TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

THESIS NO: 075/MSHPE/017

Adaptation Against Climate Change Impacts on Hydropower Generation and Irrigation Supply of Naumure Multipurpose Project, Nepal

by

Sampanna K.C.

A THESIS

SUBMITTED TO THE DEPARTMENT OF CIVIL ENGINEERING IN

PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE IN

HYDROPOWER ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

LALITPUR, NEPAL

APRIL, 2023

COPYRIGHT

TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

DEPARTMENT OF CIVIL ENGINEERING

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled **"Adaptation Against Climate Change Impacts on Hydropower Generation and Irrigation Supply of Naumure Multipurpose Project, Nepal"** submitted by Sampanna K.C. in partial fulfillment of the requirements for the degree of Master of Science in Hydropower Engineering.

____

Supervisor, Dr. Ram Krishna Regmi

Assistant Professor, Deputy HOD

Department of Civil Engineering

____

External Examiner, Dr. K.N. Dulal

Senior Expert, Hydrology and Climate

____

Program Coordinator, Dr. Mukesh Raj Kafle

M. Sc. Hydropower Engineering

Department of Civil Engineering

Date of Submission: April, 2023

ABSTRACT

Hydropower serves as a dependable and eco-friendly alternative to fossil fuels and a carbon-emission-free energy source has a crucial role in addressing climate change, yet the impacts of climate change on the hydropower project itself cannot be avoided. This study focuses on the impacts of climate change on hydrological variables (precipitation and temperature) and its implications for hydropower generation and irrigation supply in the Naumure Multipurpose Project, and the development of an adaptation strategy accounting for climate change impacts.

Six different Coupled Model Intercomparison Project, Phase 6 (CMIP6) Global Climate Models (GCMs) were downscaled, bias-corrected using a linear scaling method, and then projected for three different periods of future i.e., Near of Future (NF) period of 2015-2040 AD, Mid of Future (MF) period of 2041-2070 AD and Far of Future (FF) period of 2071-2100 AD under two different Shared Socio-economic Pathways (SSPs) scenarios i.e., SSP245 and SSP585 scenario. Projections indicate that there will be a noteworthy rise in both the maximum and minimum temperatures up to 3.67 °C and 4.97 °C respectively across various periods in the future under both scenarios. Similarly, precipitation was projected to increase between 13.95% to 90.16% at different points in the future annually however, seasonally precipitation tends to decrease in post-monsoon season and increases in pre-monsoon and monsoon seasons while winter season has no specific trend.

Hydrological model was used to project future discharge and reservoir model was used to simulate baseline and future energy generation. Flow projection reveals except in winter season of NF future under scenario SSP245 where flow decreases by up to 23%, in all other seasons, flow was projected to increase in all future periods. Hydropower generation was projected to increase up to 18% in futures, except for winter season where generation decrease by up to 5.8% while irrigation supply is projected to meet demand in all future under both scenarios.

This slight decrease in energy generation during winter season suggests the need to adjust the rule curve to maximize winter energy generation while ensuring overall energy generation and irrigation supply. Eight modified rule curves were developed and simulated, showing potential for increased winter energy generation. This study highlights the need for adaptive measures to mitigate the impact of climate change on hydropower generation and irrigation supply in the future.

Keywords: Climate change, Hydropower, Adaptation, CMIP6, SWAT, HEC-ResSim, Naumure Multipurpose Project

ACKNOWLEDGEMENTS

First of all, I am sincerely grateful to the Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, for granting me the opportunity to conduct this research work. I would like to express my sincere gratitude to my respected supervisor, **Dr. Ram Krishna Regmi** Sir for his unwavering guidance, invaluable supervision, insightful suggestions, and instructive instructions throughout this research period.

I am deeply grateful to my dear friend, **Er. Rupesh Baniya**, for his constant support and invaluable help throughout the entire duration of this thesis period. Your kindness and assistance have been instrumental in the completion of this research work. I must express special thanks to my friend **Er. Manoj Bista** for his continuous support, help, and motivation throughout this research work. Nevertheless, I am always indebted to my 075 MSHPE friends who directly or indirectly helped in my research work.

I would like to thank all the faculty members of the Master of Science in Hydropower Engineering Program, especially Program Coordinator **Asst. Prof. Dr. Mukesh Raj Kafle** Sir, for continuous support and assistance during the course of this research work.

I would also like to thank Department of Hydrology and Meteorology (DHM), Nepal and the clients of the Naumure Multipurpose Project for providing valuable dataset required for this research work.

Finally, I would like to express my heartfelt gratitude to my parents for their never-ending love, trust, and support throughout my research period.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
BC	Bias Correction
CEIWR-HEC	U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center
CFRD	Concrete Face Rockfill Dam
CMIP	Coupled Model Intercomparison Project
CMIP5	Phase 5 of the Coupled Model Intercomparison Project
CMIP6	Phase 6 of the Coupled Model Intercomparison Project
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
F.S.L.	Full Supply Level
FF	Far of Future
GCM	General Circulation Model
GIS	Geographic Information System
GIS	Geographic Information System
GON	Government of Nepal
ha	hectare
H-A-V	Height-Area-Volume
HEC-ResSim	Hydrologic Engineering Center-Reservoir Simulation
HRUs	Hydrologic Response Units
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
IPCC	Intergovernmental Panel on Climate Change
LS	Linear Scaling
LULC	Land Use and Land Cover
m	meter
masl	mean average sea level
MCM	Million Cubic Meter
MF	Mid of Future
MOL	Minimum Operating Water Level
MOS	Model Output Statistics

MW	Mega Watt
NEA	Nepal Electricity Authority
NEA	Nepal Electricity Authority
NF	Near of Future
NSE	Nash–Sutcliffe efficiency
QM	Quantile Mapping
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
ScenarioMIP	Scenario Model Intercomparison Project
SOTER	Soil and Terrain
SSPs	Shared Socio-economic Pathways
SWAT	Soil and Water Assessment Tool
USGS	United States Geological Survey
WCRP	World Climate Research Program
WORP	World Organization Research Program

CHAPTER 1: INTRODUCTION

1.1 Background

It's no secret that climate change is the hot issue and most discussed topic in modern world since its impact to the physical environment, biosphere, human life is immense and threatening. In the hydrologic system, it has notable impacts, affecting water availability, storage and runoffs in the rivers. The other effect of climate change can be felt as rise in global temperature, causing tremendous impact on global water cycles and precipitation patterns (Shrestha et al., 2016). These impacts cause important changes in the management of water, particularly on uses highly dependent on the hydrological regime, such as hydropower production (Ray & Brown, 2015).

Hydropower, being clean and reliable source of energy, is boon to both present and future world since it acts as alternative energy source against limited fossil energy in which present world is mostly depend on and being carbon emission free energy source, also contribute in climate change mitigation. Despite this, its generation is influenced by climate change as pointed out earlier. Thus, the climate change impacts on hydro-related projects should be assessed and suitable adaptation measures should be addressed to negate the probable future climate change impacts and to ensure longevity and sustainability of such hydro-related projects. In our country, existing hydropower projects like Kulekhani hydropower project been facing numerous challenges like overall performance declination, sedimentation yield problem, decrease in water availability due to climate change during its life cycle. This suggest only miniscule of studies and researches have been carried out on climate change impact assessment on hydropower projects in our country that have high potential of hydro-generation. Hence, climate change serves as a significant stressor that disrupts river hydrology and, in turn, impacts hydro power projects. Its far-reaching effects on the hydrological system underscore the need for proactive measures in managing and adapting to these changes in the context of hydropower development (Shrestha et al., 2021).

Nepal, a landlocked country nestled between India and China, boasts a remarkable elevation range of 8848 m to 58 m above mean average sea level (masl) within a narrow width of 193 km from North to South. Whole northern side of country lies in heart of great Himalayan range which is covered in snow throughout the year, has been a perennial source for numerous rivers in Nepal. Also, having numerous numbers of major rivers and their tributaries with very steep gradient, hydropower can be a boom to Nepal's economic development. However, the hydropower projects in Nepal are conceived taking into consideration only the short-term hydro-meteorological data, overlooking the potential impact of climate change on future power generation and plant operation (Shrestha et al., 2014).

Climate change studies typically for water-related projects uses global circulations models (GCM) to predict future climate and their responses. GCMs are powerful computer programs which employs complex physical processes to simulate the global climate system as closely as possible. GCMs use mathematical and analytical equations to simulate the global climate system's operation in both spatial and temporal dimensions. GCMs simulations generates scenarios of future changes in temperature and precipitation and related hydrologic variables such as snowpack, evaporation, or streamflow (Hamlet et al., 2010). The limitations of General Circulation Models (GCMs), which provide insights into global-scale climate patterns, become apparent when applied to local impact studies due to their coarse spatial resolution (usually around 50,000 km^2) and inability to capture crucial sub-grid scale features such as clouds and topography (Wilby et al., 2002). So, downscaling of GCMs to local or basin level with bias correction is necessary. Approaches for downscaling GCM simulations can be broadly classified as "statistical" and "dynamical" downscaling techniques. Statistical downscaling methods rely on robust correlations between large-scale parameters, which are accurately captured by global models, and observations at smaller spatial scales. These approaches leverage statistical relationships to bridge the gap between global-scale climate projections and localized impacts, providing valuable insights into local climate dynamics and their potential effects (Ray & Brown, 2015). Dynamic downscaling techniques utilizes Regional Climate Models (RCMs) with fine grid spacing (10-50 km), enabling explicit simulation of intricate meteorological processes and feedback mechanisms (Harrison, 2001).

As stated earlier, GCMs are useful for portraying climate patterns on a global to continental scale, but when it comes to analyzing climate impacts at the regional level, their usefulness is limited. However, regional scale information is crucial to develop adaptation measures and protect socio-economic structures and ecosystems (Kreienkamp et al., 2020). World Organization Research Program (WORP) initiated a Coupled Model Intercomparison Project (CMIP) in 1995, is a representative climate model project whose results are used in IPCC assessment reports (Ohba, 2021). The aim of the Coupled Model Intercomparison Project (CMIP) is to gain deeper insights into the historical, current, and future climate changes resulting from natural variability, unforced factors, or responses to alterations in radiative forcing, all within a multi-model framework (WCRP, 2022). The latest coupled model intercomparison project is CMIP6 which provides simulations from a new generation of climate models and is based on a new set of scenarios on different socio-economic assumptions and is better version than previous CMIP5 which uses only different scenarios of Representative Concentration Pathways (RCPs), not taking socio-economic consideration into account (Kreienkamp et al., 2020).

Main goal of adaptation is to know what to do now rather what to do in future after being victimized. It deals with making plans and robust decision for future after looking climate impact risk assessments. In case of storage projects, climate change adaptation strategy focuses on adjustments on annual reservoir operations managements (Minville et al., 2009). Modern research shows that the reservoir simulation model is the best adaptation strategy to mitigate the climate change in hydropower section. Generally, new operation policies or operating rules curves are generated which form basis for future operations of reservoir through reservoir simulations models using outputs of climate impact assessment.

1.2 Statement of Problem

Regarding the current climate change issues like global warming, natural event like hydrological cycle is the most influenced one. Fluctuations in river flows, shift in seasonal weather pattern, untimely extreme hydro-meteorological events being common nowadays; thinking on future, hydrology will definitely be influenced and might get worse. As we all know, most important parameter for hydroelectricity generation are head and discharge. Discharge being sole product of hydrology, the hydropower performance in the future might not go as expected and planned in the near future due to climate change. So, climate change impact assessment covering the whole project life period should be carried out for hydro-related projects. Chances of the project being affected by climate change impact will be always maximum. So, mitigation measures from the beginning can be illustrated and for future, adaptation measures can be developed which could maintain hydropower performance and generation efficiency at its maximum.

1.3 Rationale of the Study

The warming of our planet is undeniable and occurring at an accelerated pace. However, the uncertainties lie in the profound impacts that this warming will have on the complex interplay of climatological and hydrological processes that influence hydropower performance. In today's rapidly changing world, it is imperative to conduct comprehensive climate impact assessments and implement effective adaptation solutions for both existing and proposed hydro-related projects, ensuring their operation, efficiency and resilience in the face of climate challenges.

To address the solution for solving above problem related to the performance of the hydropower in the changing global climate, this research study focuses on assessment of climate change impact on Naumure Multipurpose Project and development of adapting capabilities and solutions against expected future hydro-meteorological changes brought by climate change in future.

1.4 Research Questions

This study tries to seek solution to the following questions.

- What would be the level of impact of climate change on climatic variables (precipitation and temperature)?
- What would be the future hydrology of the basin under impacts of climate change?
- How would be the hydropower energy generation and irrigation supply in the future?
- What could be done to adapt against the impact of changing climate in the future?

1.5 Objectives

The objectives of the study are:

- To project and assess the future climate change trend.
- To assess the projected changes on a stream discharge.
- To quantify the future energy generation under changing climate.
- To formulate and evaluate the adaptation options to minimize impacts of climate change on hydropower generation and irrigation schemes.

1.6 Scope of the Study

The major scopes of this study are listed below:

- Study and review all available literatures.
- Collection of different required data from various sources.
- Catchment area delineation using ArcGIS 10.5.
- Clipping climatic variables from CMIP6 GCMs database to basin/station level.
- Bias correction of GCMs outputs to project climatic variables.
- SWAT model development, calibration and validation using historical baseline data.
- Future flow prediction in SWAT using projected climatic variables.
- Height Area Volume (H-A-V) curve generation of related storage project using ArcGIS version 10.5.
- HEC-ResSim model development for reservoir simulations using reservoir operation data.
- Current and future energy generation trend in HEC-ResSim using baseline and future flow data.
- Adjustment and simulations of rule curve in HEC-ResSim to generate modified rule curve which act as an adaptation measure against changing climate in future.

1.7 Limitations

The limitations of this study are:

- Data from secondary sources will be trusted and used for study.
- Only few CMIP6-GCM model will be selected from large pools of GCM model for climate modelling.

1.8 Organization of Thesis

The organization of the thesis constitute major six different chapters:

- Chapter 1 include general introduction along with general background, statement of problem, objectives of study, research questions, scopes and limitations.
- Chapter 2 elaborates the various literature reviewed and studied during the course of this study.

- Chapter 3 includes the selection and description of study area, and collection and preparation of data used for this study.
- Chapter 4 illustrates the framework of methodology adopted for this study.
- Chapter 5 presents findings and discussions of various results of this study.
- Chapter 6 concludes the findings of this study and recommendations for further study.

At the beginning of this thesis, copyright, approval page, abstract, acknowledgement, table of content, list of figures, list of acronyms and abbreviations are present whereas, toward the end of this thesis, references and appendices are attached.

CHAPTER 2: LITERATURE REVIEW

Climate change is a phenomenon characterized by a statistically significant variation in the average or extremes of climatic conditions over a prolonged period, often lasting several decades or more. The changes in climatic properties such as temperature, precipitation, and wind patterns are indicators of such a change in the climate system, and they can be detected using various statistical techniques. Recent reports have indicated that climate change may be attributed to both internal processes and external forcing factors. Natural external influences like solar radiation variations and volcanisms also contribute to the overall natural variability of the climate system. However, human activity has also played a significant role in altering the atmosphere's composition, starting with the industrial revolution, adding to the external changes that impact our climate (Solomon et al., 2007).

The intricate interplay of various factors, including alterations in greenhouse gas and aerosol levels, fluctuations in solar radiation, and changes in land surface properties, all contribute to the energy balance of the climate system. These influences are quantified in terms of radiative forcing, which allows for comparisons of the warming or cooling effects driven by a diverse range of human and natural factors on the global climate (Solomon et al., 2007). Carbon dioxide, a greenhouse gas, is widely recognized as the primary driver of anthropogenic climate change. It plays a central role in trapping heat in the Earth's atmosphere, contributing to the warming of the planet. In recent times, the global atmospheric concentration of carbon dioxide has surged significantly, surpassing the natural range of 180 ppm to 300 ppm observed over the past 650,000 years determined from analysis of ice cores which are embedded deep inside ice bergs or glaciers thousands and thousands of years ago. From a pre-industrial value of around 280 ppm, the atmospheric concentration of carbon dioxide has surged to 379 ppm in 2005 AD. Furthermore, the annual growth rate of carbon dioxide concentration has accelerated in the last decade, averaging 1.9 ppm per year from 1995 to 2005 AD, surpassing the average growth rate of 1.4 ppm per year recorded from 1960 to 2005 AD, despite year-to-year variability in growth rates (Solomon et al., 2007).

These findings highlight the unprecedented changes in carbon dioxide levels, underscoring the impact of human activities on the composition of Earth's atmosphere and provide compelling evidence that human actions are responsible for the ongoing climate change phenomenon (Solomon et al., 2007).

2.1 Climate Models and Future Climate Projections

For hydro-related projects, climate change assessment studies typically uses GCMs to predict future climate and their responses. GCMs are powerful computer programs which simulate global climate change system by taking complex physical and biogeochemical processes into account. They use complex mathematical and analytical equations to simulate the global climate system's operation in both spatial and temporal dimensions.

Climate models, such as General Circulation Models (GCMs), are helpful in understanding the impacts of rising greenhouse gases on global as well as regional climate. However, they have limitations in providing local impact studies due to their coarse spatial resolution and inability to capture important local-scale features like topography and clouds. To overcome this, statistical downscaling and Regional Climate Models (RCMs) have emerged as two techniques to derive local-scale weather from regional-scale or global-scale atmospheric variables bounded within prescribed domains (Wilby et al., 2002). The first approach statistical downscaling, which draws parallels with techniques like "model output statistics" (MOS) and "perfect prog" used in short-range weather prediction. The second approach involves Regional Climate Models (RCMs) that dynamically simulate climate features at sub-GCM grid scales, utilizing time-varying atmospheric conditions from a parent GCM within a specified domain. Both approaches will continue to play a significant role in the assessment of potential climate change impacts arising from future increases in greenhouse gas concentrations (Wilby et al., 2002).

There are a lot and lots of GCM models in the world. Each model is unique in itself and could generate unique result. So, Chance of one GCM having different results than other GCMs is very high but they all foresee the future climate change in general. Selection of suitable GCMs is a challenging task in itself. Three approaches: extreme, ensemble and validation approach can be used to select future climate projections for related study and planning works from the IPCC GCMs pool (Fenech et al., 2002). The World Climate Research Program (WCRP) established CMIP, which is an international effort to improve climate models by comparing multiple model simulations to observations and to each other. These kinds of comparisons help our understanding of historic, present and future climate changes which helps to enhance our understanding of the climate system and drive improvements in climate modeling. CMIP has coordinated five past large model intercomparison projects CMIP phase1 to CMIP phase5. The latest Coupled Model Intercomparison Project is CMIP6 which provides simulations from a new generation of climate models and is based on a new set of scenarios on different socio-economic assumptions (Eyring et al., 2016). These scenarios are called Shared Socio-economic Pathways (SSPs). Based on those assumptions, SSPs generate different socio-economic scenarios and radiative forcing pathways till 2100 AD.

The Scenario Model Intercomparison Project (ScenarioMIP) is a pioneering effort within phase 6 of CMIP (CMIP6) that uses integrated assessment models aiming to generate multi-model climate projections through the integration of alternative scenarios of future emissions and land use changes (O'Neill et al., 2016). The following Figure 2.1 illustrates the Shared Socio-economic Pathways (SSPs) and year 2100 radiative forcing combinations used in ScenarioMIP along with corresponding RCPs level (O'Neill et al., 2016).

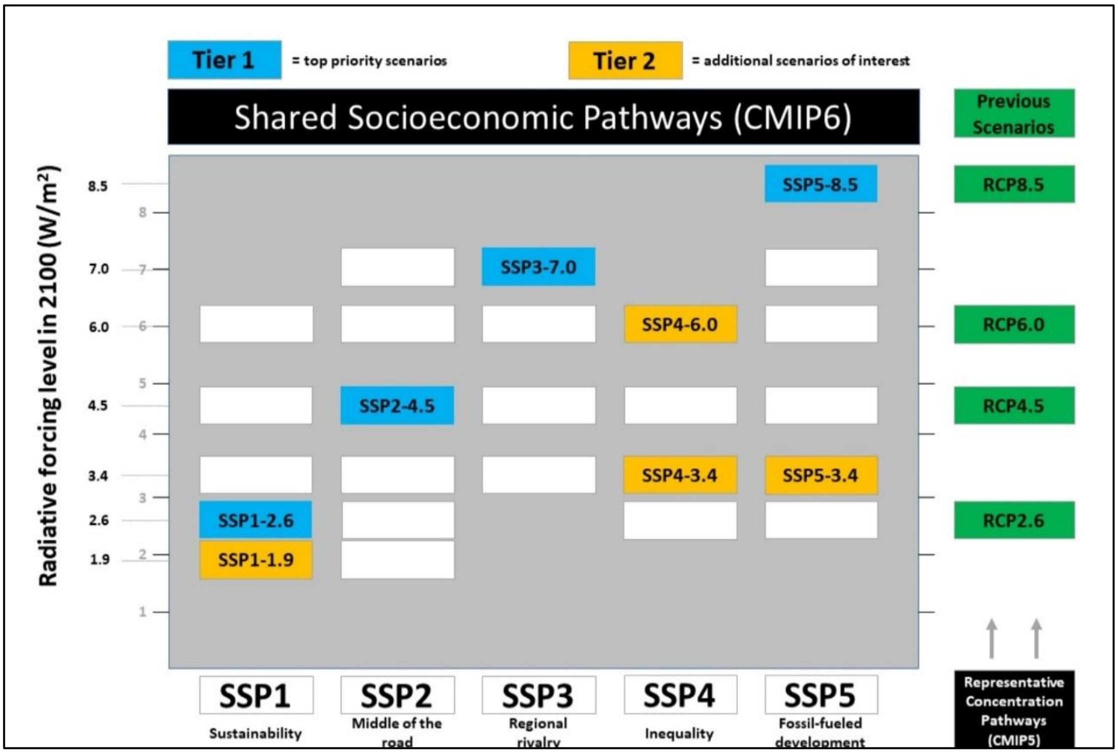


Figure 2.1: SSPs and Radiative Forcing Combinations used in ScenarioMIP

The different SSPs descriptions are described below (Cook et al., 2020):

- SSP1-2.6: Low forcing sustainability pathways (+2.6 W/m^2 imbalance)
- SSP2-4.5: Medium forcing middle of the road pathways (+4.5 W/m^2 imbalance)

- SSP3-7.0: Medium to High end forcing pathways (+7.0 W/m^2 imbalance)
- SSP5-8.5: High end forcing pathways (+8.5 W/m^2 imbalance)

As already mentioned, GCM models has implications for climate at global scales and are restricted in their usefulness for local/basin level impact studies, the bias-correction technique tries to use correction factor to correct time series variables of the model with observed variables as closely as possible. Most used and applied bias correction technique to correct GCM model biases on a daily basis are Linear Scaling (LS) and Quantile Mapping (QM). Here, it is aimed to applied Linear Scaling bias correction method due to its simplicity in application with accuracy almost equal to the complex and tedious methods (Shrestha et al., 2017). In this method, correction factors (multiplicative for precipitation whereas additive for temperature) are obtained from observed and simulated data which are then applied to obtain the corrected climate data. The following equations were used for linear scaling method (Teutschbein & Seibert, 2012; Shrestha et al., 2021):

$$P_{his}(d)^* = P_{his}(d) * [\mu_m\{P_{obs}(d)\}/\mu_m\{P_{his}(d)\}] \quad 2.1$$

$$P_{sim}(d)^* = P_{sim}(d) * [\mu_m\{P_{obs}(d)\}/\mu_m\{P_{his}(d)\}] \quad 2.2$$

$$T_{his}(d)^* = T_{his}(d) + [\mu_m\{T_{obs}(d)\} - \mu_m\{T_{his}(d)\}] \quad 2.3$$

$$T_{sim}(d)^* = T_{sim}(d) + [\mu_m\{T_{obs}(d)\} - \mu_m\{T_{his}(d)\}] \quad 2.4$$

Where, 'P' is the precipitation, 'T' is Temperature, 'd' stands for daily, 'μ_m' specifies the long-term monthly mean, an asterisk (*) indicates bias corrected value, 'his' refers to historical raw CMIP6 data, 'obs' stands for observed data and 'sim' is the raw CMIP6 future data for equation 2.1 to equation 2.4.

2.2 SWAT Hydrological Model

The Soil and Water Assessment Tool (SWAT) is an innovative, watershed-scale simulation model developed by the USDA Agricultural Research Service. It was initially introduced in the 1990s, is a powerful tool for assessing and predicting the impact of land use, land management, and climate change on the quality and quantity of surface and groundwater in small watersheds to river basins. At the heart of the SWAT model lies the water balance, which governs various processes such as plant growth, sediment transport, nutrient and pesticide movement, and pathogen fate. The model divides the study area into sub-basins and further into hydrologic response units

(HRUs) based on land use, management, and soils, and estimates runoff for each HRU separately before summing up to obtain the total runoff for the entire basin. One of the strengths of SWAT is its versatility, as it can be used with multiple GIS platforms such as ArcGIS, Map-windows (MWSWAT), or QGIS (QSWAT). Furthermore, SWAT can be integrated with MODFLOW, a groundwater modeling software, for comprehensive hydrologic and groundwater assessments. This makes SWAT a widely used tool in various fields, including hydrologic research, climate change studies, and water quality assessments related to nutrients, pesticides, and bacteria (Primer, 2020).

It is a physically based, deterministic, and continuous model that has undergone extensive evolution over a 30-year period, incorporating diverse individual models. SWAT has been rigorously tested across various regions, conditions, practices, and time scales, showcasing its versatility and robustness. Assessment of daily, monthly, and annual streamflow and pollutant outputs revealed that the SWAT model demonstrated exceptional performance across diverse watersheds, showcasing its versatility and reliability (Gassman et al., 2007). The water balance equation for the hydrological simulation in SWAT is shown below (Shrestha et al., 2021).

$$SW_t = SW_o + \sum_{i=1}^{t} \left(\mathrm{R}_{day} - \mathrm{Q}_{surf} - \mathrm{E}_a - \mathrm{W}_{seep-}\mathrm{Q}_{gw} \right) \qquad 2.5$$

Where, SW_t denotes the soil water content at the end of time step t (mm), SW_o denotes the initial soil water content in day i (mm), R_{day} denotes the amount of rainfall on day i (mm), Q_{surf} refers to the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm) and Q_{gw} is the amount of base flow from the shallow aquifer on day i (mm).

SWAT operates continuously, on a daily time step, and is designed to predict the impacts of management practices on hydrology, sediment, and water quality on an ungauged watershed (Ray & Brown, 2015). This tool encompasses a diverse array of components, including climatic inputs, sediment transport, crop growth and yield, hydrological cycling, representation of management practices, erosion processes, and pollutant (nutrient, pesticide, and pathogen) cycling and transport. The model is typically operated at a daily time step, although options for sub-daily time steps are also available, allowing for flexibility in application and analysis (Tan et al., 2020). The integration with geographic information systems (GIS) was pioneered by Srinivasan and Arnold in 1994 AD. This tool is a versatile model that operates at small watershed to river basin-scale, simulating surface and ground water quantity and quality, and predicting the environmental impact of land use, management practices, and climate change. The application of this technique is pervasive in evaluating and managing soil erosion mitigation, controlling non-point-source pollution, and overseeing and managing regional watershed sustainably. SWAT is known for its high-quality user interface and user-friendly nature, making it accessible to a wide range of users (Ray & Brown, 2015).

2.3 Reservoir Simulation in HEC-ResSim

The Hydrologic Engineering Center-Reservoir System Simulation (HEC-ResSim) software, developed by the U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center (CEIWR-HEC), is a valuable tool for modeling reservoir operations with the aim of achieving specific operational goals and adhering to constraints (Klipsch et al., 2021). It was designed to aid engineers and planners in conducting water resources studies, providing insights into reservoir behavior and supporting reservoir operators in making real-time release decisions during routine and emergency operations (Klipsch & Evans, 2010).

The model emulates the decision-making process that reservoir operators utilize to meet diverse operating criteria for hydro energy generation, flood management, and environmental releases, by employing a unique rule-based methodology. This approach enables the model to closely replicate the actual decision-making process employed by reservoir operators, making it an effective tool for simulating a range of operational scenarios (Seyoum & Theobald, 2014). It uses a unique rule-based logic system to represent reservoir operating goals and constraints, designed specifically to emulate the decision-making process of reservoir operations (Klipsch & Evans, 2010). So, having high flexibility and greater ability to model reservoir systems for variety of operational goals and constraints, HEC-ResSim model is chosen for reservoir simulation works.

HEC-ResSim model includes three modules namely watershed module, reservoir network module, and simulation module to create watershed configurations, connect project components and add data for analysis, and simulate results for viewing and analysis respectively (Klipsch et al., 2021).

2.4 Adaptation Strategies

Climate change has inevitable impact on hydropower and irrigation projects since climate change in future alter river discharge and affects water storage and availability for sure. So, Adaptation against climate change is main focus of this study which deals with making plans, robust decision and developing strategies for future against climate impact risks. In case of storage projects, climate change adaptation strategy focuses on adjustments on annual reservoir operations managements (Minville et al., 2009). In most of the study, they indicate that utilizing reservoir simulation models as an adaptation strategy holds significant promise in effectively mitigating the impacts of climate change on the water related sector. In general, new operation policies or operating rules curves are generated which form basis for future operations of reservoir through reservoir simulations models using outputs of climate impact assessment.

Reservoir operation rules provide a framework for addressing problems about how storage should be managed, specifically how much water should be released at the next time step given a certain reservoir status (Klipsch et al., 2021). The operational decisions concerning the release of water from reservoirs, which play a crucial role in managing water resources, are typically guided by reservoir operational rules. These rules determine how the storage capacity and water discharges are allocated among various reservoirs and different water uses, taking into account varying periods and conditions, as part of a strategic approach to reservoir management (Klipsch et al., 2021). Developing modified rule curves which copes with future climatic scenario and maintain optimal hydropower generation and provide plenty irrigation supply is main goal of this study.

CHAPTER 3: STUDY AREA AND DATA

3.1 Study Area

Naumure Multipurpose Project lies within the West Rapti River basin, of whose catchment area at the Nepal-India border is about 6475 km², and the length of the mainstream channel is 258 km. The river originates from the middle mountains of Nepal, then enters the terai flat area and finally drains to India to join the Ganges River. This river is not snow-fed river. Monsoon rainfall and groundwater contributes most for runoff. The study area experiences diverse climates, with the upper basin having a deciduous climate and the lower basin around Banke district having a tropical to subtropical climate. The seasons range from hot and dry in March to June, hot and humid in July to August, pleasant in September to October, and cold and dry in November to February, with temperatures reaching up to 46 °C in summer and dropping below 2 °C in winter. The location map illustrating West Rapti Basin and project locations is shown in Figure 3.1.

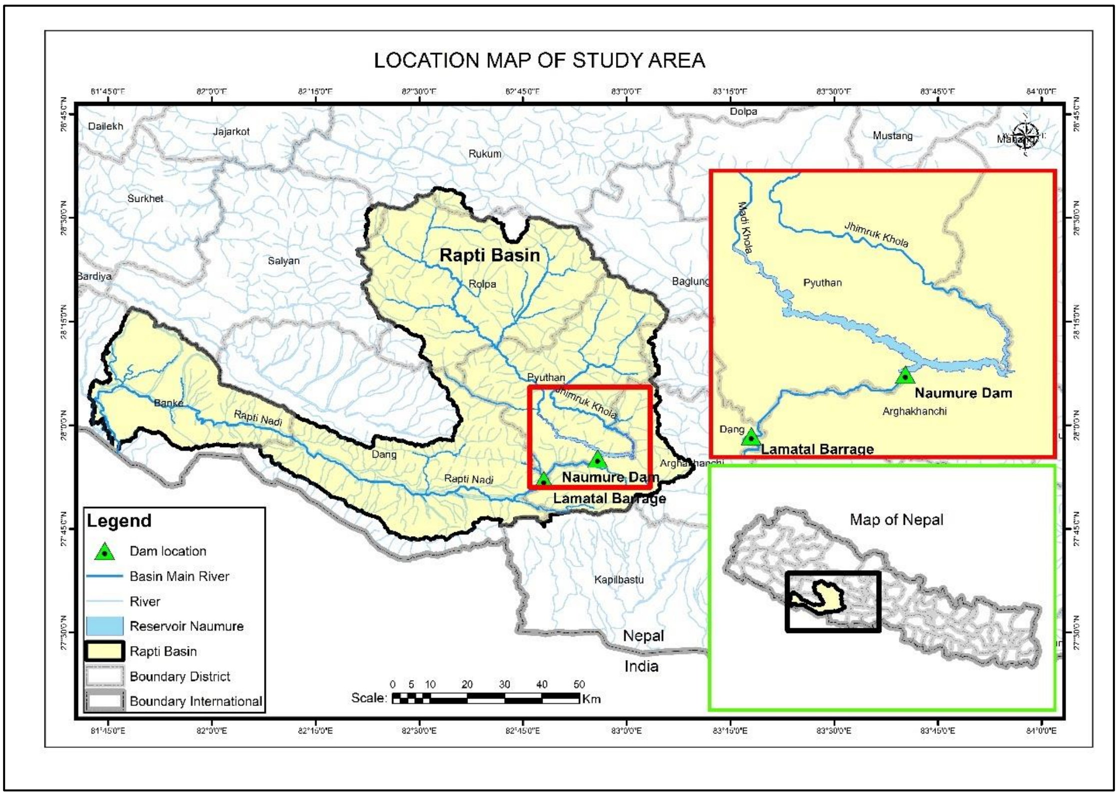


Figure 3.1: Location Map of Study Area

Naumure Multipurpose Project is the reservoir-based project which includes multiple hydropower and irrigation scheme. Under this multipurpose project, three hydro schemes are proposed, Naumure Hydro Scheme 218.34 MW, Lamatal Hydro Scheme 8 MW, and Surainaka Hydro Scheme 54.7MW and one irrigation scheme Kapilvastu irrigation project (29,736 ha) is proposed. Two existing irrigation projects: Deukhuri irrigation project (10,800 ha) and Banke irrigation project (42,766 ha) lies very far downstream of the same river. Naumure dam is located at Rapti river just below confluence of Mari and Jhimruk rivers on the border of Arghakhanchi and Pyuthan districts. The co-ordinate of Naumure Multipurpose Project at dam location is 82° 55' 48" Easting and 27° 55' 12" Northing. The catchment area of Naumure project at dam site is found to be around 3415 km^2 and watershed perimeter was found to be 389 km. The maximum and minimum elevation was found to be 3615 m and 345 m respectively. This suggest that the catchment lies way below snow line and river is not snow-fed river. The basin receives mean annual rainfall of around 1480 mm. The average flow of Rapti river at around dam site area is 98.3 m^3/s. Naumure reservoir dam is proposed to be Concrete Faced Rockfill Dam (CFRD). The height of proposed dam is 169 m at an elevation of 531 masl. The gross head of the project will be 164 m while net head of the project is estimated to be 160.3 m. The hydro reservoir capacity is planned to be 1067 Mm^3 at an elevation of 524 m with the submergence area of 18.03 km^2. The hydropower scheme proposed at Naumure dam has installed capacity of 218.34 MW with the design discharge of 154 m^3/s. The tail water level of dam was fixed at 360 m.

