasible when high inflows reach the flood pool and lift up storage above the guide curve or secondly to limit discharges to the minimum required amounts essential to assure buffer, preservation, or power demands whenever inflows are low and storage level is lowered under the guide curve. The releasing decision judgment in HEC-ResSim initiates and finishes with the guide curve. The entire operating rule and physical restrictions act as a control of the reservoir in order to meet the ultimate target of return the pool to the guide curve level. In absence of these rules, the reservoir will be limited only by physical capacity of the exits to achieve and to be at the guide curve level. Simulation uses inflow discharges, operations rules and mass balance of the basin which is utilized to represent the hydrological characteristics of the reservoir scheme.

6.3. Application of HEC Res Sim

A research paper has presented the case study regarding the operation of the existing Tucurui Dam, Brazil. The dam had been built as the large-scale hydropower project along with the multipurpose use of the reservoir for Tocantins river basin in the country. the study has been carried out taking into consideration the daily flow from 2001 to 2006, using the storage – elevation-area curve, flood zone, conservation zone and inactive zone elevations data, operation levels between 2001 and 2006, seasonal precipitation and evaporation heights, inflow outflow time series between for said duration on daily time step and the outlet type and capacity. Simulations performed on the daily basis and the HEC Res Sim model was employed to reproduce the operation pattern of the dam. The operation rules were re-evaluated according to the storage characteristic, capacity of spillway of the reservoir and the downstream drainage capacity because the dam had only been built to regulate the hydrological pattern and not for the flood control due to which the town D/S of dam gets flooded every year. The study supported in understanding that the set of operations rules that the Tucurui Dam owns can be improved, by reducing the uncertainties associated with the outflow forecast and support in the flood warning system, hence warning system can be developed in the real time as well. The study suggested for testing the various operation scenarios and producing the operation plan accordingly (Lara et al. 2014).

Jebbo and Awchi (2016) built a simulation model for the existing Mosul Dam in Tigris River, Iraq using HEC Res Sim 3.0 and assess the models suitability in doing so. The reservoir being used for multipurpose such as hydropower, irrigation, fisheries and tourist centre, the study aimed to analyze the reservoir characteristics at the time of design and at present (at the time of study). Simulation has been carried out for 19 yrs (1998 – 2006) on monthly time step and the simulated data was compared to the observed data and the convergence was assessed by three statistical measures namely, coefficient of correlation, coefficient of efficiency and index of agreement. The match was found in the spillway operation as well as the hydropower generation. However, the rule curve derived from the simulation and original rule curve showed the operation difference, because of the due to the presence of large amount of gypsum present in the foundation. Hence the study came out with conclusion of filling the reservoir to the less elevation to prevent the danger of collapse. Hence the study suggested to reduce the water storage for the safe functioning of the dam and also concluded the suitability of the adoption of HEC Res Sim for the reservoir simulation.

A paper by Modini (2010) explored the technical, strategic aspects of complete model migration of the then developed models at 1950; Stream flow synthesis and reservoir regulation (SSAR/ AUTOREG), jointly developed by corps of Engineers and National weather service to a user friendly and competent software when it could be no longer in use because of the non availability of the model developers and those responsible for maintenance. Those models constituted the capacity of stream flow analysis, stream flow forecast and reservoir regulation. The paper has described the technical challenges, the strategies used, success measures and the result of the model migration though the idea of migration had been discussed in previous papers. The work has been done for the Columbia River Treaty Flood Control Operating Plan (FCOP).The paper highlighted that HEC Res Sim model along with its future variants can serve the similar purpose with much efficiency and hence is the model flexible enough to accommodate the change in the FCOP strategy since the current terms and condition of FCOP expires in 2024.

A study has been carried to examine the impact of change in climate in the hydropower production. The study area for this research is Kulekhani watershed Nepal. HEC Res Sim has been used for the reservoir simulation to quantify the power production from the existing Kulekhani Hydropower Project (60MW). The future climatic condition has been predicted using the Had CM3 global circulation Model A2 and B2 scenario for three time periods (2020s, 2050s and 2080s respectively). The average precipitation scenarios were expected to decrease for all future time periods, which have been reflected in the stream flow simulated from the HEC-HMS hydrological model. However when the seasonal variation in the flow is assessed, the wet season flow(July and August) has been expected to decrease but increase in most of the dry month is expected. The impact of which is seen in the future power production from the Kulekhani power plant. Imitating the baseline operation of 7h/day for future, the power production is expected to decrease by 30%. However, least reduction of 8-13% is expected when the reservoir operates for 10h/day in dry and 3h/day in wet months.

The study also revealed that the guide curve developed for the operation should be revised in order to maintain/ increase the power production for future scenarios.(Sangam Shrestha et al. 2014)

6.4. Methodology of Study

6.4.1. Model development

Model has been set up three distinct stages; watershed setup module, reservoir module and simulation module.

Watershed module has been set up by importing the basic shape files from Arc GIS such as basin boundary, stream network and the reservoir location and the location of hydrological station as the background layers. The configuration of the project was finalized after the stream network was developed using the tools available in the watershed module.

A reservoir network was developed with the configuration generated in the watershed setup module. The reservoir network setup of the Kankai Multipurpose Project in HEC ResSim has been presented in Figure 6.2. After the physical and operation data input, different operation sets were developed as per the intended scenarios, and the alternatives were set thereafter.

The simulation module is a gateway to the output and has been used while running the software when everything was finalized about the model input.

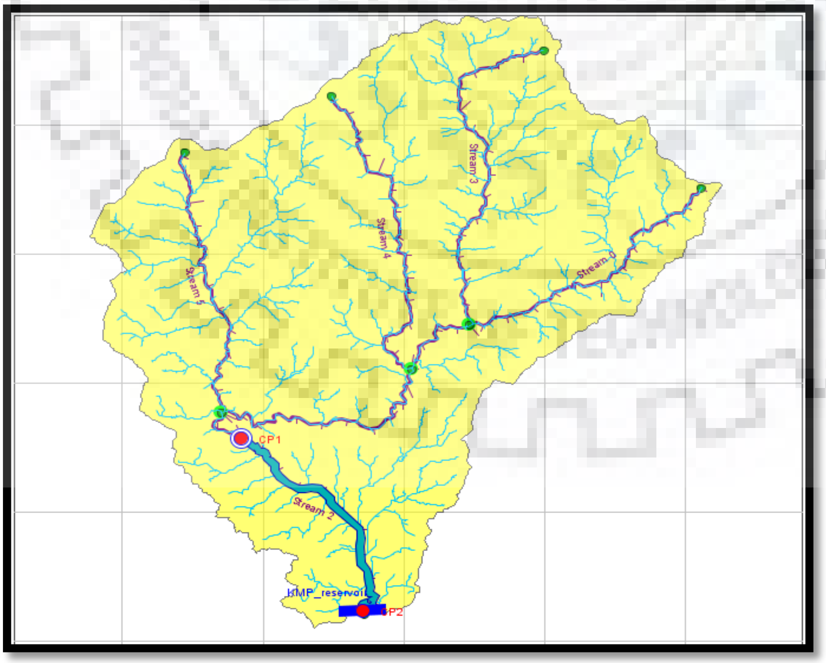

Figure 6.2 Reservoir network of Kankai Multipurpose Project

6.4.2. Input for HEC ResSim model Setup

The data required can basically be categorized as the hydrological data, physical data, and the operational data.

6.4.2.1. Hydrological data

The basic information/ data required for the reservoir operation if the time series of the stream flow records at the gauging site. Monthly stream flows are often used in the case where the daily data are not available or the daily variation of the flow is not significantly different. Department of Hydrology and Meteorology, under the Ministry of Water Resources, Energy and Irrigation, operates and maintains all the gauging stations in Nepal including the one used herein. The stream flow records of the gauging station 795, Mainachuli have been used which nearly coincides with the dam axis. The daily stream flow record of 8 yrs (2004 to 2011) of Mainachuli Station has been used. The time series is stored and saved as the HEC-DSS system which is a system designed to efficiently store and retrieve the scientific data which is typically sequential. After converting the continuous time series in the HEC- DSS format, it can be used later in the alternative setup for simulation, by setting the path to this particular DSS file for the inflow time series.
The flow characteristics of the stream are presented in
Table 6.1 Average flow data), Figure 6.3 Flow duration curve) and Figure 6.4 Hydrograph of the daily inflow at Mainachuli gauging station)

Table 6.1 Average flow data

Flow variants	Flow	Date
Minimum flow	7.02 cumec	Mar 31, 2008
Mean of minimum flow	7.62 cumec	2004-2011
Maximum flow	5675 cumec	Aug 16, 2009
Average flow	66.52 cumec	-
Average flow in Driest year	51.9 cumec	2005
Average flow in Wettest year	106.6 cumec	2008

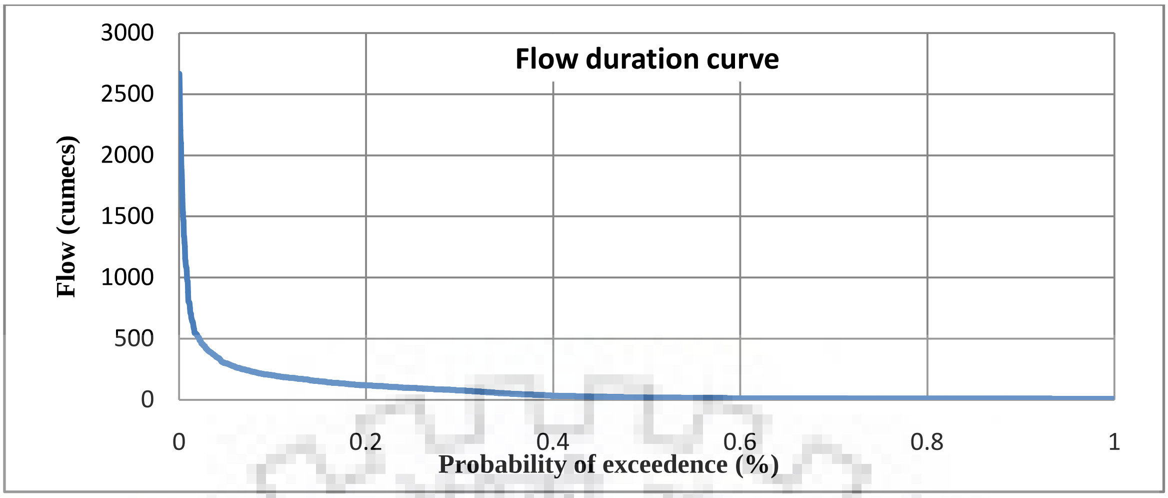

Figure 6.3 Flow duration curve of Kankai River at Mainachuli

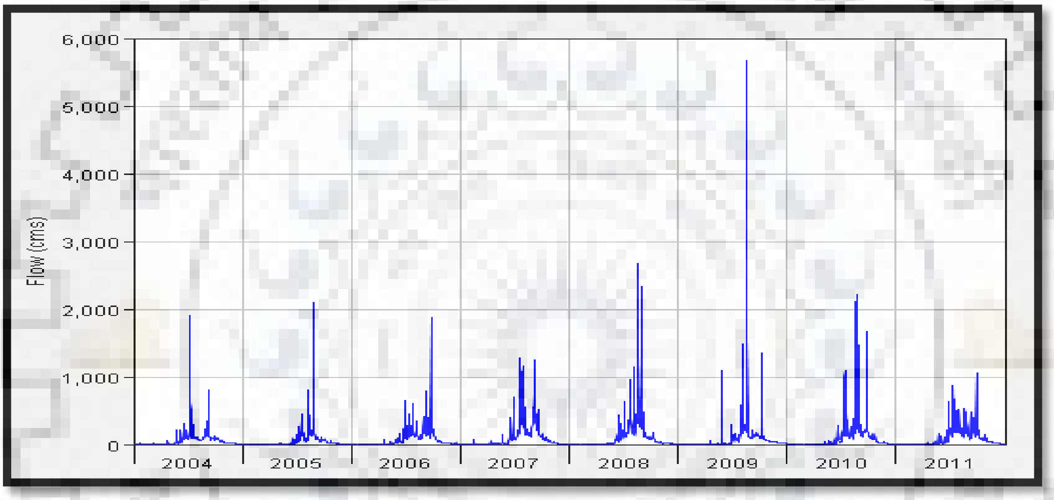

Figure 6.4 Hydrograph of the daily inflow at Mainachuli gauging station

The model determines the net inflow considering the evaporation phenomenon for each time period based on the average reservoir area during the considered time interval. Net evaporation is normally expressed in terms of average values in mm. The evaporation values are taken from the Project documents and is presented in the Figure 6.5

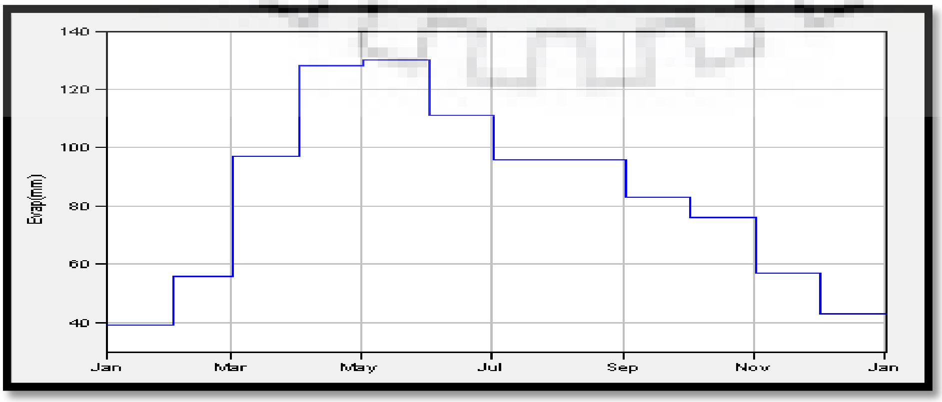

Figure 6.5 Monthly evaporation

Environmental flow

To maintain the downstream minimum water regime and the ecosystem balance, environmental flow is to be released whatsoever hydraulic structures is constructed for the regulation of flowing water. The general practice of the environmental flow is 10% of the minimum flow. However the environmental flow should be set on the basis of the detailed study of downstream water needs and the ecosystem. The environmental release flow considered in this study is based on mean of the minimum flow of the period 2004-2011 as tabulated in Table 5.3, and the environmental flow considered is 1 cumec.

6.4.2.2. Physical data

The most important input in the HEC ResSim model is the physical data. The data required are the physical dimension and the characteristics of the components of the reservoir project, which are extracted from the project description and includes the components as given in the Table 6.2

Table 6.2 Physical data requirement

Components	Parameters
1. Reservoir	Storage- area- elevation relationship
2. Dam	Crest level
3. Intake	• Intake rating curve • Gates
4. Spillway	• Spillway length • Discharge capacity
5. Power plant	• No. of units of turbine • Installed capacity • Efficiency • Losses/ station use

Computation of Storage- Area- Elevation curve

The volume of the storage of the reservoir and the surface area corresponding to the different elevations has been worked using GIS. The elevation storage area curve at the dam site is presented in Figure 6.6 and storage at important elevations is presented in Table 6.3.

Table 6.3 Storage - Elevation

Elevation	storage
165	400
173.5	600
195	1370
202.5	1680
205	1800

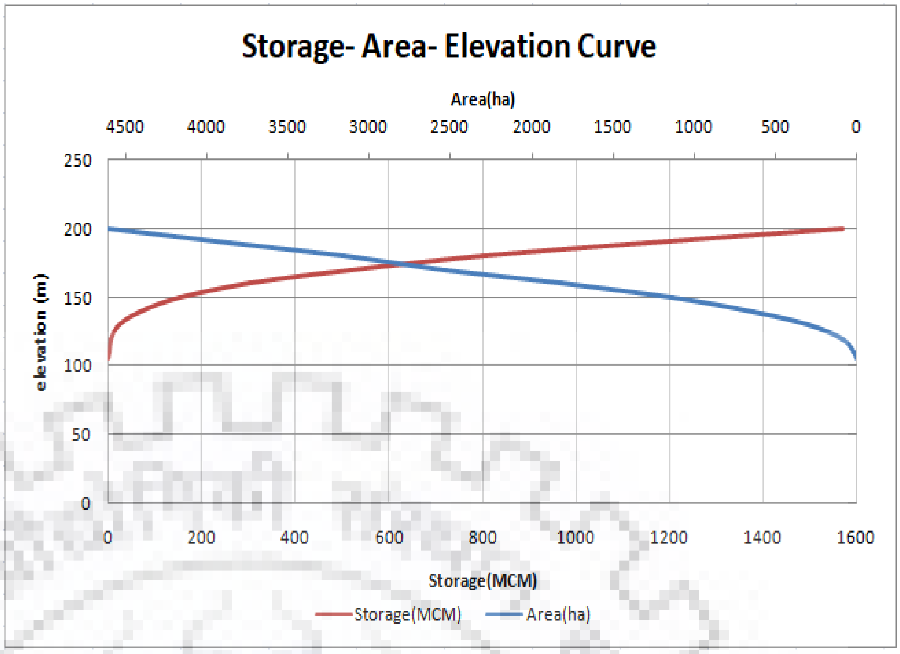

Figure 6.6 Storage elevation Curve

6.4.2.3. Operational data

Reservoir operation policy, driven by the intended objective and purpose, divides the storage capacity into several pools. The operation data includes the zone definition along with the rules which governs the operation in each zone.

In this study, the model is simplified to contain three zones, namely, flood control zone, conservation zone and the inactive zone. The zones and corresponding levels are summarized in Table 6.4.

Table 6.4 Important zones in Reservoir

Zone	Elevation	Remarks
Flood control Zone	202.5 m	
Conservation zone	195m	Guide curve
Inactive zone	173.5 m	Minimum draw down level

Priortization

The prioritization of the water allocation is specified as

Priority 1: Environmental Flow

Priority 2: Irrigation Water Requirement

Priority 3: Power plant requirement

Priority 4: Uncontrolled Spillway (to be minimized)

6.4.3. Simulation Scenarios Formulation

After environmental flow, taking Irrigation water demand as the necessary condition to be fulfilled under any case, the simulation has been carried out under different cases of varying time step and different installed capacity. The guide curve has been set to the conservation zone.

Since Irrigation water demand has been given the prime importance, minimum operating hours of the plant so as to fulfill the irrigation demand as given in Table 2.2 was worked out initially for every month and for every scenarios formulated.

Then after, considering the flow pattern and the reservoir capacity and the national demand-supply gap of the energy as presented in Figure 6.7, the total energy required in a month are fixed. January, February, March being sensitive months, the operating hours are kept relatively high so as generate maximum possible energy during that duration. Once operating hours are fixed, Operating pattern is also fixed on the basis of existing peak load (morning and evening peaks).

On this basis, the simulating scenarios are formulated for the historical time series and are presented in Table 6.5. Similarly, the simulating scenarios for the future flows are presented in Table 6.6

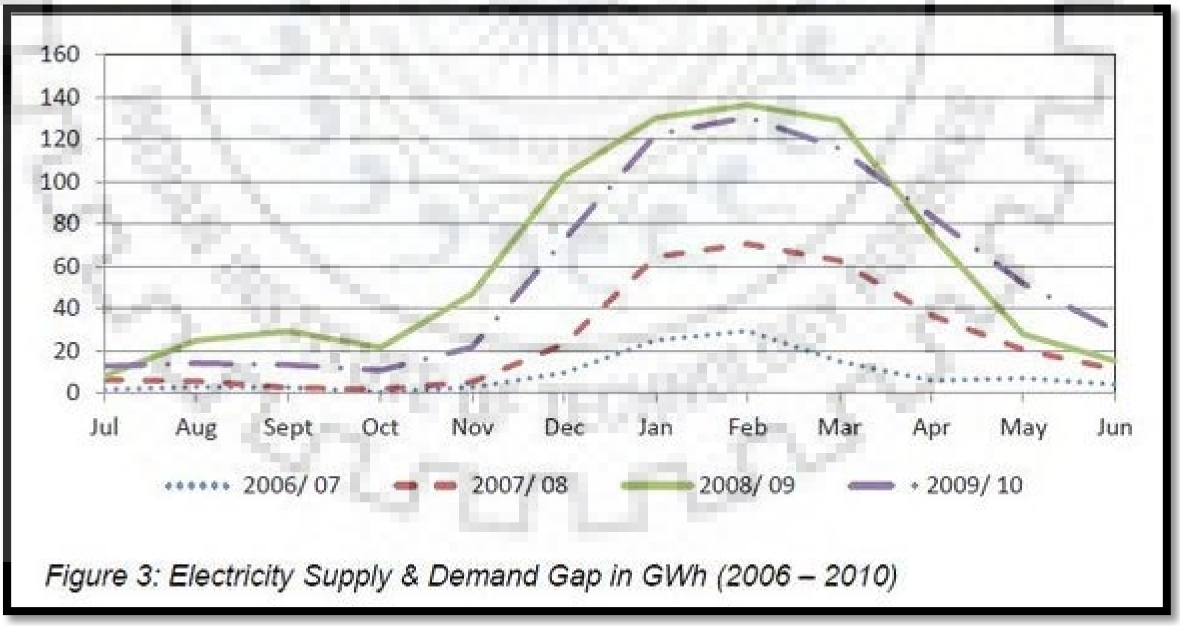

Figure 6.7 Electricity demand and supply gap in GWh(2006-2010)

Table 6.5 Simulation Scenarios (Historical time series)

Scenarios	Time step	Irrigation command area (ha)	Installed Capacity (MW)	Remarks
Rule: Monthly energy requirement corresponding to (operation pattern OP 1) Time step: daily				
S1-S8	daily	67450	60,70,80,90, 100, 110,120,130	OP 1
Rule: Monthly energy requirement corresponding to (operation pattern OP 1) Time step: hourly				
S9-S11	hourly	67450	60,90,120	OP 1
Rule: Monthly energy requirement adjusting the operating hours to confine the energy violation within the predefined limit of 10% Time step: hourly				
S12	hourly	67450	60	OP1
S13		67450	90	OP2
S14		67450	120	OP3

Details of OP1, OP2, OP3 is in presented in Result and Discussion part.

Table 6.6 Simulation Scenarios (Simulated/Future time series)

Scenarios	Time step	Simulation	Remarks
S15	hourly	RCP 4.5 (2063-2070)	OP 2
S16		RCP 8.5 (2063-2070)	
S17		Simulated (1993-1998)	

6.5. Result and Discussion

6.5.1. Scenarios S1-S8

For Historical time series, for the scenarios generated are S1 to S8, as presented in Table 6.7, Monthly Energy Requirement rule as presented in Table 6.9 is applied corresponding to the Operation pattern 1(OP1) presented in Table 6.8

Table 6.7 Scenarios description for S1-S8

Scenarios	Time step	Irrigation command area (ha)	Installed Capacity (MW)	Remarks
Rule: Monthly energy requirement corresponding to (operation pattern OP 1) Time step: daily				
S1	Daily	67450	60	OP 1
S2		67450	70	
S3		67450	80	
S4		67450	90	
S5		67450	100	
S6		67450	110	
S7		67450	120	
S8		67450	130	

Table 6.8 Operation pattern 1(OP1)

Hrs in a day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-1	0	0	0	0	0	0	0	1	1	0	0	0
1-2	0	0	0	0	0	0	0	1	1	0	0	0
2-3	0	0	0	0	0	0	0	1	1	0	0	0
3-4	0	0	0	0	0	0	0	1	1	0	0	0
4-5	0	0	0	0	0	0	0	1	1	0	0	0
5-6	1	1	1	1	1	0	0	1	1	0	0	0
6-7	1	1	1	1	1	1	1	1	1	1	1	1
7-8	1	1	1	1	1	1	1	1	1	1	1	1
8-9	1	1	1	1	1	1	1	1	1	1	1	1
9-10	1	1	1	1	1	1	1	1	1	1	1	1
10-11	0	0	0	0	0	0	0	1	1	0	0	0
11-12	0	0	0	0	0	0	0	1	1	0	0	0
12-13	0	0	0	0	0	0	0	1	1	0	0	0
13-14	0	0	0	0	0	0	0	1	1	0	0	0
14-15	0	0	0	0	0	0	0	1	1	0	0	0
15-16	0	0	0	0	0	0	0	1	1	0	0	0
16-17	0	0	0	0	0	0	0	1	1	0	0	0
17-18	1	1	1	1	1	0	0	1	1	0	0	0
18-19	1	1	1	1	1	1	1	1	1	1	1	1
19-20	1	1	1	1	1	1	1	1	1	1	1	1
20-21	1	1	1	1	1	1	1	1	1	1	1	1
21-22	1	1	1	1	1	1	1	1	1	1	1	1
22-23	0	0	0	0	0	0	0	1	1	0	0	0
23-24	0	0	0	0	0	0	0	1	1	0	0	0
TOT HRS	10	10	10	10	10	8	8	24	24	8	8	8

Total Energy requirement in MWhr (input) for different S1 to S8 are given in Table 6.9

Table 6.9 Total energy requirement in MWhr (input) for different S1 to S8

scenario	S1	S2	S3	S4	S5	S6	S7	S8
Installed capacity (MW)	60	70	80	90	100	110	120	130
Jan	18600	21700	24800	27900	31000	34100	37200	40300
Feb	16800	19600	22400	25200	28000	30800	33600	36400
Mar	18600	21700	24800	27900	31000	34100	37200	40300
Apr	18000	21000	24000	27000	30000	33000	36000	39000
May	18600	21700	24800	27900	31000	34100	37200	40300
Jun	14400	16800	19200	21600	24000	26400	28800	31200
Jul	14880	17360	19840	22320	24800	27280	29760	32240
Aug	44640	52080	59520	66960	74400	81840	89280	96720
Sep	43200	50400	57600	64800	72000	79200	86400	93600
Oct	14880	17360	19840	22320	24800	27280	29760	32240
Nov	14400	16800	19200	21600	24000	26400	28800	31200
Dec	14880	17360	19840	22320	24800	27280	29760	32240

For Scenario S1- S8, the daily time step has been adopted to simulate the flow so that it will be clear enough from the figures to understand the pattern of flow, energy, power, storage and elevation variation with the change in the installed capacity. Here are presented six types of characteristic curves within three graphs as mentioned below for every individual scenarios.

i. **The Reservoir Flow and Storage Curves** includes
   a. Flow curves (Net inflow, uncontrolled outflow, Environmental Release and flow power)
   b. Storage curves (Flood control storage zone, conservation storage zone, Inactive zone and the pool storage zone)

ii. **Reservoir Elevation and Power Curves** includes
   a. Elevation curves (Flood control elevation, conservation elevation, Inactive elevation and the pool elevation)
   b. Power curves (Power generated and power required)

iii. **Energy and Power head Curves** includes
   a. Energy curves (Energy generated, Energy required and energy violated)
   b. Power head curve

From section 6.5.1.1 up to section 6.5.1.8, i.e. from scenarios S1 to S8, the curves as mentioned above are shown in order to observe the gradual variation in the curve characteristic for S1 to S8.

- Reservoir flow and storage curves for S1 to S8 are presented in Figure 6.8, Figure 6.11, Figure 6.14, Figure 6.17, Figure 6.20, Figure 6.23, Figure 6.26 and Figure 6.29 respectively.
- Reservoir Elevation and power curves for S1 to S8 are presented in Figure 6.9, Figure 6.12, Figure 6.15, Figure 6.18, Figure 6.21, Figure 6.24, Figure 6.27and Figure 6.30 respectively.
- Energy and power head curves for S1 to S8 are presented in Figure 6.10, Figure 6.13, Figure 6.16, Figure 6.19, Figure 6.22, Figure 6.25, Figure 6.28 and Figure 6.31

6.5.1.1. Scenario S1 (60 MW/ daily time step)

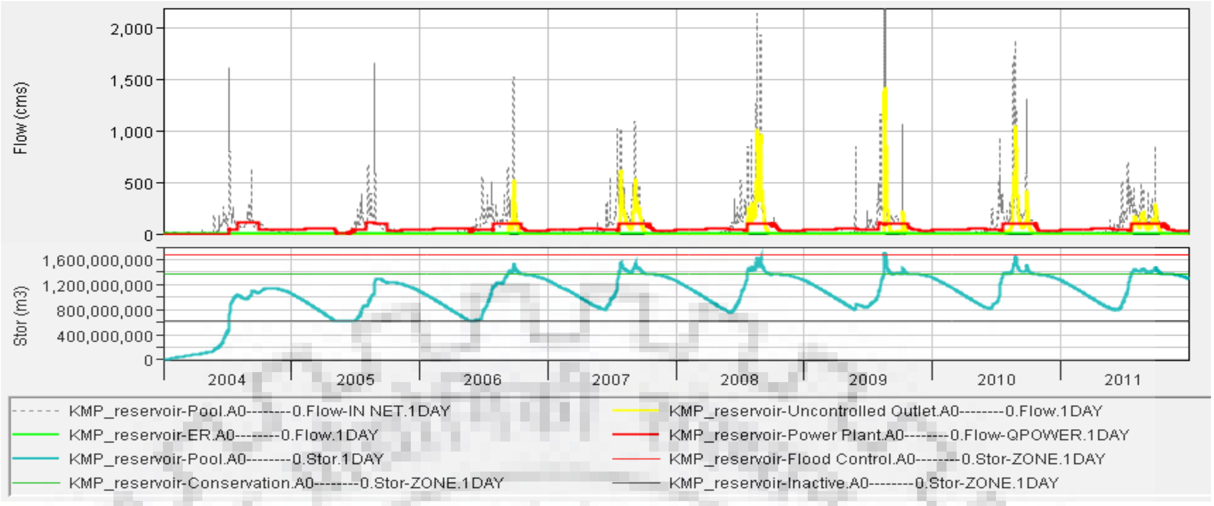

Figure 6.8 Reservoir Flow and Storage Curves for S1 (60 MW)

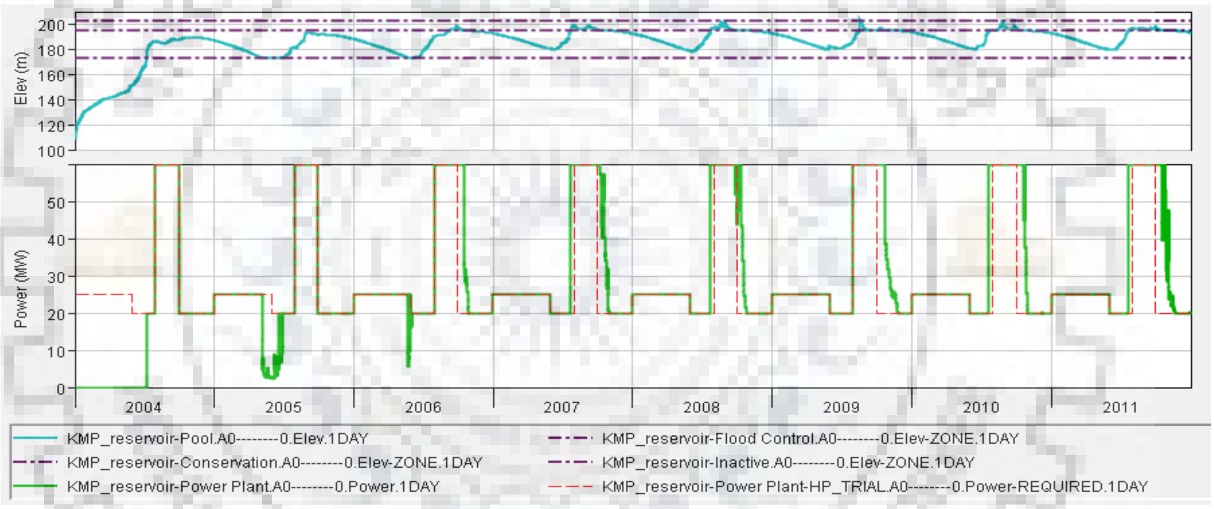

Figure 6.9 Reservoir Elevation and Power Curves for S1 (60 MW)

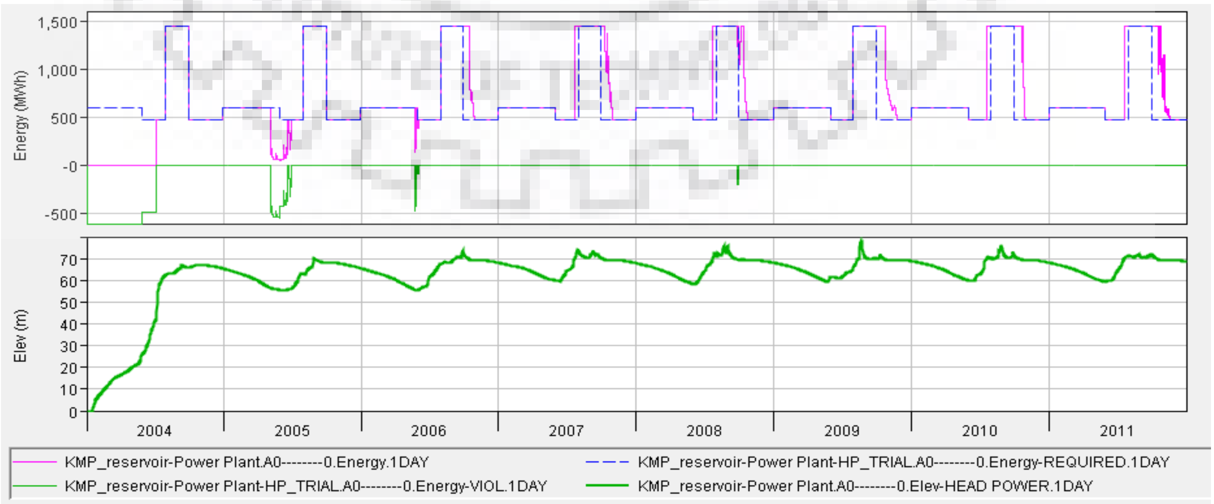

Figure 6.10 Energy and Power head Curves for S1 (60 MW)