At around 6 km downstream of Naumure dam, Lamatal barrage is proposed for Lamatal hydro scheme and flow diversion to Surainaka hydro scheme which then ultimately discharge to Kapilvastu irrigation project. The site coordinates of Lamatal barrage are 82° 53' 22" Easting and 27° 54' 30" Northing. The type of barrage proposed at Lamatal barrage is Re-regulating type R.C.C. Barrage. The installed capacity of 8 MW was proposed at Lamatal hydro scheme with design discharge of 136.2 m^3/s. The hydropower project has gross head of 7 m while net head of around 6.65 m. Flow of maximum 41.6 m^3/s is diverted form Lamatal barrage to Surainaka hydro scheme and then to Kapilvastu irrigation project at Kapilvastu district. The installed capacity of proposed Surainaka hydropower is 54.7 MW with the design discharge of 41.6 m^3/s. This hydropower scheme has gross head of around 160 m while net head of 148.66 m is estimated. The same discharge is then used for proposed Kapilvastu irrigation project to irrigate the land of around 29,736 ha. The irrigation demand of Kapilvastu irrigation project is 647 Mm^3 (Executive summary report Naumure, 2021).

3.2 Data and Materials

3.2.1 Topographical and river basin data

Topography of the river basin is studied with the help of Digital Elevation Model (DEM) map. For DEM map, aster map of 30 m × 30 m resolution was downloaded from United States Geological Survey (USGS) website. Then, the catchment area at dam site was delineated in ArcGIS v. 10.5 and was found to be around 3415 km² and watershed perimeter was found to be 389 km. The maximum and minimum elevation was found to be 3615 m and 345 m respectively while the mean elevation was found to be around 1622 m. This suggest that the catchment lies way below snow line and river is not snow-fed river. The catchment area map at Naumure dam site is shown in Figure 3.2.

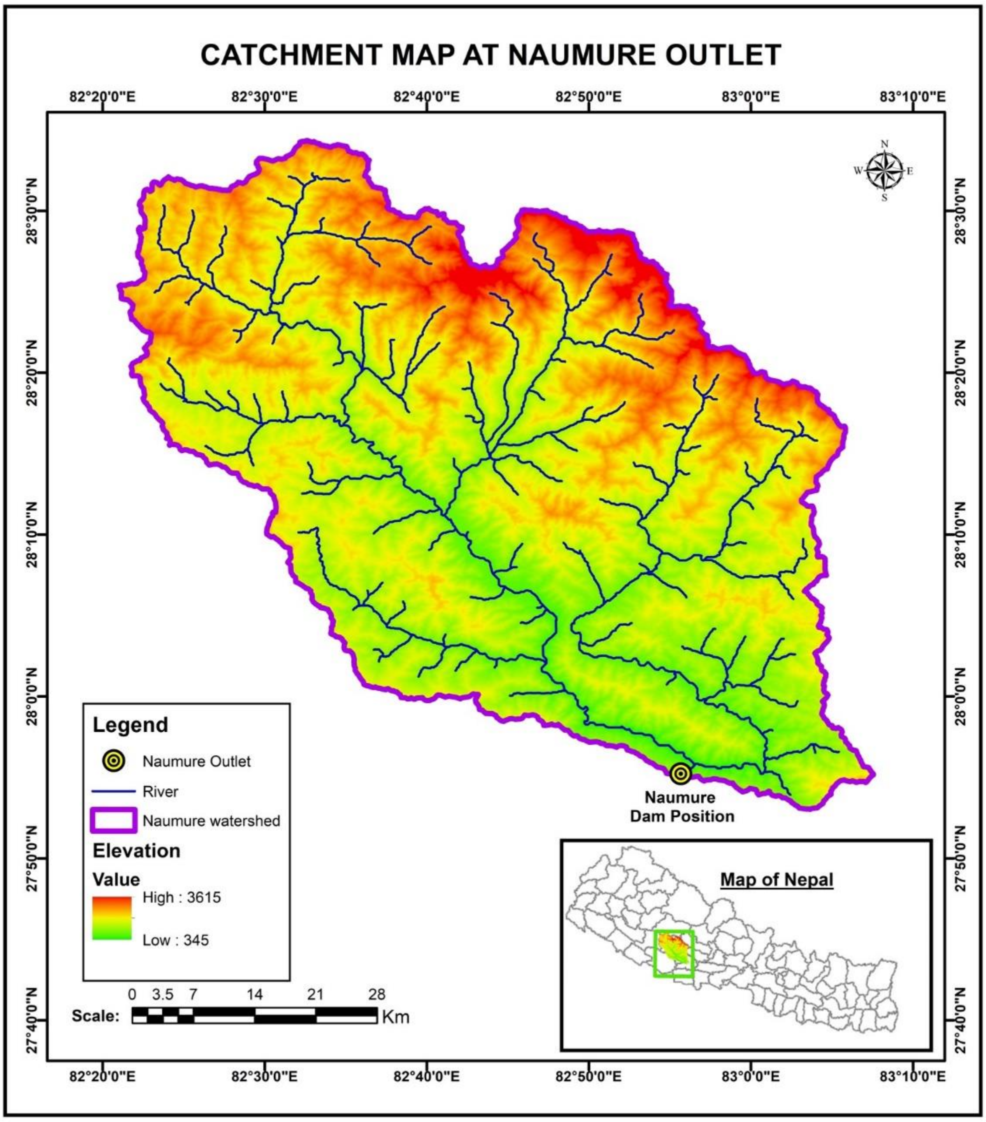


Figure 3.2: Catchment Area at Naumure Dam Site

Naumure Dam site is ungauged station. For any hydrological analysis, the nearest hydrological station from the Naumure project site which is Bagasoti gauging station, which is 18.5 km downstream of the dam site is taken into consideration. The hydro-physiological aspects and parameter of both station is almost same. The catchment area at Bagasoti station point is 3836 km^2. The difference in the basin area between Bagasoti and Naumure is just around 400 km^2. The quality of the data at Bagasoti, as published by the DHM is fair. This station is used as a reference station for hydrological analysis of Naumure project. The catchment area at Bagasoti outlet is shown in Figure 3.3.

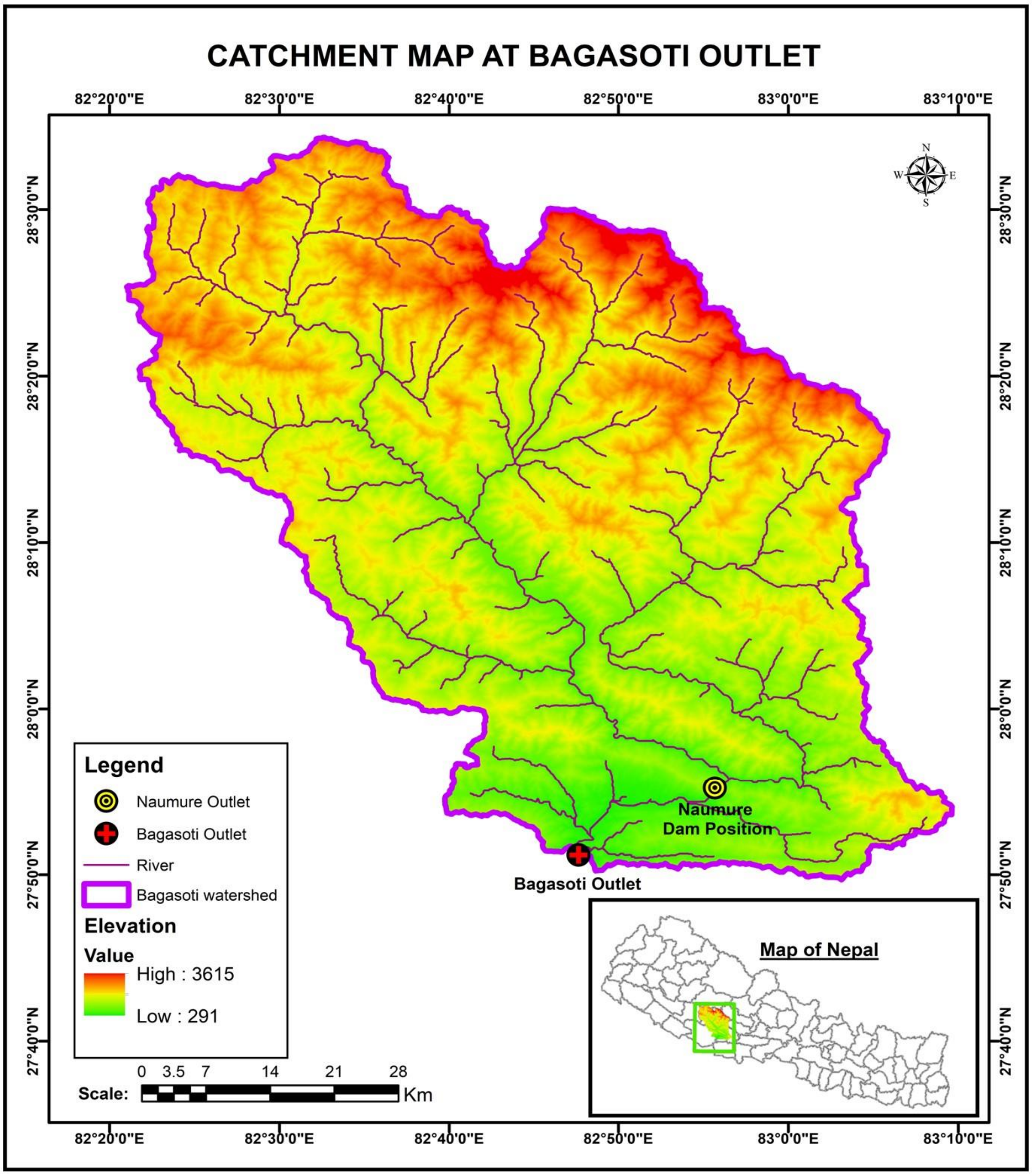


Figure 3.3: Catchment Area at Bagasoti Outlet

3.2.2 Hydro-Meteorological Data

The Naumure dam site, being an ungauged station, requires hydrological analysis to rely on the data from the nearest gauging station, which is Bagasoti gauging station (Station index no: 350) located 18.5 km downstream of the dam site. This data serves as a crucial reference for understanding the hydrological characteristics of the Naumure project site. Also, Mari khola gauging station (Station index no: 330) is present inside the basin catchment in Mari khola located at Nayagaon. So, data from these two stations was used in this study for hydrological purpose. Details of hydrological station considered for this study is presented in Table 3.1.

Table 3.1: List of Hydrological Stations

S.N.	Station Index	River name	Latitude	Longitude	Elevation	Location
1	330	Mari khola	28.06	82.8	536	Nayagaon
2	350	Rapti river	27.85	82.79	381	Bagasoti

Five climatological stations are considered for this study which are within and nearby the study basin. Stations 504 and 505 are within the basin. Stations 514, 515 and 715 are the stations nearest to the basin. Their details are shown in Figure 3.4 and Table 3.2.

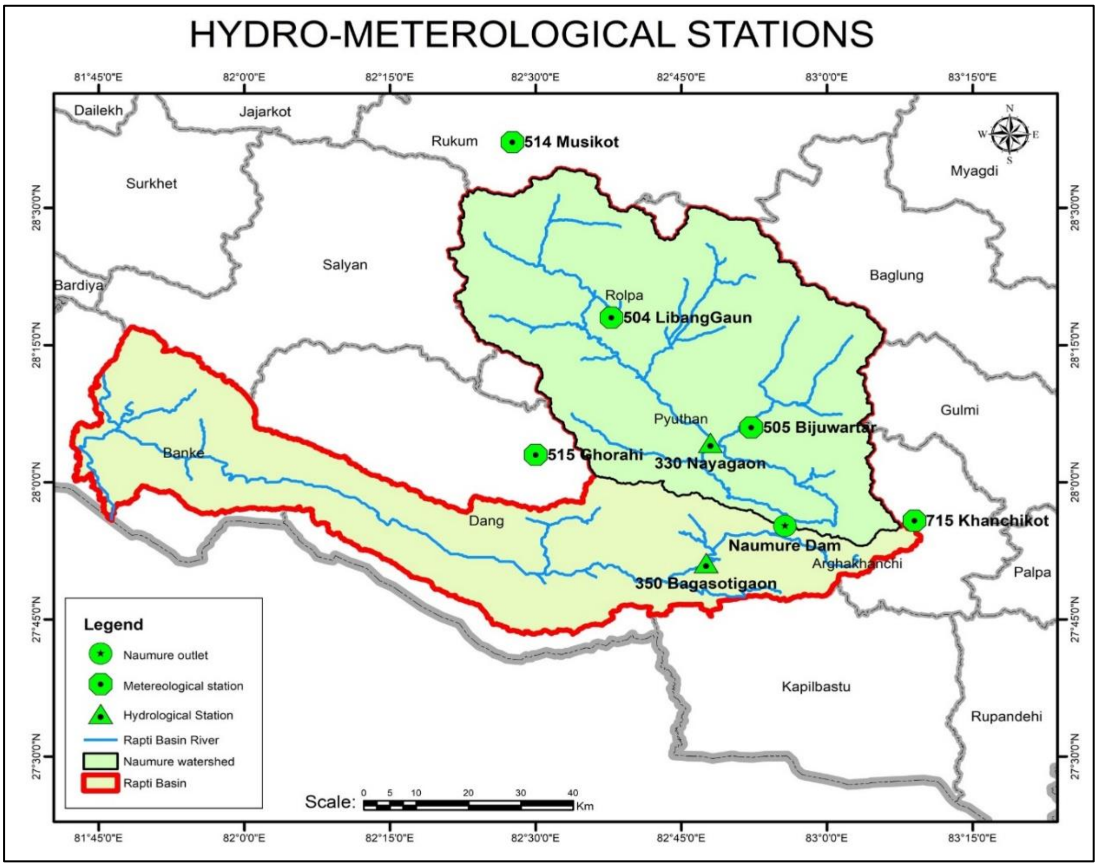


Figure 3.4: Map Showing Hydro-meteorological Stations

Table 3.2: List of Meteorological Stations

SN	Station Name	Station Index	Location	Latitude	Longitude	Elevation	Type
1	LibangGaun	504	Rolpa	28.3	82.63	1270	PCP
2	Bijuwartar	505	Pyuthan	28.1	82.87	823	PCP
3	Ghorahi	515	Dang	28.05	82.5	634	PCP, Temp
4	Khanchikot	715	Arghakhachi	27.93	83.15	1760	PCP, Temp
5	Musikot	514	Rukum	28.62	82.46	1412	Temp

Among those five stations, four of them measures rainfall. The Thiessen weightage of these meteorological station is shown in Figure 3.5.

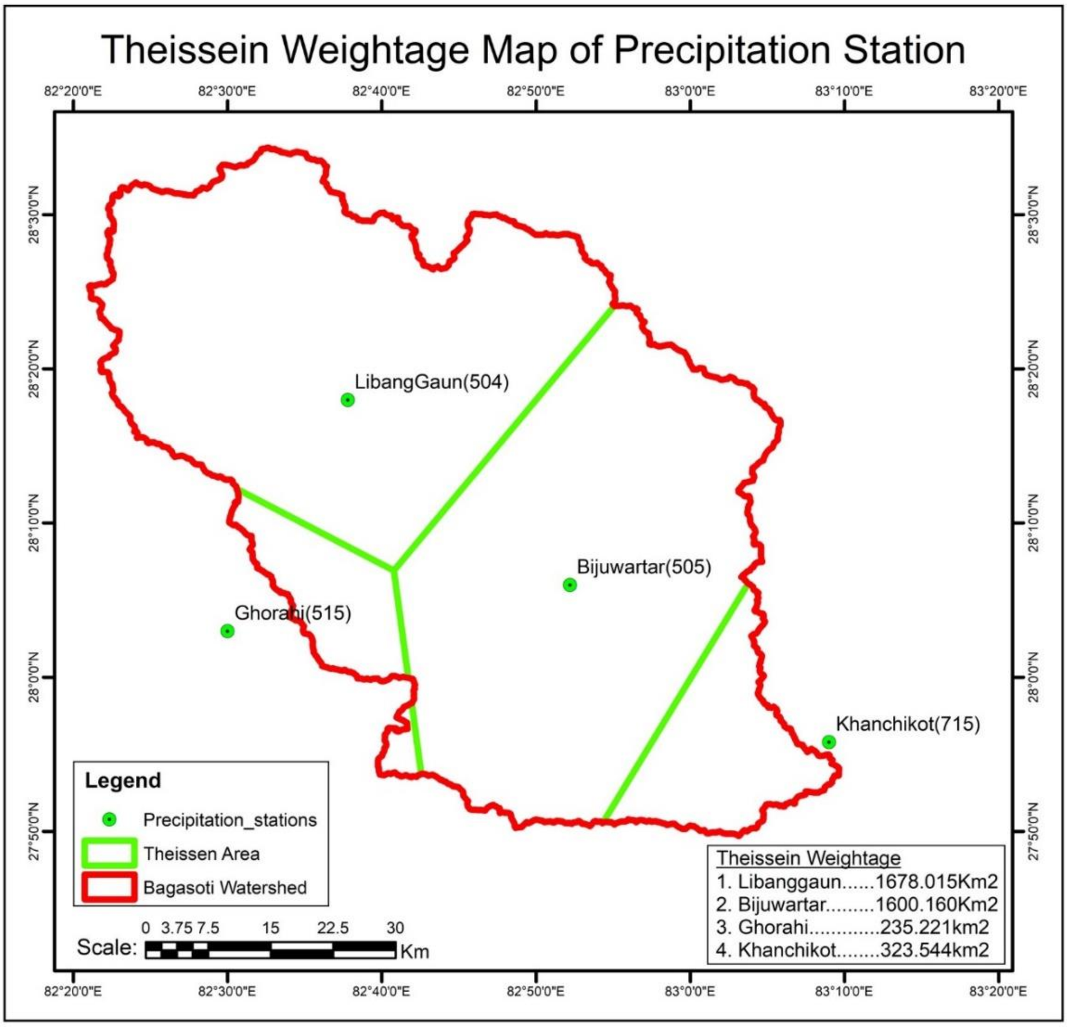


Figure 3.5: Thiessen Weightage of Rainfall Stations

For Hydro-meteorological analysis, 2 hydrological and 5 climatological stations within or at vicinity of basin are used in this study. Their daily data from 2000 AD to 2015 AD was obtained from Department of Hydrology and Meteorology (DHM), Nepal. The quality of data is fairly good.

3.2.3 DEM map for SWAT model

Hydrological model setup was done in Arc SWAT v. 2012 interface in ArcGIS software. The necessary input data for SWAT model is prepared in Arc-GIS tool. The Aster map of resolution 30 m × 30 m is used to create DEM map. The watershed delineation of DEM map at Bagasoti outlet for hydrological modelling for SWAT is shown in Figure 3.6.

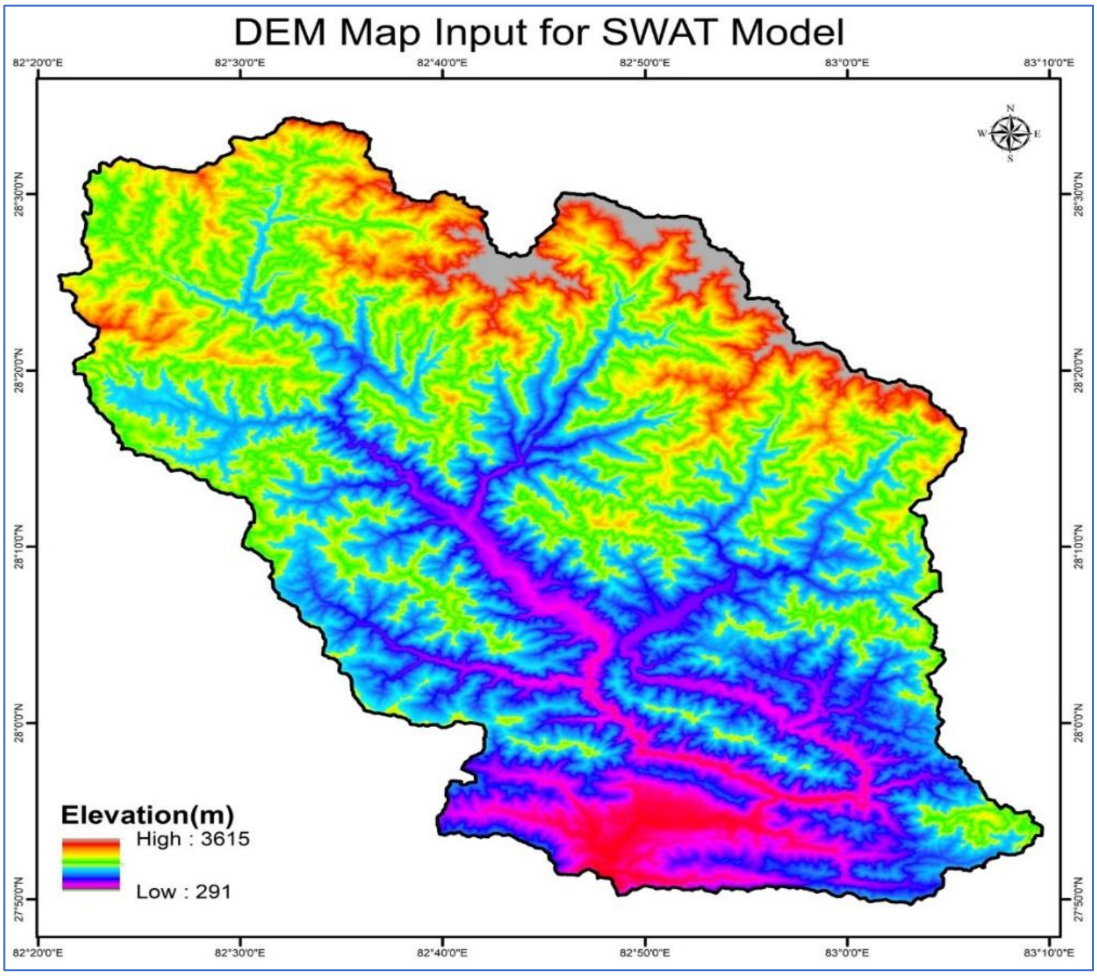


Figure 3.6: DEM Map Input for SWAT Model

3.2.4 Land Use Map

Land Use Map is most important input for SWAT model as it is used to create and refine Hydrological Response Units (HRUs) in SWAT. Land Use and Land Cover (LULC) map for Nepal as of 2010 AD was obtained from International Centre for Integrated Mountain Development (ICIMOD) website and was processed and clipped to basin area in ArcGIS v. 10.5 software. The resulting map is shown in Figure 3.7.

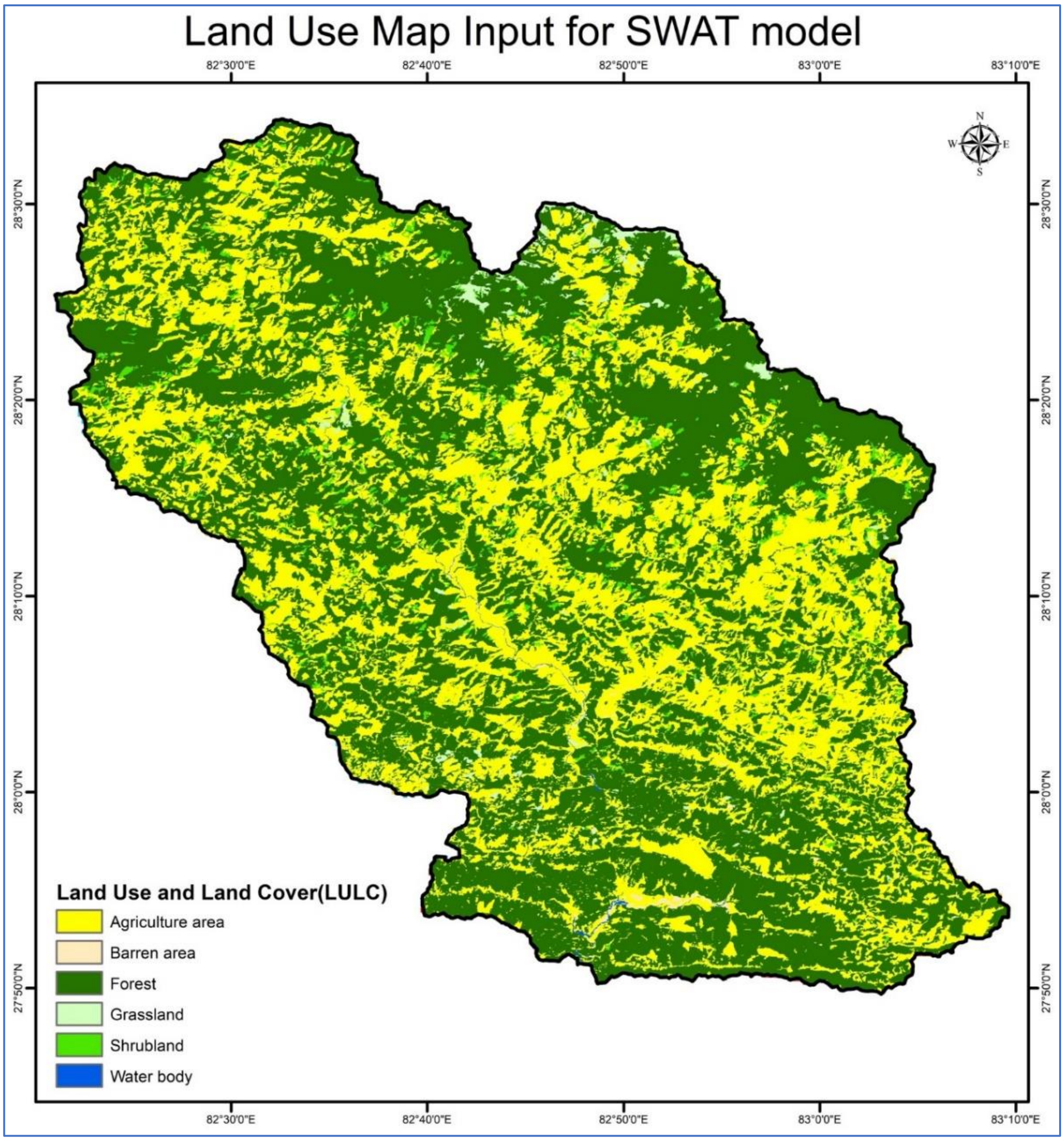


Figure 3.7: Land Use and Land Cover Map for SWAT Model

3.2.5 Soil and Terrain Map

Soil and Terrain Map is also important input for SWAT model as it is also used to create and refine Hydrological Response Units (HRUs) in SWAT. Soil and Terrain Map for Nepal as of 2009 AD required for SWAT model setup is downloaded from Soil Terrain Database (SOTER) of scale 1 in 1 million. It is processed and clipped to basin area in ArcGIS v. 10.5 software. Seven major different types of soil were found in this basin. The resulting map is shown in Figure 3.8.

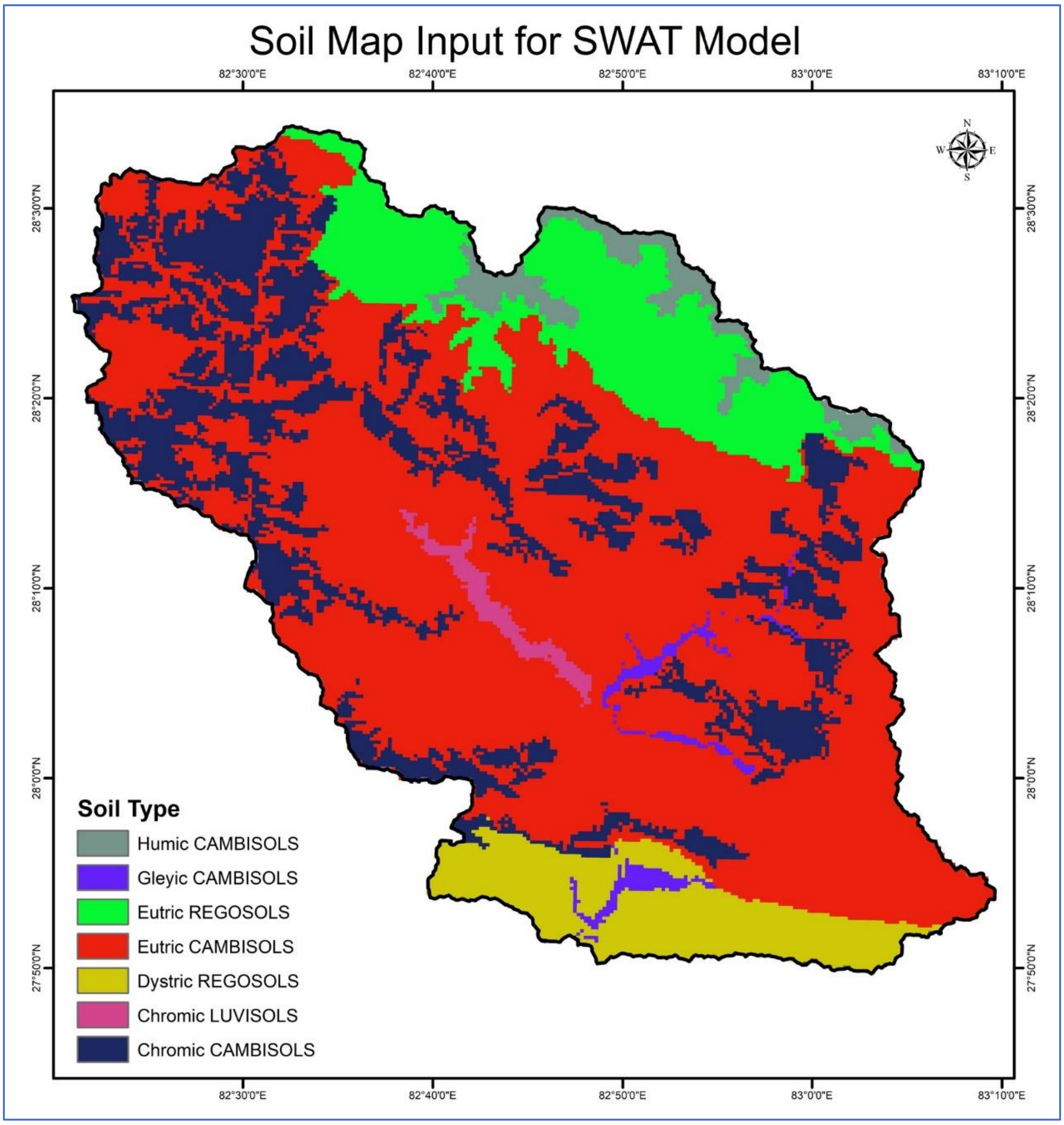


Figure 3.8: Soil Map for SWAT Model

3.2.6 Reservoir and Hydropower Data

Naumure Multipurpose Project includes three proposed hydro scheme and one proposed irrigation scheme with two existing irrigation scheme. Reservoir data and all necessary data of each of those proposed schemes are used as input in reservoir modelling. The necessary reservoir data of Naumure Multipurpose Project required for HEC-ResSim software is extracted from executive summary report provided by clients of respective project. The important reservoir data and salient features of each proposed hydropower and irrigation scheme of Naumure Multipurpose Project is shown in Table 3.3 to Table 3.6 respectively.