6.5.1.2. Scenario S2 (70 MW/ daily time step)

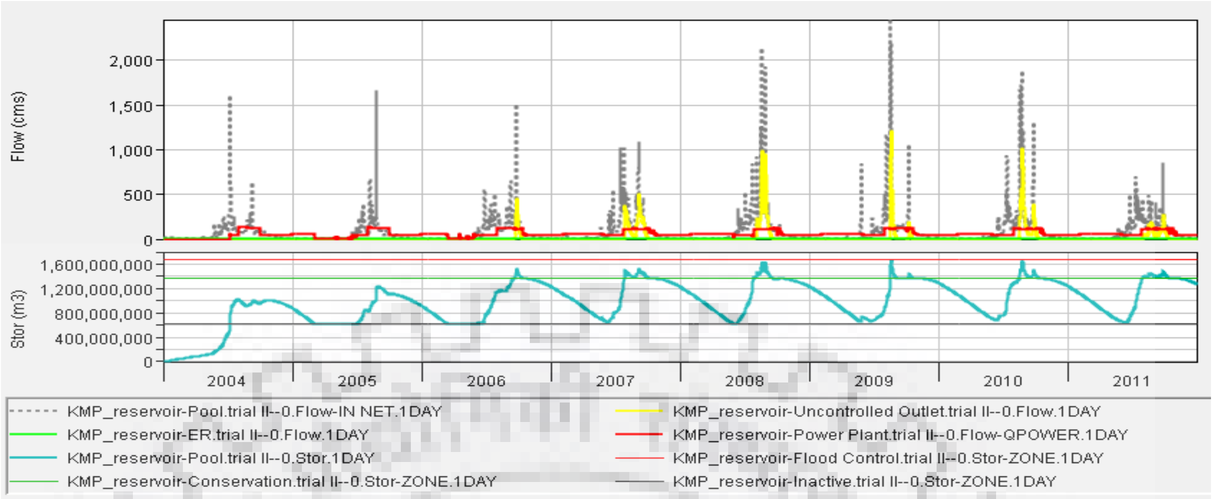

Figure 6.11 Reservoir Flow and Storage Curves for S2 (70 MW)

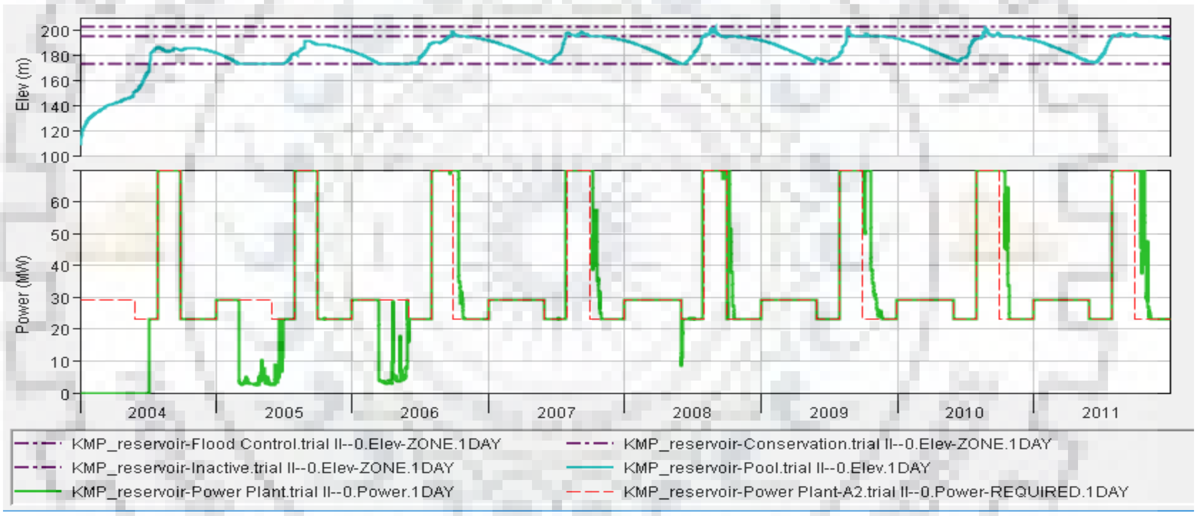

Figure 6.12 Reservoir Elevation and Power Curves for S2 (70 MW)

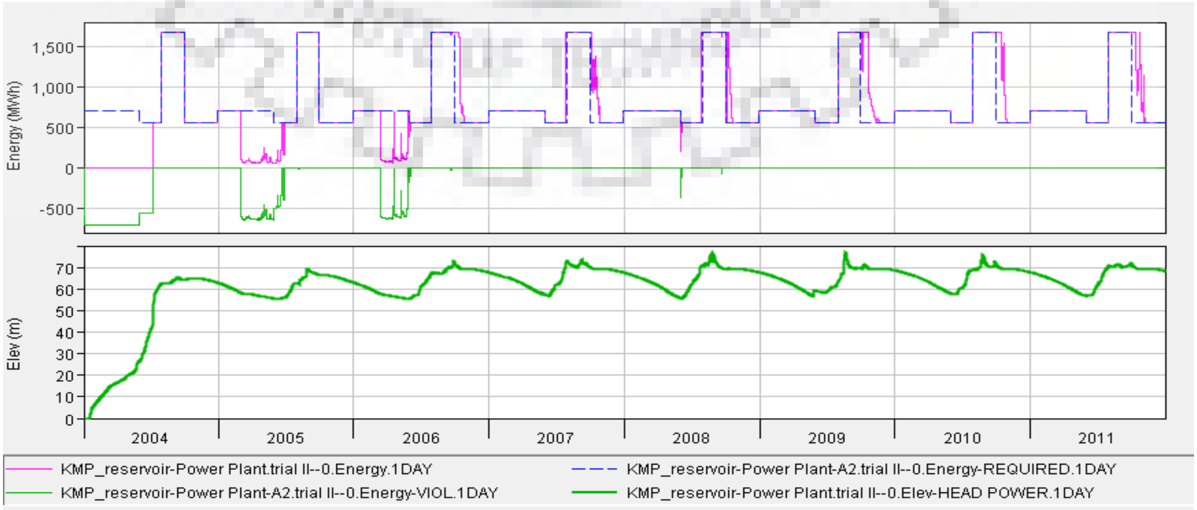

Figure 6.13 Energy and Power head Curves for S2 (70 MW)

6.5.1.3. Scenario S3 (80 MW/ daily time step)

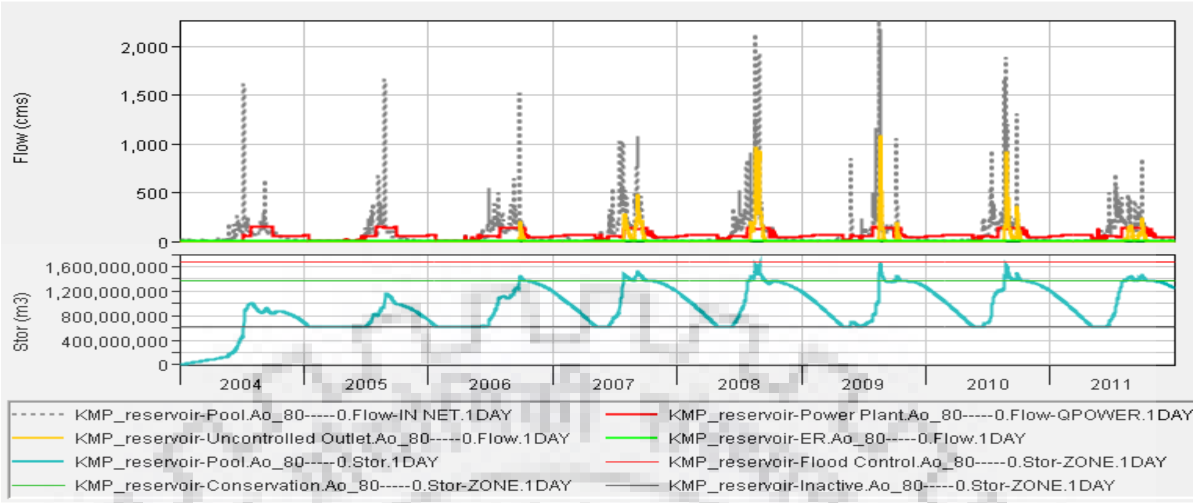

Figure 6.14 Reservoir Flow and Storage Curves for S3 (80 MW)

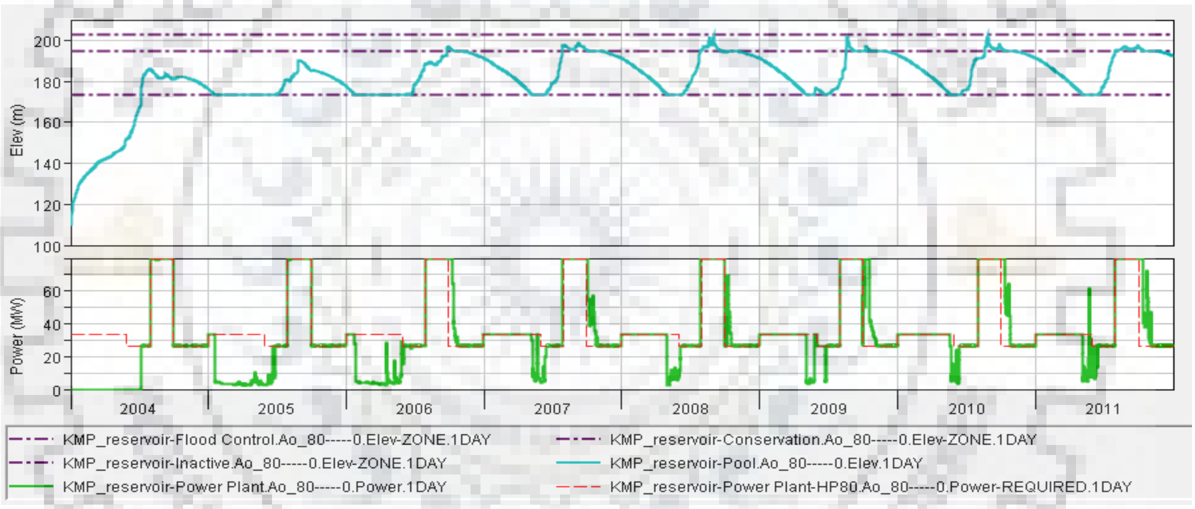

Figure 6.15 Reservoir Elevation and Power Curves for S3 (80 MW)

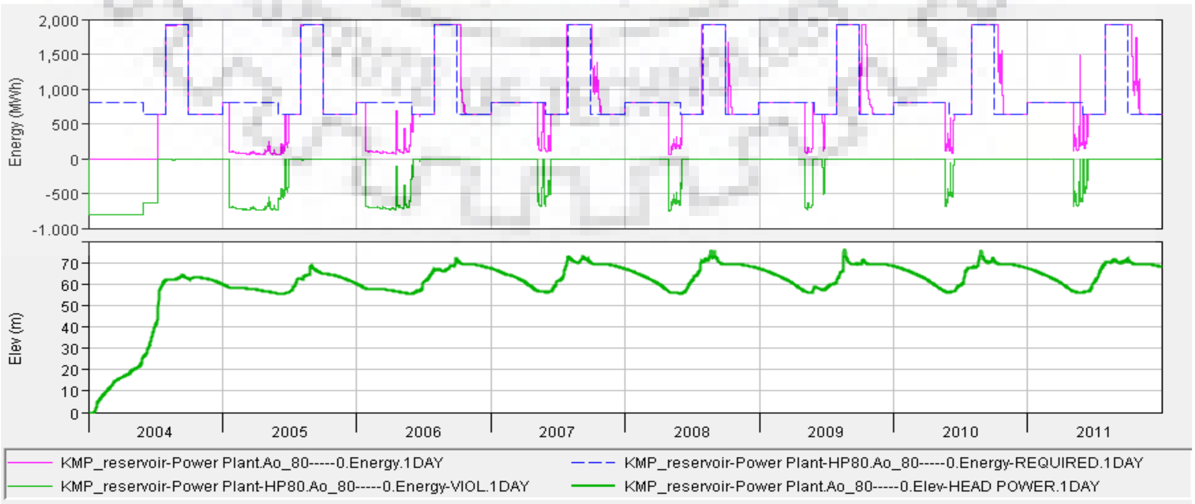

Figure 6.16 Energy and Power head Curves for S3 (80 MW)

6.5.1.4. Scenario S4 (90 MW/ daily time step)

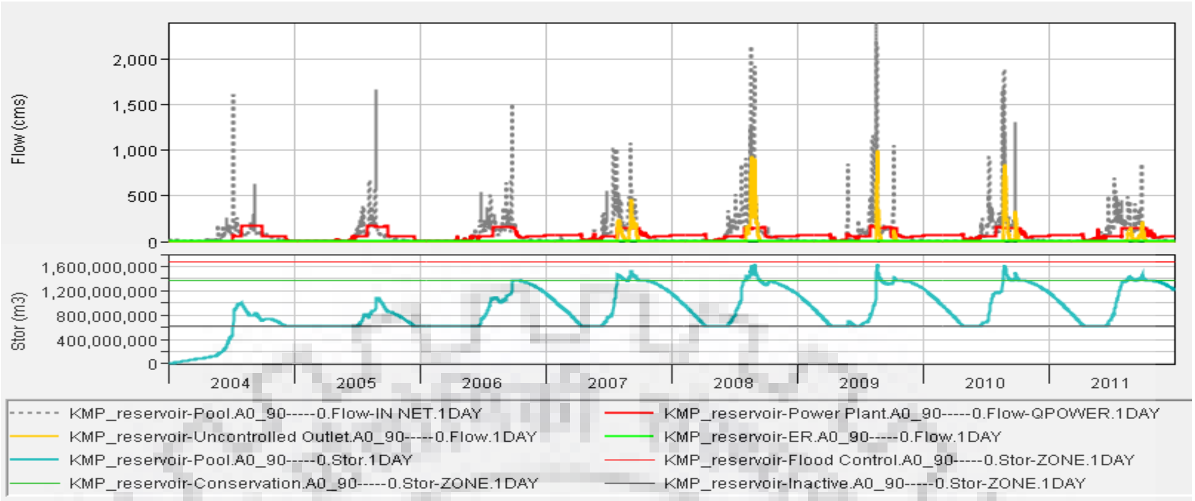

Figure 6.17 Reservoir Flow and Storage Curves for S4 (90 MW)

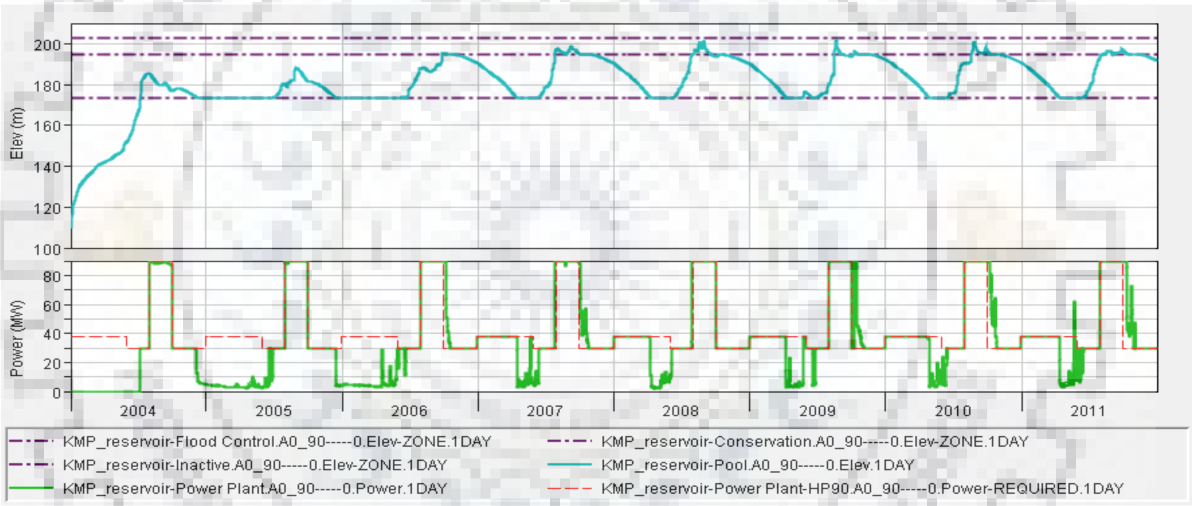

Figure 6.18 Reservoir Elevation and Power Curves for S4 (90 MW)