Table 3.3: Reservoir Data of Naumure Reservoir

S.N.	Sailent Feature	Naumure Reservoir Project
1	Dam Type	Concrete Face Rockfill Dam (CFRD)
2	Installed Capacity	218.34 MW
3	Gross Head	164 m
4	Net Head	160.3 m
5	Design Discharge	154 m^3/s
6	Full Supply Level (FSL)	524 masl
7	Minimum Operating Level (MOL)	473 masl
8	Dam Height (from the river bed)	169 m
9	Dam Crest Level	531 masl
10	Minimum Drawdown Level	473 masl
11	Tail water elevation	360 masl
12	Gross Storage	1066.85 MCM
13	Active Storage	694.33 MCM
14	Dead Storage	259.29 MCM
15	Average River Bed Elevation	362 masl

Table 3.4: Sailent Features of Lamatal Hydro Scheme

S.N.	Sailent Feature	Lamatal Hydro Scheme
1	Dam Type	Concrete Barrage
2	Installed Capacity	8 MW
3	Gross Head	7 m
4	Net Head	6.65 m
5	Design Discharge	136.20 m^3/s
6	Tailrace Water Level	352 masl
7	Full Supply Level (FSL)	359 masl
8	Minimum Operating Level (MOL)	356 masl
9	Barrage Crest Elevation	360.5 m (1.5 m freeboard)
10	Gross Storage	6.46 MCM
11	Active Storage	3.02 MCM

Table 3.5: Sailent Features of Surainaka Hydro Scheme

S.N.	Sailent Feature	Surainaka Hydro Scheme
1	Installed Capacity	54.7 MW
2	Gross Head	160 m
3	Net Head	148.66 m
4	Design Discharge	41.6 m^3/s

Table 3.6: Sailent Features of Kapilvastu Irrigation Scheme

S.N.	Sailent Feature	Kapilvastu Irrigation Scheme
1	Proposed Area	29,736 ha
2	Irrigation Demand	647 Mm^3

3.2.7 Height-Area-Volume Curve of Naumure reservoir

Important input for reservoir simulation for HEC-ResSim software is Height-Area-Elevation (H-A-V) curve of respective reservoir. The H-A-V curve for respective reservoir is created in ArcGIS 10.5 using special storage capacity script available in ArcGIS spatial analyst supplemental tool script. H-A-V curve up to required elevation and at 5 m interval is created. H-A-V curve of Naumure reservoir is shown in Figure 3.9 below.

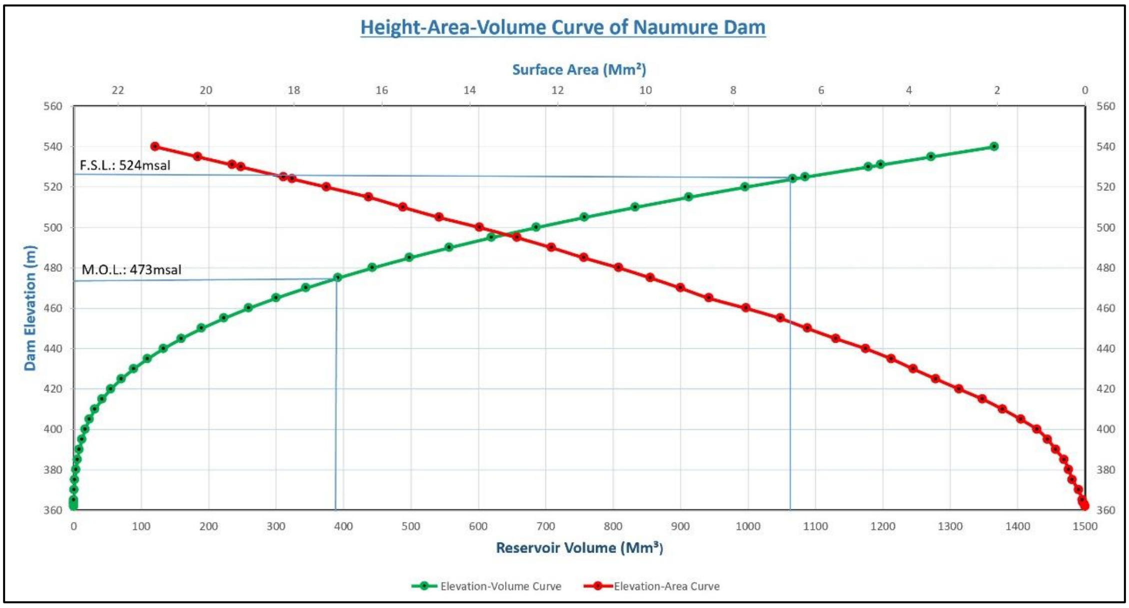


Figure 3.9: H-A-V Curve of Naumure Reservoir

CHAPTER 4: METHODOLOGY

The methodology of this study work has been dynamic. During the course of this study period, whenever necessary arises, the methodology has been refined multiple time as per requirement. Necessary data required for this study work was obtained from Department of Hydrology and Meteorology (DHM), authentic institutions, authentic websites, research papers and global database. Only secondary source data has been used in this study. For hydrological modelling, SWAT model was chosen, and for reservoir modelling and simulation, reservoir model was setup up in the HEC-ResSim software for this study.

Figure 4.1 illustrates the finalized flowchart which demonstrates the sequence of activities and overall framework of this study work.

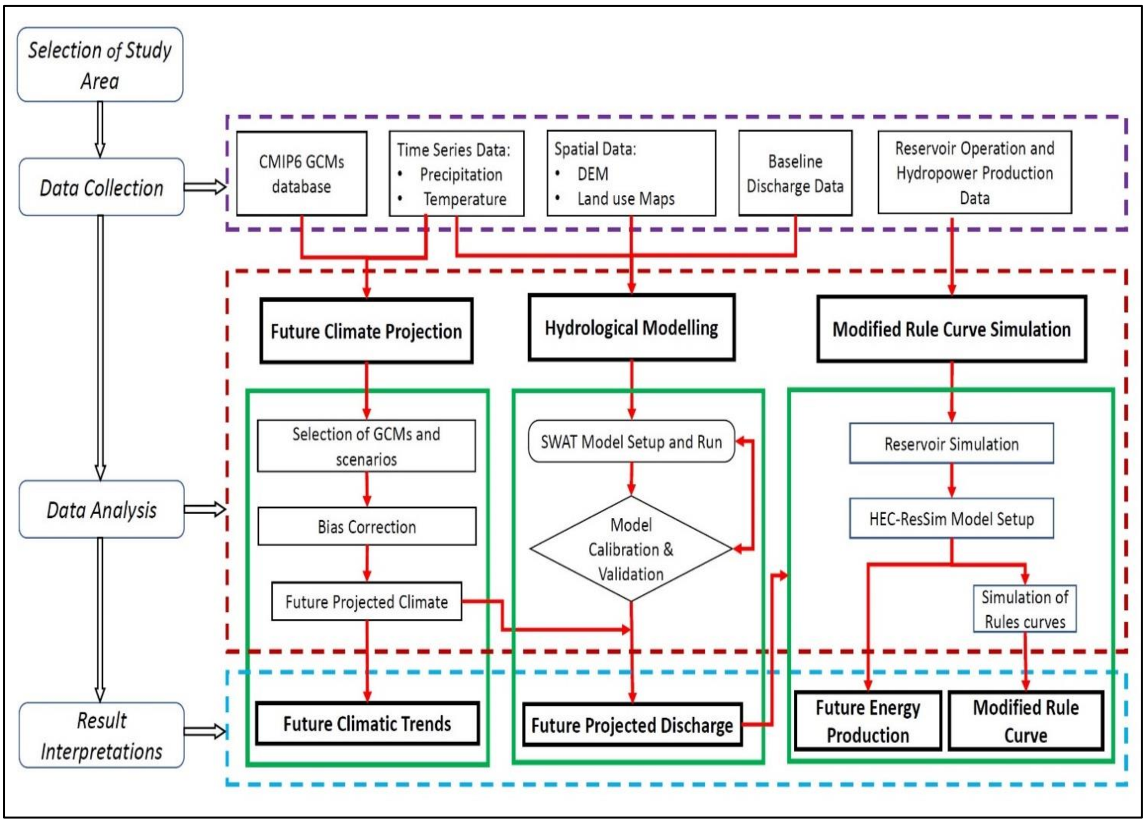


Figure 4.1: Flowchart of Methodology

4.1 Selection of Study Area

Naumure Multipurpose Project, reservoir project was selected for this study which includes three proposed hydropower schemes, one proposed irrigation scheme and two existing irrigation schemes. Details of study area was already discussed in earlier section.

4.2 Data Collection

Data required for the project can be obtained from two different sources.

4.2.1 Primary Data

No primary data was used for the project.

4.2.2 Secondary Data

This study relies mainly on secondary data. Different data required for this study work were collected as mentioned below:

- Hydrological and Meteorological Data:
  Daily observed precipitation, daily maximum and minimum temperature, and daily discharge data for required period has been bought from Department of Hydrology and Meteorology (DHM).
- River Basin Data:
  Digital Elevation Model (DEM) aster map of 30 m × 30 m resolution was downloaded from United States Geological Survey (USGS) website. Land use and Land Cover map, and Soil and Terrain map were downloaded from ICIMOD and SOTER website respectively.
- Climate data
  Intermediate-Biased corrected six CMIP6-GCMs model data gridded at 0.25° × 0.25° resolution were downloaded from zenodo database for this study. URL for the website is: https://zenodo.org/record/3873998#.ZEdrfHZBztU
- Reservoir and Hydropower Data:
  All necessary project related data like reservoir operation data, hydropower production data and irrigation supply details data required for this study was acquired from related clients.

4.3 Data Analysis and Methodology Step

4.3.1 Data Preparation

- Time series Daily Precipitation, Maximum and Minimum Temperature, Discharge data was put on a chronological order in excel and data management tool like HEC-DSSVue software.
- Missing any precipitation or temperature data was generated and filled using available methods like arithmetic or normal methods.

4.3.2 GIS work

- Location Map, Catchment Area Map, Hydrometeorological Map, Thiessen weightage Map and other necessary maps were created in ArcGIS software.
- H-A-V curve was generated in ArcGIS using Spatial analyst supplementary tools.

4.3.3 Future Climate Projection

- Climatic variable data's (Precipitations, Maximum and Minimum Temperature) were downloaded from selected CMIP6-GCMs database for period up to 2100 under two scenarios (SSP245 and SSP585) and was extracted to basin scale, then downscaled to station level through analysis and grid generation in GIS software.
- Then, GCM outputs were bias corrected using linear scaling method to remove biases and to get accurate climatic model output as close to actual conditions which then can used for further applications.
- Future climatic scenarios and trends were thoroughly analyzed and interpreted for different periods of future annually and seasonally.

4.3.4 SWAT hydrological modelling

- DEM map, Land use and land cover map, and Soil and terrain map for SWAT model setup was prepared in ArcGIS software.
- After creating required weather generated (.wgen) files, SWAT model was setup up and initial run was performed.
- SWAT model calibration and validation was conducted in SWAT cup software.
- Future hydrology (projected discharge) was then projected in SWAT model using future projected climate output.

4.3.5 Reservoir Simulation

- Reservoir model was setup in HEC-ResSim software using H-A-V curve, available reservoir operation and hydropower production data.
- Future energy generation trend was projected through reservoir modelling using future hydrology data.
- Comparison of future and current energy production trend was performed to determine the degree of climate change impact on the project.
- Rule curve was adjusted and simulated in same HEC-ResSim model to generate modified rule curves which can be recommended for future use, which act as adaptation measures against possible future climate change impacts which keeps hydropower generation at its maximum while meeting irrigation demands.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Future Climatic Projection

GCMs is must for doing climate modelling works and predicting future climate. There are thousands and thousands of GCMs model available in the world. Mishra et al., 2020 did intermediate biased correction to 13 CMIP6 GCMs to 0.25° × 0.25° resolution for South Asia region and made publicly available for further use also mentioning in their paper the quality of model and can be used for study and analysis if lies within the region (Mishra et al., 2020). So, six GCMs were selected among 13 CMIP6 GCMs and used for this study. These GCMs data are downloaded from zenodo database https://zenodo.org/record/3873998#.ZEdrfHZBztU website. Details and description of these six selected GCMs was given in Table 5.1.

Table 5.1: Details of CMIP6 GCM Models

SN	GCM name	Description	Modelling institution
1	ACCESS-CM2	Australian Community Climate and Earth System Simulator Climate Model Version 2	CSIRO-ARCCSS, Australia
2	CanESM5	The Canadian Earth System Model Version 5	Canadian Centre for Climate Modelling and Analysis, Canada
3	EC-Earth3	EC-EARTH Climate Model Version 3	EC-EARTH consortium, Europe
4	INM-CM4-8	Institute for Numerical Mathematics Climate Model	Institute of Numerical Mathematics of the Russian Academy of Science, Russia
5	MPI-ESM1-2-HR	Max Planck Institute Earth System Model	Max Planck Institute for Meteorology, Germany
6	NorESM2-MM	The Norwegian Earth System Model	Norwegian Climate Center, Norway

These CMIP6 GCM models were downscaled at each station level under two scenarios SSP245 and SSP585. GCM model, being of border scale and is of coarser resolution, definitely have biases when it comes to basin or station level. So, Bias correction is necessary. In this study, Bias correction was performed using simple linear scaling method.

The performance of the model before and after bias correction is always significant. Based on this, we can also categorize and rank the GCMs model. The performance check result of GCM model at Ghorahi station was shown in Table 5.2 to Table 5.4.

Table 5.2: Performance Check at Ghorahi Station for Precipitation

Performance Parameter	Nash-Sutcliffe efficiency (Ƞ)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	-0.01	0.27	0.68	0.27	-10.09	0
CanESM5	-0.93	-0.74	-0.31	0.36	12.64	0.09
EC-EARTH3	0.44	0.44	0.81	0.75	-0.51	0
INM-CM4-8	0.51	0.55	0.73	0.76	14.07	0.04
MPI-ESM1-2-hr	0.56	0.57	0.78	0.8	8.48	0
NorESM2-MM	0.39	0.45	0.77	0.76	-0.7	0

Table 5.3: Performance Check at Ghorahi Station for Maximum Temperature

Performance Parameter	Nash-Sutcliffe efficiency (Ƞ)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	0.14	0.85	0.88	0.93	11.99	0
CanESM5	0.09	0.85	0.77	0.92	9.76	0.06
EC-EARTH3	0.23	0.82	0.9	0.91	11.49	0
INM-CM4-8	0.35	0.87	0.92	0.94	10.72	0.06
MPI-ESM1-2-hr	0.21	0.87	0.92	0.94	12.19	-0.01
NorESM2-MM	0.14	0.86	0.89	0.93	12.31	0.07

Table 5.4: Performance Check at Ghorahi Station for Minimum Temperature

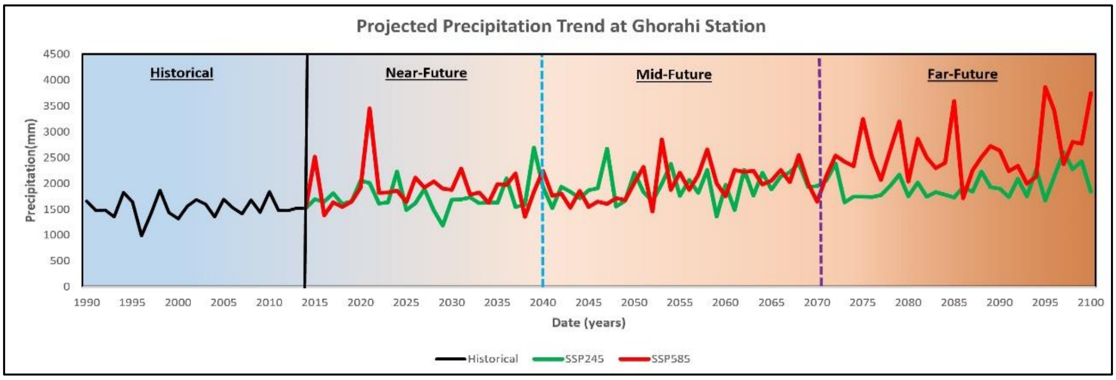
Performance Parameter	Nash-Sutcliffe efficiency (Ƞ)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	0.81	0.96	0.97	0.98	14.9	0
CanESM5	0.8	0.95	0.95	0.97	12.86	0.05
EC-EARTH3	0.8	0.95	0.97	0.98	14.85	0
INM-CM4-8	0.79	0.96	0.97	0.98	15.49	0.05
MPI-ESM1-2-hr	0.77	0.95	0.97	0.98	16.52	0
NorESM2-MM	0.75	0.96	0.96	0.98	16.92	0.04

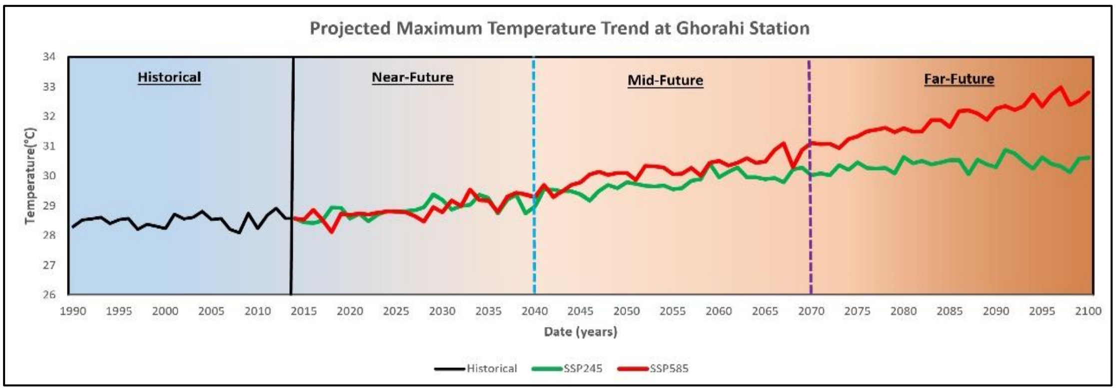
These performance parameters check result can be used to rank CMIP6-GCMs model. Especially, two-performance evaluation parameters (Nash-Sutcliffe efficiency (Ƞ), Coefficient of Determination (R^2)) are important and used to rank GCMs. Ranking is important because it can be helpful in selecting appropriate GCMs model for further and future water resource studies in the same basin. Based on Ghorahi station performance check, the GCMs were ranked as shown in Table 5.5.

Table 5.5: Ranking of GCM Models

Rank	GCM	Nash-Sutcliffe efficiency (η)	Coefficient of Determination (R^2)
1	MPI-ESM1-2-hr	0.80	0.90
2	INM-CM4-8	0.79	0.89
3	NorESM2-MM	0.76	0.89
4	EC-EARTH3	0.74	0.88
5	ACCESS-CM2	0.69	0.88
6	CanESM5	0.35	0.75

In this study, ensemble approach was utilized in future climate projection works. According to ensemble approach, the mean of all GCM model is taken and is used for further analysis. So, in this study, ensemble of six GCM model was taken and future climatic variables (Precipitation, Maximum Temperature, Minimum Temperature) was projected for each stations up to 2100 AD for two scenarios SSP245 and SSP585. Each projection was then looked out for three futures: NF (Near of Future, 2015-2040 AD), MF (Mid of Future, 2040-2070 AD) and FF (Far of Future, 2070-2100 AD). Climatic Analysis was carried out both on yearly basis and on seasonal basis (Winter, Pre-Monsoon, Monsoon, Post Monsoon) in all three futures (NF, MF, FF) for each station and for all climatic variables. The projected future trend of climatic variables on Ghorahi and Libanggaun stations were illustrated in Figure 5.1 and Figure 5.2 respectively.





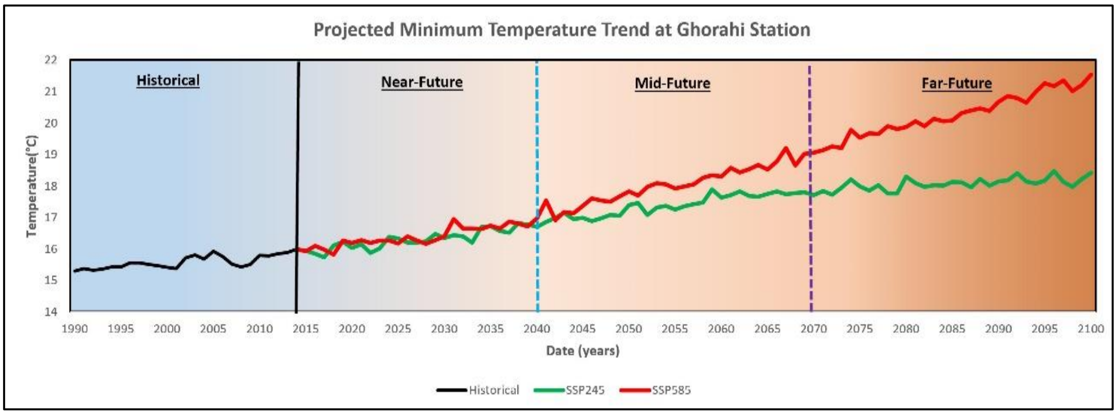


Figure 5.1: Future Climate Trend at Ghorahi Station

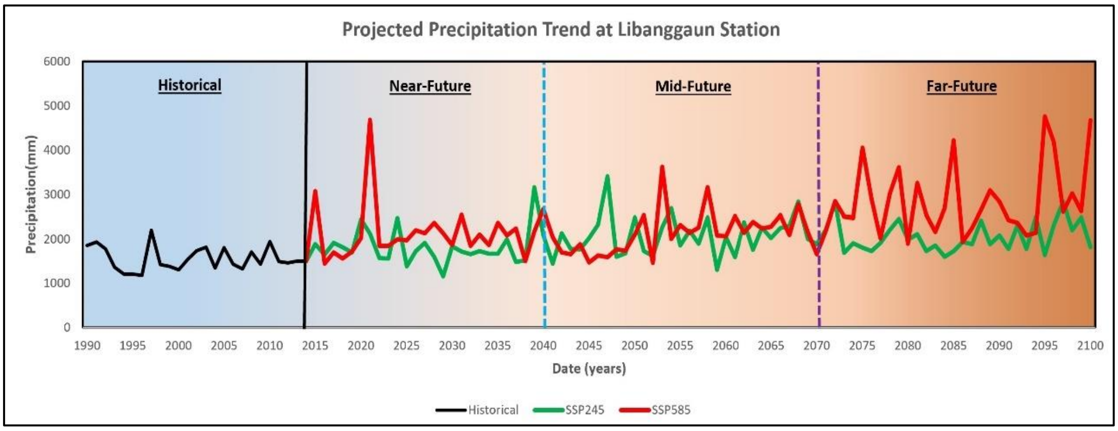


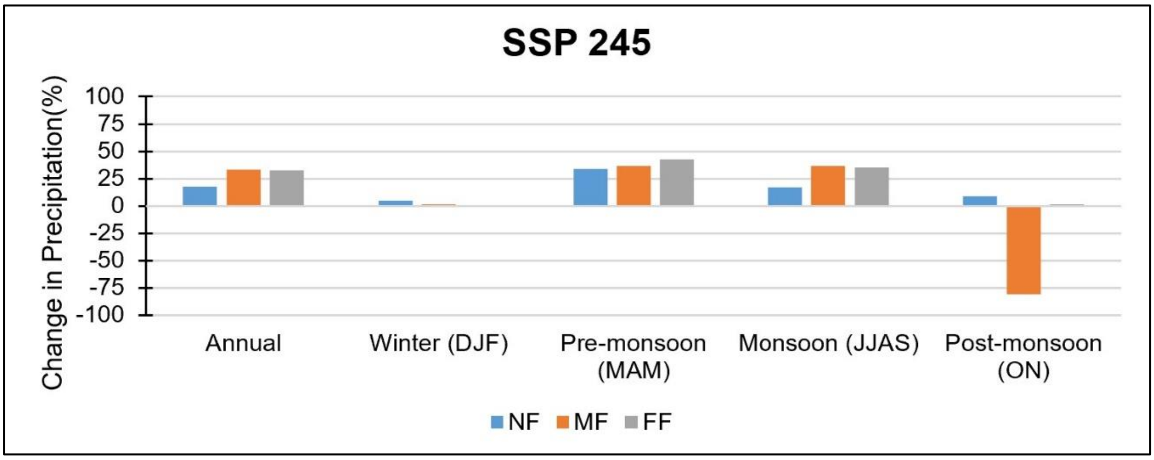
Figure 5.2: Future Precipitation Trend at Libanggaun Station

This above trend graphs suggest both temperature and precipitation variable were projected to increase under both SSP245 and SSP585 scenario in all the future. The precipitation was projected to increase between 13% to 90% at different period of future. The maximum temperature was projected to increase up to 14.41% (up to 3.7 °C) and the minimum temperature was projected to increase up to 38.89% (up to 4.97 °C) both in FF future under scenario SSP585.

Seasonal variation future trend analysis suggests significant decrease in precipitation in case of post-monsoon season period while precipitation increase significantly in both pre-monsoon and monsoon season and precipitation trend only deviate slightly in case of winter season. In case of maximum and minimum temperature, seasonal trend analysis suggests the increase in both maximum and minimum temperature in all of the season for all station under both scenario SSP245 and SSP585 while, in case of SSP585 scenario, the increase was quite large and significant. Seasonal variation of climatic variables in Ghorahi and Libanggaun station were illustrated in between Table 5.6 to Table 5.9 and Figure 5.3 to Figure 5.6.

Table 5.6: Seasonal Variation in Projected Precipitation at Libanggaun Station

Precipitation (mm)	**Annual**	**Winter (DJF)**	**Pre-monsoon (MAM)**	**Monsoon (JJAS)**	**Post-monsoon (ON)**
Baseline	1546.7	99.12	167.98	1229.51	50.09
SSP245-NF (%)	17.89	4.55	33.76	17.17	8.92
SSP245-MF (%)	33.41	1.44	36.31	36.75	-80.67
SSP245-FF (%)	32.59	0.19	42.95	35.06	1.44
SSP585-NF (%)	38.89	14.04	36.2	43.28	-10.5
SSP585-MF (%)	37.78	-0.16	41.93	42.06	-81.75
SSP585-FF (%)	85.19	-3.38	67.87	96.17	49.25



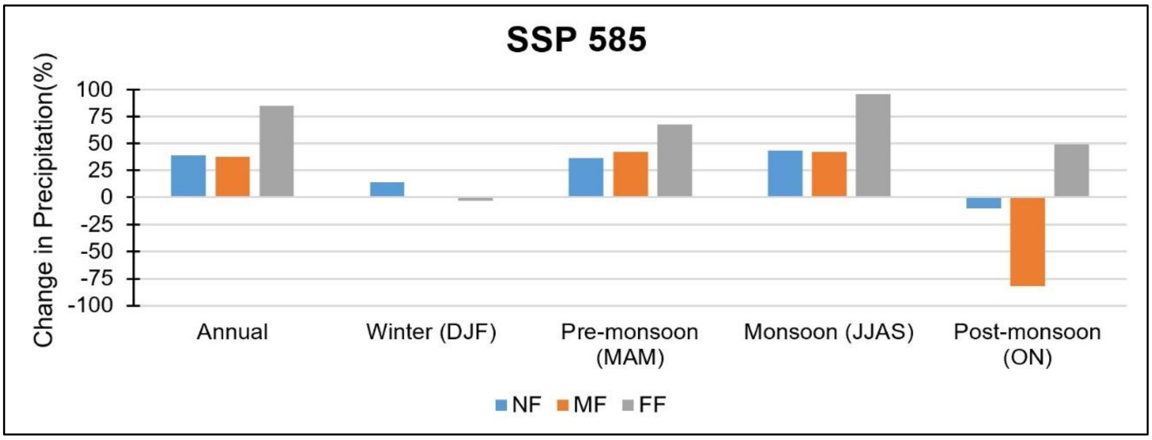
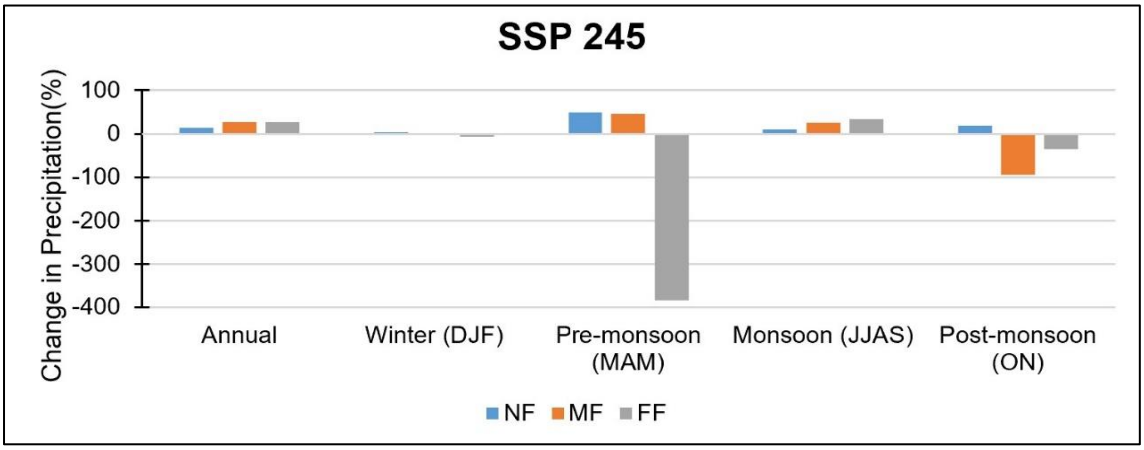


Figure 5.3: Percentage Change in Projected Precipitation at Libanggaun Station

Table 5.7: Seasonal Variation in Projected Precipitation at Ghorahi Station

	Annual	Winter (DJF)	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ON)
Baseline P (mm)	1533.48	-3.86	57.93	25.92	10.93
SSP245-NF (%)	13.95	4.08	49.59	10.16	18.7
SSP245-MF (%)	26.51	-1.54	46.6	25.8	-94.91
SSP245-FF (%)	27.5	-7	-383.9	33.6	-35
SSP585-NF (%)	25.85	12.26	50.86	24.67	-2.99
SSP585-MF (%)	29.37	-1.24	54.17	28.75	-95.23
SSP585-FF (%)	70.24	29.6	-41.1	28.6	-5.8



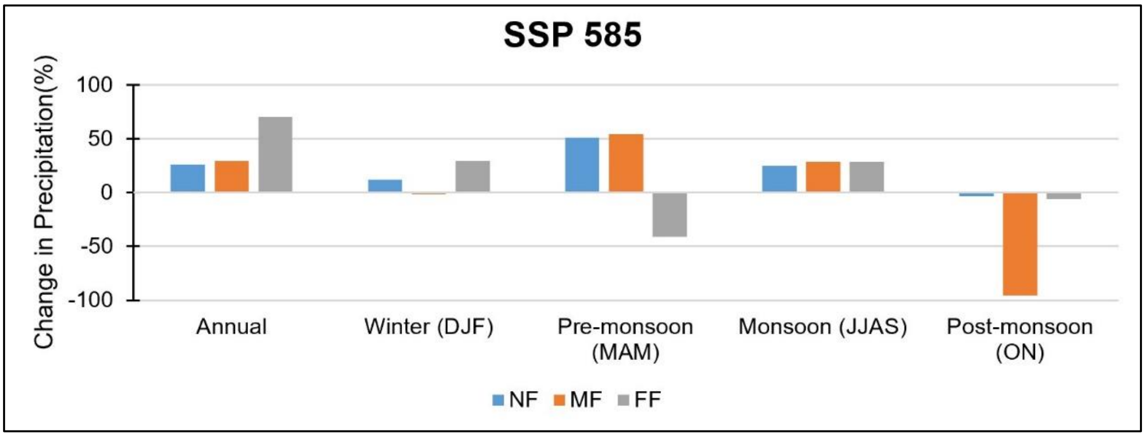


Figure 5.4: Percentage Change in Projected Precipitation at Ghorahi Station

Table 5.8: Seasonal Variation in Projected Maximum Temperature at Ghorahi Station

	Annual	**Winter (DJF)**	**Pre-monsoon (MAM)**	**Monsoon (JJAS)**	**Post-monsoon (ON)**
Baseline T_{max} (°C)	28.52	22.41	32.08	30.94	27.52
SSP245-NF (%)	1.30	2.45	0.72	1.17	1.18
SSP245-MF (%)	4.42	8.70	3.25	3.24	-6.20
SSP245-FF (%)	6.56	12.14	4.68	5.47	5.41
SSP585-NF (%)	1.30	2.97	0.61	0.88	1.45
SSP585-MF (%)	6.00	10.92	4.37	4.86	-4.41
SSP585-FF (%)	11.92	21.12	9.72	9.58	9.90