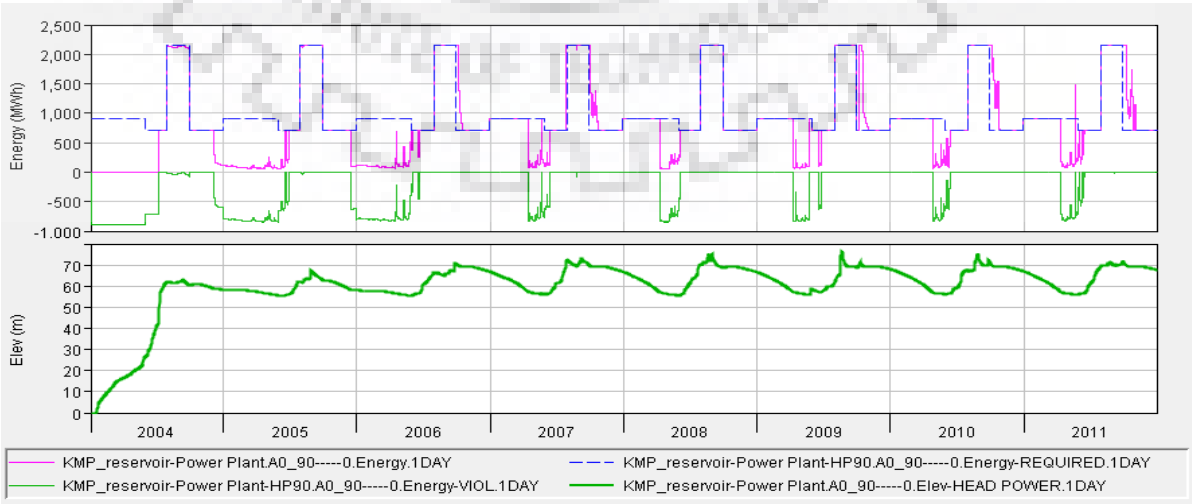

Figure 6.19 Energy and Power head Curves for S4 (90 MW)

6.5.1.5. Scenario S5 (100 MW/ daily time step)

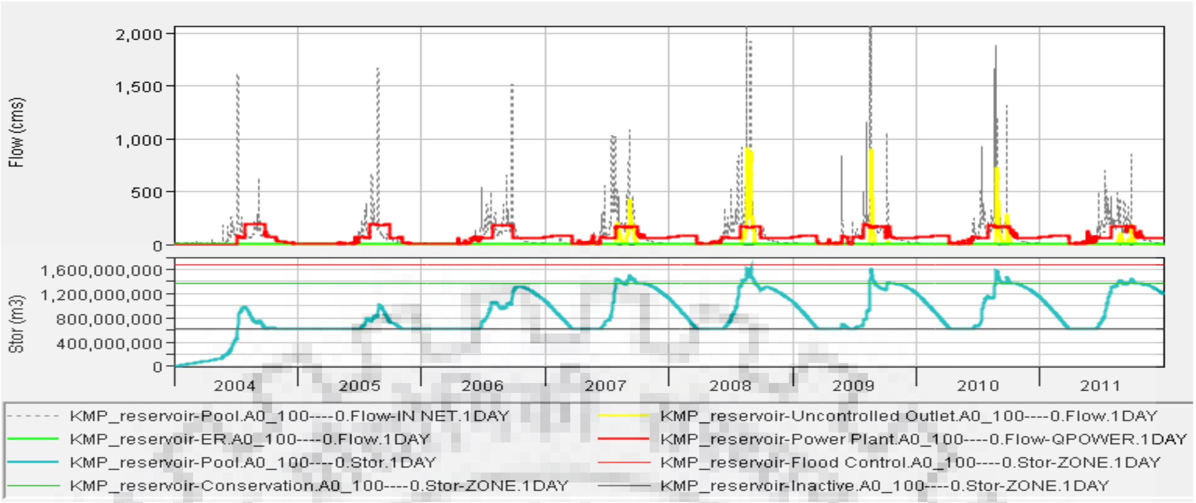

Figure 6.20 Reservoir Flow and Storage Curves for S5 (100 MW)

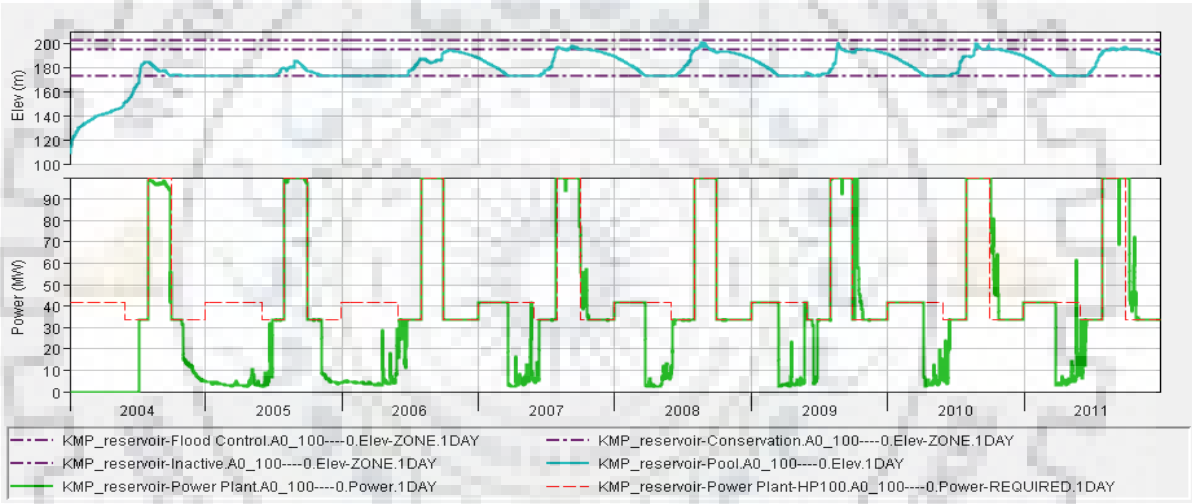

Figure 6.21 Reservoir Elevation and Power Curves for S5 (100 MW)

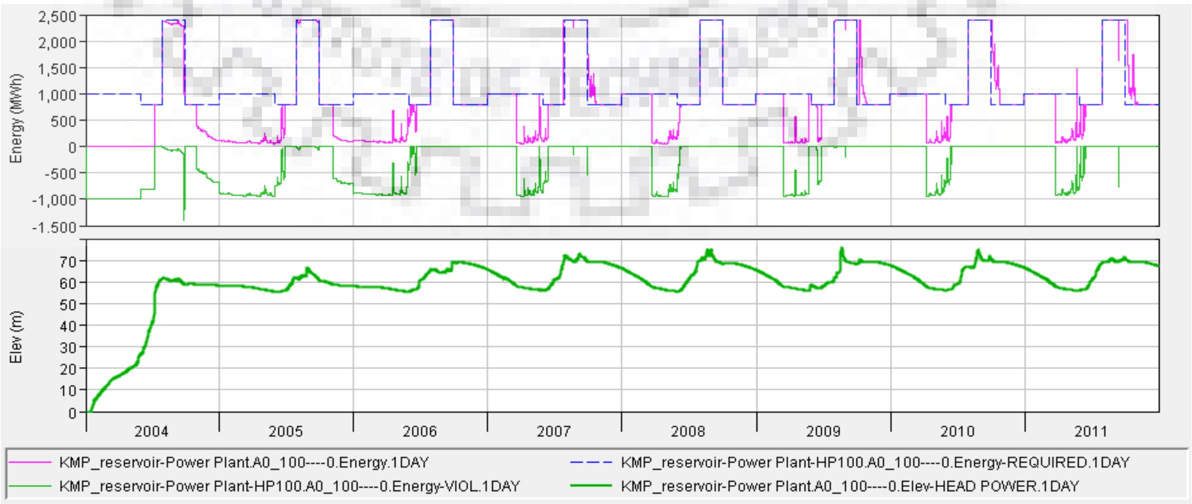

Figure 6.22 Energy and Power head Curves for S5 (100 MW)

6.5.1.6. Scenario S6 (110 MW/ daily time step)

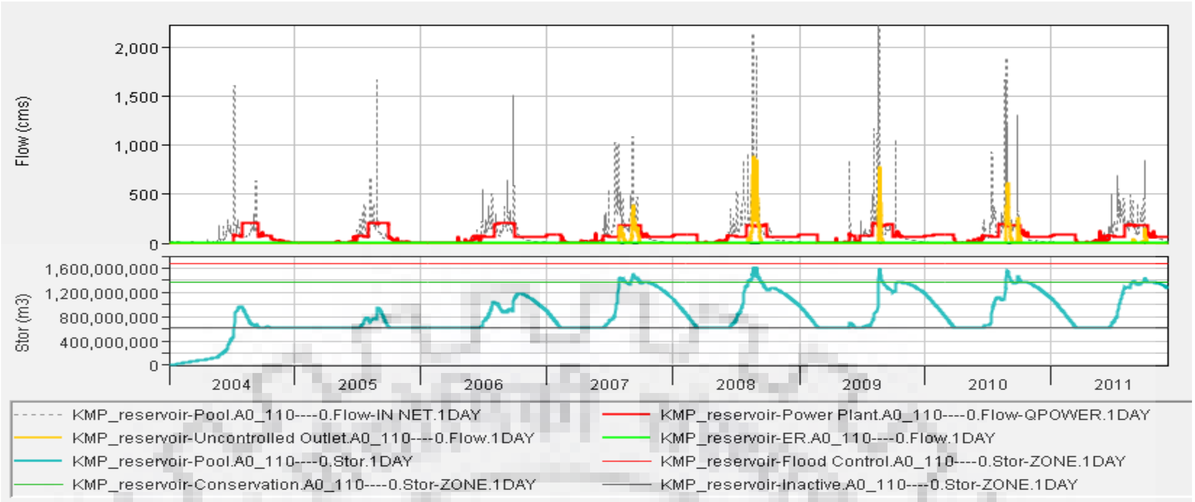

Figure 6.23 Reservoir Flow and Storage Curves for S6 (110 MW)

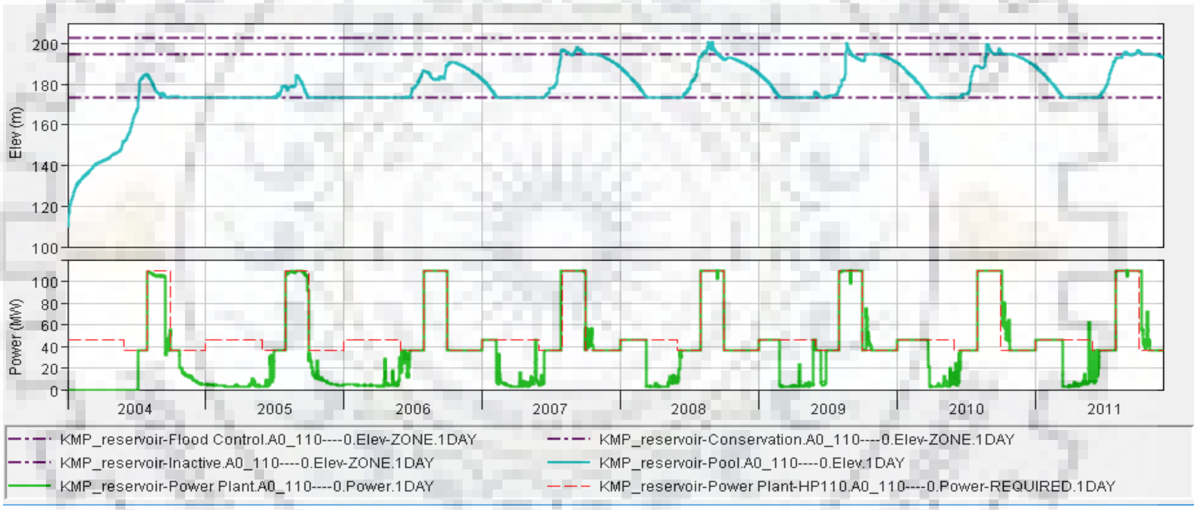

Figure 6.24 Reservoir Elevation and Power Curves for S6 (110 MW)

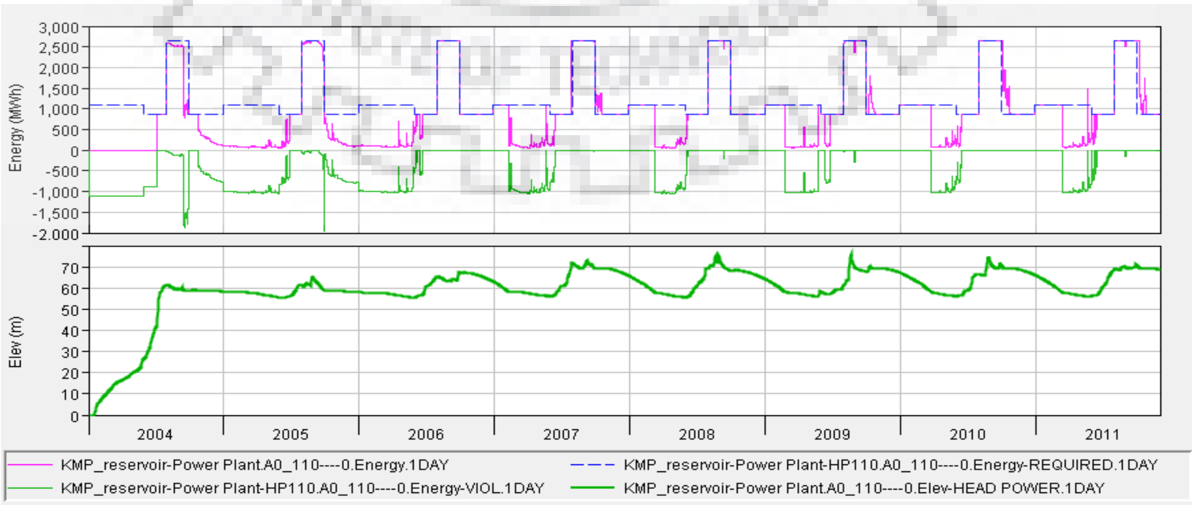

Figure 6.25 Energy and Power head Curves for S6 (110 MW)

6.5.1.7. Scenario S7 (120 MW/ daily time step)

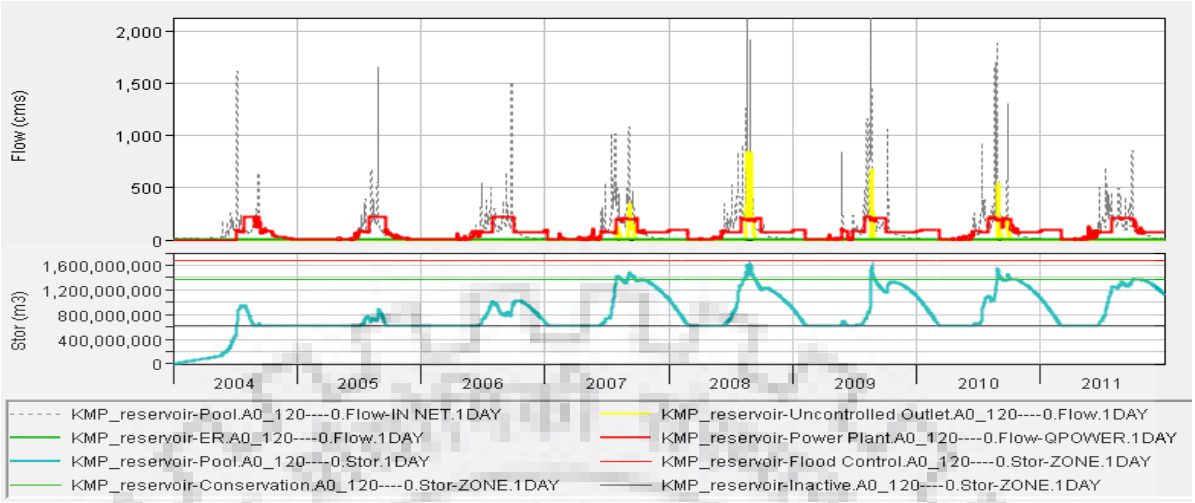

Figure 6.26 Reservoir Flow and Storage Curves for S7 (120 MW)

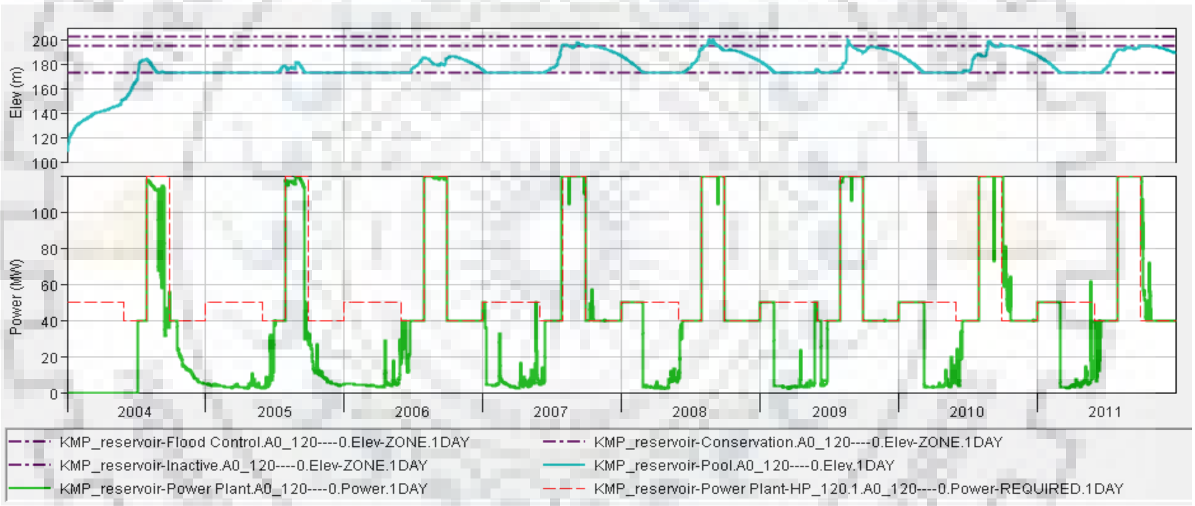

Figure 6.27 Reservoir Elevation and Power Curves for S7 (120 MW)