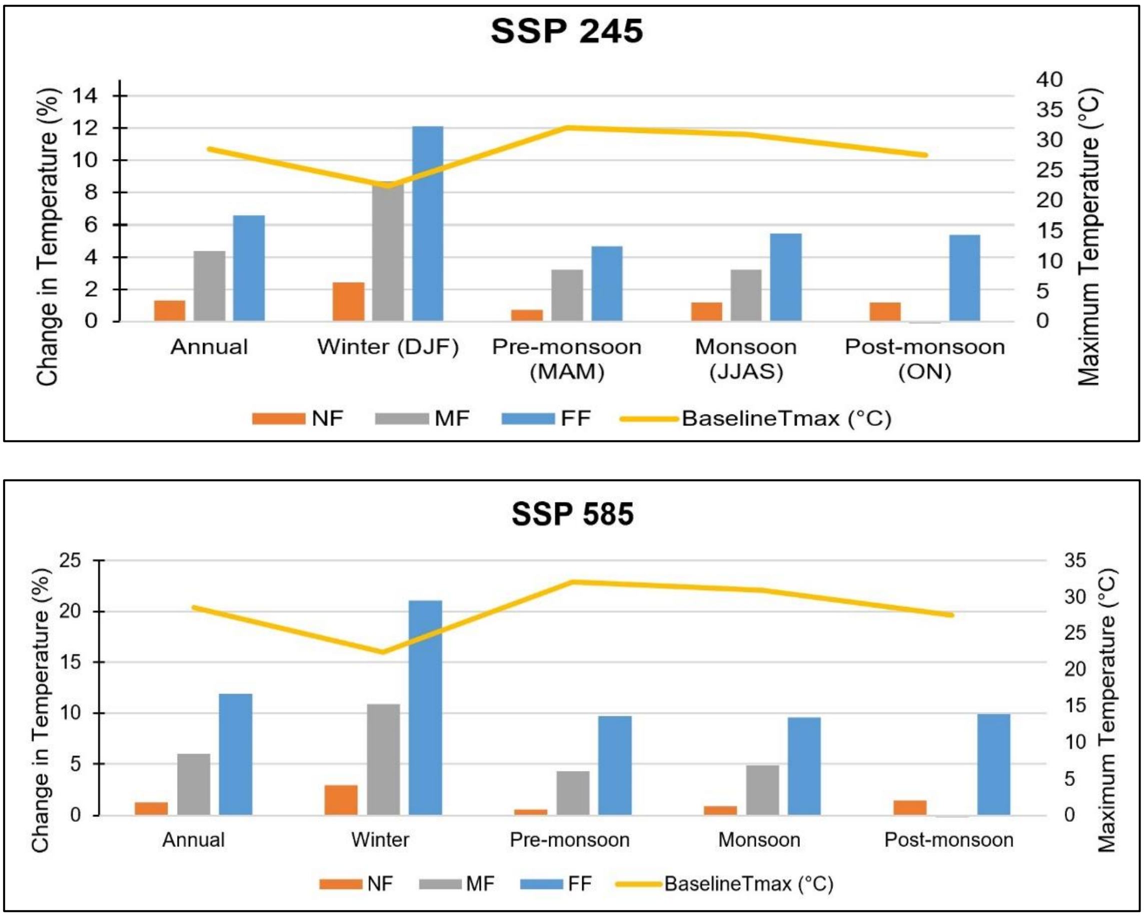
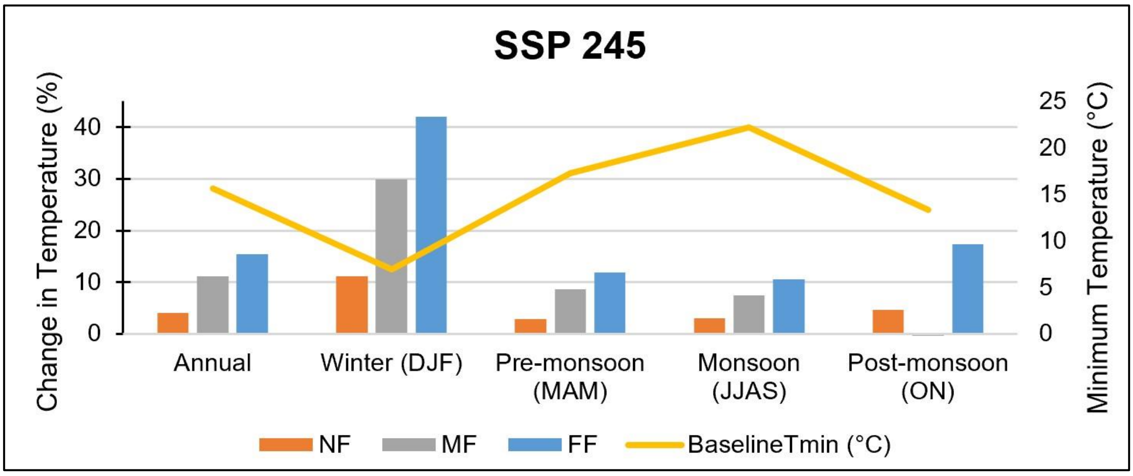


Figure 5.5: Percentage Change in Projected Max. Temperature at Ghorahi Station

Table 5.9: Seasonal Variation in Projected Minimum Temperature at Ghorahi Station

	Annual	Winter (DJF)	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ON)
Baseline T_{max}(°C)	15.67	6.95	17.25	22.18	13.38
SSP245-NF (%)	4.08	11.13	2.84	3.00	4.60
SSP245-MF (%)	11.10	29.99	8.66	7.39	-20.64
SSP245-FF (%)	15.38	42.03	11.92	10.50	17.38
SSP585-NF (%)	4.72	11.42	3.50	3.62	5.57
SSP585-MF (%)	15.44	40.55	11.80	10.80	-15.33
SSP585-FF (%)	29.61	79.70	23.30	20.18	33.79



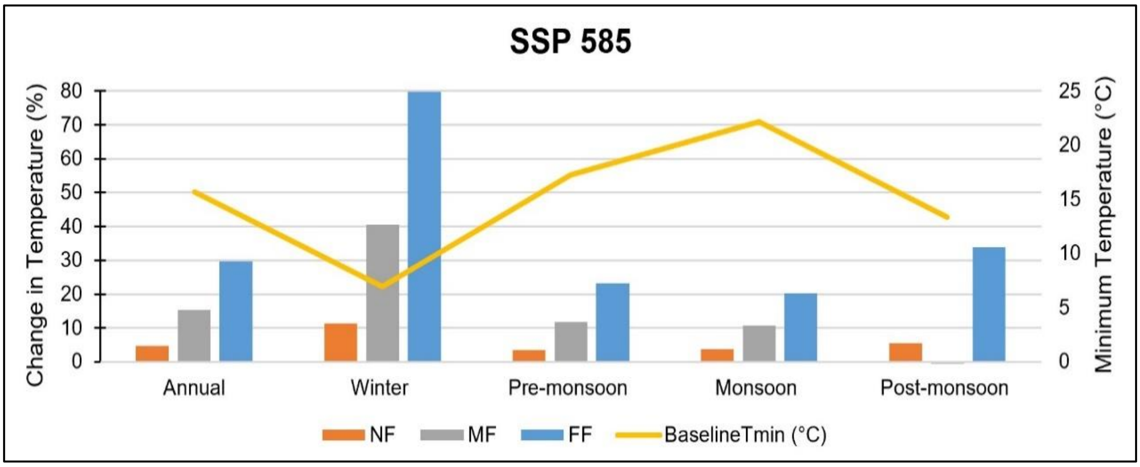


Figure 5.6: Percentage Change in Projected Min. Temperature at Ghorahi Station

5.2 Flow Projection

For Hydrological modelling, SWAT software was used in this study. For model setup, ArcSWAT version 2012 was used and for calibration and validation, SWAT-CUP version 2016 was used for this study. Hydrological model was developed in order to simulate daily discharge at outlets of interest. For hydrological model setup in SWAT, two hydrological station data and five climatological stations within or at vicinity of basin were taken for analysis. Two hydrological stations used for SWAT hydrological modelling works were Mari-khola/Nayagaon station (Station index no: 330) in Mari River and Bagasoti station (Station index no: 350) in Rapti river. Precipitation, Temperature and Discharge daily data for period 2000-2015 AD was used for this study. For calibration purpose, two hydrological outlet daily discharge for period 2002-2010 AD, and for validation purpose, daily hydrological data for period 2011-2015 AD were used.

5.2.1 SWAT model setup

Hydrological model setup was done in ArcSWAT v. 2012 interface in ArcGIS software. The necessary input data for SWAT model were DEM map, Land Use and Land Cover (LULC) map, and Soil and Terrain map which were prepared in Arc-GIS tool. Land Use and Soil Use Map were most important input for SWAT model as they were used to create and refine Hydrological Response Units (HRUs) in SWAT.

Firstly, watershed was delineated, stream was created, outlets was defined and sub-basin parameter were calculated in watershed delineator section in ArcSWAT. Then, on the HRUs analysis, land use, soils, slope of the basin were defined using DEM map, land use and land cover map, soil and terrain map as an input and by adding lookup table for land use and soil map to create a HRUs of a basin. The weather files were created as per SWAT weather input format (in form of pcp, temp forks) and they were loaded in SWAT model after updated in SWAT database by creating weather generator file (.wgen file). Then, model was setup in ArcSWAT after fulfilling all necessary steps and also editing few settings (example, changing to Hargevaes method for evapotranspiration estimation than simple method as it results better outputs).

After model setup, SWAT created a total of 33 sub-basin and 126 Hydrological Response Units (HRUs). The sub-basin map that the SWAT created was illustrated in the Figure 5.7.

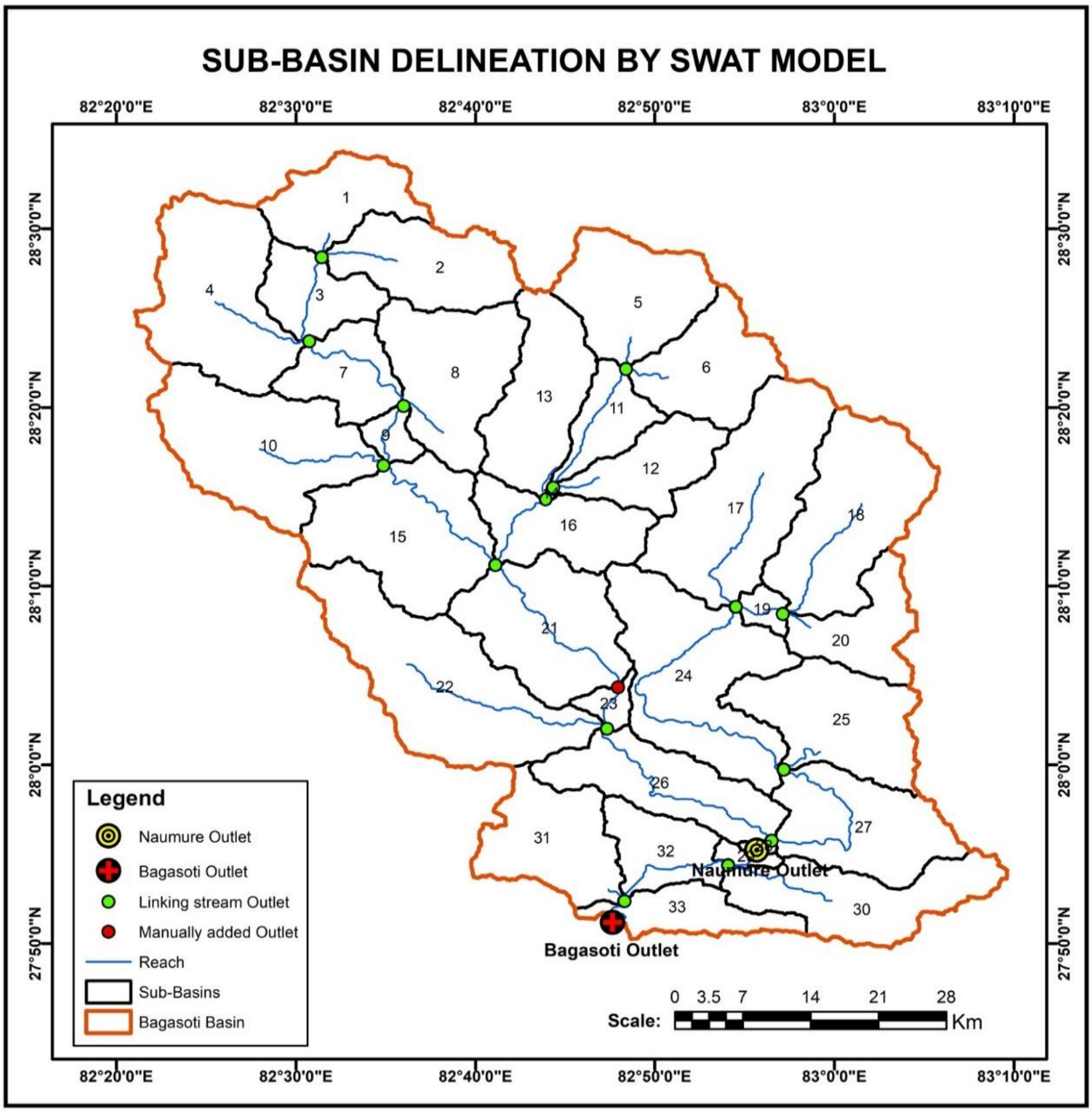


Figure 5.7: Sub-Basin Delineation by SWAT Model

The initial impression of SWAT-model was examined after checking SWAT error check and were noted which could be helpful in SWAT calibration and validation work.

5.2.2 Model Performance Evaluation

Calibration and validation work was carried out in SWAT-CUP software. For calibration, time period of 2000-2010 AD and for validation purpose, time period of 2011-2015 AD were used. For number of warm up period, initial two-year 2000-2001 AD was allocated. The calibration was performed using SUFI-2 optimization algorithm available in SWAT-CUP program. For performance check of calibration, performance evaluation parameters Nash-Sutcliffe efficiency (Ƞ), Coefficient of Determination (R^2), and Percentage of Bias (PBIAS) were used in this study.

For hydrological simulation in SWAT-CUP, different initial parameters were selected based on literature review, SWAT model outputs, dummy simulation result. The parameter that was mainly used in SWAT CUP calibration for this study belongs to surface runoff, ground water, soil, sub-basin parameters. The parameter that were considered in this study was illustrated in the Table 5.10.

Table 5.10: List of Parameters Used in SWAT Calibration Process

SN	Parameter	Description
1	CN2	SCS runoff curve number f
2	SOL_AWC	Available water capacity of the soil layer
3	SOL_K	Saturated hydraulic conductivity
4	CANMX	Maximum Canopy Storage
5	GWQMN	Threshold depth of water in the shallow aquifer required for return flow
6	GW_REVAP	Groundwater "revap" coefficient
7	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm).
8	GW_DELAY	Groundwater delay (days)
9	RCHRG_DP	Deep aquifer percolation fraction
10	ALPHA_BF	Baseflow alpha factor (days)
11	ALPHA_BNK	Baseflow alpha-factor for Bank storage (days)
12	CH_K2	Effective hydraulic conductivity in main channel
13	CH_N2	Manning's "n" value of main channel
14	SLSUBBSN	Average slope length
15	LAT_TTIME	Lateral flow travel time
16	HRU_SLP	Slope for Overland Flow
17	ESCO	Soil evaporation compensation factor
18	OV_N	Manning's "n" value for overland flow
19	PLAPS	Precipitation lapse rate
20	TLAPS	Temperature lapse rate

Using these parameter, Calibration and validation work was performed in daily time step at both Nayagaon and Bagasoti stations and in monthly time step at Bagasoti station. Many iterations, for each about 500 to 1500 simulations was performed and fairly good result was achieved. When calibrated in daily time scale, model seemed to underestimate peak flow at some points but had a good match for most of the flow. The Nash-Sutcliffe efficiency (Ƞ) of at least 0.75 for calibration and over 0.7 for validation and Coefficient of Determination (R^2) of at least 0.75 for both calibration and validation in both station outlet were achieved. While calibrating model in monthly time scale at Bagasoti station, simulated flow was almost matched with observed one with NSE of 0.88 for calibration and NSE of 0.83 for validation were achieved. The Flow Duration curve and long-term monthly flow plot between observed and simulated flow also show good correlation and was shown in Figure 5.11 to Figure 5.13.

The daily time scale calibration and validation result chart at both Mari-khola and Bagasoti stations were shown in Figure 5.8 and Figure 5.9 respectively.

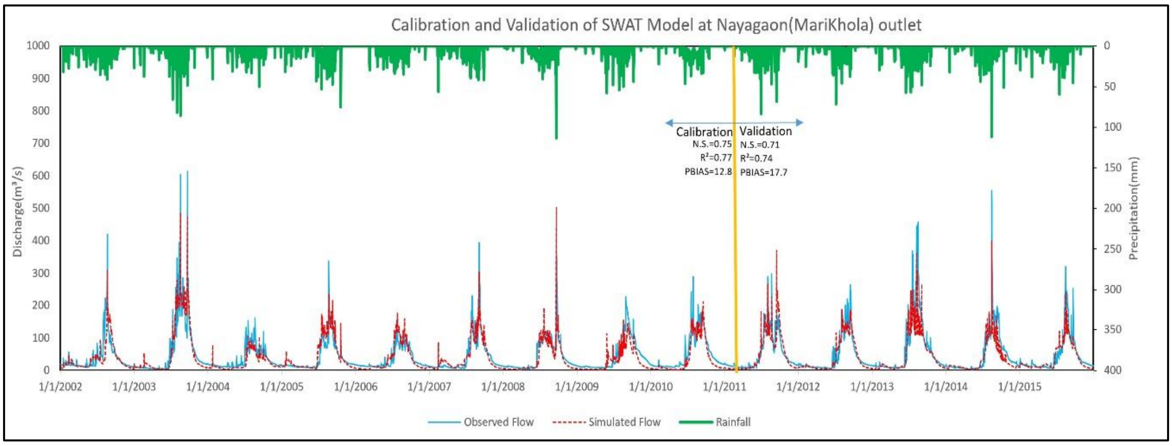


Figure 5.8: Calibration and Validation of SWAT Model at Marikhola Outlet

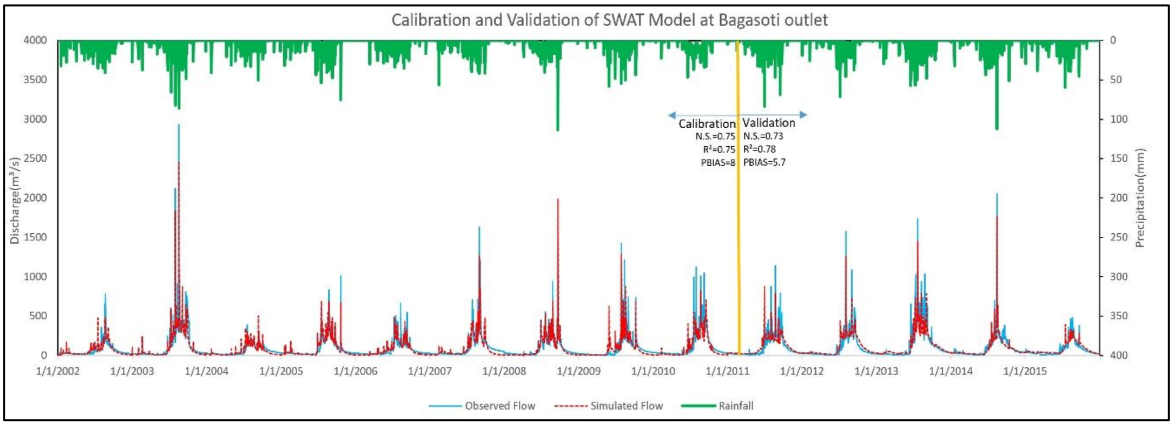


Figure 5.9: Calibration and Validation of SWAT Model at Bagasoti Outlet

The monthly time scale calibration and validation result chart at Bagasoti station was shown in Figure 5.10.

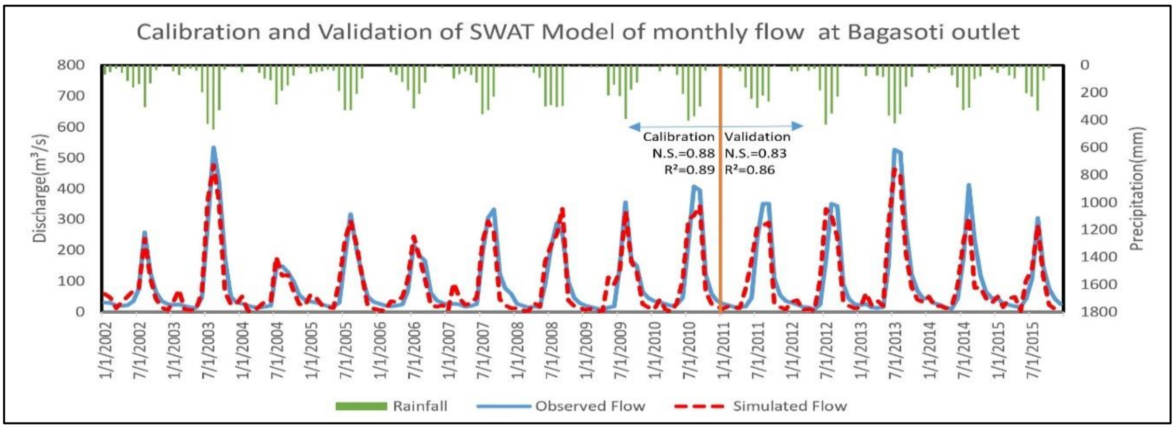


Figure 5.10: Monthly Calibration and Validation of SWAT Model at Bagasoti Outlet

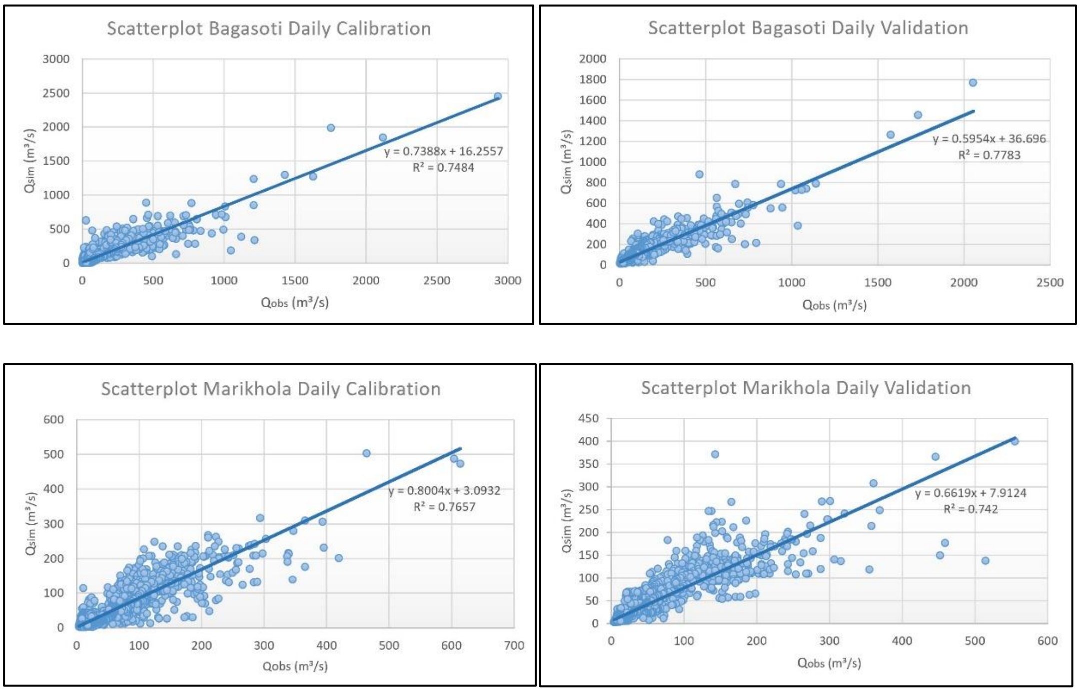


Figure 5.11: Scatterplot of Observed and Simulated Discharge at Marikhola and Bagasoti Outlets

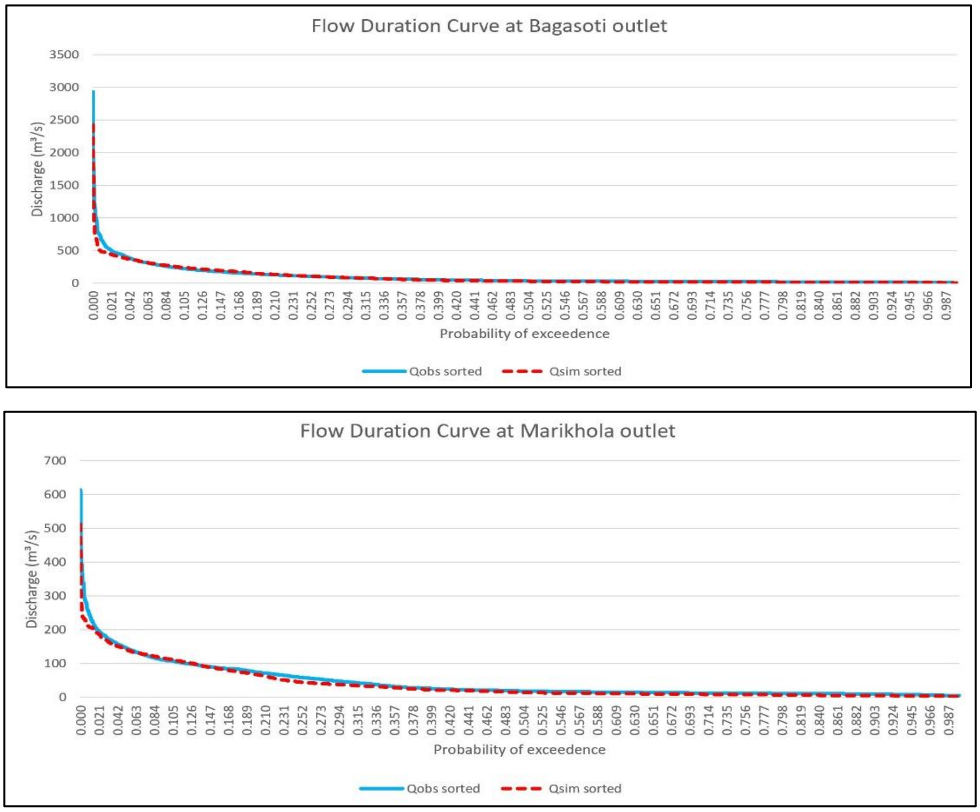
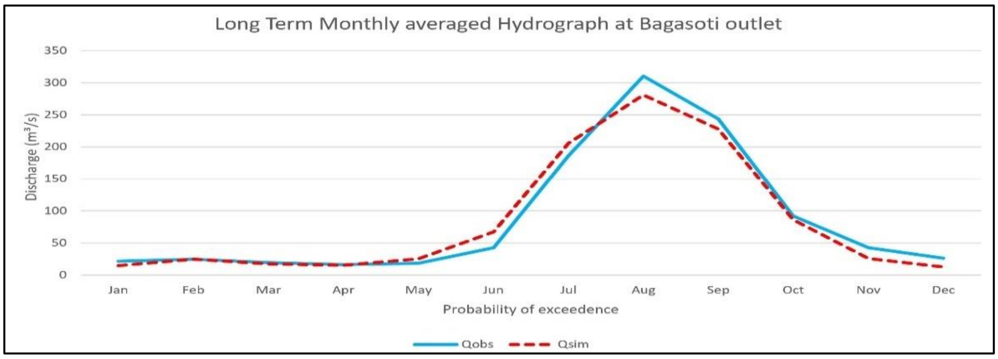


Figure 5.12: Observed and Simulated Daily Flow Duration Curve



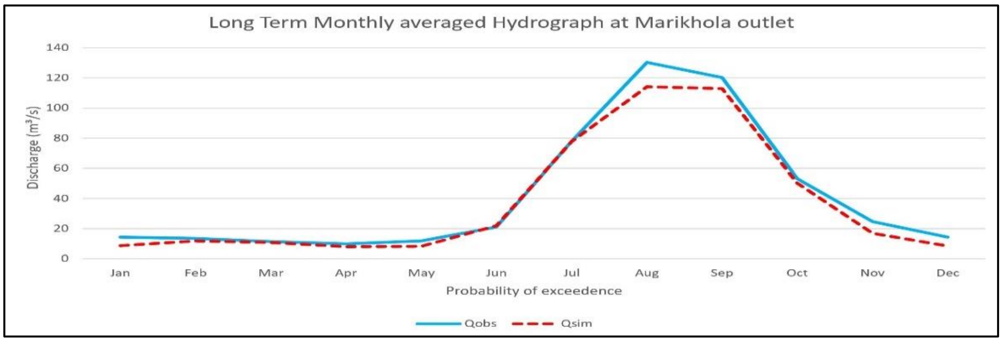


Figure 5.13: Observed and Simulated Long-term Monthly Averaged Hydrograph

Three performance indices: Nash-Sutcliffe efficiency (Ƞ), Coefficient of Determination (R^2), Percentage of Bias (PBIAS) were used to check performance of model. Moriasi statistical criteria indices values was used to categorize the model. According to Moriasi statistical criteria, if model has NSE and R^2 of more than 0.75 and PBIAS of less than 10%, model fall into 'very good' category while NSE and R^2 of more than 0.5 and PBIAS of less than 25% can be satisfactory acceptable model (Moriasi, et al., 2015). The performance parameter indices values of our model were shown in Table 5.11 and Table 5.12. Most of above indices value were fall in 'very good' category which shows that model have 'very good' performance rating. So, model can be used for further analysis and future prediction/projection works.

Table 5.11: Performance Parameter Indices Value for Daily Calibration

Station	Calibration			Validation		
	NSE(Ƞ)	R^2	PBIAS	NSE(Ƞ)	R^2	PBIAS
MariKhola station (330)	0.75	0.77	12.8	0.71	0.74	17.7
Bagasoti station (350)	0.75	0.75	8	0.73	0.78	5.7

Table 5.12: Performance Parameter Indices Value for Monthly Calibration

Station	Calibration			Validation		
	NSE(Ƞ)	R^2	PBIAS	NSE(Ƞ)	R^2	PBIAS
Bagasoti station (350)	0.88	0.89	4.1	0.83	0.86	5.9

5.2.3 Sensitivity Analysis

Sensitivity analysis was performed in global sensitivity analysis of SWAT-CUP. They were performed to know the most influencing parameter among all the initial parameter that are selected initially through model setup initial result, literature review, basin characteristics for hydrological modelling. These most influencing and sensitive parameter were then analyzed and calibrated carefully so that good model performance can be achieved. Sensitive parameters are categorized based on t-stat and p-values in SWAT-CUP. The parameter having high t-stat values represent most sensitive parameter and low p-values (as close to zero) indicates the parameter having high significance of sensitivity (Abbaspour, 2015).

Parameter belonging to main channel properties, HRUs-related and ground water parameters were found most sensitive. The 10 most sensitive parameter were listed below.

Table 5.13: Most Sensitive Parameters and their Fitted Value from SWAT Calibration

RANK	Parameter	t-Stat	P-Value	Fitted_Value	Min_value	Max_value
1	V__ALPHA_BNK.rte	17.98526	9.47E-63	0.216717	0	1
2	V__CH_K2.rte	-9.33565	6.48E-20	32.657658	0	250
3	V__CH_N2.rte	-7.30608	5.68E-13	0.171622	0	0.3
4	V__LAT_TTIME.hru	-2.31336	0.020908	9.459459	0	180
5	V__CANMX.hru	-1.85508	0.063884	77.427429	0	100
6	V__SLSUBBSN.hru	1.60935	0.107861	32.772774	10	150
7	V__GWQMN.gw	-1.24943	0.211804	2170.670654	0	3000
8	R__CN2.mgt	1.242836	0.214224	0.175776	-0.2	0.2
9	R__SOL_K(..).sol	-0.90153	0.367528	-0.022222	-0.3	0.3
10	V__ALPHA_BF.gw	-0.74458	0.456705	0.752252	0	1

5.2.4 Future Flow Scenario

Flow was projected from 2016 to 2100 AD in same SWAT hydrological model using the projected future precipitation and temperature time series data which was generated from ensemble of the six GCMs model in previous climate modelling section. The future flow was deduced at Naumure dam point location. The projected flow was then analyzed in both annually and season wise for all three futures (Near Future, Mid Future, Far Future) under both scenarios SSP245 and SSP585. Both annual and season wise projected flow in all three futures were compared with baseline flow of 2002-2015 AD to analyze the changes and deviations in future flow.

Result shows that average annual flow increases in all future under both SSP245 and SSP585 scenario. Flow increases by 25.24%, 51.21% and 49.75% in NF, MF, FF future respectively under scenario SSP245 and by 119.01%, 117.59% and 179% in NF, MF, FF future respectively under scenario SSP585. Seasonal-wise analysis shows that projected flow increases in all season under both scenario except in winter season under SSP245 scenario. Flow decreases by up to 23% in winter season in NF future under SSP245 scenario. While flow increases in all other season in all future under SSP245 scenario where monsoon of MF future has maximum increase of flow by 62% as shown in table and figure below. Flow increases in all season in all future under SSP585 scenario where flow increase by minimum of 14% in MF future of winter season to maximum of 459% in FF future of monsoon season. The detail of change of projected flow under both scenario SSP245 and SSP585 was shown in table and figure below.