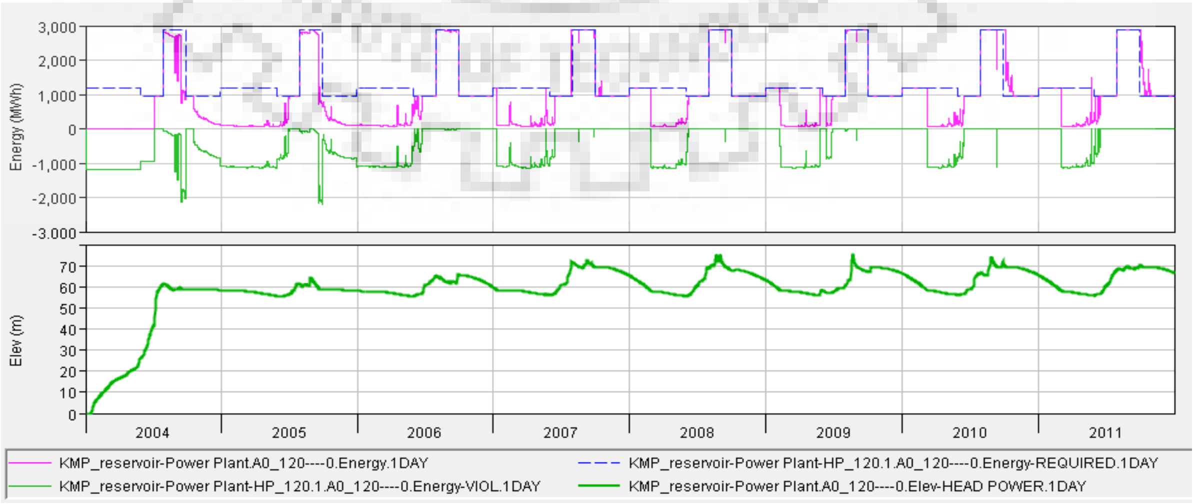

Figure 6.28 Energy and Power head Curves for S7 (120 MW)

6.5.1.8. Scenario S8 (130 MW/ daily time step):

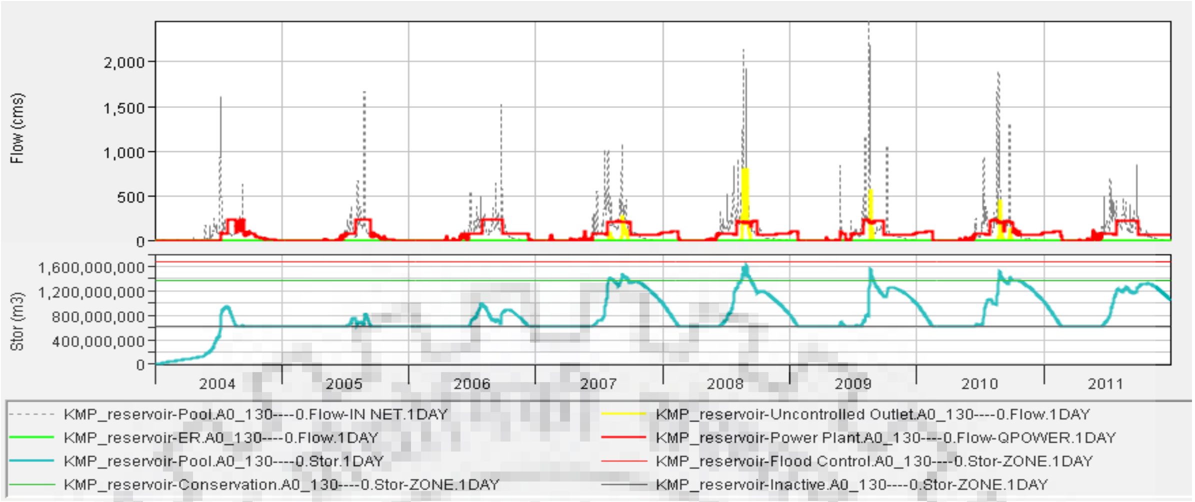

Figure 6.29 Reservoir Elevation and Power Curves for S8 (130 MW)

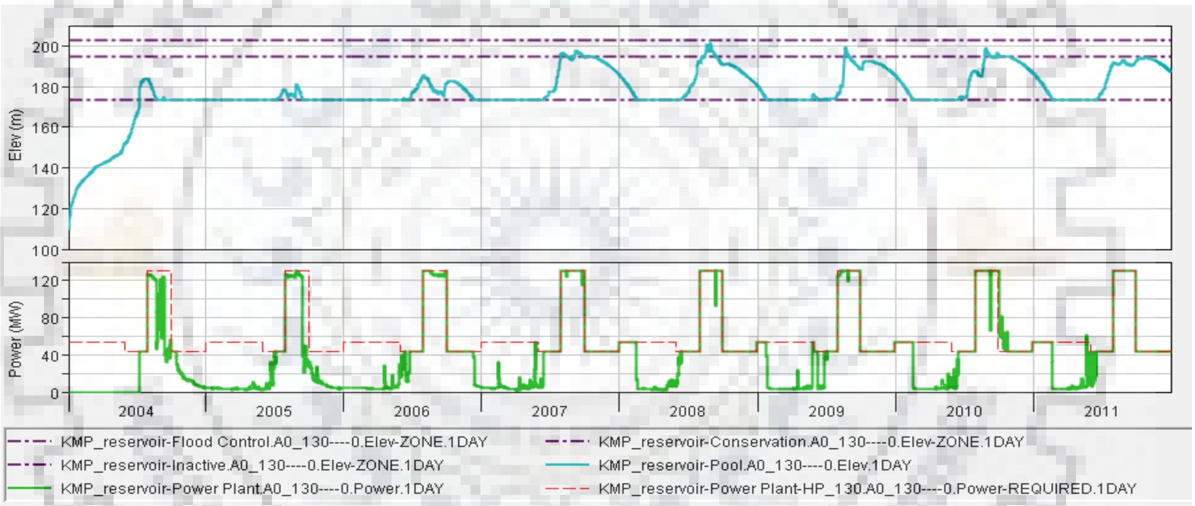

Figure 6.30 Reservoir Elevation and Power Curves for S8 (130 MW)

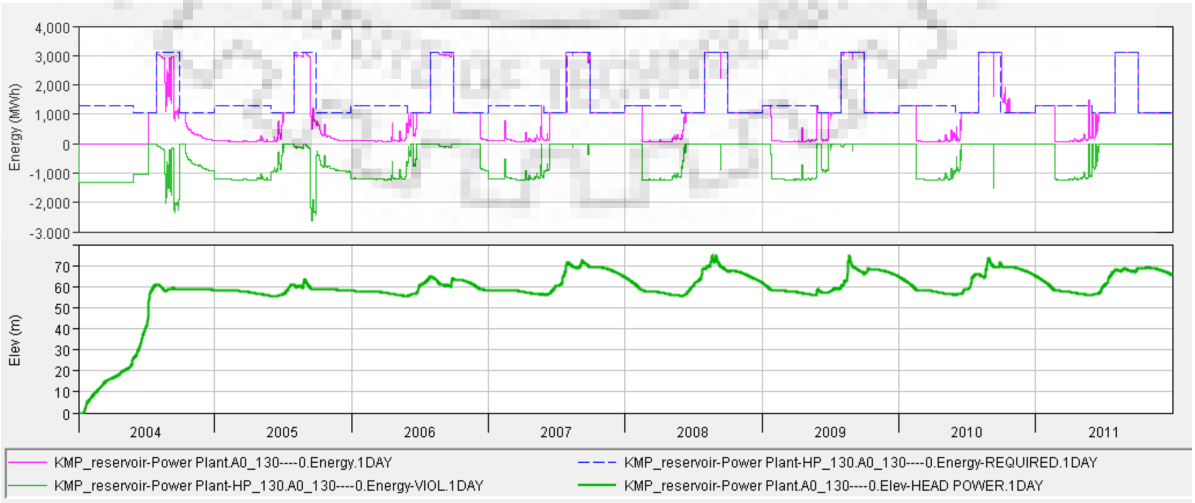

Figure 6.31 Energy and Power head Curves for S8 (130 MW)

6.5.1.9. Summary of scenarios S1 to S8

The summary of the scenarios are presented in Table 6.10 and graphically presented in Figure 6.32

Table 6.10 Summary of scenarios S1 to S8

Scenarios		S1	S2	S3	S4	S5	S6	S7	S8
Installed capacity (MW)		60	70	80	90	100	110	120	130
Flow in (cumecs)	average	85.4	85.4	85.4	85.4	85.4	85.4	85.4	85.4
	min	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
	max	4310.6	4310.6	4310.6	4310.6	4310.6	4310.6	4310.6	4310.6
Evap flow (cumecs)	average	1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.1
	min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	max	1.9	1.9	1.8	1.8	1.7	1.7	1.7	1.7
Q uncontrolled (cumecs)	average	24.3	18.8	15.4	12.9	10.8	8.9	7.2	5.9
	max	1412.9	1209.6	1081.3	993.9	907.6	878.5	844.8	805.5
	total/ yr	8874.0	6855.8	5630.0	4690.5	3928.2	3253.3	2639.3	2148.7
Q power (cumecs)	average	55.3	61.4	65.2	68.2	70.7	73.0	75.2	77.1
	min	5.1	4.8	4.7	4.6	4.5	4.5	4.5	4.5
	max	113.0	132.0	151.0	170.0	189.0	208.0	226.0	245.0
Elevation pool (m)	average	185.7	183.6	182.1	181.0	180.0	179.1	178.4	177.6
	min	109.3	109.3	109.3	109.3	109.3	109.3	109.3	109.3
	max	203.5	202.3	201.9	201.6	201.3	201.2	201.1	201.0
Storage pool (m3)	average	1055.1	983.3	933.6	897.8	866.0	836.3	809.9	783.7
	min	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	max	1717.9	1666.9	1649.4	1636.8	1625.3	1620.8	1616.5	1611.8
Power Head (m)	average	65.7	64.6	63.8	63.2	62.7	62.2	61.7	61.3
	min	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2
	max	77.7	77.0	76.6	76.4	76.1	75.7	75.3	75.0
Energy generated (GWH)	Annual avg	255.9	280.8	296.8	309.3	319.5	328.4	337.1	344.0
Energy requirement (GWH)	Annual avg	238.4	278.1	317.8	357.5	397.3	436.6	476.7	516.4
Energy violation (GWH)	Annual avg	-3.0	-13.8	-35.5	-60.1	-86.6	-115.0	-144.4	-174.9
Plant Factor	average	0.5	0.5	0.5	0.4	0.4	0.4	0.3	0.3
	min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	max	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

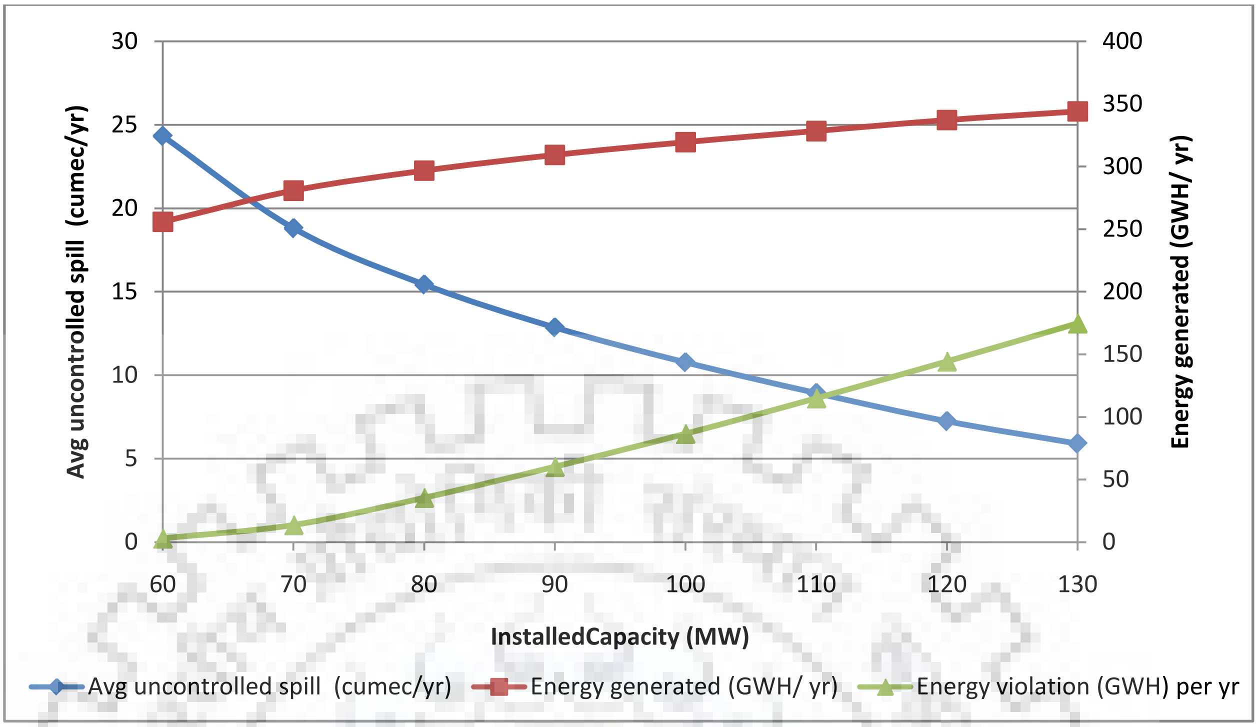

Figure 6.32 Uncontrolled spill Vs Energy generated and violated (Scenario: S1 to S8)

The curves representing change in flow, power, energy, elevation and storage for every individual scenarios are presented in figures from Figure 6.8 to Figure 6.31 as well as in summary

Table 6.11 and summary Figure 6.32. It has been observed that, as the installed capacity increases,

- Average Evaporation rate is in falling as it is the function of the reservoir area,
- Uncontrolled spill is in falling trend as flood flows are absorbed to generate power,
- Pool elevation is falling because of the heavy drawdown of water,
- Pool storage is falling because of the heavy drawdown of water,
- Power head is falling because of the lowering of the pool elevation,
- Energy generated is rising because of increased capacity of the intake/ physical structures,
- Energy violation is rising because of limited low season flow to meet the energy requirement.

6.5.2. Scenario S9-S11:

Scenarios S9-S11 is carried out in the same modality as in the case of S1-S8 in terms of the operation pattern and corresponding monthly energy requirement. But the time step for these

scenarios is hourly unlike the previous cases since the reservoir simulation in the hourly time step is more precise than the daily. The details of the scenarios are given in
Table 6.11

Table 6.11 Scenarios description for S9-S11

Scenarios	Time step	Irrigation command area (ha)	Installed Capacity (MW)	Remarks
Rule: Monthly energy requirement corresponding to (operation pattern OP 1) Time step: hourly				
S9	hourly	67450	60	OP 1
S10		67450	90	
S11		67450	120	

As mentioned previously, for Scenario S9- S11, the hourly time step has been adopted to simulate the flow so that more precise pattern of flow, energy, power, storage and elevation variation with the change in the installed capacity can beestimated . Here are presented four types of characteristic curves within two graphs as mentioned below for every individual scenario.

i. **Power and Energy Curves** includes
   c. Power curves (Power generated and power required)
   d. Energy curves (Energy generated, Energy required and energy violated)

ii. **Reservoir Elevation and Flow Curves** includes
   a. Elevation curves (Flood control elevation, conservation elevation, Inactive elevation and the pool elevation)
   b. Flow curves (Net inflow, uncontrolled outflow, Environmental Release and flow power)

From section 6.5.2.1 up to section 6.5.2.3, i.e. from scenarios S9 to S11, the curves as mentioned above are shown in order to observe the gradual variation in the curve characteristic for S9 to S11.

Power and energy curves for S9 to S11 are presented in Figure 6.33, Figure 6.35 and Figure 6.37 respectively.

Reservoir elevation and flow curves for S1 to S8 are presented in Figure 6.34, Figure 6.36 and Figure 6.38 respectively.

6.5.2.1. Scenario S9 (60 MW/ hourly time step)

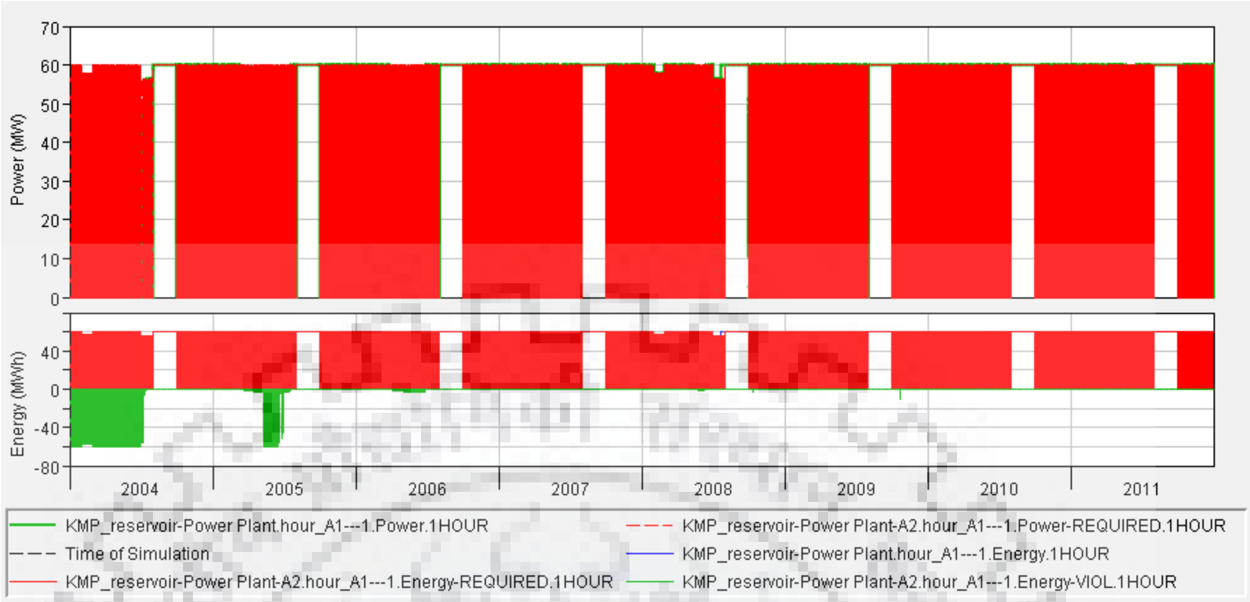

Figure 6.33 Power and Energy curves for S9 (60 MW)

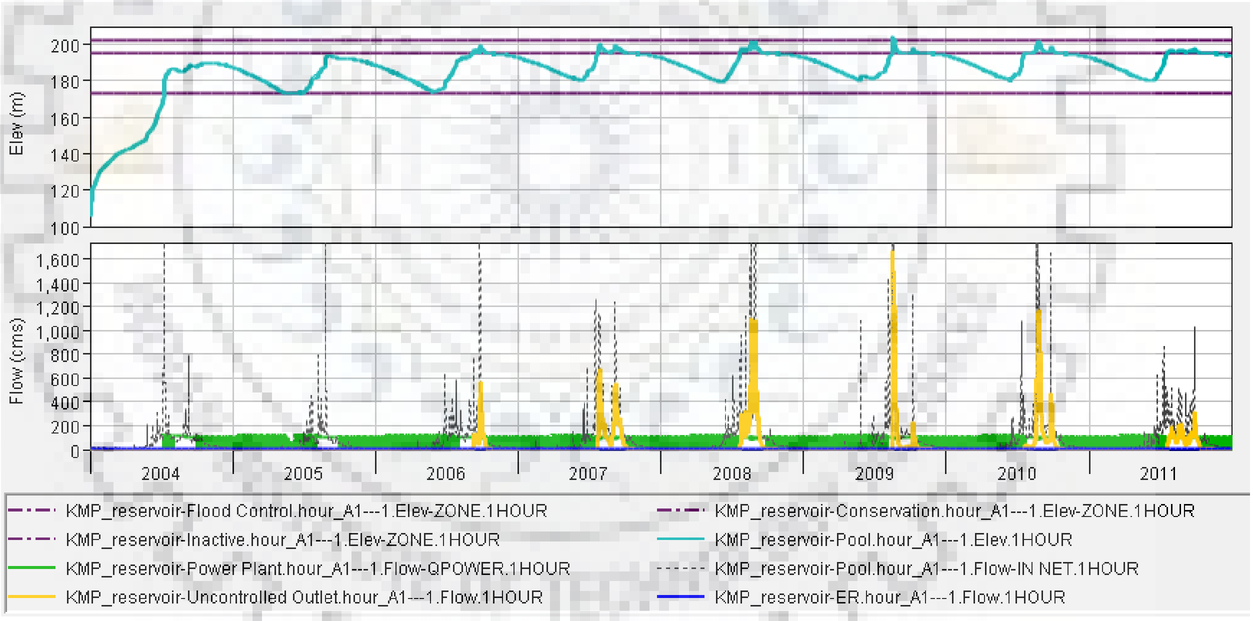

Figure 6.34 Reservoir elevation and Flow curves for S9 (60 MW)

6.5.2.2. Scenario S10 (90 MW/ hourly time step)

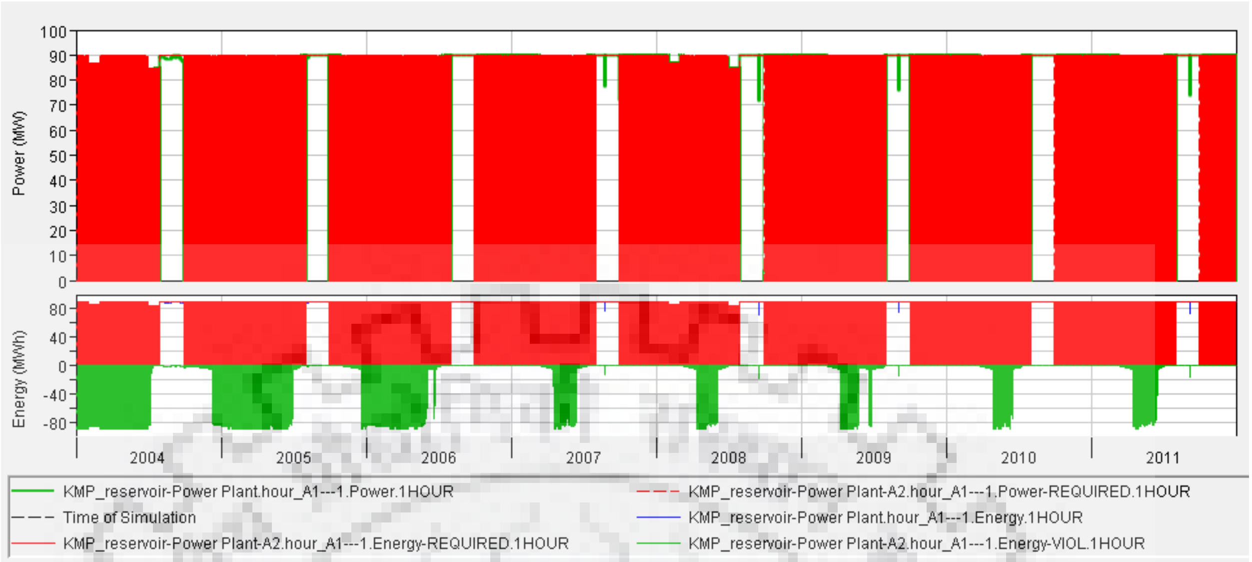

Figure 6.35 Power and Energy curves for S10 (90 MW)

Figure 6.36 Reservoir elevation and Flow curves for S10 (90 MW)

6.5.2.3. Scenario S11 (60 MW/ hourly time step)

Figure 6.37 Power and Energy curves for S11 (120 MW)

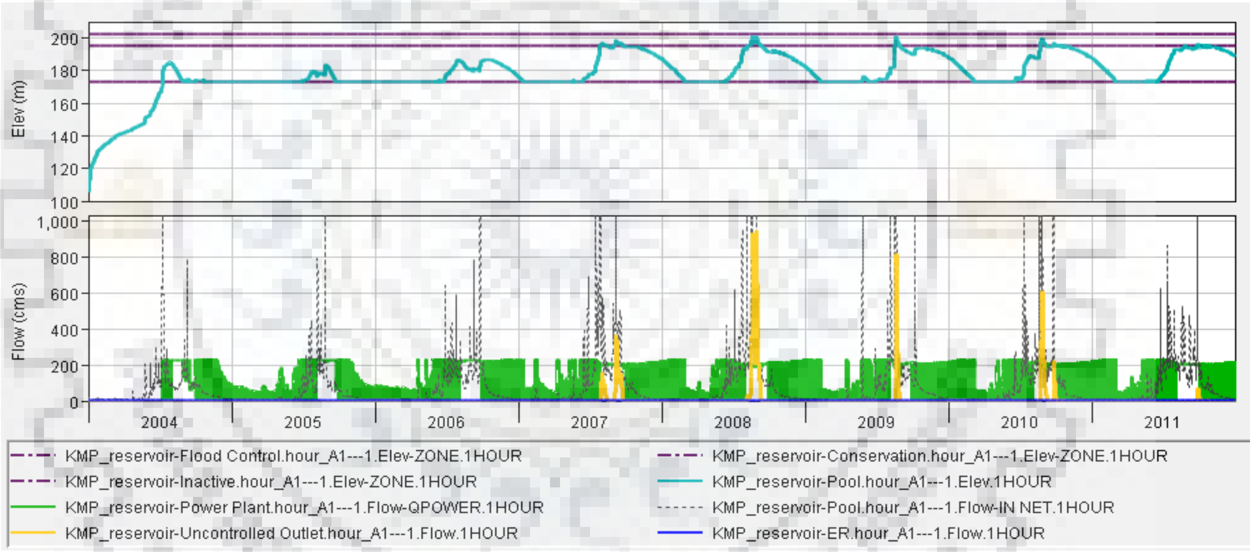

Figure 6.38 Reservoir elevation and Flow curves for S11 (120 MW)

6.5.2.4. Summary of scenarios S9-S11

The summary for the scenarios S9- S11 are tabulated in Table 6.12

Table 6.12 Summary of energy violation and uncontrolled spill (S9-S11)

Parameters	unit	60 MW	90 MW	120 MW
Energy Generated	GWhr	2045.99	2476.78	2695.30
Energy Generated per year	GWhr	255.75	309.6	336.9
Energy violation (hour)	hour	5381	14527	19046
	%	7.68	20.73	27.18
Energy violation (Energy)	GWhr	22.26	474.29	1153.56
	%	7.17	16.59	30.26
Avg Uncontrolled spill	cumecs	26.50	14.02	8.17

The curves representing flow, power, energy and elevation for every individual scenarios as well as the summary Table 6.12, it is more clear that, as the installed capacity increases,

- Uncontrolled spill is falling as flood flows are absorbed to generate power,
- Pool elevation is falling because of the heavy drawdown of water,
- Energy generated is rising because of increased capacity of the intake/ physical structures,
- Energy violation is rising because of limited low season flow to meet the energy requirement.

6.5.3. Scenarios S12 to S14

In these scenarios, the monthly energy generation requirement is so adjusted as to limit the energy violation resulted from the scenarios S9-S11 within 10%. As the energy violation for 60 MW hourly is already within the limit, S12=S9. The details of the scenarios are presented in Table 6.13

Table 6.13 Scenarios description for S12-S14

Scenarios	Time step	Irrigation command area (ha)	Installed Capacity (MW)	Remarks
Rule: Monthly energy requirement adjusting the operating hours to confine the energy violation within the predefined limit of 10% Time step: hourly				
S12=S9	hourly	67450	60	OP1
S13		67450	90	OP2
S14		67450	120	OP3

For Scenario S12- S14, the hourly time step has been adopted to simulate the flow so that it will be clear enough from the figures to understand the pattern of energy and power variation with the change in the installed capacity. Here are presented, two types of characteristic curves within a graph as mentioned below for every individual scenario.

Energy and Power head Curves includes

a. Energy curves (Energy generated, Energy required and energy violated)
b. Power head curve (Power generated and power required)

From section 6.5.3.1 up to section 6.5.1.3, i.e. from scenarios S12 to S14, the curves as mentioned above are shown in order to observe the gradual variation in the curve characteristic for S12 to S14.

6.5.3.1. Scenario S12 (60 MW/ hourly time step/ OP1)

For this scenario, there is no need to adjust the operation pattern since the energy violation for S9 (hourly time step result of 60 MW installed capacity) is already within the limit. So for this scenario, S12=S9 and the plot will be similar to the one presented in scenario S9 in Figure 6.33

6.5.3.2. Scenario S13 (60 MW/ hourly time step/ OP2)

For this scenario, the operation pattern has been derived by multiple trials so as to limit the energy violation resulting from S10, within 10% and make the agreement with the energy demand as described in the methodology section. The operation pattern (OP)2 defined for this scenario is presented in Table 6.14

Table 6.14 Operation Pattern (OP) 2

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-1	0	0	0	0	0	0	0	1	1	0	0	0
1-2	0	0	0	0	0	0	0	1	1	0	0	0
2-3	0	0	0	0	0	0	0	1	1	0	0	0
3-4	0	0	0	0	0	0	0	1	1	0	0	0
4-5	0	0	0	0	0	0	0	1	1	0	0	0
5-6	0	0	0	0	0	0	0	1	1	0	0	0
6-7	1	1	1	1	1	1	1	1	1	1	1	1
7-8	1	1	1	1	1	1	1	1	1	1	1	1
8-9	1	1	1	1	0	0	0	1	1	0	1	1
9-10	1	1	1	1	0	0	0	1	1	0	0	1
10-11	0	0	0	0	0	0	0	1	1	0	0	0
11-12	0	0	0	0	0	0	0	1	1	0	0	0
12-13	0	0	0	0	0	0	0	1	1	0	0	0
13-14	0	0	0	0	0	0	0	1	1	0	0	0
14-15	0	0	0	0	0	0	0	1	1	0	0	0
15-16	0	0	0	0	0	0	0	1	1	0	0	0
16-17	0	0	0	0	0	0	0	1	1	0	0	0
17-18	0	0	0	0	0	0	0	1	1	0	0	0
18-19	1	1	1	1	1	1	1	1	1	1	1	1
19-20	1	1	1	1	1	1	1	1	1	1	1	1
20-21	1	1	1	1	1	1	1	1	1	1	1	1
21-22	1	1	1	1	1	1	1	1	1	1	1	1
22-23	0	0	0	0	0	0	0	1	1	0	0	0
23-24	0	0	0	0	0	0	0	1	1	0	0	0
TOT HRS	8	8	8	8	6	6	6	24	24	6	7	8

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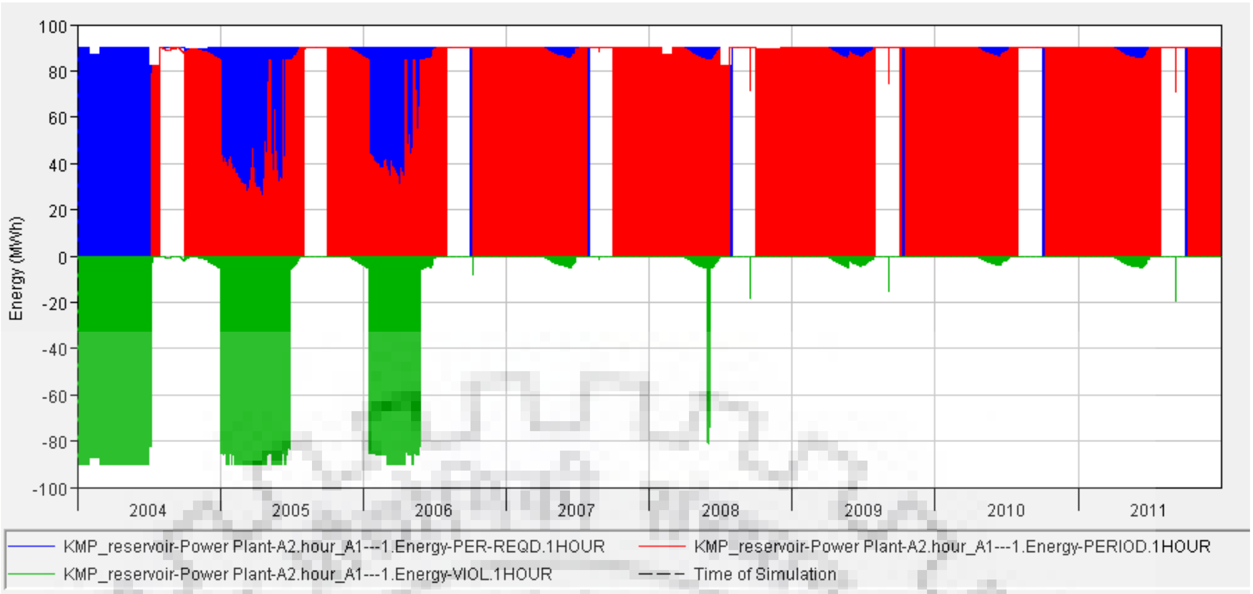