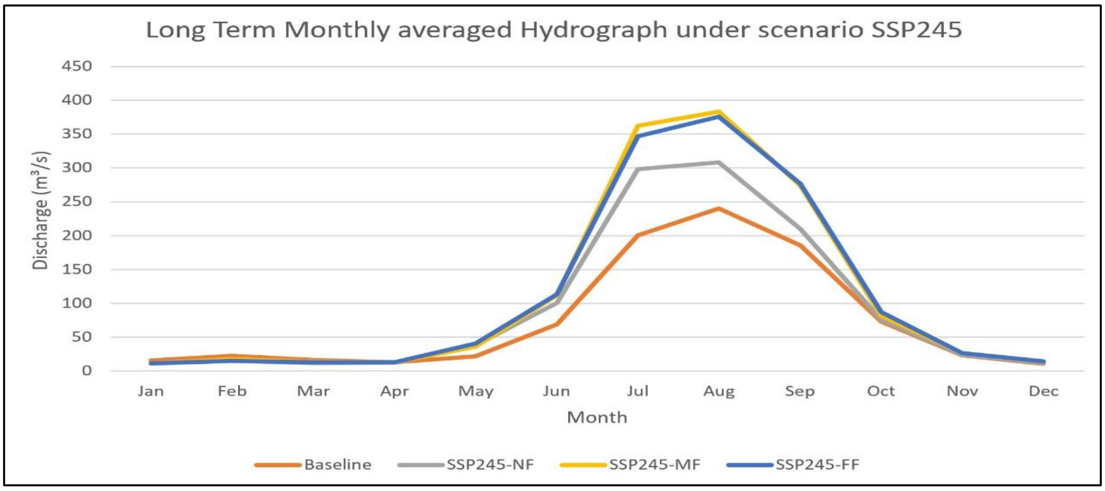


Figure 5.14: Long-term Monthly Averaged Hydrograph under Scenario SSP245

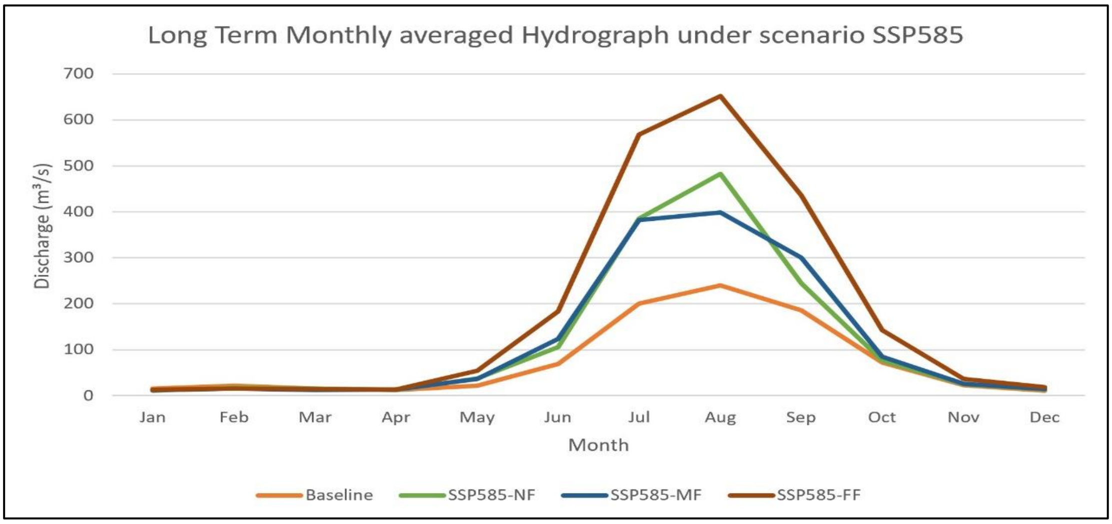


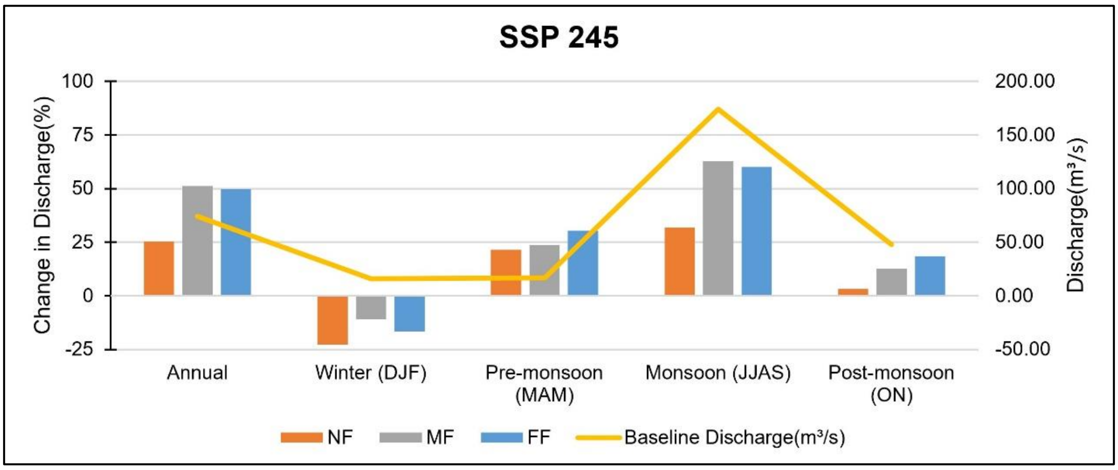
Figure 5.15: Long-term Monthly Averaged Hydrograph under Scenario SSP585

Table 5.14: Long-term Monthly Averaged Projected Flow on Different Futures

Month	Baseline Q	SSP245-NF	SSP245-MF	SSP245-FF	SSP585-NF	SSP585-MF	SSP585-FF
Jan	15.36	10.46	11.32	11.52	11.09	11.76	13.39
Feb	22.11	14.91	17.36	14.5	18.09	15.77	15.84
Mar	15.96	11.62	13.54	12.71	15.39	12.42	14.11
Apr	12.81	11.87	12.87	12.97	12.39	13.3	13.71
May	21.69	37.82	35.93	40.07	37.73	36.77	54.01
Jun	68.89	100.33	112.13	113.51	106.34	123.87	183.75
Jul	200.05	298.36	383.4	346.87	482.96	388.99	651.86
Aug	240.39	308.22	362.15	375.73	385.48	382.14	568.22
Sep	185.77	209.66	274.3	276.48	244.75	300.62	435.18
Oct	72.73	75.67	81.4	87.03	76.03	85.09	142.47
Nov	23	23.18	26.48	26.46	24.63	26.05	36.65
Dec	10.75	11.93	14.22	14.25	13.2	14.3	18.78

Table 5.15: Percentage Change in Projected Flow on Different Season in Future

Future-scenario	Annual	Winter (DJF)	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ON)
Baseline Q(m^3/s)	74.13	16.07	16.82	173.78	47.87
SSP245-NF (%)	25.24	-22.65	21.52	31.86	3.26
SSP245-MF (%)	51.21	-11.01	23.54	62.85	12.68
SSP245-FF (%)	49.75	-16.49	30.32	60.06	18.55
SSP585-NF (%)	119.01	14.13	21.84	304.88	50.33
SSP585-MF (%)	117.59	13.94	20.83	298.91	55.57
SSP585-FF (%)	179	16	27.28	459.75	89.56



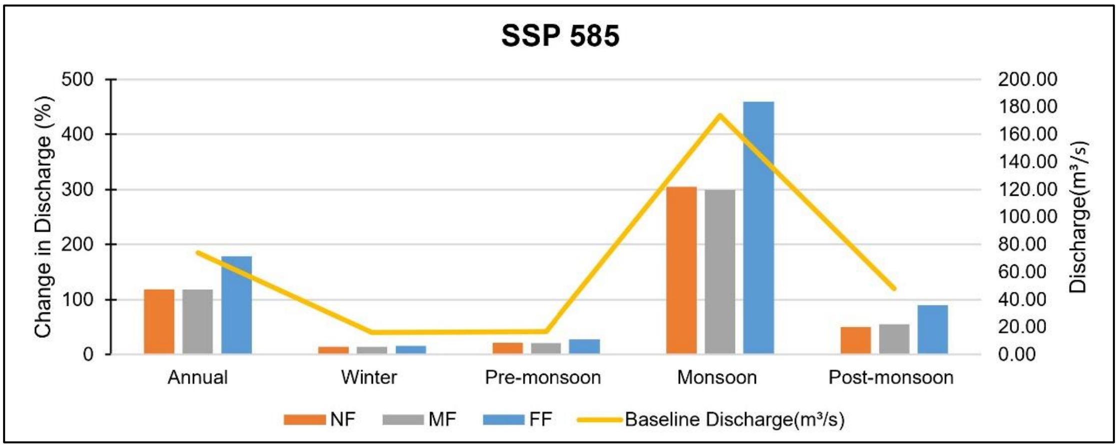


Figure 5.16: Seasonal Variation in Projected Flow at Naumure Dam Site

This projected flow result was used for further analysis of this study in reservoir modelling and simulation section to evaluate power, energy generation, irrigation supply in future of Naumure Multipurpose Project to assess the level of impact of climate change and to develop the adaptation strategies, if necessary.

5.3 Reservoir Simulation

Reservoir Simulation of Naumure reservoir was performed in HEC-ResSim modelling software. Naumure reservoir is for multi-purpose projects. Projects include number of hydropower schemes along with irrigation projects. Water allocation for each sub-projects will be done from same reservoir. Under this multi-purpose project, three hydro schemes are proposed namely, Naumure Hydro Scheme 218.34 MW, Lamatal Hydro Scheme 8 MW, and Surainaka Hydro Scheme 54.7 MW and one irrigation scheme named Kapilvastu irrigation project (29,736 ha) is proposed. Two existing irrigation projects: Deukhuri irrigation project (10,800 ha) and Banke irrigation project (42,766 ha) lies very far downstream of the same river. Project schematic diagram, reservoir data, hydropower production data, H-A-V curve are important input data for HEC-ResSim modelling work. The schematic framework of Naumure Multipurpose Project is shown in flowchart diagram in Figure 5.17.

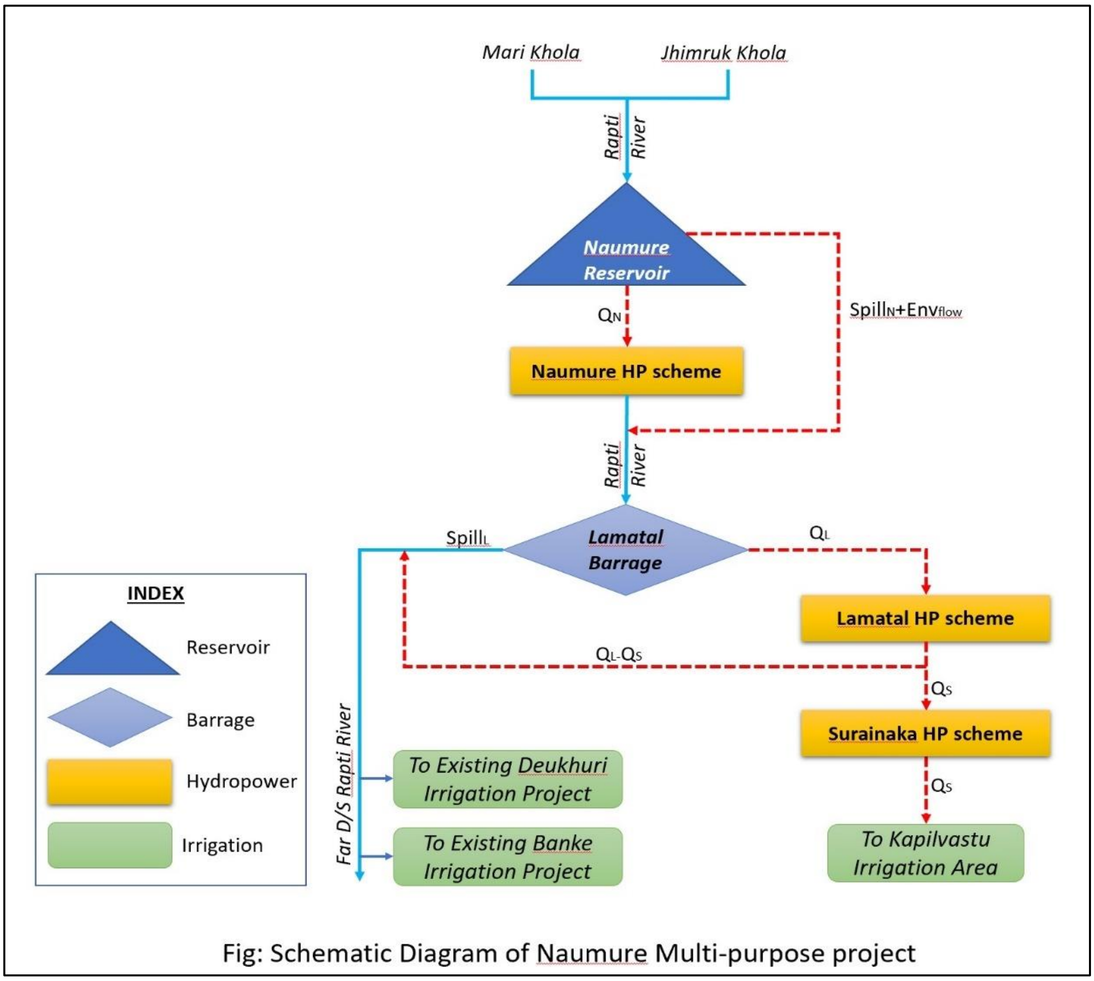


Figure 5.17: Schematic Diagram of Naumure Multipurpose Project

Source: Naumure executive summary report,2021

5.3.1 HEC-ResSim Model Development

Using project schematic flow diagram, H-A-V curve, reservoir and hydropower production data, reservoir model was setup in HEC-ResSim software. HEC-ResSim model comprises of three set of modules which are watershed module, reservoir network module and the simulation module. In the watershed module, schematic representations of the project's physical components like reservoir, stream, diversion, computational points were linked and watershed configuration was created. In reservoir network module, stream reaches and project components like reservoir, diversion were connected through reach element tool in the watershed configuration created in watershed module and physical and operational data of reservoir and all necessary data are added in this section. By the creation of alternatives, all hydrological time series data of desired time period of analysis at required computational points, reservoir initial state and other initial release and flow data were added in this section. Then, finally at simulation module, model was simulated for desired period and all result were viewed and analyzed in this section.

In this study, HEC-resSim model setup include one reservoir which is Naumure reservoir for Naumure hydropower scheme, computational point for Lamatal barrage for Lamatal hydropower scheme, one diversion which is Lamatal diversion where flow is diverted to Surainaka hydropower scheme and then same flow transferred to Kapilvastu irrigation project and other computational points for inflow to Naumure reservoir, additional flow to Lamatal barrage and outflow to downstream of Rapti river. Monthly hydrological time series discharge data was added for baseline period from 2002 to 2015 AD and for future 2016 to 2100 AD under both scenario SSP245 and SSP585 by creating multiple alternatives. Baseline operational rule curve was taken from executive summary report and added to model. The HEC-ResSim model setup developed for this study was shown in Figure 5.18 below.

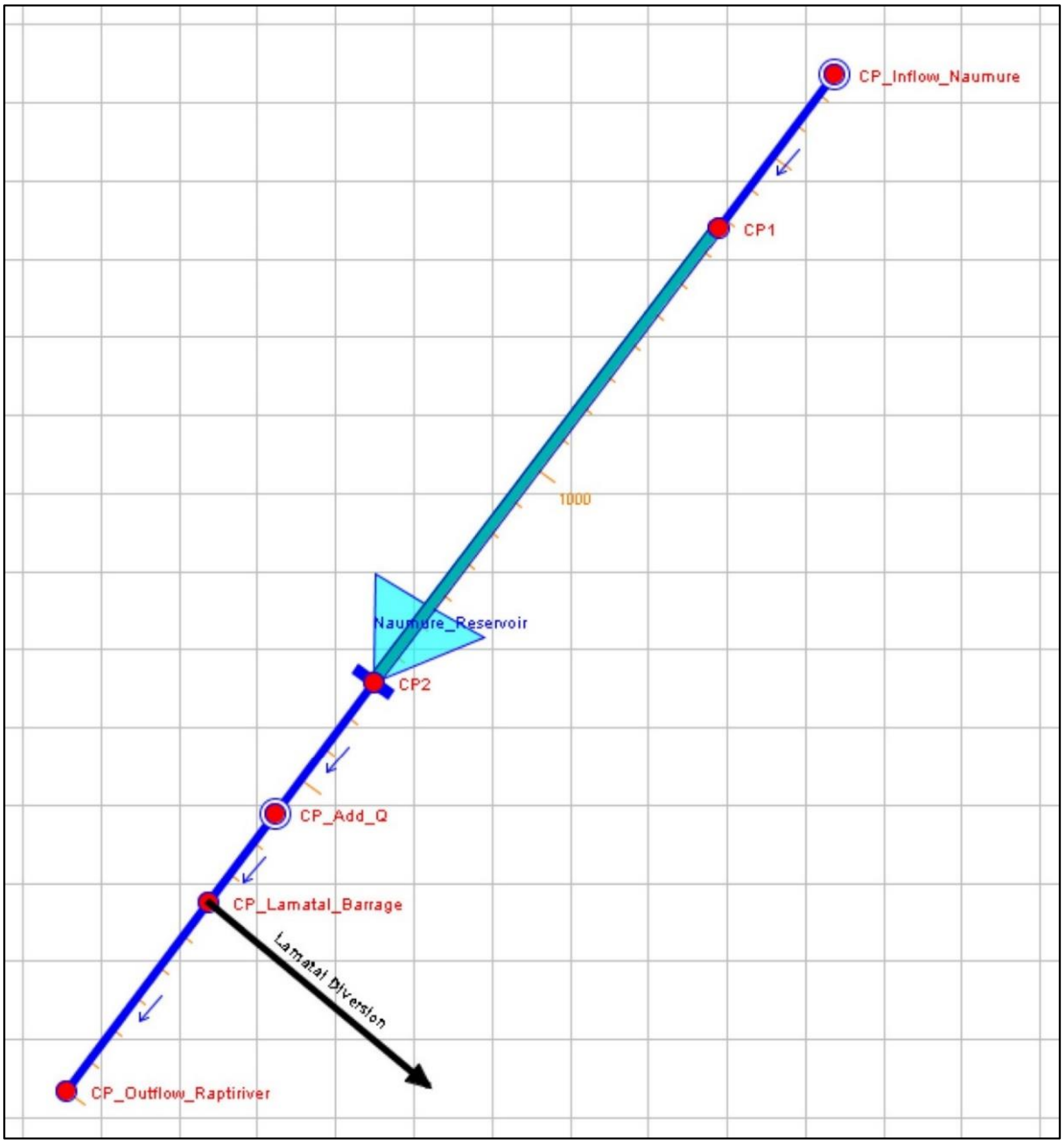


Figure 5.18: HEC-ResSim Model Setup

5.3.2 Future Reservoir Operation

After model was setup, simulation was done for baseline period from 2002 to 2015 AD and for future 2016 to 2100 AD under both scenario SSP245 and SSP585 using monthly hydrological time series data. Hydropower energy generation was projected in all three futures (NF, MF, FF) under both scenario SSP245 and SSP585, and compared with baseline period along with analysis of available water for irrigation supply to deduce level of climate change impact. The elevation and flow curve for baseline and future simulation was shown in Figure 5.19 to Figure 5.21 below.

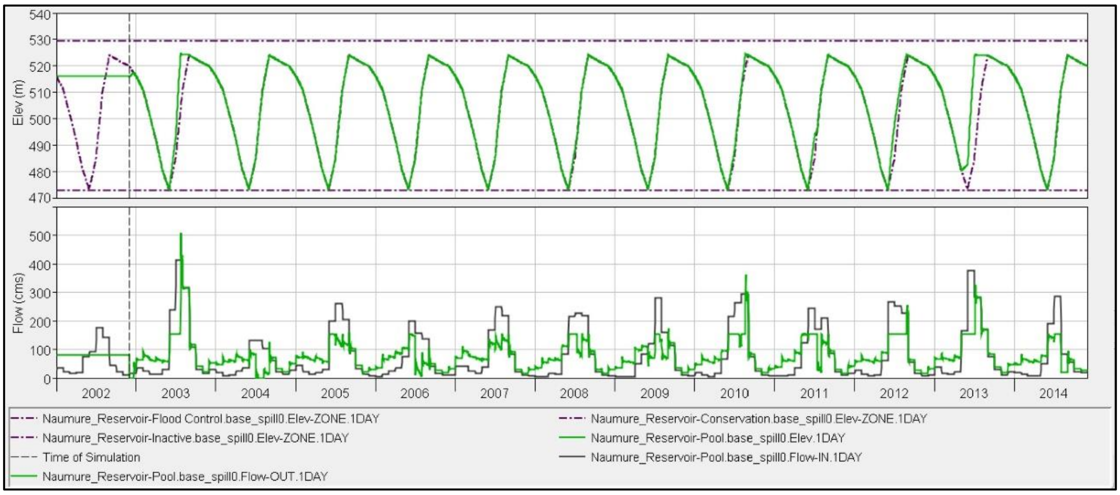


Figure 5.19: Elevation and Flow Curve of Naumure Reservoir for Baseline Period

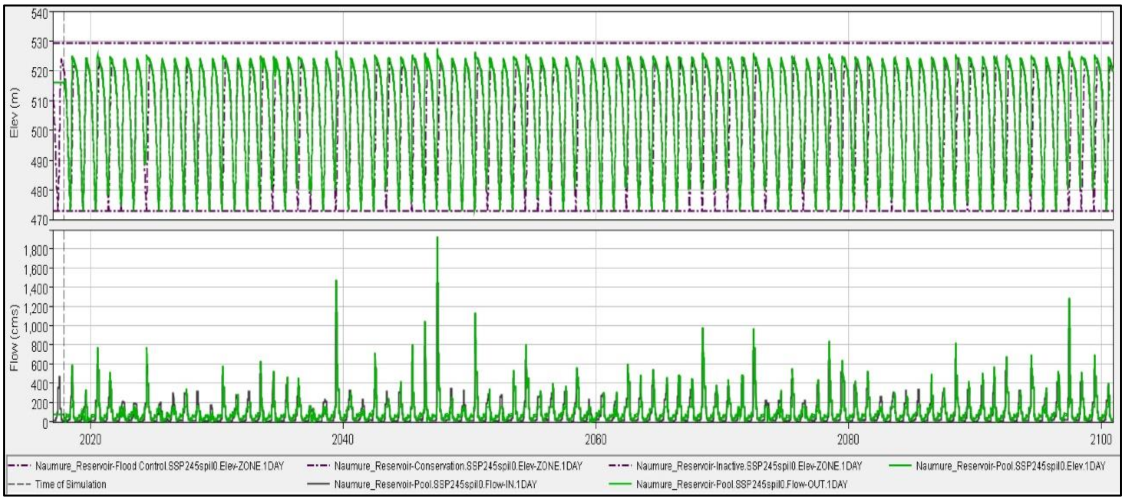


Figure 5.20: Elevation and Flow Curve of Naumure Reservoir under SSP245 Scenario

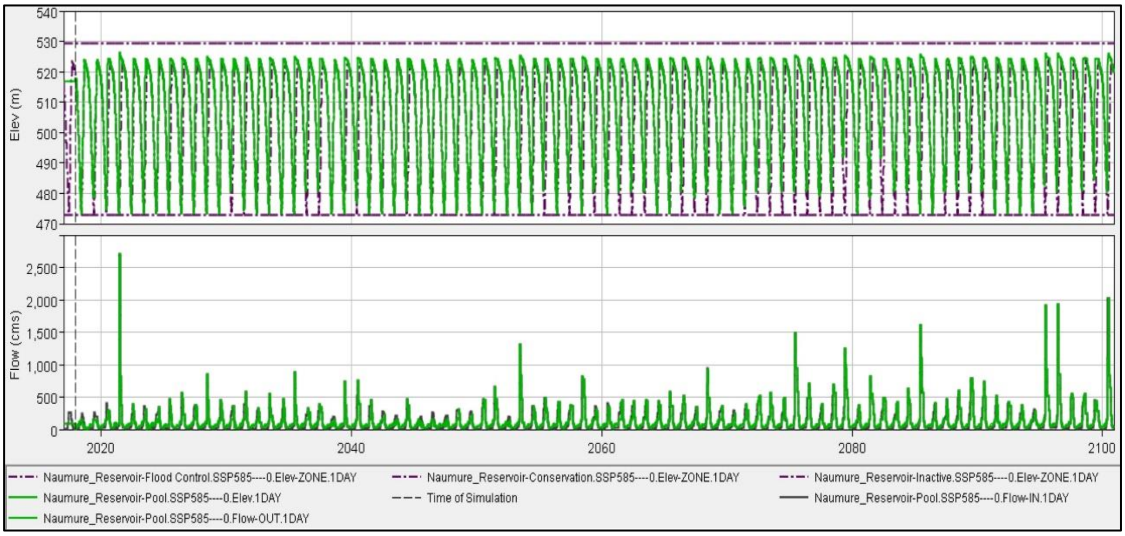
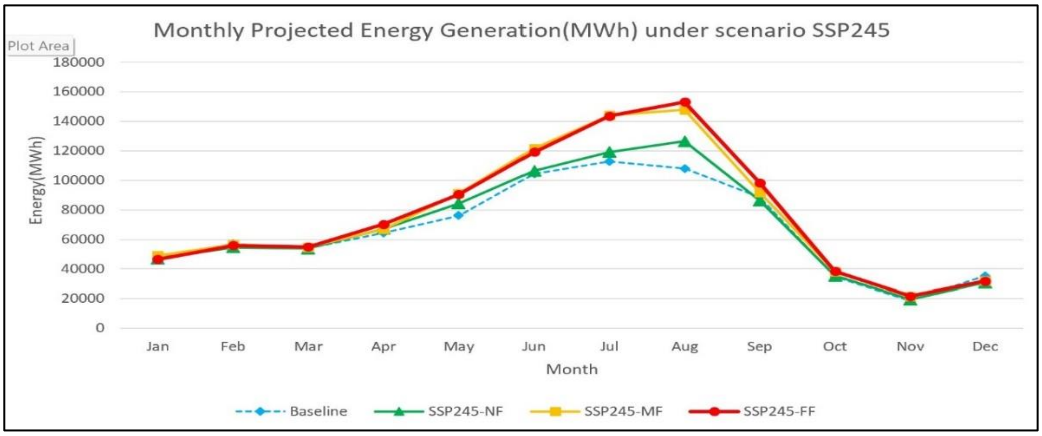


Figure 5.21: Elevation and Flow Curve of Naumure Reservoir under SSP585 Scenario

The projected future hydropower generation of Naumure hydropower scheme was compared with the baseline annual generation of 802.3 GWh and presented in table below. The percentage change in the generation in all future increases from 3.55% to 26.37% with maximum increase being in FF future under Scenario SSP585 and minimum increase being in NF future under scenario SSP245. Month wise analysis shows decrease in hydropower generation in some month of winter season of NF and MF future of both scenario while in almost all other months of future, energy generation quite increases. Seasonal variation shows that hydropower generation will decrease in winter season under scenario SSP245 with maximum decrease of 5.81% in winter of NF under scenario SSP245 whereas in all other season of future under both scenarios, the hydropower generation increases with maximum increase of 37.48% in Monsoon season of FF future under scenario SSP585. Further, details of projected hydropower generation yearly, monthly and season-wise in Naumure hydropower scheme was illustrated in the figures and table below.



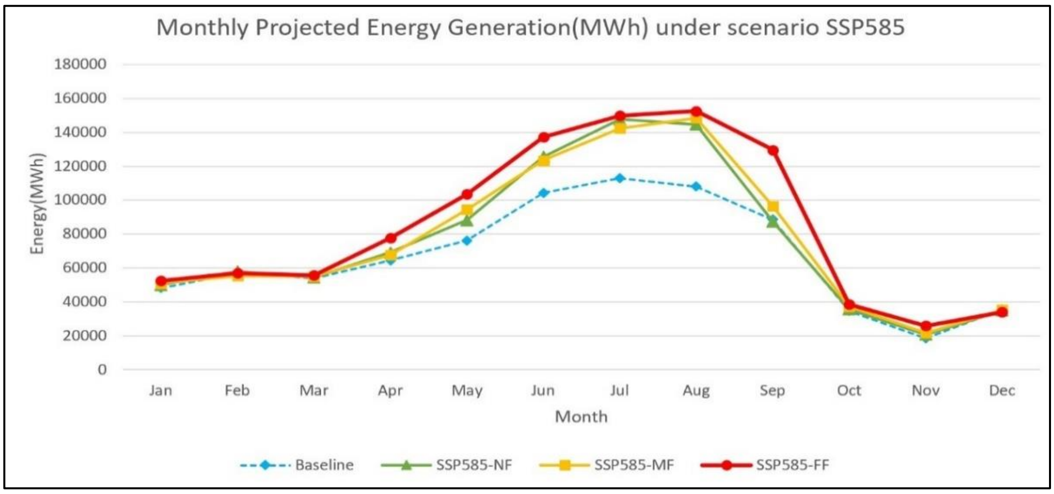


Figure 5.22: Monthly Averaged Projected Future Hydropower Generation of Naumure Hydropower under Both Scenarios with Baseline Generation

Table 5.16: Monthly Projected Energy Generation at Naumure Hydropower at Different Futures

Month	Baseline Energy (GWh)	SSP245-NF	SSP245-MF	SSP245-FF	SSP585-NF	SSP585-MF	SSP585-FF
Jan	48.243	47.012	49.154	46.499	50.052	51.048	52.59
Feb	57.103	54.689	56.462	55.853	58.024	55.491	56.986
Mar	54.022	53.82	54.721	54.954	54.374	55.075	55.608
Apr	64.436	67.158	66.892	70.243	69.137	67.62	77.841
May	76.2	84.266	91.233	90.402	88.211	94.576	103.579
Jun	104.427	106.465	121.697	119.373	125.494	123.478	137.183
Jul	112.952	119.316	144.237	143.734	147.743	142.493	149.929
Aug	108.023	126.484	147.931	153.171	144.541	148.44	152.507
Sep	88.658	86.226	91.761	98.344	87.437	96.38	129.611
Oct	34.581	35.363	38.017	38.372	35.703	37.293	38.501
Nov	18.601	19.469	21.604	21.674	20.695	21.675	25.902
Dec	35.394	30.868	31.975	31.831	35.063	35.305	34.028

**all energy is in GWh.*

Table 5.17: Seasonal-Wise Energy Generation at Naumure Hydropower at Different Futures

Energy (GWh)	Annual	Winter (DJF)	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ON)
Baseline	802.64	140.74	194.66	414.06	53.18
SSP245-NF	831.13	132.57	205.24	438.49	54.83
SSP245-MF	915.69	137.59	212.85	505.63	59.62
SSP245-FF	924.45	134.18	215.6	514.62	60.05
SSP585-NF	916.47	143.14	211.72	505.21	56.4
SSP585-MF	928.87	141.84	217.27	510.79	58.97
SSP585-FF	1014.26	143.6	237.03	569.23	64.4

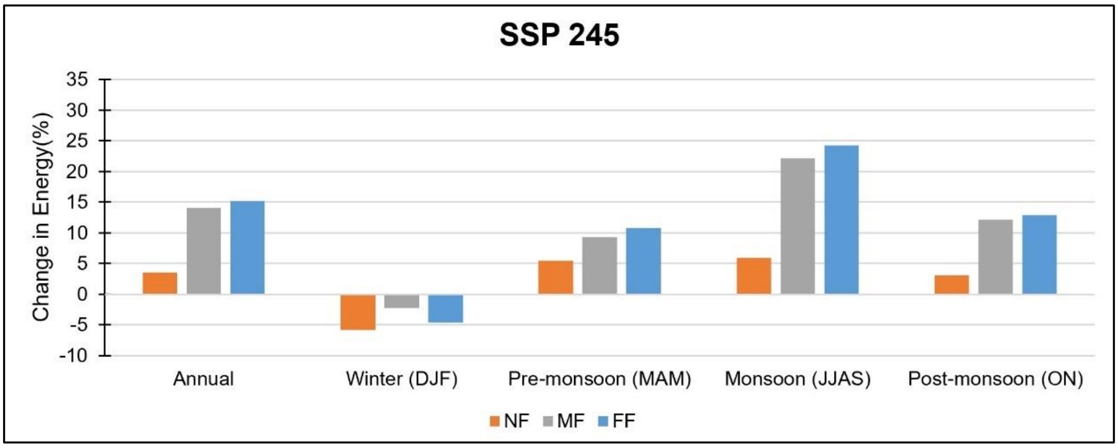


Figure 5.23: Percentage Change in Seasonal Energy Generation at Naumure Hydropower Scheme under Scenario SSP245

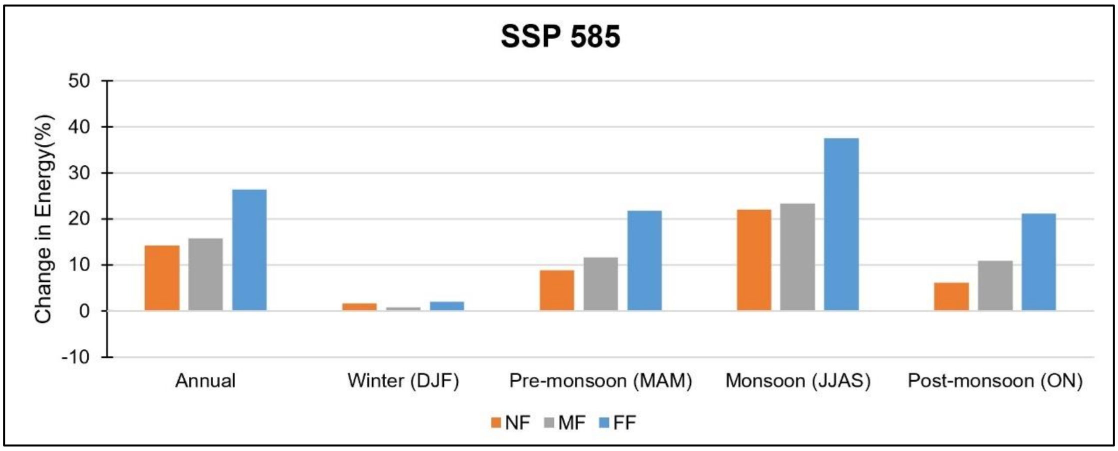


Figure 5.24: Percentage Change in Seasonal Energy Generation at Naumure Hydropower Scheme under Scenario SSP585

At Lamatal hydropower scheme, the energy of about 41.38 GWh was generated at baseline period while the projected energy generation seems to increase in all futures between 2.97% to 13.34%. Similarly, at Surainaka hydropower scheme, the energy of about 376.9 GWh was generated at baseline period while the projected energy generation seems to increase in all futures between 0.29% to 2.17%. Regarding irrigation demand and supply at Kapilvastu irrigation project, project seems to meet required demand in all futures. The projected future hydropower generation from all scheme with its percentage change to baseline generation was shown in Table 5.18.