Figure 6.39 Energy curves for S13 (90 MW)

6.5.3.3. Scenario S14 (120 MW/ hourly time step/ OP3):

For this scenario, the operation pattern has been derived by multiple trials so as to limit the energy violation resulting from S11, within 10% and make the agreement with the energy demand as described in the methodology section. The operation pattern (OP3) defined for this scenario is presented in Table 6.15

Table 6.15 Operating Pattern (OP) 3

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-1	0	0	0	0	0	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0	0	0	0	0	0
2-3	0	0	0	0	0	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0	1	1	0	0	0
4-5	0	0	0	0	0	0	0	1	1	0	0	0
5-6	0	0	0	0	0	0	0	1	1	0	0	0
6-7	1	1	1	1	0	0	0	1	1	0	1	1
7-8	1	1	1	1	0	0	0	1	1	0	0	1
8-9	0	0	0	0	0	0	0	1	1	0	0	0
9-10	0	0	0	0	0	0	0	1	1	0	0	0
10-11	0	0	0	0	0	0	0	1	1	0	0	0
11-12	0	0	0	0	0	0	0	1	1	0	0	0
12-13	0	0	0	0	0	0	0	1	1	0	0	0
13-14	0	0	0	0	0	0	0	1	1	0	0	0
14-15	0	0	0	0	0	0	0	1	1	0	0	0
15-16	0	0	0	0	0	0	0	1	1	0	0	0
16-17	0	0	0	0	0	0	0	1	1	0	0	0
17-18	0	0	0	0	0	0	0	1	1	0	0	0
18-19	1	1	1	1	1	1	1	1	1	1	1	1
19-20	1	1	1	1	1	1	1	1	1	1	1	1
20-21	1	1	1	1	1	1	1	1	1	1	1	1
21-22	1	1	1	1	1	1	1	1	1	1	1	1
22-23	0	0	0	0	0	0	0	1	1	0	0	0
23-24	0	0	0	0	0	0	0	0	0	0	0	0
TOT HRS	6	6	6	6	4	4	4	20	20	4	5	6

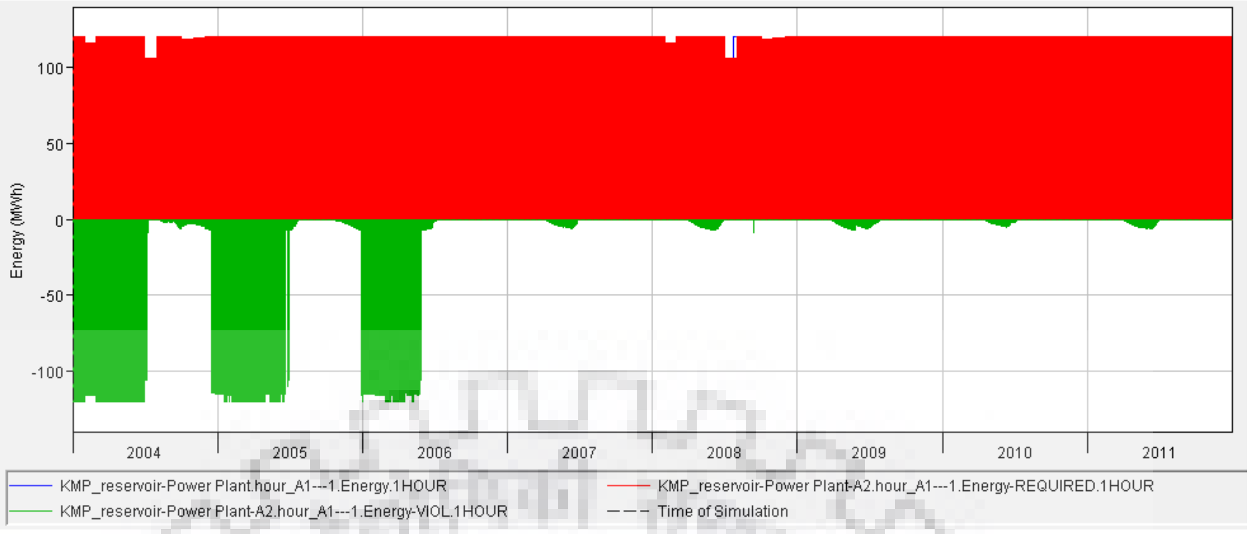

Figure 6.40 Energy curves for S14 (120 MW)

6.5.3.4. Summary for S12-S14:

Summary for S12 to S14 (60 MW, 90 MW and 120 MW) is presented in Table 6.16 and graphically presented in Figure 6.41. This gives the idea about the variation in the generation of energy, violation of the energy and the uncontrolled spill.

Table 6.16 Energy generation/ violation and spill comparison for S12/13/14

Parameters	unit	Scenarios		
		S12 (60 MW)	S13 (90 MW)	S14 (120 MW)
Energy Generated	GWhr	255.75	309.60	336.91
Energy violation in terms of hour	percent	7.68	11.87	9.37
Energy violation in terms of energy	percent	7.17	7.82	8.11
Average Uncontrolled spill	Cumec	26.50	15.77	11.97

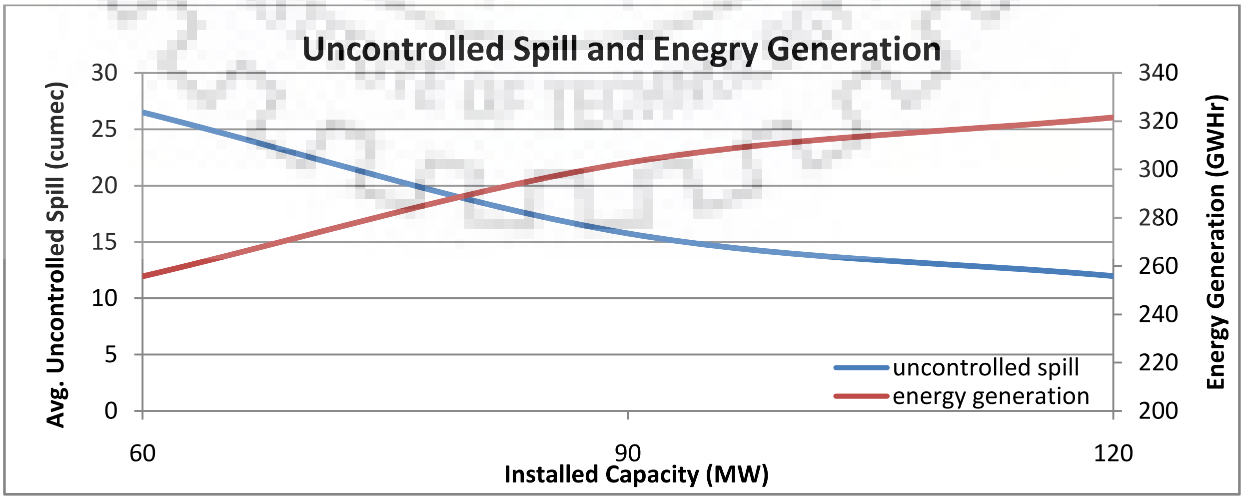

Figure 6.41 Uncontrolled spill and energy generation for different installed capacity

6.5.4. Fixation of Installed Capacity

Considering the water availability and the major criteria and the system being constrained by specified environmental release, the irrigation demand fulfillment, and the national energy demand gap picture, the current study suggests the installed capacity based on flow duration and power duration curves as well as the incremental impact on most sensitive parameter such as energy generation and the uncontrolled spill.

6.5.4.1. Flow Duration Curve and Power Duration Curves

Given below in Figure 6.42 is the flow duration and power duration curves, and the summary of which as power generated at different % excedence of time showing firm power and secondary power has been presented in Table 6.17. From the table and figures presented, the performance of the system at 90 MW is considered better.

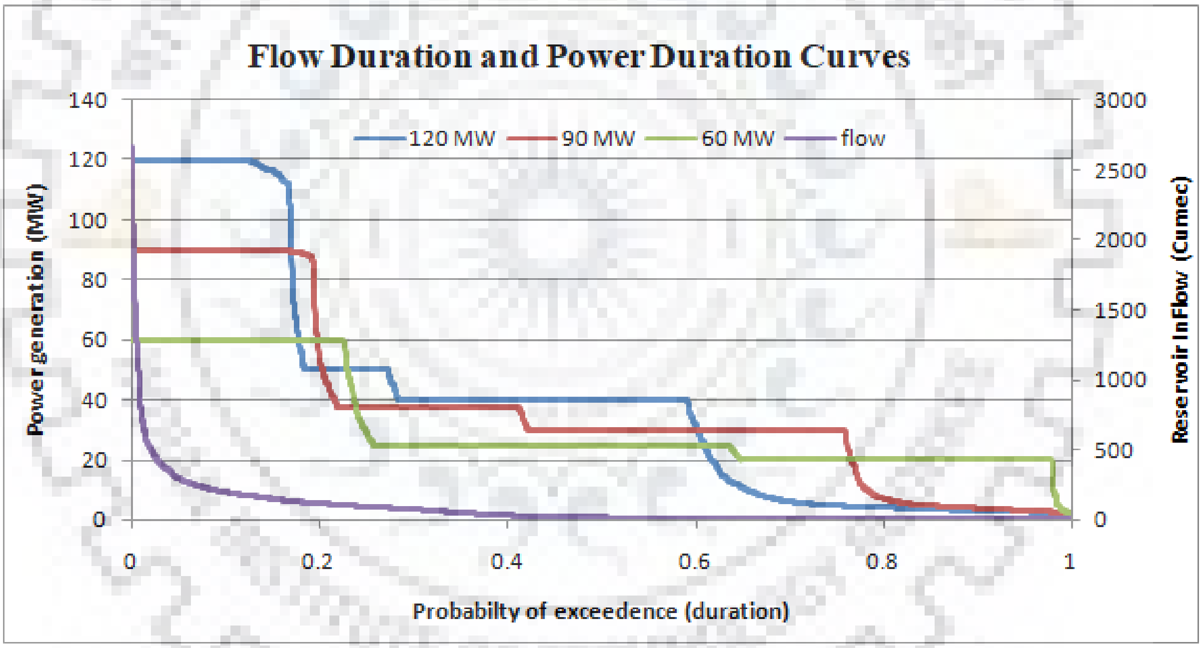

Figure 6.42 Flow duration and Power Duration Curves

Table 6.17 Summary of Power Duration curve

Prbobability of exceedence	60 MW	90 MW	120 MW	
90%	20	4.01	3.15	
75%	20	30	4.73	Firm Power
50%	25	30	40	Secondary Power
25%	29.4	37.5	50	Dumped power

6.5.4.2. Incremental Analysis:

The pattern of change in parameters is worth to note, with the change in installed capacity. This change has been presented in the form of incremental analysis in Table 6.18 and graphically represented in Figure 6.41. From the table, the performance of the system at 90 MW is considered better.

Table 6.18 Incremental analysis

incremental effect on parameters	% Change		
	From 60 MW to 90 MW	From 90 MW to 120 MW	remarks
Energy Generation	18.44	6.15	% increase
Uncontrolled spill	40.50	24.11	% decrease

6.5.5. Climate Change Impact in Reservoir Operation

These are the scenarios wherein the impact of climate change has been observed. The simulation has been carried out using the flow time series for RCP 4.5 and RCP 8.5 for the mid- century forecast (2064-2070). The simulation has been done for the installed capacity of 90 MW with operation pattern 2 (OP2) as given in Table 6.14 Operation Pattern (OP) 2. The base case considered for these scenarios is S13.

Before carrying out the simulation for projected climate data, the comparison of the flow was considered to be important since the observed data window used for flow calibration in SWAT and that for HEC Res Sim Simulation were different. The comparison of cumulative flow for different scenarios/ different time periods is summarized in Table 6.20 and presented in Figure 6.43.

Table 6.19 Flow characteristic for different scenarios

Scenarios	Flow_obs	Flow_SWAT Simulated	Flow RCP 4.5	Flow RCP 8.5	Flow_obs Hec Res Sim
Period	1993-1998	1993-1996	2064-2070	2064-2070	2004-2011
Average flow(cumec)	54.02	44.87	53.14	60.76	84.82
Min. Flow (cumec)	4.59	1.334	1.536	2.265	7.02
Max. Flow (cumec)	1960	1233	2959	4146	5675

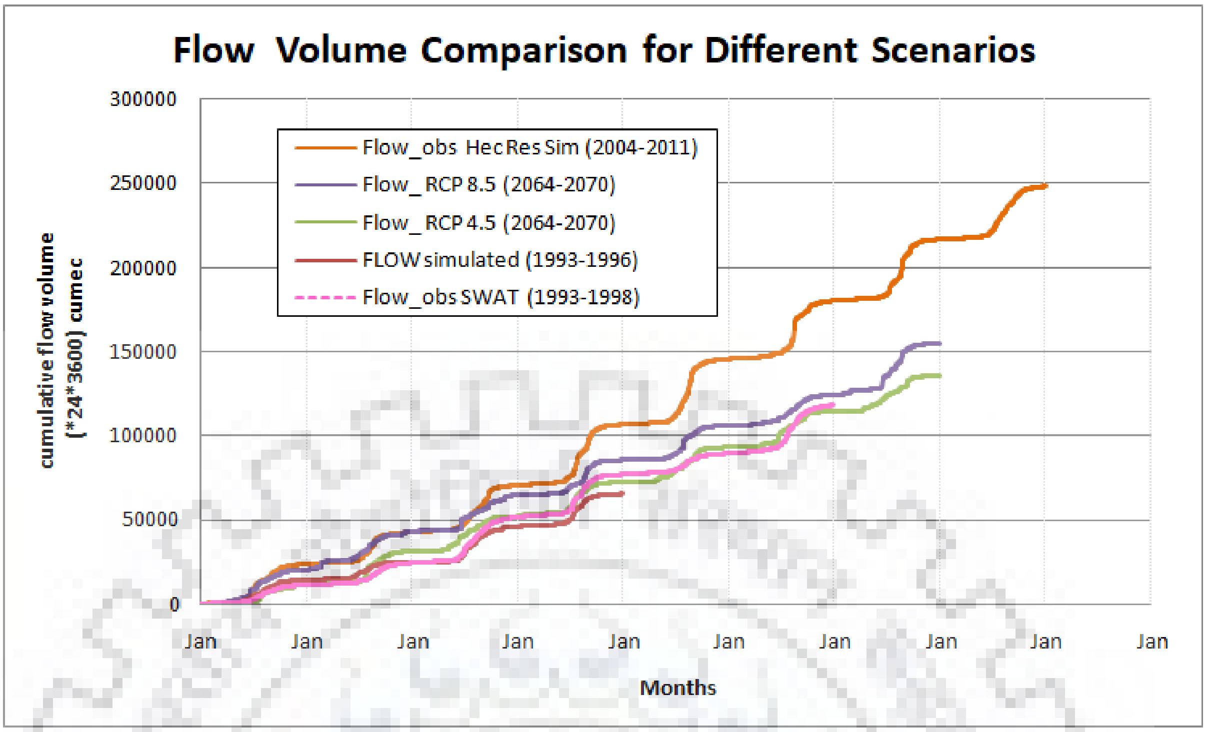

Figure 6.43 Flow volume comparison for different scenarios

Looking at the curve characteristics in the figure as well as table, it was felt important to compare the reservoir operation simulation result for the future flow with the simulated flow as well in addition to the observed flow. Hence along with the future flow adhering RCP 4.5 and RCP 8.5, the reservoir simulation has been carried out for the base period simulation i.e. SWAT simulated flow of duration 1993 to 1998. The simulation details for S15-17 are presented in Table 6.20

Table 6.20 Scenario description for S15-17

Scenarios	Time step	Simulation	Operation Pattern
S15	hourly	RCP 4.5 (2063-2070)	OP 2
S16		RCP 8.5 (2063-2070)	
S17		Simulated (1993-1998)	

For all these scenarios, here are presented two types of characteristic curves within a single figure as mentioned below for every individual scenario.

Reservoir Elevation and Reservoir Flow curve includes

a. Elevation curves (Flood control elevation, conservation elevation, Inactive elevation and the pool elevation)
b. Flow curves (Net inflow, uncontrolled outflow and flow power)

From section 6.5.5.1 up to section 6.5.5.3 i.e. from scenarios S15 to S17, the curves as mentioned above are shown in order to observe the variation in the curve characteristic.
Since the HEC Res Sim is not capable of simulating the flow with future dates, the time series for the future flow was made to enter into the software with the historical date. Hence the dates mentioned in the figures 2004-2010 represent 2064 -2070 future time period.