In a nutshell, combining energy generation from all hydropower scheme, the projected energy generation increases by up to 18% while also meeting irrigation demand at Kapilvastu irrigation project on all futures. This shows that there will be minimal negative climate change impact on Naumure Multipurpose Project. The overall summary was presented in Table 5.19.

Table 5.18: Projected Future Hydropower Generation Summary Compared with the Baseline Generation

Scheme	Scenario	Hydropower generation(GWh)				Percentage change in generation(%)		
		Baseline	NF	MF	FF	NF	MF	FF
Naumure hp	SSP245	802.64	831.13	915.69	924.45	3.55	14.08	15.18
	SSP585		916.47	928.87	1014.26	14.18	15.73	26.37
Lamatal hp	SSP245	41.38	42.61	43.93	44.29	2.97	6.16	7.03
	SSP585		43.48	44.07	46.9	5.07	6.5	13.34
Surainaka hp	SSP245	376.9	378.01	384.76	385.09	0.29	2.09	2.17
	SSP585		383.77	384.2	384.02	1.82	1.94	1.89

Table 5.19: Overall Energy Generation and Irrigation Status Summary

Scenario	Period	Total Hydropower generation(GWh)		Kapilvastu Irrigation Demand(Mm³)		
		Naumure+Lamatal+Surainaka hp	% change	Irrigation Demand	Available supply	% monthly meet
Baseline	-	1220.92	-	647	1065.949	91.67
SSP245	NF	1251.75	2.53	647	1062.817	100
	MF	1344.38	10.11	647	1081.888	100
	FF	1353.83	10.89	647	1082.777	100
SSP585	NF	1343.72	10.06	647	1078.904	100
	MF	1357.14	11.16	647	1080.237	100
	FF	1445.18	18.37	647	1079.831	100

5.3.3 Adaptation strategy: Modification of Rules Curves

It looked like the baseline operational rule works satisfactory in all the futures as targeted annual energy was generated and irrigation demand was met in all futures. Therefore, it might not be necessary to modify rule curve for future scenario. However, to maximize generation based on future scenario and to increase seasonal dry energy production, rule curve can be somewhat modified and recommended as an adaptation option to changing climate scenario of future.

Depending upon future flow projection, seasonal flow distribution, future meteorological changes and shift, baseline operational rule curve of Naumure reservoir was modified in such a way it tries to suit well with future climatic changes. In a way, total of eight rule curves were created whose corresponding monthly reservoir elevation level is shown in Figure 5.25.

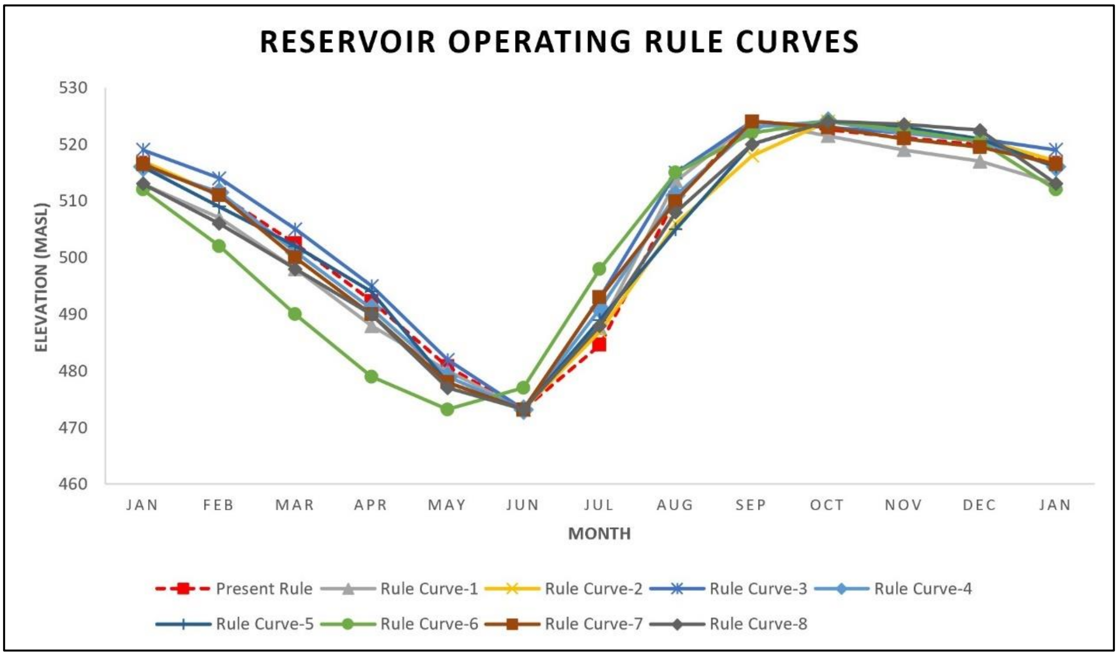


Figure 5.25: Modified Reservoir Operating Rule Curves for Naumure Reservoir

Each of the rule curve was simulated on the same reservoir model and its corresponding annual hydropower generation was compared with baseline annual generation of 802.64 GWh for different period of future as shown in the Table 5.20.

Table 5.20: Comparison of Hydropower Generation by Modified Rules Curves with the Baseline Generation at Naumure Hydro Scheme

Rule-curve	Scenario	Baseline GWh/yr	Hydropower generation(GWh/yr)			Percentage change in generation(%)		
			NF	MF	FF	NF	MF	FF
Present	SSP245	802.64	831.13	915.69	924.45	3.55	14.08	15.18
	SSP585		916.47	928.87	1014.26	14.18	15.73	26.37
Rule-1	SSP245		830.54	913.4	931.71	3.48	13.8	16.08
	SSP585		911.88	928.14	1017.03	13.61	15.64	26.71
Rule-2	SSP245		831.08	916.59	936.44	3.54	14.2	16.67
	SSP585		913.37	928.23	1016.64	13.8	15.65	26.66
Rule-3	SSP245		835.07	916.48	942.43	4.04	14.18	17.42
	SSP585		914.54	931.49	1018.66	13.94	16.05	26.91
Rule-4	SSP245		833.39	916.58	922.66	3.83	14.2	14.95
	SSP585		912.98	930.52	1021.16	13.75	15.93	27.23
Rule-5	SSP245		831.57	917.08	934.87	3.6	14.26	16.47
	SSP585		911.84	929.08	1018.75	13.61	15.75	26.92
Rule-6	SSP245		829.12	907.62	911.87	3.3	13.08	13.61
	SSP585		902.24	924.4	1011.04	12.41	15.17	25.96
Rule-7	SSP245		833.45	915.79	936.44	3.84	14.1	16.67
	SSP585		912.6	929.86	1015.36	13.7	15.85	26.5
Rule-8	SSP245		833.11	916.31	940.87	3.8	14.16	17.22
	SSP585		911.18	928.43	1017.75	13.52	15.67	26.8

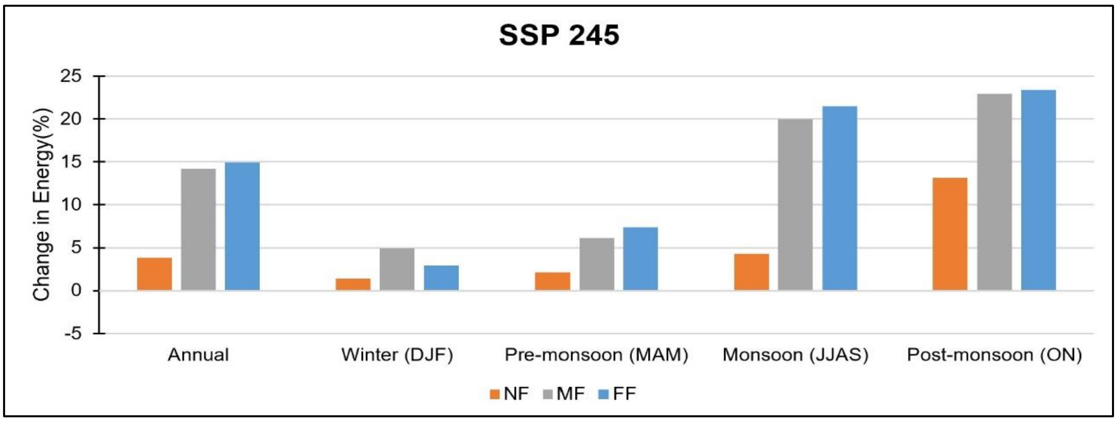
The hydropower generation of Naumure hydro scheme in all of the modified rule curves seems to be increasing within the range of 3.3% to 27.23% as shown in table above. Even though hydropower energy generation seems increasing annually in all of the modified rule curve, however season wise generation analysis suggests that only rule curves 2, 4, 5 and 7 has increasing trend of energy generation in all of the season of the future while other rule curve has decrease in energy generation in at least one of the seasons especially in either winter or post monsoon season when compared with baseline seasonal energy generation. Regarding deficit of energy generation at winter season of NF future under SSP245 scenario by baseline operational rule curve, Rule curves: Rule 2, 4, 5 and rule 7 can be recommend and suitably applied as a reservoir operational rule curve when we consider Naumure hydro scheme only.

The seasonal energy generation and percentage change in generation compared with baseline at different period of future as per rule 4 and rule 7 at Naumure hydro scheme was shown in Table 5.21 and Table 5.22, and in Figure 5.26 and Figure 5.27 below.

Table 5.21: Seasonal Variation in Energy Generation of Naumure Hydro Scheme in Future as per Rule Curve 4

Season	Baseline	SSP245-NF	SSP245-MF	SSP245-FF	SSP585-NF	SSP585-MF	SSP585-FF
Winter	140.74	142.68	147.7	144.86	151.7	146.42	148.92
Pre-Monsoon	194.66	198.75	206.62	209.05	205.25	212.27	243.57
Monsoon	414.06	431.78	496.87	503.14	489.31	506.3	553.75
Post-Monsoon	53.18	60.18	65.39	65.61	66.72	65.53	74.92
Annual Energy	**802.64**	**833.39**	**916.58**	**922.66**	**912.98**	**930.52**	**1021.16**

*all units are in GWh



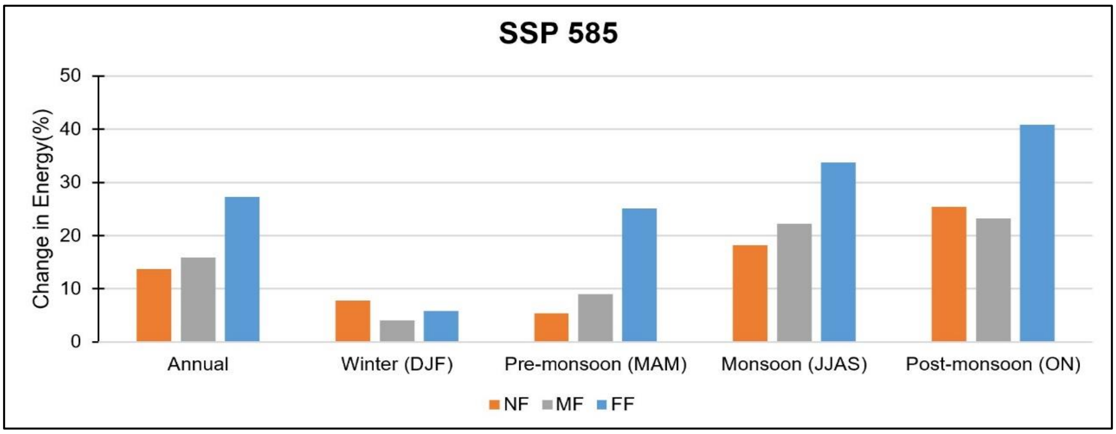


Figure 5.26: Seasonal-wise Percentage Change in Energy Generation of Naumure Hydro Scheme in Future under Both Scenario as per Rule Curve 4

Table 5.22: Seasonal Variation in Energy Generation of Naumure Hydro Scheme in Future as per Rule Curve 7

Season	Baseline	SSP245-NF	SSP245-MF	SSP245-FF	SSP585-NF	SSP585-MF	SSP585-FF
Winter	140.74	140.82	145.82	158.56	151.95	144.54	142.23
Pre-Monsoon	194.66	194.96	202.24	204.42	200.98	207.62	231.65
Monsoon	414.06	437.43	502.61	507.94	493.34	512.67	562.28
Post-Monsoon	53.18	60.24	65.12	65.52	66.33	65.03	79.2
Annual Energy	**802.64**	**833.45**	**915.79**	**936.44**	**912.6**	**929.86**	**1015.36**

*all units are in GWh

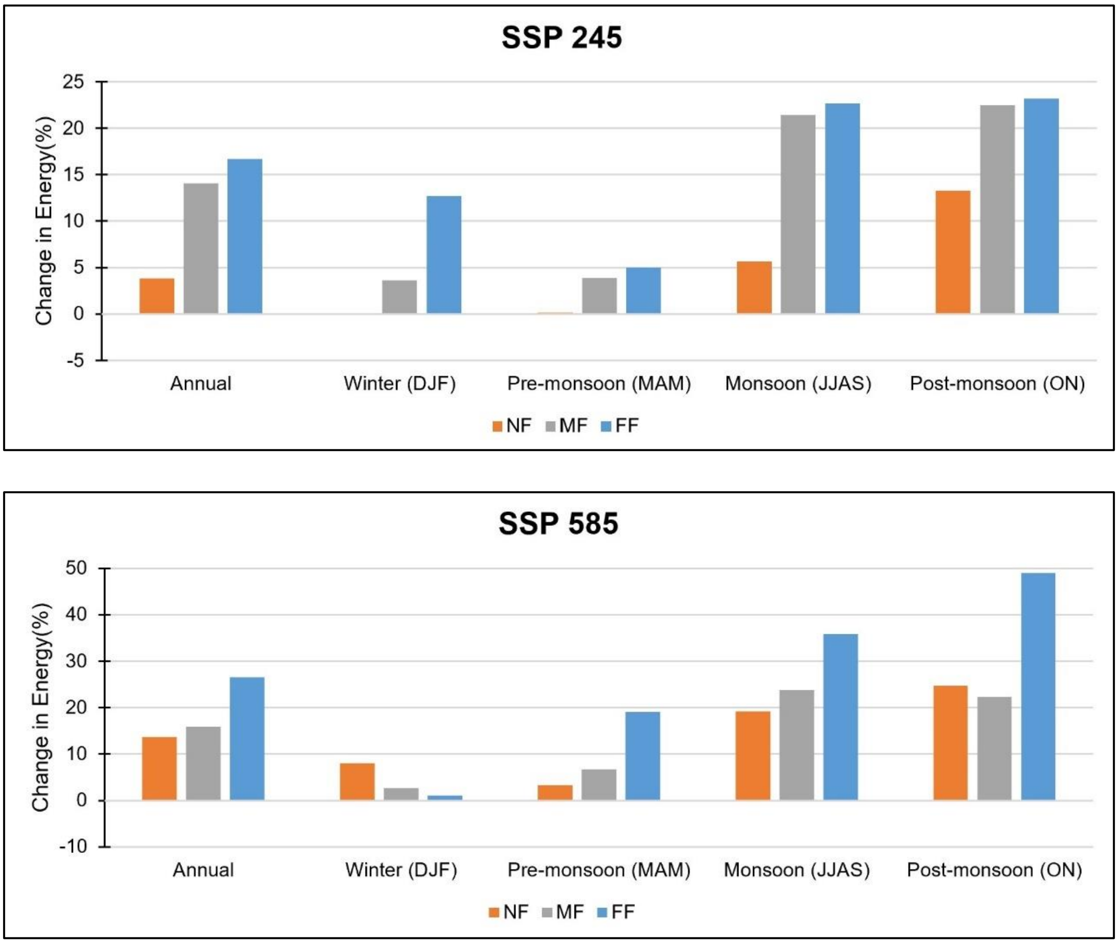


Figure 5.27: Seasonal-wise Percentage Change in Energy Generation of Naumure Hydro Scheme in Future under Both Scenario as per Rule Curve 7

All modified rule curves seem to generate more energy annually at both Lamatal and Surainaka hydro scheme in all of the future. At Lamatal hydro scheme, the projected energy generation seems to increase between 1.47% to 17.3% than baseline generation lower being produced during NF future under SSP245 scenario from rule curve 2 while higher being produced during FF future under SSP585 scenario from rule curve 6. Similarly, at Surainaka hydro scheme, except rule curve 3 all other modified rule curve seems to generate energy as expected as the generation from this hydro scheme depend on the flow diversion for Kapilvastu irrigation project.

So, looking at all scheme, the total energy generation seems to increase between 1.87% to 18.81% than baseline generation, 1.87% more energy being produced during NF future under SSP245 scenario from rule curve 3 while 18.81% more energy being produced during FF future under SSP585 scenario from rule curve 4.

The details of energy production of Lamatal hydro scheme, Surainaka hydro scheme and overall energy generation from all hydro schemes by all modified operational rule curves with comparison with baseline generation was shown in Table 5.23 and Table 5.24.

Table 5.23: Summary of Hydropower Generation by Modified Rules Curves of Lamatal and Surainaka Hydro Scheme

Rule-curve	Scenario	Lamatal HP generation(GWh/yr)				Surainaka HP generation(GWh/yr)			
		Baseline	NF	MF	FF	Baseline	NF	MF	FF
Present	SSP245	41.38	42.61	43.93	44.29	376.9	378.01	384.76	385.09
	SSP585		43.48	44.07	46.9		383.77	384.2	384.02
Rule-1	SSP245		42.72	44.04	44.35		383.97	385.39	385.34
	SSP585		43.61	44.24	46.92		384.62	385.45	381.92
Rule-2	SSP245		41.99	43.8	44.14		378.94	380.15	380.47
	SSP585		43.2	44.06	47.63		382.63	379.91	381.92
Rule-3	SSP245		42.44	43.68	44.08		366.24	373.08	373.35
	SSP585		43.4	43.86	46.7		372.41	372.73	376.93
Rule-4	SSP245		42.54	43.99	44.28		384.56	381.92	381.92
	SSP585		43.48	44.3	47.47		381.92	381.92	381.92
Rule-5	SSP245		42.16	43.81	44.2		377.01	380.33	380.48
	SSP585		43.32	44.14	47.51		380.3	379.93	381.92
Rule-6	SSP245		42.17	43.66	43.82		380.41	383.81	383.87
	SSP585		43.04	43.97	48.54		383.55	383.33	381.92
Rule-7	SSP245		42.73	44.09	44.37		381.63	379.97	379.9
	SSP585		43.62	44.38	47.43		378.72	380.18	382.5
Rule-8	SSP245		42.22	43.93	44.24		377.01	380.42	380.48
	SSP585		43.37	44.18	47.78		378.22	376.55	384.36

Table 5.24: Comparison of Hydropower Generation by Modified Rules Curves with the Baseline Generation of all Hydro Scheme of Naumure Multipurpose Project

Rule-curve	Scenario	Baseline GWh/yr	Hydropower generation(GWh/yr)			Percentage change in generation(%)		
			NF	MF	FF	NF	MF	FF
Present	SSP245	1220.9	1251.75	1344.38	1353.83	2.53	10.11	10.89
	SSP585		1343.72	1357.14	1445.18	10.06	11.16	18.37
Rule-1	SSP245		1257.23	1342.83	1361.4	2.97	9.99	11.51
	SSP585		1340.11	1357.83	1445.87	9.76	11.21	18.42
Rule-2	SSP245		1252.01	1340.54	1361.05	2.55	9.8	11.48
	SSP585		1339.2	1352.2	1446.19	9.69	10.75	18.45
Rule-3	SSP245		1243.75	1333.24	1359.86	1.87	9.2	11.38
	SSP585		1330.35	1348.08	1442.29	8.96	10.42	18.13
Rule-4	SSP245		1260.49	1342.49	1348.86	3.24	9.96	10.48
	SSP585		1338.38	1356.74	1450.55	9.62	11.12	18.81
Rule-5	SSP245		1250.74	1341.22	1359.55	2.44	9.85	11.35
	SSP585		1335.46	1353.15	1448.18	9.38	10.83	18.61
Rule-6	SSP245		1251.7	1335.09	1339.56	2.52	9.35	9.72
	SSP585		1328.83	1351.7	1441.5	8.84	10.71	18.07
Rule-7	SSP245		1257.81	1339.85	1360.71	3.02	9.74	11.45
	SSP585		1334.94	1354.42	1445.29	9.34	10.93	18.38
Rule-8	SSP245		1252.34	1340.66	1365.59	2.57	9.81	11.85
	SSP585		1332.77	1350.16	1449.89	9.16	10.59	18.75

Regarding irrigation demand and supply at Kapilvastu irrigation project, only rule curve 1, 4, 7 seems to meet required irrigation demand of all month in all the futures. Other rule curves fail to meet the irrigation demand of October month while fulfilling demand of other remaining months. The details of irrigation demand and available supply along with percentage of monthly demand met was illustrated in the Table 5.25.

Table 5.25: Summary of Irrigation Demand and Available Supply with Percentage of Monthly Demand Met by Different Modified Rule Curves

Rule-curve	Scenario	Baseline Demand (Mm³)	Available Irrigation supply(Mm³)			Percentage monthly Demand met?		
			NF	MF	FF	NF	MF	FF
Present	SSP245	647	1062.817	1081.888	1082.777	100	100	100
	SSP585		1078.904	1080.237	1079.831	100	100	100
Rule-1	SSP245		1079.697	1083.768	1083.607	100	100	100
	SSP585		1081.572	1083.929	1073.858	100	100	100
Rule-2	SSP245		1065.314	1068.796	1069.706	91.67	91.67	91.67
	SSP585		1075.84	1068.126	1073.858	91.67	91.67	100
Rule-3	SSP245		1029.245	1048.585	1049.37	91.67	100	100
	SSP585		1046.563	1047.555	1059.582	91.67	91.67	100
Rule-4	SSP245		1081.366	1073.858	1073.858	100	100	100
	SSP585		1073.858	1073.858	1073.858	100	100	100
Rule-5	SSP245		1059.823	1069.331	1069.736	91.67	91.67	91.67
	SSP585		1069.224	1068.18	1073.858	91.67	91.67	100
Rule-6	SSP245		1069.546	1079.268	1079.429	91.67	100	100
	SSP585		1078.518	1077.876	1073.858	100	100	100
Rule-7	SSP245		1072.972	1068.26	1068.073	100	100	100
	SSP585		1064.698	1068.876	1075.492	100	100	100
Rule-8	SSP245		1059.823	1069.572	1069.736	91.67	91.67	91.67
	SSP585		1063.197	1058.509	1080.822	91.67	91.67	100

So, only rule curve 4 and rule curve 7 was able to successfully fulfill all these goals in all the futures under both SSP245 and SSP585 scenario: enough dry season energy generation than baseline generation, more hydropower energy generation and successfully meeting monthly irrigation demand of Kapilvastu irrigation project. Result also shows some rule curves works way better than other in some specific period of future.

It is not always mandatory to stick with the same rules and principles. Being flexible can surely yield benefits too. Different rules curves which cope with climate impact at different period of future can be wisely adopted in order to maximize the hydropower energy generation and supply sufficient irrigation demands. Since, Rule curve 4 and Rule curve 7 has high benefits and works well in all the futures, they can be recommended as an adaptation strategy for Naumure Multipurpose Project.

5.4 Discussion

This study was based on the projection of climatic variables (precipitation and temperature) and development of hydrological model to evaluate changes on the river discharge followed by development of reservoir model to quantify fluctuations in the hydropower generation and irrigation supply in the future due to climate change. For climate projection work, six CMIP6 GCM models were selected, downscaled and bias corrected using simple linear scaling method. Future climate variables were projected taking ensemble of all GCMs outputs. Hydrological model was setup, calibrated and validated in SWAT software. Future discharge was projected in SWAT hydrological model using projected climatic variable data. Finally, reservoir model was developed in HEC-ResSim software to evaluate current and future projected energy generation and irrigation supply and to adjust rule curve through some modification which could cope with the future climate change accordingly. The maximum and minimum temperatures were projected to increase in all futures under both SSP245 and SSP585 scenario. The maximum temperature was projected to increase by 14.41% (up to 3.7 °C) and the minimum temperature was projected to increase by 38.89% (up to 4.97 °C) both in FF future under scenario SSP585. Season wise analysis also suggest the increase in both maximum and minimum temperature in all of the season under both scenario SSP245 and SSP585 while, in case of SSP585 scenario, the increase is quite large and significant. The increase in minimum temperature is expected to be higher than maximum temperature which is indicator of climate change. Further, the precipitation was projected to increase between 13% to 90% at different period of future under both SSP245 and SSP585 scenario. Season wise variation analysis suggest that the significant decrease in precipitation in case of post-monsoon season (up to 90% at some point in future) while precipitation increases significantly in both pre-monsoon (up to 84%) and monsoon season (up to 96.5%) and precipitation trend only deviates slightly in case of winter season.

Average annual flow was projected to increase in all future under both SSP245 and SSP585 scenario. Flow increases by 25.24%, 51.21% and 49.75% in NF, MF, FF future respectively under SSP245 scenario and by 119.01%, 117.59% and 179% in NF, MF, FF future respectively under SSP585 scenario. Season wise analysis suggest that except in winter season under SSP245 scenario, projected flow increases in all season under both SSP245 and SSP585 scenario. Under SSP245 scenario, flow decreases by maximum of 23% in winter season in NF future under SSP245 scenario while flow increases in remaining season in all future where monsoon of MF future has maximum increase of flow by 62%. Under SSP585 scenario, flow increases in all season in all future where flow increase by minimum of 14% in MF future of winter season to maximum of 459% in FF future of monsoon season.

This seasonal fluctuation in flow is expected to disrupt the baseline rule curve operation in the future of Naumure Multipurpose Project. Reservoir simulation model result suggest Naumure reservoir hydro scheme generate the baseline energy of 802.64 GWh/yr and Lamatal hydro scheme and Surainaka hydro scheme generate the baseline energy of 41.38 GWh/yr and 376.9 GWh/yr respectively. The future hydropower generation was projected in the same reservoir model and result shows that energy generation from all three hydro scheme combined increases by up to 18% while also meeting irrigation demand at Kapilvastu irrigation project on all futures.

At Naumure hydro scheme, annual energy generation analysis suggests increase in energy generation in all future under both SSP245 and SSP585 scenario between 3.55% to 26.37% with maximum increase being in FF future under scenario SSP585 and minimum increase being in NF future under scenario SSP245. However, season wise analysis at Naumure hydro scheme shows decrease in hydropower generation in winter season under SSP245 scenario while energy generation quite increases in all other season of future under both scenarios. Here, hydropower energy generation will decrease in winter season under scenario SSP245 with maximum decrease of 5.81% in winter of NF under scenario SSP245 whereas in all other season of future under both SSP245 and SSP585 scenario, the hydropower energy generation increases with maximum increase of 37.48% in Monsoon season of FF future under scenario SSP585 at Naumure hydro scheme. At Lamatal hydropower scheme, the projected energy generation seems to increase in all futures between 2.97% to 13.34%. Similarly, at Surainaka hydropower scheme, the projected energy generation seems to increase in all futures between 0.29% to 2.17%. Regarding irrigation demand and supply at Kapilvastu irrigation project, project seems to meet required demand in all futures.

This shows that there will be minimal negative climate change impact on Naumure Multipurpose Project. Still season wise analysis suggest a slight decrease in energy generation in winter season. Since winter season generation has a prominent concern in our country, it is recommended to adjust rule curve which would increase and maximize winter energy generation along with keeping overall energy generation from all hydro scheme more than baseline generation and supply sufficient monthly irrigation demand at Kapilvastu irrigation project. Therefore, eight modified rule curves were developed and simulated to maximize all these goals. Rule curve 4 increases the winter energy generation than baseline winter generation by 1.38% to 7.79% at different point of future and rule curve 7 increase the winter energy generation by 0.1% to 12.66% at different point of future. Also, overall hydropower generation by rule curve 4 and rule curve 7 increases up to 18.81% and up to 18.75% respectively while sufficiently fulfilling irrigation monthly demand at Kapilvastu irrigation project. So, rule curve 4 and 7 can be recommended as a reservoir operating rule policy for future which act as adaptation strategy against impact of climate change in future since these two-rule curve has significant more winter and overall energy generation while supplying enough water for irrigation scheme.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study utilized climate projections, hydrological modeling, and reservoir modeling to evaluate the impacts of climate change on river discharge, hydropower generation, and irrigation supply. Six CMIP6 GCMs models were used for climate projections, hydrological modeling was done in SWAT software, and reservoir modeling was conducted in HEC-ResSim software. The study aimed to assess current and future energy generation and irrigation supply, and recommend adjustments to the rule curve to address potential climate change effects. Following conclusions were drawn from this study:

- Climatic projection implies an increase in annual precipitation (up to 90%) and temperature (up to +5 °C) in future.
- River flow is projected to increase up to two folds annually across all time scales. However, seasonal analysis suggest flow decreases by up to 23% in winter season under scenario SSP245 at some period of future.
- Future energy generation is projected to increase annually up to 18% in future while also meeting irrigation demand. However, seasonal analysis suggest energy generation decreases by up to 6% in winter season at some point in future under scenario SSP245.
- With some adjustment in rule curves, winter energy generation increases up to 12.6% in future ensuring targeted energy generation and sufficient irrigation supply in future. These rule curves can be recommended as adaptation option for future operations.

So, there will be minimal negative climate change impact on Naumure Multipurpose Project in term of energy production and irrigation supply. Annually, river flow and energy generation both increases in future, however season wise analysis suggest a slight decrease in energy generation in winter season which forced us to adjust baseline operational rule curve that would increase and maximize winter energy generation, also ensuring overall energy generation more than baseline generation and supply sufficient monthly irrigation demand. However, the increment in flow in future also possess operational and safety threats due to increase in frequency and magnitude of flow which should be looked out on further studies.

6.2 Recommendations

This study focuses on the impacts of climate change on hydrological processes, hydropower generation and irrigation supply in the Naumure Multipurpose Project and the development of an adaptation strategy through adjustment of operating rule curves accounting for climate change impacts. Such study is recommended for all proposed and existing reservoir projects for smooth and efficient operation in the future.

To project stakeholder, following recommendations can be suggested:

- Flexible operating rules are required in changing flow under climate change scenarios in future.
- Since winter energy generation is of prominent concern in our country, it's advised to optimize the rule curve which would maximize winter energy generation.
- Irrigation demand can be increased considering the future water availability. This does not seem to impact energy generation because of increased flow in future.

To enhance the excellence of this study and the research similar to this, following recommendations can be suggested and incorporated in further studies.

- While this study focuses on hydropower generation and irrigation supply aspects of the Naumure Multipurpose Project, future study should also incorporate additional objectives of the project especially flood management and other objectives like fisheries development, recreation activities etc.
- Further studies should explore the inclusion of sedimentation analysis and land use change as they have profound influence in hydropower generation.
- Incorporating a multi-model approach could be an ideal enhancement to this study, as relying solely on a single hydrological model may limit the comprehensiveness and robustness of the findings.
- An effective approach to yield better result would be to incorporate climate change in future through basin optimization, rather than solely relying on simulation techniques.
- The reservoir rule curve operation policy in simulations studies can be evaluated using different performance indicators like reliability, vulnerability and resilience parameters for better result.

REFERENCES

Abbaspour, K. C., 2015. *SWAT-CUP: SWAT Calibration and Understanding Programs - A User Manual,* s.l.: s.n.

Abbaspour, K. et al., 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology,* Volume 524, pp. 733-752.