6.5.5.1. Simulation for future Climate RCP 4.5

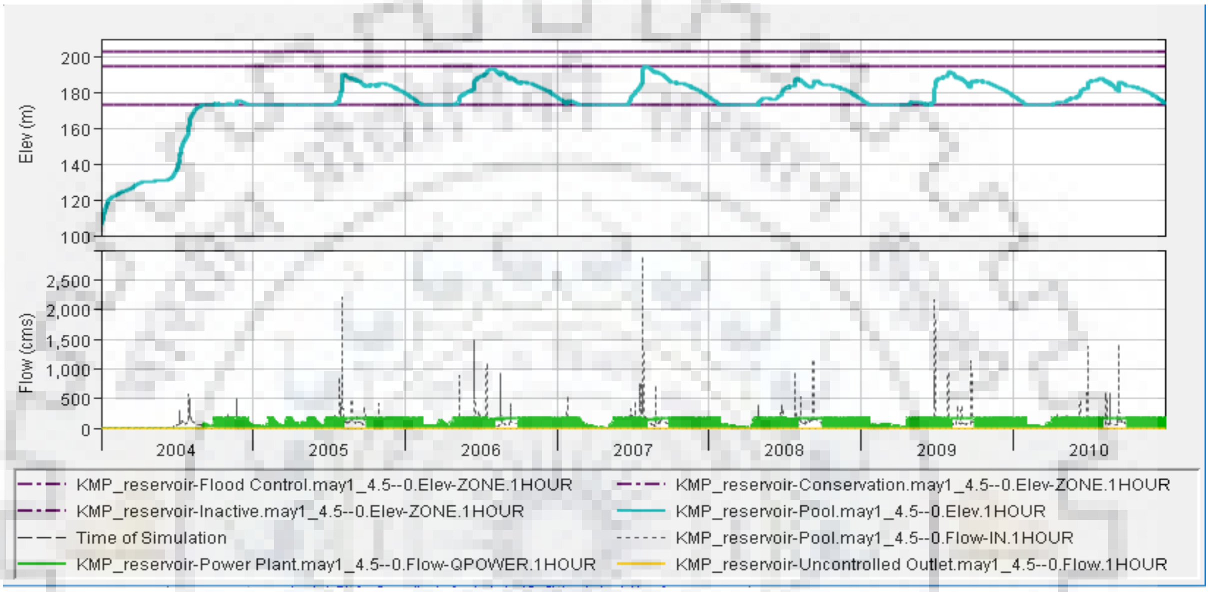

Figure 6.44 Reservoir elevation and flow curves for RCP 4.5 (2064-2070)

6.5.5.2. Simulation for future Climate RCP 8.5

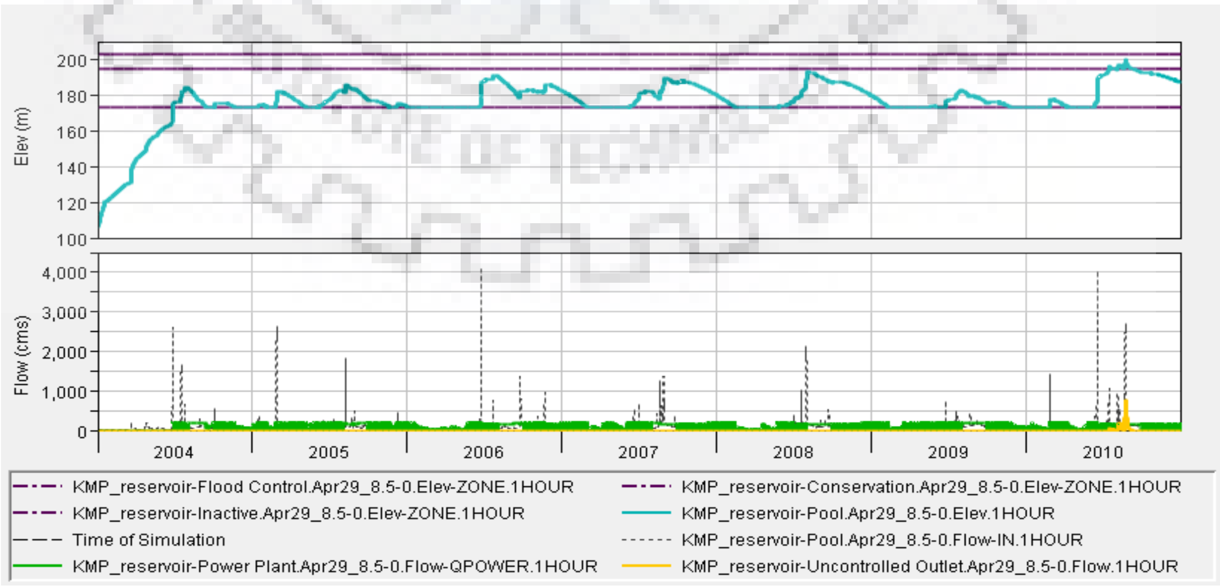

Figure 6.45 Reservoir elevation and flow curves for RCP 8.5 (2064-2070)

6.5.5.3. Simulation for base SWAT simulated flow

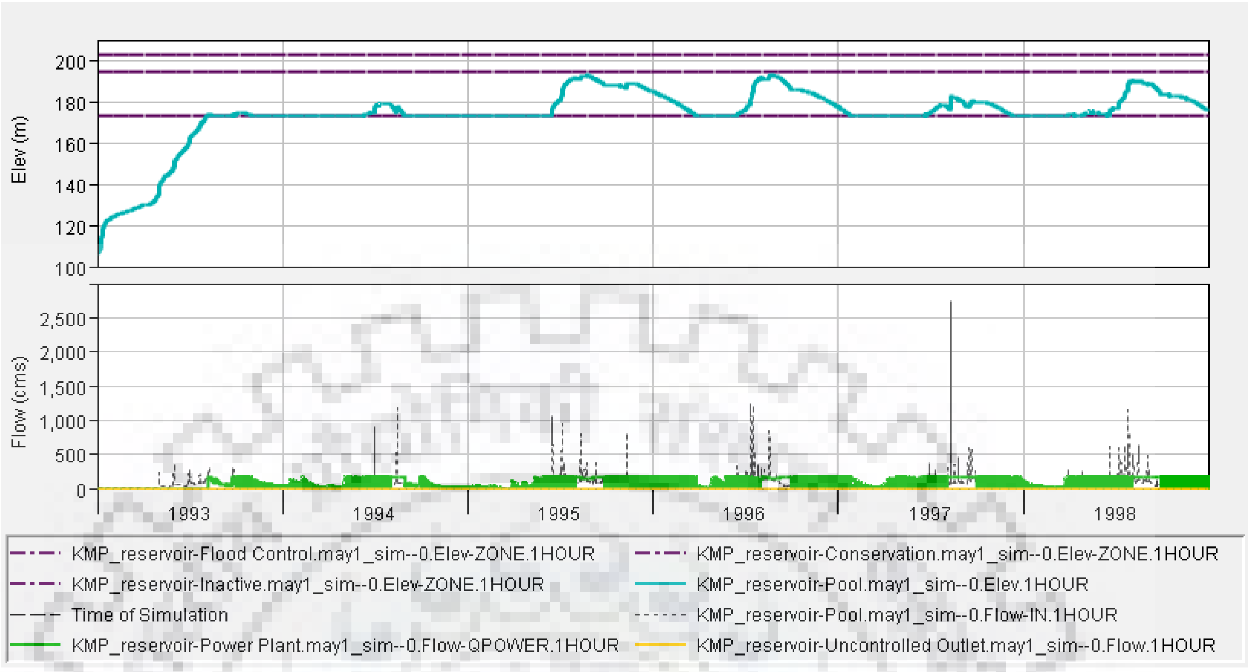

Figure 6.46 Reservoir elevation and flow curves for SWAT simulated flow (1993-1998)

6.5.5.4. Summary for the Climate Impacts in Reservoir Simulation (S15-S17)

The summary of the climate impacts in the reservoir simulation has been presented in along with the comparison with the historical simulation result and SWAT simulate flow results in Table 6.21 and incremental analysis in Table 6.22. The same has been graphically presented in Figure 6.47

Table 6.21 Impact of climate change in reservoir simulation

Parameters	unit	Historical	Simulated	RCP 4.5	RCP 8.5
Energy Generated	GWhr	302.90	199.47	226.93	243.14
Energy violation (in terms of hour)	%	11.87	24.93	18.76	22.46
Energy violation (in terms of energy)	%	7.82	34.76	36.02	21.93
Uncontrolled spill	Average	15.77	0.00	0.00	1.85

Table 6.22 Incremental analysis table

incremental effect on	RCP 4.5		RCP 8.5		remarks
	w.r.t observed	w.r.t simulated	w.r.t observed	w.r.t simulated	
Energy Generated	(25.08)	13.77	(19.73)	21.89	% increase
Uncontrolled spill	(100.00)	-	(88.25)	-	% increase

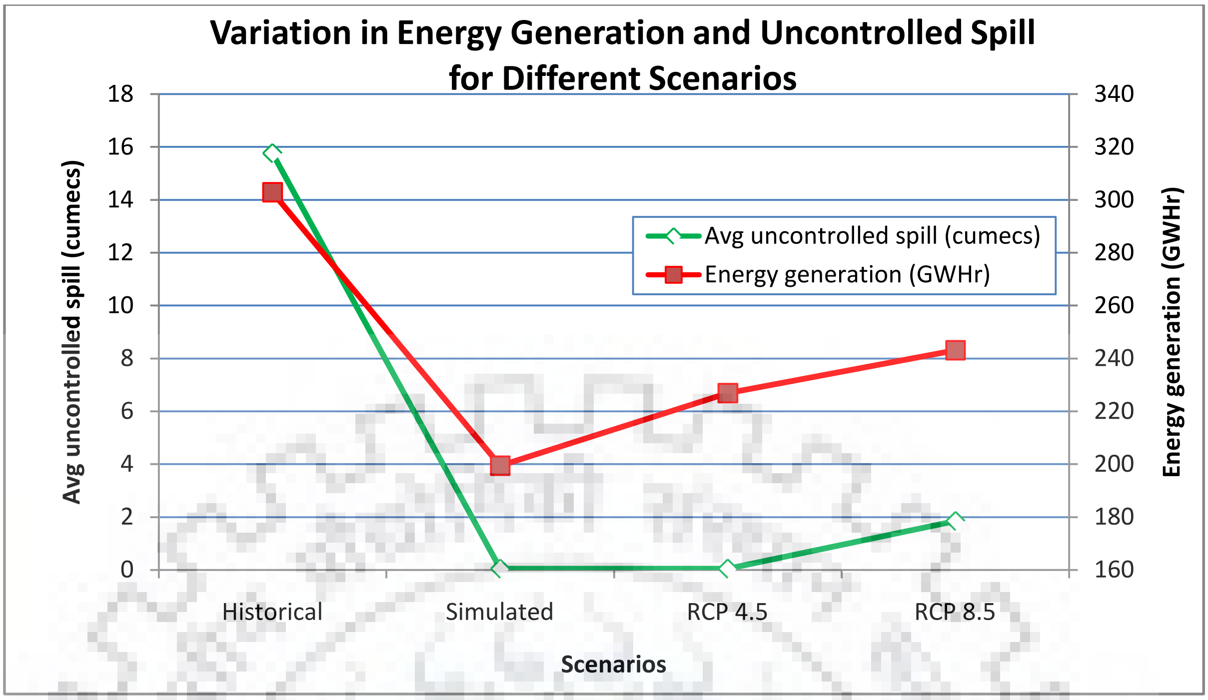

Figure 6.47 Uncontrolled spill and energy generation for different scenarios under climate change

From the tables and graphs, it is evident that it is wise to compare the impact of climate change with the SWAT simulated flow rather than the historical flow used for the initial simulation.

Comparing the results of simulation of the future flow with the SWAT simulated flow; it can be observed that

- the energy generation is expected to increase in both RCP 4.5 scenario and RCP 8.5, highest being for RCP 8.5.
- On the contrary, the energy violation is showing some strange pattern, as violation in terms of hour, highest violation is for the simulated historical flow, whereas lowest is for RCP 4.5. For the violation in terms of energy, highest violation is for RCP 4.5 whereas lowest is for RCP 8.5
- Uncontrolled spill is nil for simulated historical flow as well as RCP 4.5 but it is observed for RCP 8.5.

6.6. Summary

Reservoir simulation has been carried out for the historical data as well as the future predicted flow data. 14 different simulation scenarios have been formulated to examine the reservoir simulation outputs using the historical flow and 3 different simulation scenarios have been formulated to examine the reservoir simulation outputs using future/ flows.

Considering the historical flow time series data of duration 8 years of period 2004-2011, after provision of environmental release of 1 cumec and fulfilling the irrigation water demand, it has been observed that the installed capacity of the power plant should be fixed at 90 MW. The annual energy generation calculated is 309.6 GWHr with the average annual uncontrolled spill of 15.6 cumec and 30 MW of energy generation at 75% excedence.

Regarding the reservoir simulation under the changing climate, the RCP 4.5 flow and RCP 8.5 flows are taken into consideration for the mid century (2064-2070). Since the future flows were more comparable to SWAT simulated flow rather than the observed historical flow, the reservoir simulation has been carried out for the simulated historical flow for the purpose of comparing the output of future flows. In this regard 3 scenarios were formulated, the base case considered was 90 MW installed capacity. The impact of climate change has been presented by comparing the future flow output with the simulated flow instead of the observed historical flow. The impact in reservoir operation in terms of uncontrolled spill and energy generation is expected to increase for both RCP 4.5 and RCP 8.5, highest being for RCP 8.5. The energy generated is expected to increase by 13.8% and 28.9% for RCP 4.5 and RCP 8.5 respectively. The uncontrolled spill showed no definite pattern of change.

CHAPTER SEVEN
CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

From the study, following conclusions are drawn,

1. The monthly, seasonal and annual trend were analyzed for temperature, precipitation and stream flow using monthly mean values. In some of the stations, it has been observed that the annual maximum mean temperature is in the rising trend whereas the annual minimum mean temperature is in falling trend.
2. The trend in precipitation is not very much significant in most of the stations except for one station wherein mostly falling trend is observed.
3. The result shows that even thought there is not significant change in precipitation, there has been observed overall rising trend of flow especially in the monsoon, which might have resulted due to the change in the land use pattern.
4. For the calibration using SWAT model, NS efficiency and the coefficient of determination for the calibration period is 0.6 and 0.70 respectively whereas for validation period, it is 0.69 and 0.70 respectively. The model had performed somewhat better for the validation period in comparison to the calibration period.
5. Although the value of the objective functions chosen for simulating the flow, Nash Sutcliff Efficiency and coefficient of determination indicates that the performance of the model is satisfactory, however, for some time, the model has either underestimated or overestimated the flows. This might be attributed to the four sources of uncertainties viz. uncertainties in input, model structure, model parameters and output associated with the modeling exercise. It may be noted that the modeler may be able to reduce the uncertainties in the only the model parameters through calibration whereas other sources of uncertainties would be inherent during the modeling. Sometimes it leads to the erroneous results of model simulations if there are larger uncertainties prevailing at the time of modeling.
6. The future climate data for temperature and precipitation extracted for the mid century 2061-2070 for RCP 4.5 and RCP 8.5 scenarios from CNRM-CM5 model after bias correction was used for generating the future flows employing the pre-calibrated SWAT model. The bias corrected future flow showed the agreement with the calibrated historical flow rather than the observed historical flow. The reason behind

this is the SWAT model performance. Same errors had carried over while generating the flow for future scenarios.

7. Considering the historical flow time series data of duration 8 years, after provision of environmental release of 1 cumec and fulfilling the irrigation water demand, it has been observed that the installed capacity of the power plant should be fixed at 90 MW. The annual energy generation is 309.6 GWHr with the average annual uncontrolled spill of 15.6 cumec and 30 MW of energy generation at 75% exceedence.
8. The simulated flow did not correspond much to the observed flow during hydrological modeling, the same error was carried over in the Future flows (RCP 4.5 and RCP 8.5). Because of this impact of climate change has been presented by comparing the future flow output with the simulated flow instead of the observed historical flow. The impact in reservoir operation in terms of uncontrolled spill and energy generation is expected to increase for both RCP 4.5 and RCP 8.5, highest being for RCP 8.5. The energy generated is expected to increase by 13.8% and 28.9% for RCP 4.5 and RCP 8.5 respectively. The uncontrolled spill showed no definite pattern of change.

7.2. Limitations of the study

1. Due to non-availability of Long-term daily data for maximum & minimum temperature and precipitation, the calibration and validation for SWAT model have been carried out using the available short period data.
2. The global soil map used for SWAT simulation might have resulted in the errors in the model output as it is very sensitive to the soil data.
3. Spill energy has not been accounted for separately in reservoir simulation.

7.3. Recommendations

1. Use of site specific local soil database for SWAT modeling is recommended.
2. Revisit of the irrigation command area and irrigation water demand is recommended.
3. As the output delivered by the HEC Res Sim has is mostly governed by the reservoir inflows; it is a recommended to have the simulation done with considerably long term flows.

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