Arnold, J. G. et al., 2012. SWAT: MODEL USE, CALIBRATION, AND VALIDATION. *Transactions of the ASABE,* 55(4), pp. 1491-1508.

Bista, M., Regmi, R. K., Basnyat, D. B. & Bhattarai, U., 2021. Simulation of Trade-Off among Planned Reservoir Projects and Inter-Basin Transfer Project: A Case Study of Sunkoshi River in Koshi Basin, Nepal. *IOE 10th Graduate Conference,* Volume 10, pp. 993-1000.

Cook, et al., 2020. Twenty-First Century Drought Projections in the CMIP6 Forcing Scenarios.. *Earth's Future,* 8(6).

Department of Civil Engineering, I., 2013. *Water availability, demand and adaptation option assessment of the Ganges Basin under climate change,* New Delhi: s.n.

Doughlas-Mankin, K. R., Srinivasan, R. & Arnold, J. G., 2010. Soil and Water WsseementTtool (SWAT) Model: Current Developments and Applications. *Transactions of the ASABE,* 53(5), pp. 1423-1431.

ERMC, Ingenieria, A. & Ness, 2021. *Feasibility and EIA Study of Naumure Multipurpose Project,* s.l.: s.n.

Eyring, V. et al., 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.,* Volume 9, p. 1937–1958.

Fenech, A., Comer, N. & Gough, B., 2002. Selecting a Global Climate Model for Understanding Future Projections of Climate Change. *Linking Climate Models to Policy and Decision Making,* pp. 133-145.

Gassman, P. W., Reyes, M. R., Green, C. H. & Arnold, J. G., 2007. The Soil and Water Assessment Tool: Historical development, applications, and future directions. *Trans. ASABE* , 50(4), pp. 1211-1250.

Hamlet, A. F., Salathé, E. P. & Carrasco, P., 2010. Statistical Downscaling Techniques for Global Climate Model Simulations of Temperature and Precipitation with Application to Water Resources Planning Studies.

Harrison, G. P., 2001. *An Assessment of the Impact of Climate Change on Hydroelectric Power,* Edinburg, UK: The University of Edinburgh.

Huang, J., Zhang, J. & Zhang, Z., 2011. Estimation of future precipitation change in the Yangtze River basin by using statistical downscaling method. *Stoch Environ Res Risk Assess,* Volume 25, pp. 781-792.

IHA, 2019. *IHA Annual Report* , s.l.: s.n.

Kafle, M., 2020. Comparative Study of Flood Impacts and Damages by Major Trans-Boundary Rivers in Nepal using MCDM. *Journal of Water Resources and Pollution Studies,* 5(2), pp. 2581-5326.

Klipsch, J. D. et al., 2021. *Hec-ResSim, Reservoir system simulation software version 3.3,* s.l.: Hydrologic Engineering Center, US Army corps of Engineering..

Klipsch, J. & Evans, T., 2010. Reservoir Operations Modelling with HEC-ResSim. *Resedrvoir Operations Modelling with HEC-ResSim, 8.*

Kreienkamp, F., Lorenz, P. & Geiger, T., 2020. Statistically Downscaled CMIP6 Projections Show Stronger Warming for Germany. *Atmosphere,* 11(11).

Minville, M., Brissette, F., Krau, S. & Leconte, R., 2009. Adaptation to climate change in the management of a Canadian water-resources system exploited for hydropower.. *Water Resources Management,* 23(14), pp. 2965-2986.

Mishra, V., Bhatia, U. & Tiwari, A. D., 2020. Bias-corrected climate projections for South Asia from Coupled Model Intercomparison Project-6. *Scientific Data,* Volume 7.

Moriasi, D., Gitau, M., Pai, N. & Daggupati, P., 2015. Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. *Transactions of the ASABE,* 58(6), pp. 1763-1785.

Ohba, M., 2021. Chapter 2 - Precipitation under climate change. In: J. Rodrigo-Comino, ed. *Precipitation.* s.l.:s.n., pp. 21-51.

O'Neill, et al., 2016. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.,* pp. 3461–3482 https://doi.org/10.5194/gmd-9-3461-2016.

Primer, M., 2020. *Soil Water Assessment Tool (SWAT),* s.l.: World Bank.

Ray, P. A. & Brown, C. M., 2015. *Confronting Climate Uncertainity in Water Resouces Planning and Project Design: The Decision Tree Framework,* Washington, DC: World Bank.

Seyoum, T. & Theobald, S., 2014. Modeling of Cascade Dams and Reservoirs Operation for Hydropower Energy Generation. pp. 109-117.

Shrestha, A. et al., 2021. Adapting hydropower production to climate change: A case study of Kulekhani Hydropower Project in Nepal. *Journal of Cleaner Production,* Volume 279.

Shrestha, M., Acharya, S. & Shrestha, P., 2017. Bias correction of climate models for hydrological modelling – are simple methods still useful?. *Meteorological Applications,* 24(3), pp. 531-539.

Shrestha, S., Babel, M. S. & Bajracharya, A. R., 2016. Assessment of risks due to climate change for the Upper Tamakoshi Hydropower Project in Nepal. *Climate Risk Management,* pp. 27-41.

Shrestha, S., Khatiwada, M., Babel, M. S. & Parajuli, K., 2014. Impact of Climate Change on River Flow and Hydropower Production in Kulekhani Hydropower Project of Nepal. *Environmental Processes,* Volume 1, pp. 231-250.

Solomon, S. et al., 2007. *IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment,* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Tan, M. L., Gassman, P. W., Yang, X. & Haywood, J., 2020. A review of SWAT applications, performance and future needs for simulation of hydro-climatic extremes. *Advances in Water Resources 1,* Volume 43.

Teutschbein, C. & Seibert, J., 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology.*

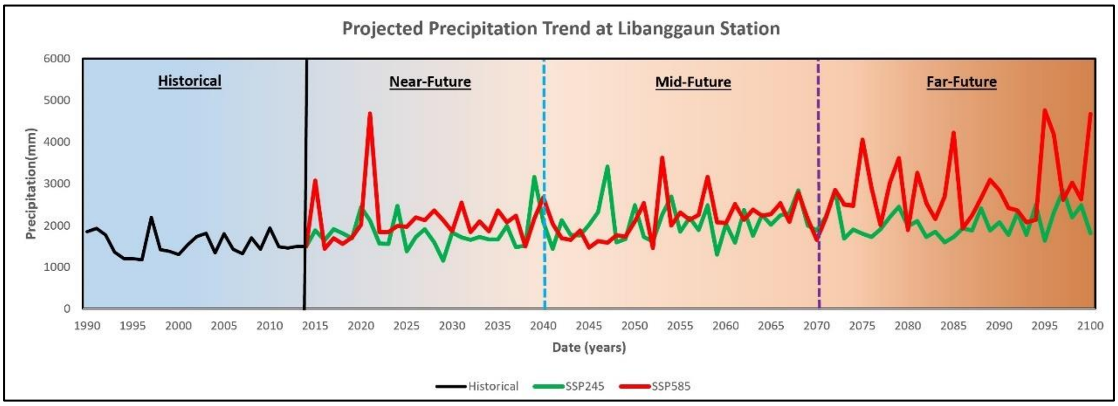
US Army Corps of Engineers, n.d. *HEC-ResSim.* [Online] Available at: https://www.hec.usace.army.mil/software/hec-ressim/ [Accessed 2023].

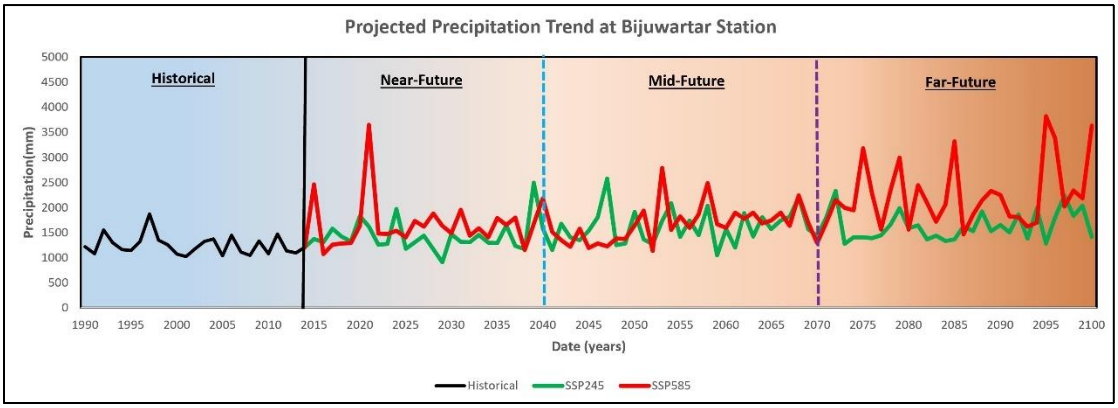
WCRP, 2022. *WCRP Coupled Model Intercomparison Project (CMIP).* [Online] Available at: https://www.wcrp-climate.org/wgcm-cmip [Accessed 2023].

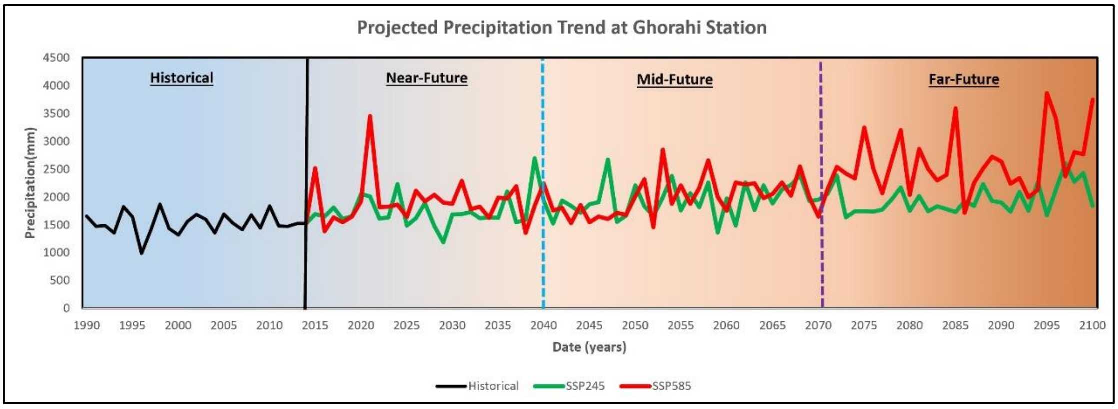
Wilby, R. L. & Dawson, C. W., 2007. *SDSM 4.2 — A decision support tool for the assessment of regional climate change impacts: User Manual*, UK: UK Department of the Environment, Transport and the Regions.

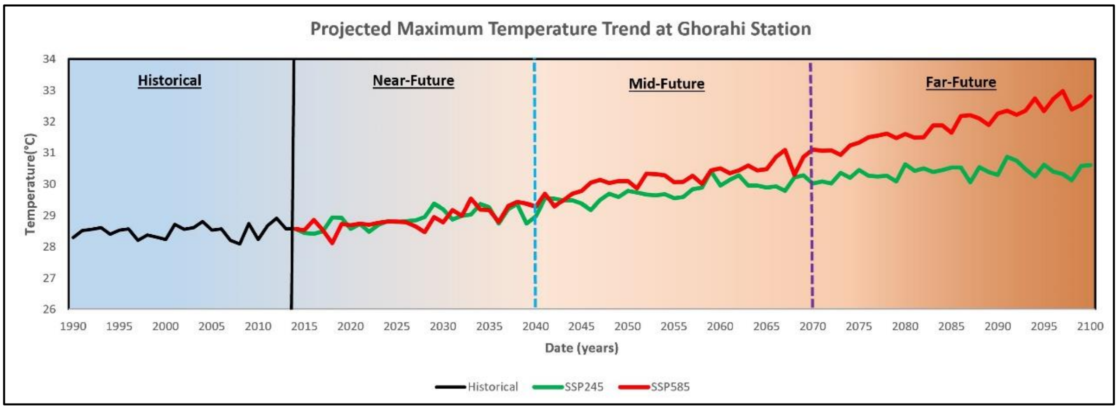
Appendix A: Climate Projections

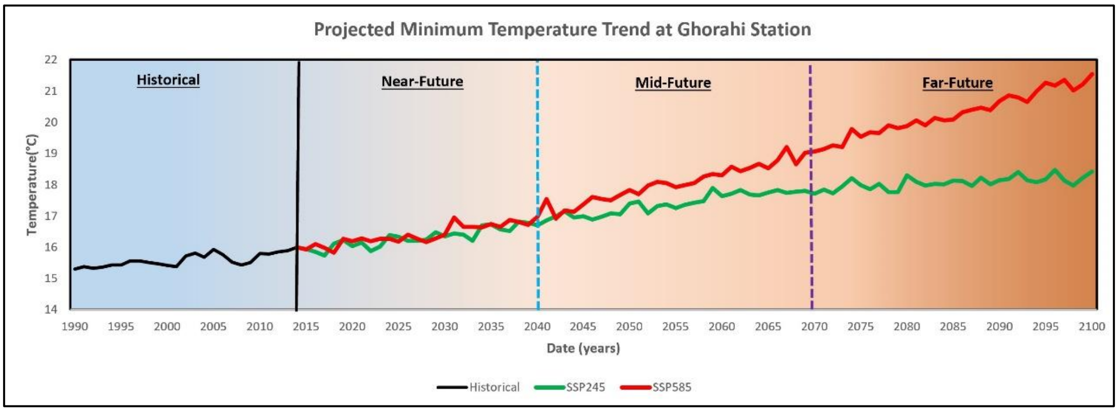
1. Projected Climatic Variable Trend Graphs in Future

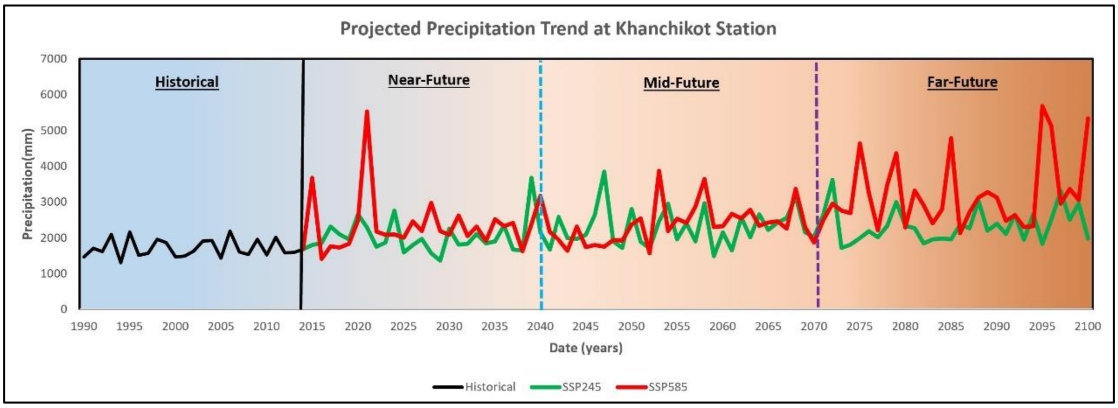


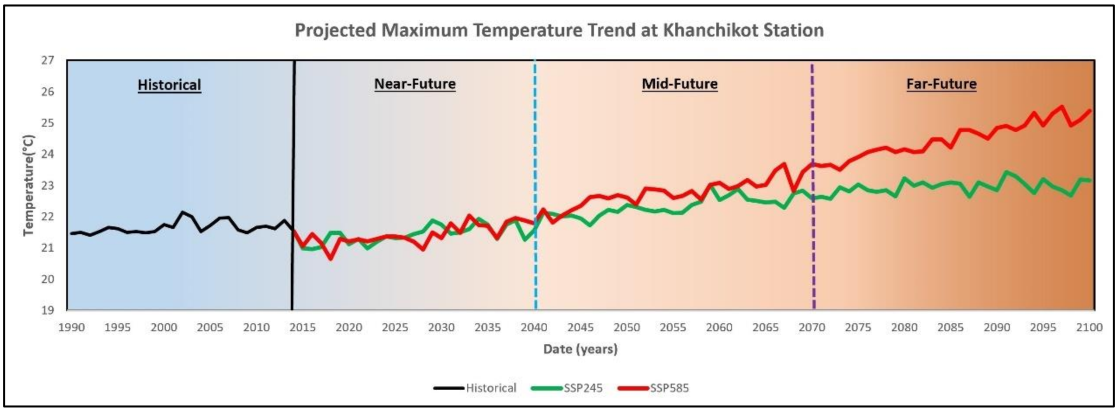


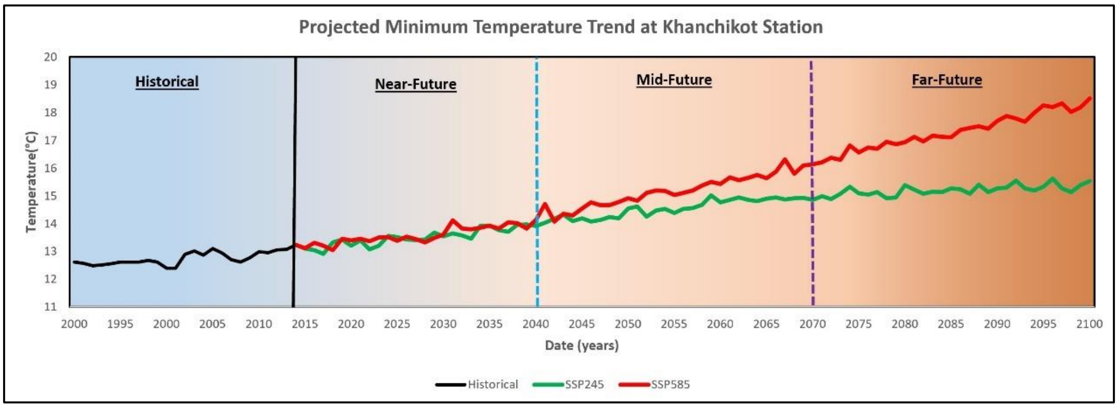


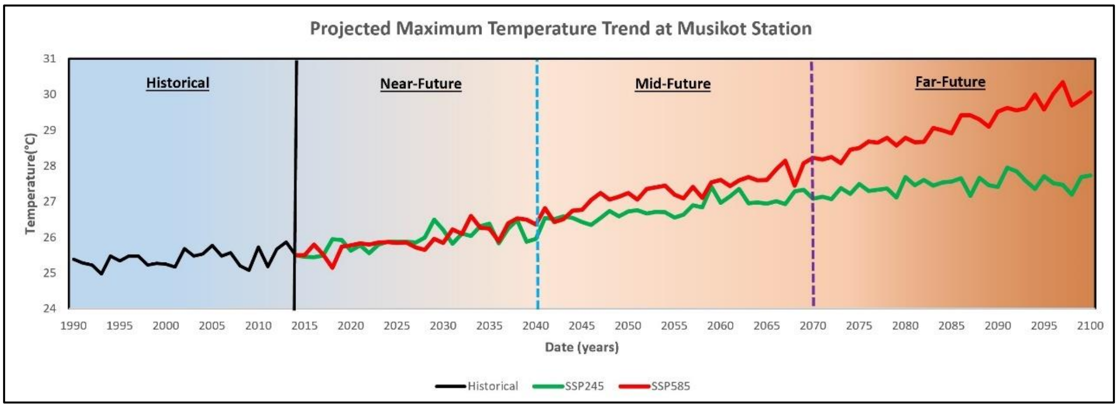


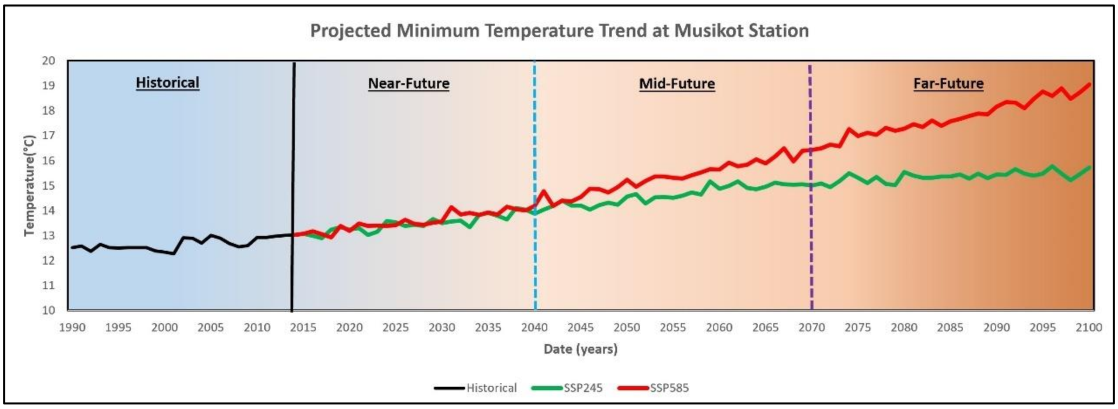

Projected Minimum Temperature Trend at Ghorahi Station
Historical
Near-Future
Mid-Future
Far-Future
Temperature(°C)
Date (years)
Historical
SSP245
SSP585


Projected Precipitation Trend at Khanchikot Station
Historical
Near-Future
Mid-Future
Far-Future
Precipitation(mm)
Date (years)
Historical
SSP245
SSP585


Projected Maximum Temperature Trend at Khanchikot Station
Historical
Near-Future
Mid-Future
Far-Future
Temperature(°C)
Date (years)
Historical
SSP245
SSP585


Projected Minimum Temperature Trend at Khanchikot Station
Historical
Near-Future
Mid-Future
Far-Future
Temperature(°C)
Date (years)
Historical
SSP245
SSP585


Projected Maximum Temperature Trend at Musikot Station
Historical
Near-Future
Mid-Future
Far-Future
Temperature(°C)
Date (years)
Historical
SSP245
SSP585


Projected Minimum Temperature Trend at Musikot Station
Historical
Near-Future
Mid-Future
Far-Future
Temperature(°C)
Date (years)
Historical
SSP245
SSP585

2. Summary of Seasonal Wise Projected Climatic Variable at Different Futures at each Stations:

Future-Scenario	STN Name	LibangGaun	Bijuwartar	Ghorahi			Khanchikot			Musikot	
	STN Index	504	505	515			715			514	
	Season	Pcp (mm)	Pcp (mm)	Pcp (mm)	Tmax (°C)	Tmin (°C)	Pcp (mm)	Tmax (°C)	Tmin (°C)	Tmax (°C)	Tmin (°C)
Baseline	DJF	99.12	61.52	49.26	22.41	6.95	70.87	16.67	6.16	20.05	5.72
	MAM	167.98	152.85	144.40	32.08	17.25	182.16	24.23	14.05	27.67	12.82
	JJAS	1229.51	951.03	1290.31	30.94	22.18	1391.34	24.50	17.70	28.30	18.44
	ON	50.09	29.61	49.51	27.52	13.38	53.81	21.30	11.48	24.66	11.97
NF-SSP245	DJF	103.63	65.20	51.27	22.96	7.72	74.85	16.39	6.94	20.67	6.52
	MAM	224.69	223.58	216.01	32.31	17.74	274.15	23.47	14.55	27.98	13.36
	JJAS	1440.60	1106.47	1421.40	31.30	22.85	1362.11	23.99	18.33	28.77	19.24
	ON	54.56	35.31	58.77	27.85	13.99	66.93	20.79	12.13	25.06	12.58
MF-SSP245	DJF	100.55	61.75	48.50	24.36	9.03	70.64	17.88	8.26	21.96	7.82
	MAM	228.97	220.52	211.69	33.12	18.75	266.78	24.29	15.54	28.81	14.35
	JJAS	1681.40	1292.32	1623.17	31.94	23.82	1879.16	24.63	19.21	29.48	20.42
	ON	9.68	5.48	2.52	25.82	10.62	9.29	19.11	9.91	23.66	9.97
FF-SSP245	DJF	99.31	59.73	47.36	25.13	9.87	67.37	18.69	9.10	22.68	8.67
	MAM	240.12	241.07	228.05	33.58	19.31	302.42	24.75	16.09	29.32	14.95
	JJAS	1660.62	1297.94	1624.82	32.63	24.51	1905.09	25.31	19.85	30.27	21.22
	ON	50.81	34.40	54.92	29.01	15.70	68.95	21.95	13.80	26.27	14.29
NF-SSP585	DJF	113.04	69.64	55.30	23.08	7.74	80.57	16.49	6.97	20.81	6.52
	MAM	228.79	225.48	217.84	32.27	17.86	270.33	23.44	14.66	27.96	13.48
	JJAS	1761.60	1349.55	1608.64	31.21	22.98	1739.04	23.90	18.45	28.69	19.41
	ON	44.83	29.32	48.03	27.92	14.12	55.13	20.87	12.23	25.16	12.73
MF-SSP585	DJF	98.96	60.40	48.65	24.86	9.76	69.37	18.39	8.99	22.46	8.58
	MAM	238.42	234.57	222.62	33.48	19.29	293.70	24.64	16.06	29.22	14.94
	JJAS	1746.62	1337.99	1661.21	32.44	24.58	1937.33	25.13	19.89	30.09	21.31
	ON	9.14	5.31	2.36	26.31	11.33	8.85	19.62	10.62	24.17	10.71
FF-SSP585	DJF	95.77	57.90	46.37	27.15	12.48	67.05	20.80	11.72	24.68	11.29
	MAM	281.98	280.57	272.77	35.19	21.27	326.57	26.36	17.99	31.09	17.00
	JJAS	2411.88	1869.59	2210.82	33.90	26.66	2748.86	26.56	21.77	31.78	23.75
	ON	74.76	48.31	80.60	30.25	17.90	86.83	23.14	15.93	27.65	16.54

Seasons Description:

Winter: DJF: December, January, February

Pre-Monsoon: MAM: March, April, May

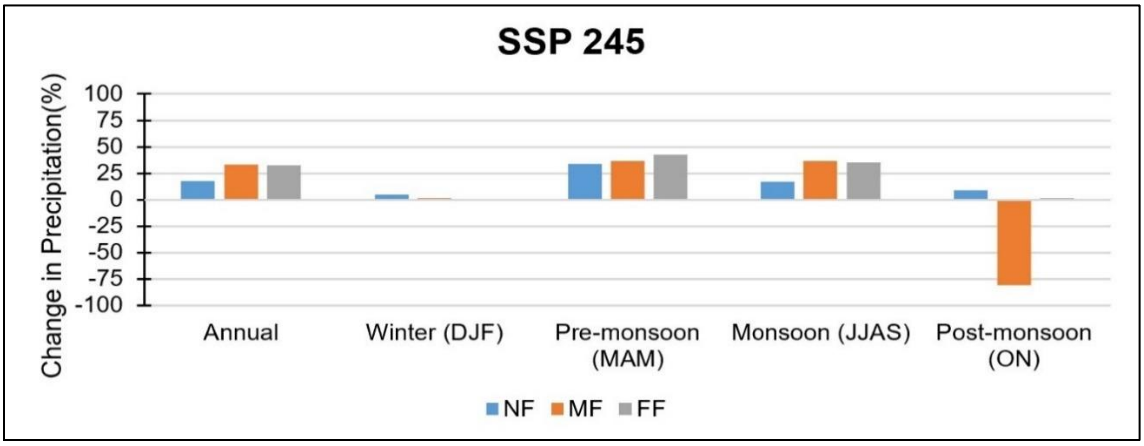
Monsoon: JJAS: June, July, August, September

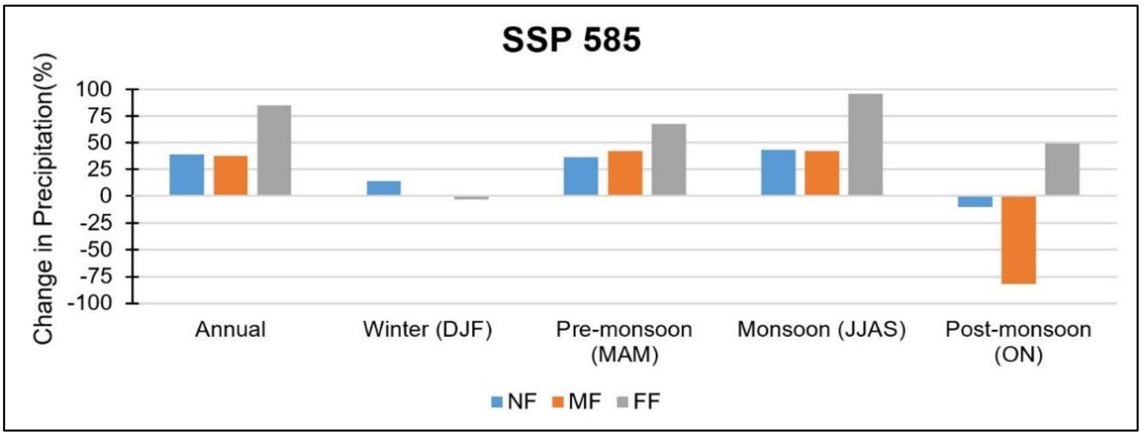
Post-Monsoon: ON: October, November

3. Seasonal Wise Variation of Climatic Variable at Different Stations

- Seasonal variation in projected precipitation at Libanggaun station

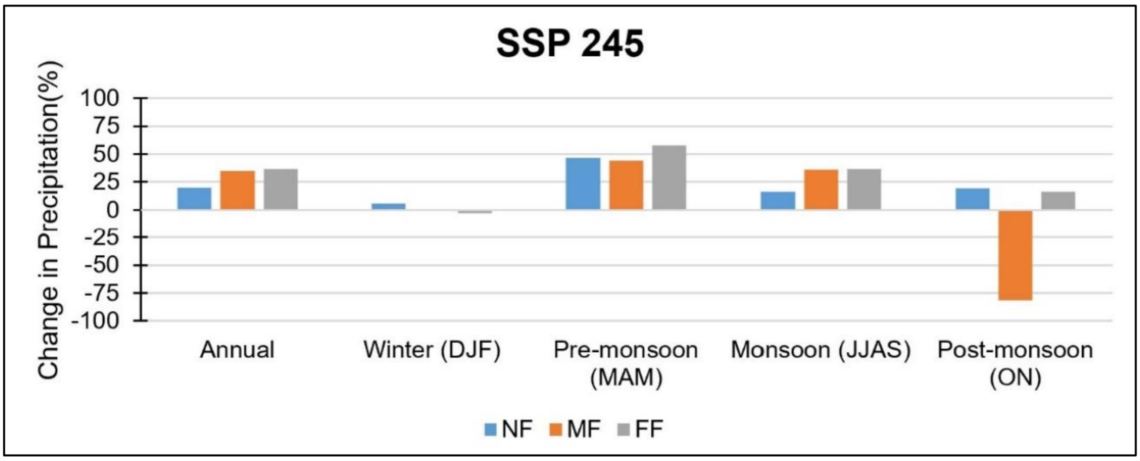
Precipitation (mm)	Annual	Winter (DJF)	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ON)
Baseline (mm)	1546.7	99.12	167.98	1229.51	50.09
SSP245-NF (%)	17.89	4.55	33.76	17.17	8.92
SSP245-MF (%)	33.41	1.44	36.31	36.75	-80.67
SSP245-FF (%)	32.59	0.19	42.95	35.06	1.44
SSP585-NF (%)	38.89	14.04	36.2	43.28	-10.5
SSP585-MF (%)	37.78	-0.16	41.93	42.06	-81.75
SSP585-FF (%)	85.19	-3.38	67.87	96.17	49.25

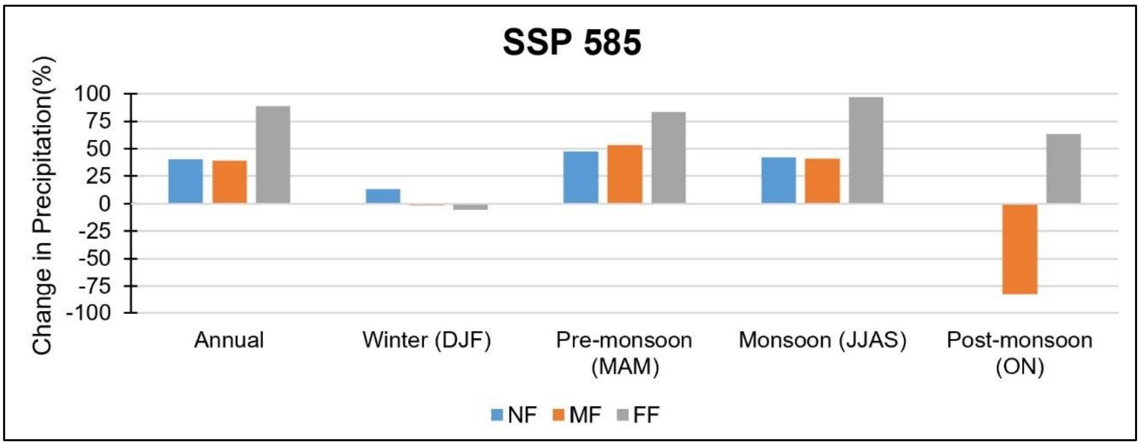




- Seasonal variation in projected precipitation at Bijuwartar station

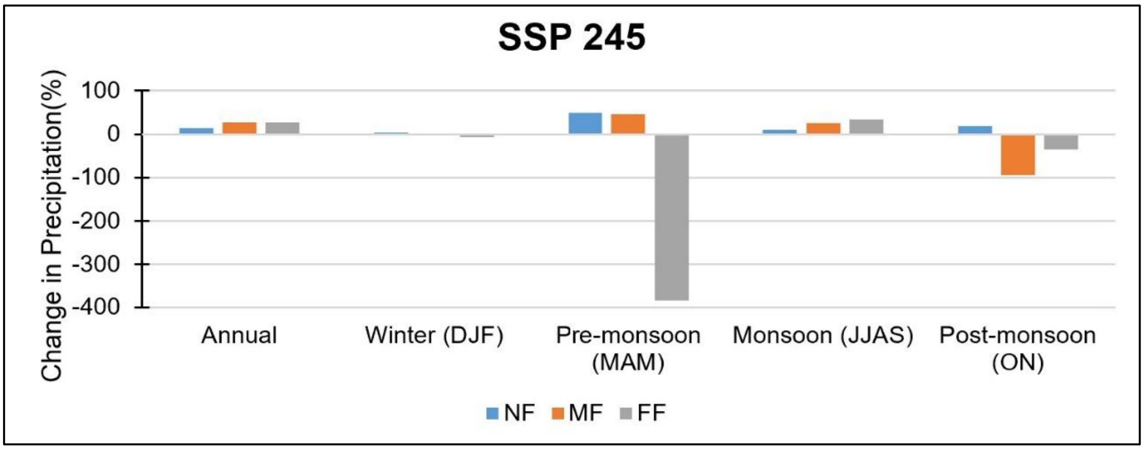
Precipitation (mm)	**Annual**	**Winter (DJF)**	**Pre-monsoon (MAM)**	**Monsoon (JJAS)**	**Post-monsoon (ON)**
Baseline (mm)	1195.01	61.52	152.85	951.03	29.61
SSP245-NF (%)	19.71	5.98	46.27	16.34	19.25
SSP245-MF (%)	34.65	0.37	44.27	35.89	-81.49
SSP245-FF (%)	36.66	-2.91	57.72	36.48	16.18
SSP585-NF (%)	40.08	13.2	47.52	41.9	-0.98
SSP585-MF (%)	39.27	-1.82	53.46	40.69	-82.07
SSP585-FF (%)	88.82	-5.88	83.56	96.59	63.15

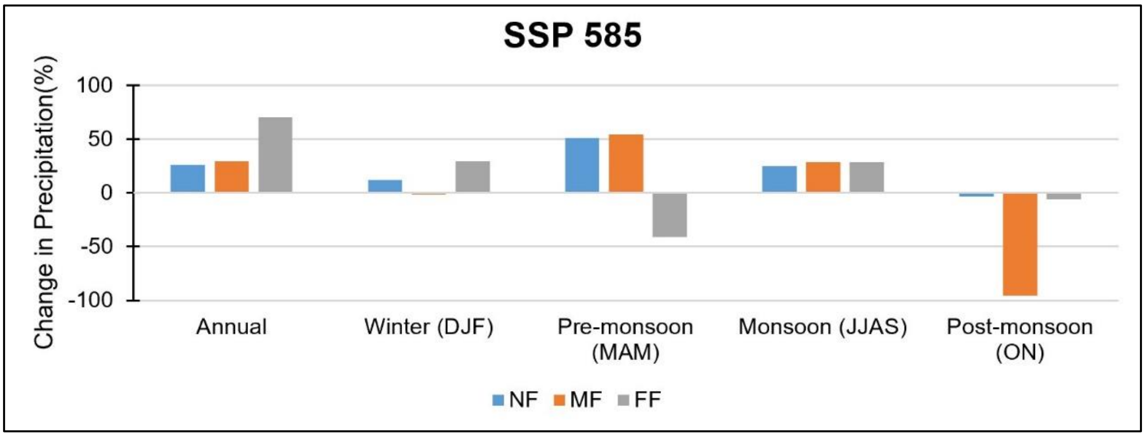




- Seasonal variation in projected precipitation at Ghorahi station

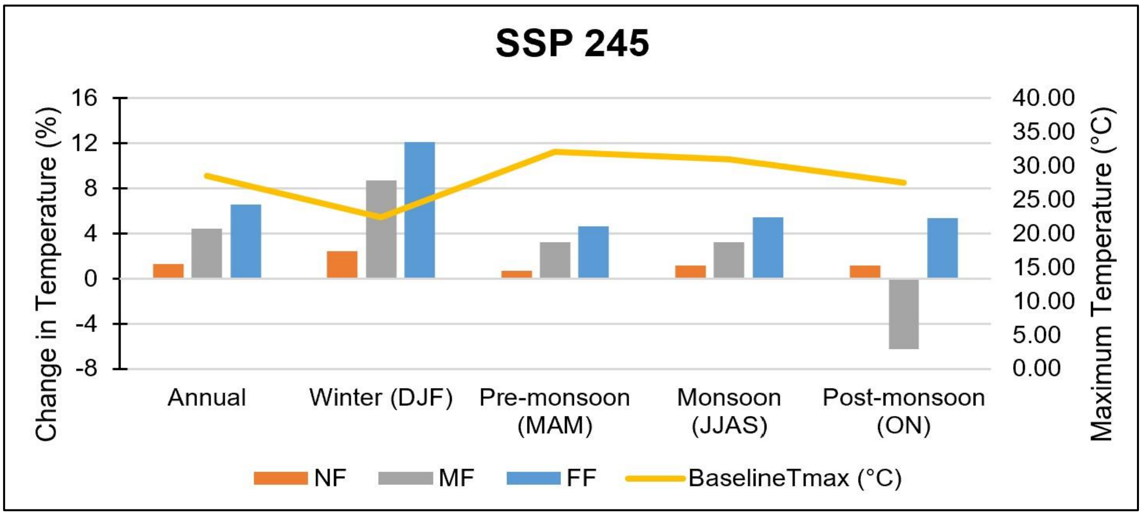
Precipitation (mm)	**Annual**	**Winter (DJF)**	**Pre-monsoon (MAM)**	**Monsoon (JJAS)**	**Post-monsoon (ON)**
Baseline (mm)	1533.48	-3.86	57.93	25.92	10.93
SSP245-NF (%)	13.95	4.08	49.59	10.16	18.7
SSP245-MF (%)	26.51	-1.54	46.6	25.8	-94.91
SSP245-FF (%)	27.5	-7	-383.9	33.6	-35
SSP585-NF (%)	25.85	12.26	50.86	24.67	-2.99
SSP585-MF (%)	29.37	-1.24	54.17	28.75	-95.23
SSP585-FF (%)	70.24	29.6	-41.1	28.6	-5.8

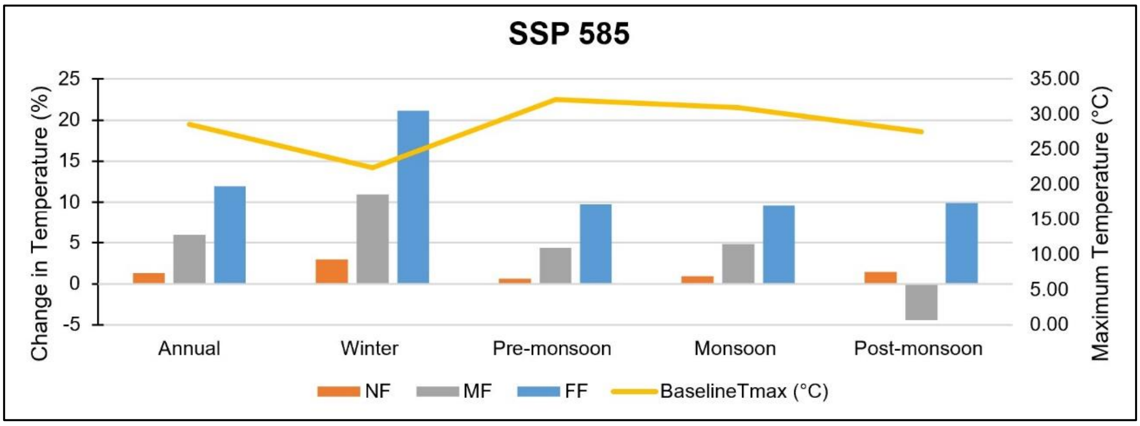




- Seasonal variation in projected Maximum Temperature at Ghorahi station

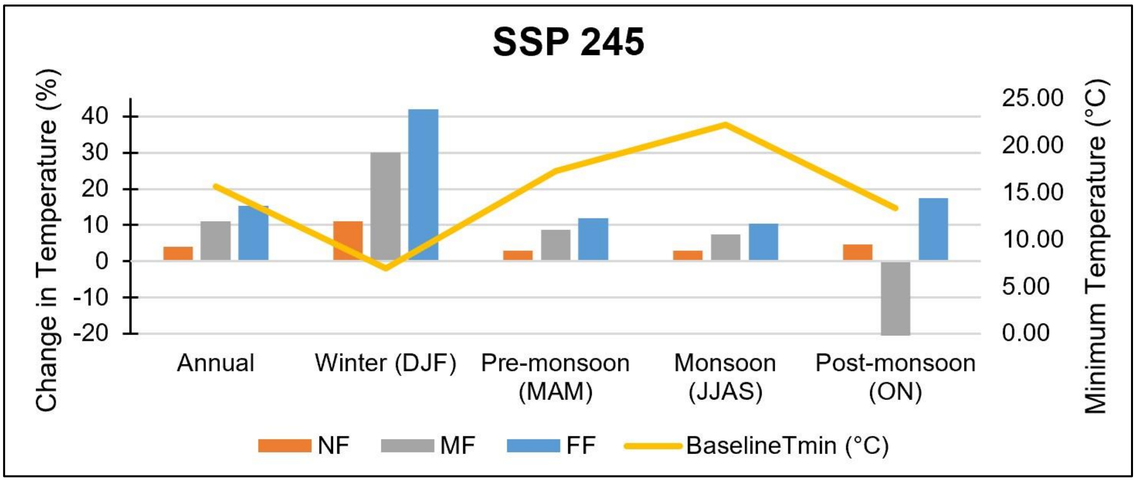
Maximum Temperature	Annual	Winter (DJF)	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ON)
Baseline (°C)	28.52	22.41	32.08	30.94	27.52
SSP245-NF (%)	1.30	2.45	0.72	1.17	1.18
SSP245-MF (%)	4.42	8.70	3.25	3.24	-6.20
SSP245-FF (%)	6.56	12.14	4.68	5.47	5.41
SSP585-NF (%)	1.30	2.97	0.61	0.88	1.45
SSP585-MF (%)	6.00	10.92	4.37	4.86	-4.41
SSP585-FF (%)	11.92	21.12	9.72	9.58	9.90

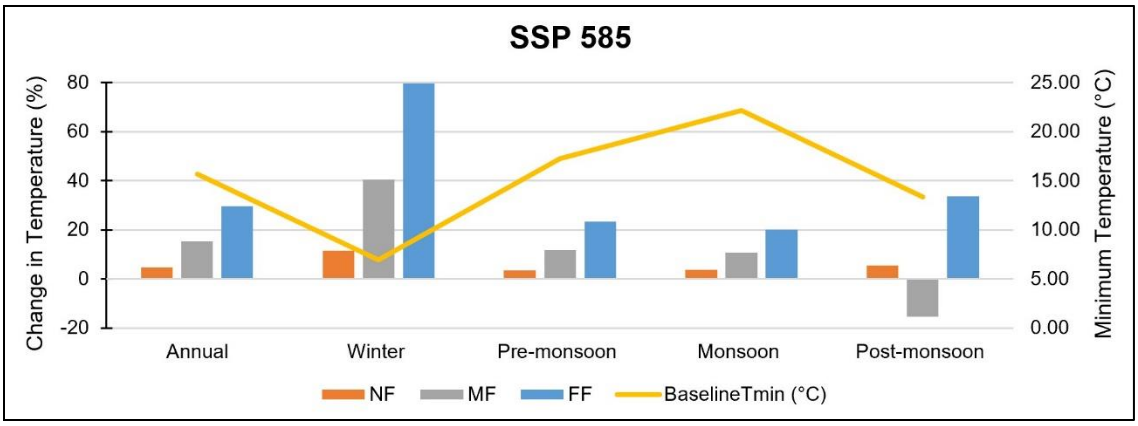




- Seasonal variation in projected Minimum Temperature at Ghorahi station

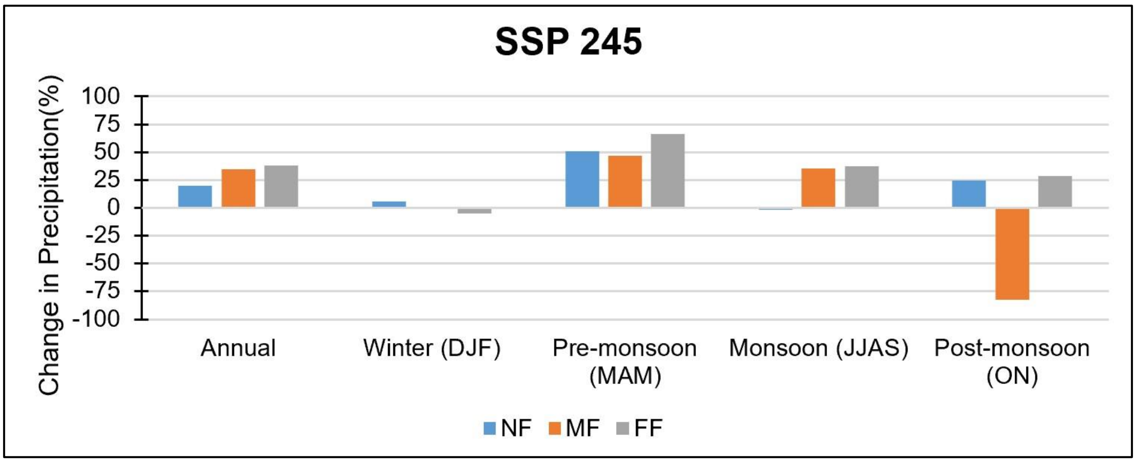
Minimum Temperature	Annual	Winter (DJF)	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ON)
Baseline (°C)	15.67	6.95	17.25	22.18	13.38
SSP245-NF (%)	4.08	11.13	2.84	3.00	4.60
SSP245-MF (%)	11.10	29.99	8.66	7.39	-20.64
SSP245-FF (%)	15.38	42.03	11.92	10.50	17.38
SSP585-NF (%)	4.72	11.42	3.50	3.62	5.57
SSP585-MF (%)	15.44	40.55	11.80	10.80	-15.33
SSP585-FF (%)	29.61	79.70	23.30	20.18	33.79

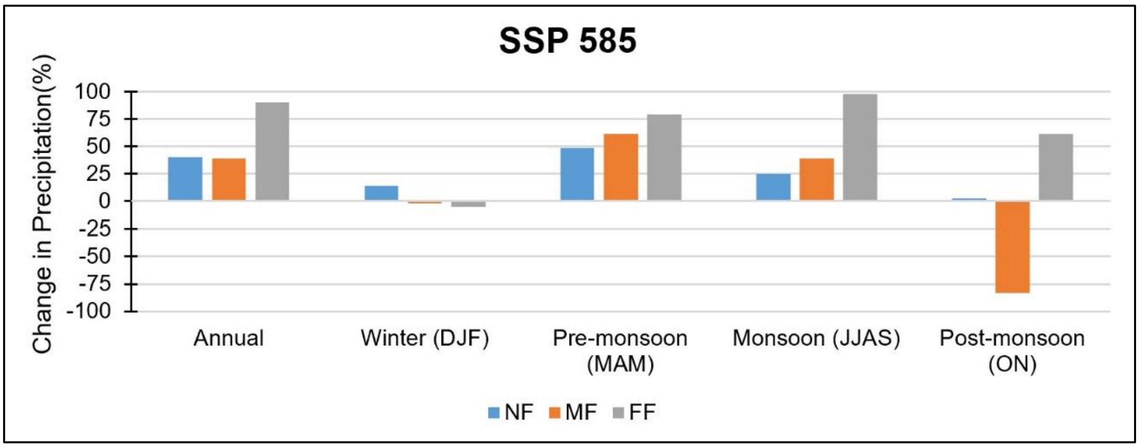




- Seasonal variation in projected precipitation at Khanchikot station

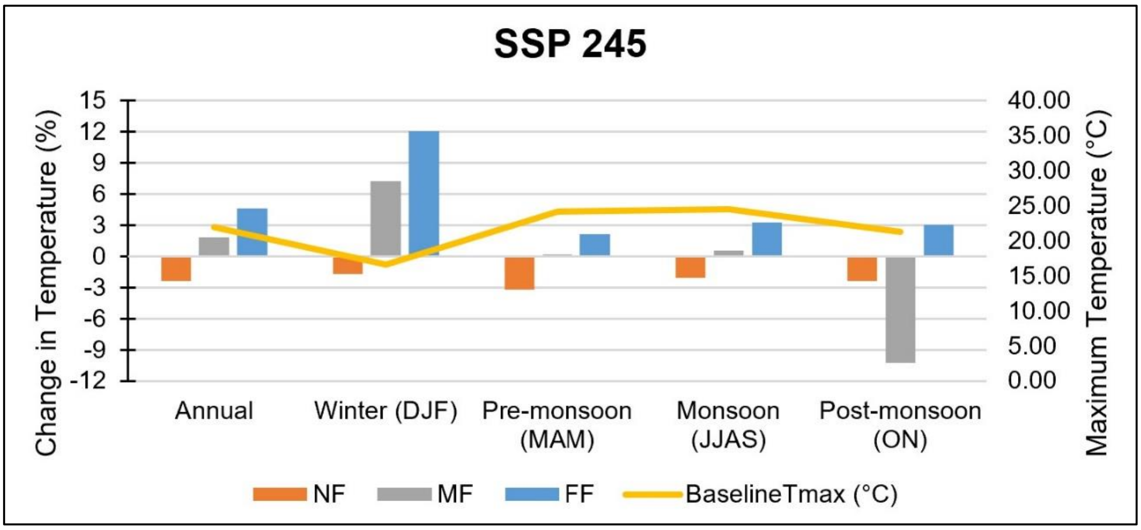
Precipitation (mm)	**Annual**	**Winter (DJF)**	**Pre-monsoon (MAM)**	**Monsoon (JJAS)**	**Post-monsoon (ON)**
Baseline (mm)	1698.19	70.87	182.16	1391.34	53.81
SSP245-NF (%)	19.62	5.62	50.5	-2.1	24.38
SSP245-MF (%)	34.48	-0.32	46.45	35.06	-82.74
SSP245-FF (%)	38.02	-4.94	66.02	36.92	28.14
SSP585-NF (%)	40.36	13.69	48.4	24.99	2.45
SSP585-MF (%)	38.95	-2.12	61.23	39.24	-83.55
SSP585-FF (%)	90.16	-5.39	79.28	97.57	61.36

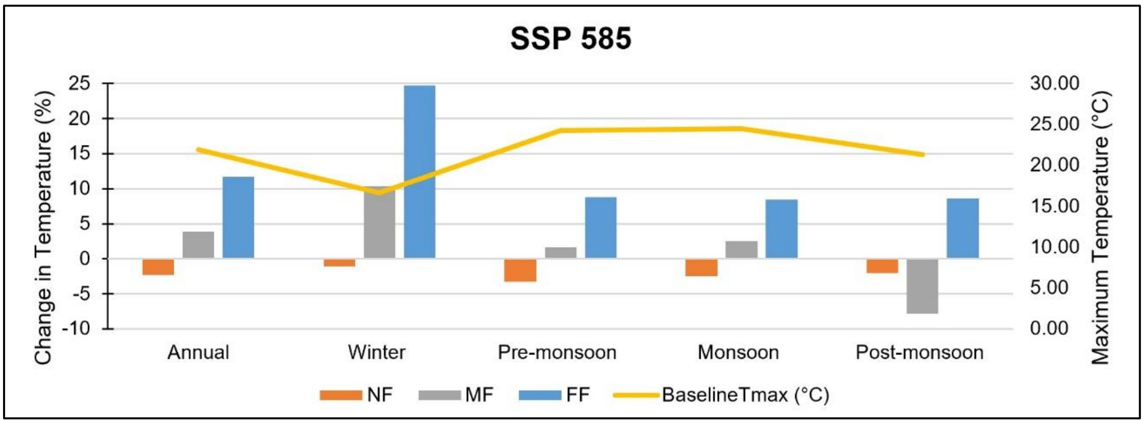




- Seasonal variation in projected maximum temperature at Khanchikot station

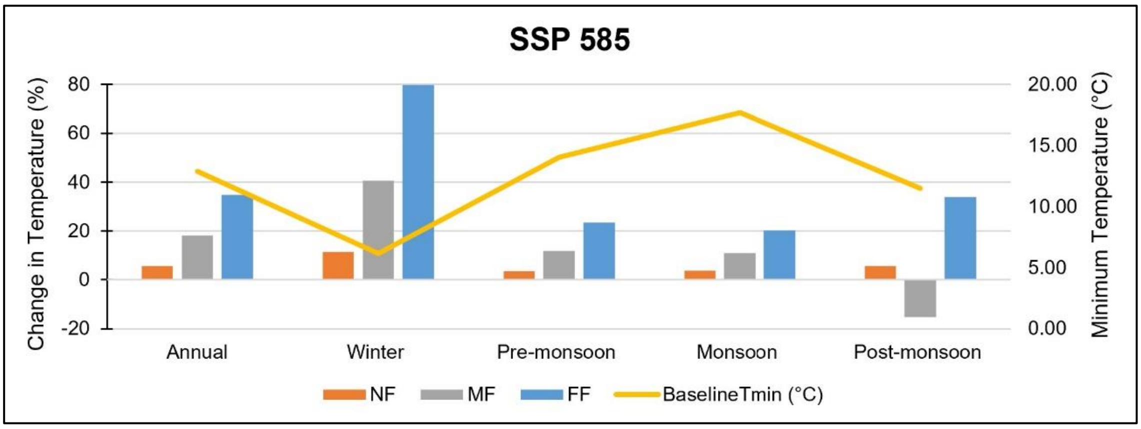
Maximum Temperature	**Annual**	**Winter (DJF)**	**Pre-monsoon (MAM)**	**Monsoon (JJAS)**	**Post-monsoon (ON)**
Baseline (°C)	21.94	16.67	24.23	24.50	21.30
SSP245-NF (%)	-2.32	-1.68	-3.14	-2.07	-2.37
SSP245-MF (%)	1.82	7.28	0.23	0.54	-10.26
SSP245-FF (%)	4.60	12.10	2.15	3.31	3.08
SSP585-NF (%)	-2.32	-1.08	-3.29	-2.44	-2.00
SSP585-MF (%)	3.87	10.34	1.68	2.56	-7.89
SSP585-FF (%)	11.67	24.76	8.79	8.41	8.64

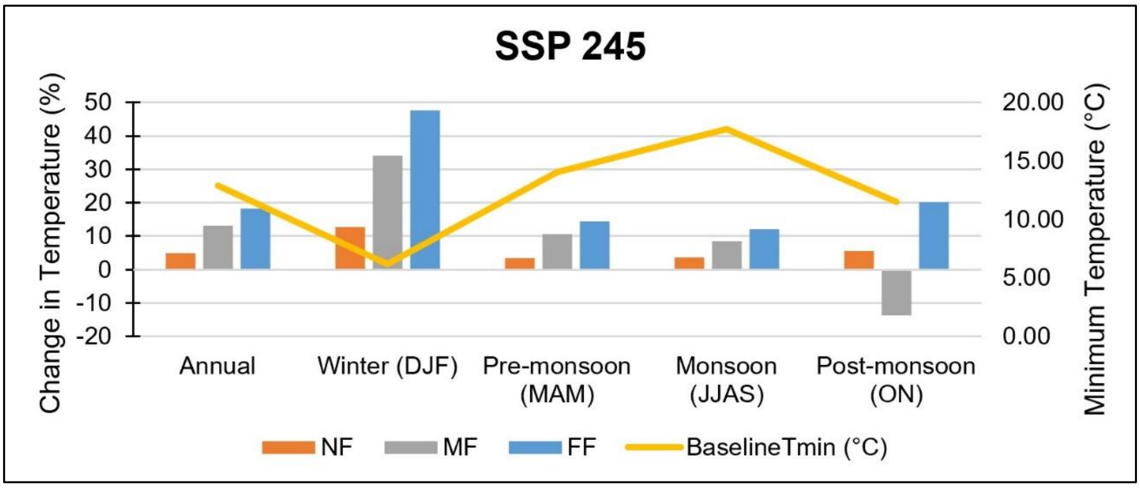




- Seasonal variation in projected minimum temperature at Khanchikot station

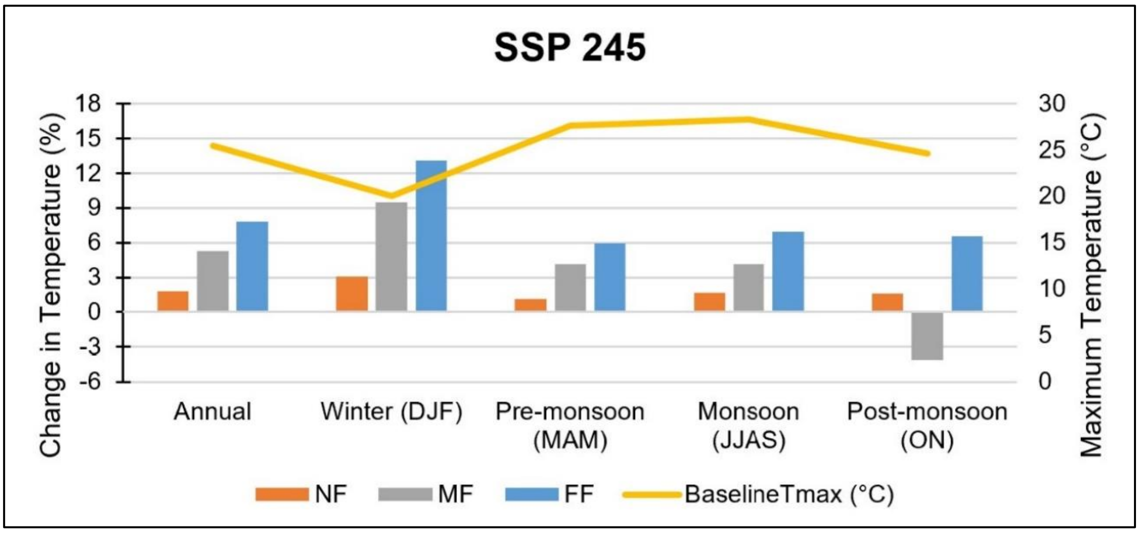
Minimum Temperature	Annual	Winter (DJF)	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ON)
Baseline (°C)	12.87	6.16	14.05	17.70	11.48
SSP245-NF (%)	4.90	12.72	3.51	3.56	5.62
SSP245-MF (%)	13.13	34.04	10.56	8.55	-13.72
SSP245-FF (%)	18.18	47.73	14.52	12.12	20.17
SSP585-NF (%)	5.67	11.42	3.50	3.62	5.57
SSP585-MF (%)	18.10	40.55	11.80	10.80	-15.33
SSP585-FF (%)	3473	79.70	23.30	20.18	33.79

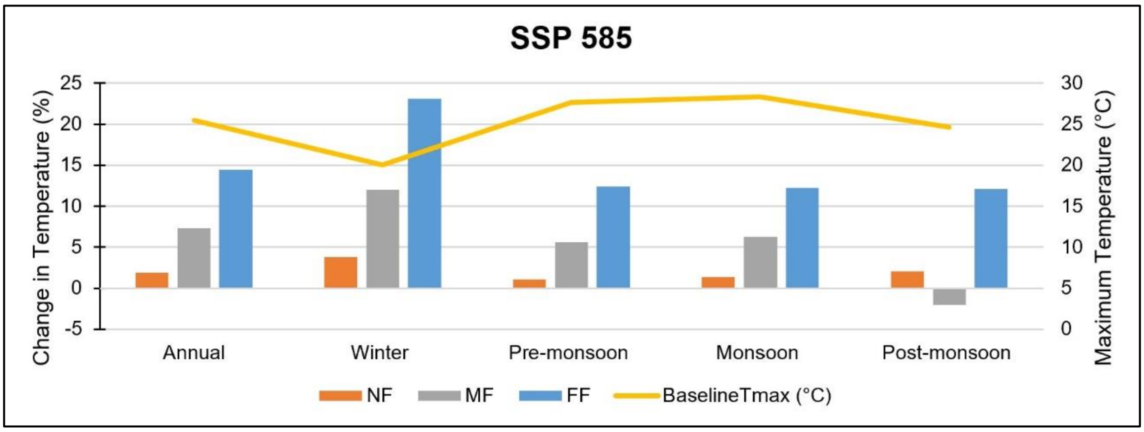




- Seasonal variation in projected Maximum temperature at Musikot station

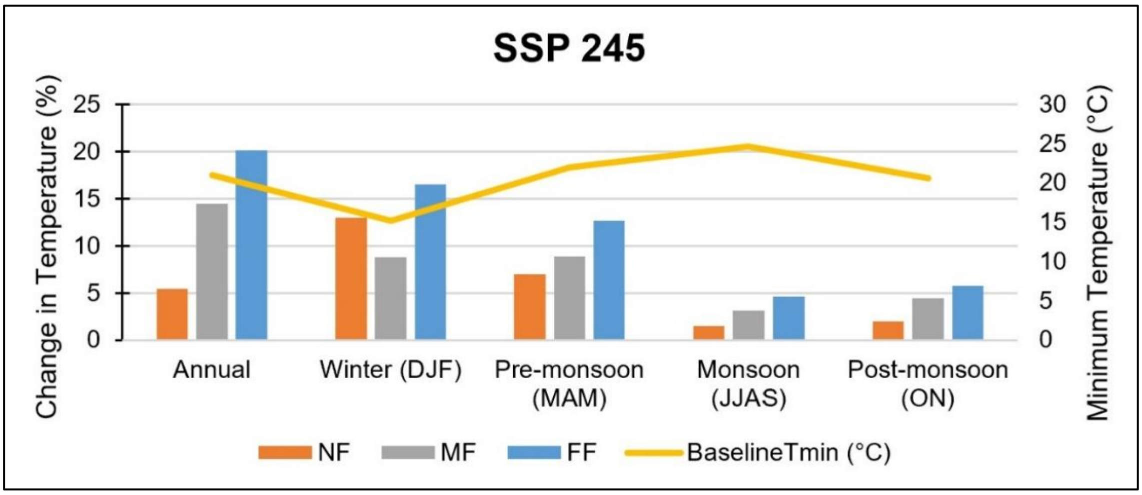
Maximum Temperature	Annual	Winter (DJF)	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ON)
Baseline (°C)	25.47	20.05	27.67	28.3025	24.66
SSP245-NF (%)	1.81	3.09	1.13	1.63	1.62
SSP245-MF (%)	5.3	9.51	4.13	4.15	-4.08
SSP245-FF (%)	7.85	13.13	5.96	6.95	6.53
SSP585-NF (%)	1.88	3.79	1.07	1.38	2.01
SSP585-MF (%)	7.3	12.04	5.6	6.3	-2.01
SSP585-FF (%)	14.41	23.11	12.37	12.27	12.1

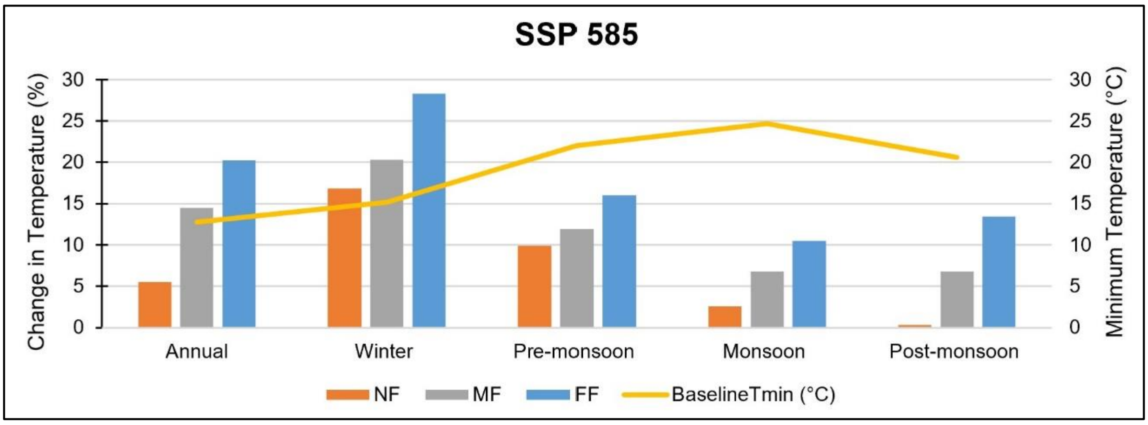




- Seasonal variation in projected Minimum temperature at Musikot station

Minimum Temperature	Annual	Winter (DJF)	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ON)
Baseline (°C)	21	15.2	22	24.7	20.6
SSP245-NF (%)	5.3	13	7	1.5	2
SSP245-MF (%)	6	8.8	8.9	3.2	4.5
SSP245-FF (%)	9.3	16.5	12.7	4.6	5.8
SSP585-NF (%)	6.9	16.8	9.9	2.6	0.3
SSP585-MF (%)	10.9	20.3	11.9	6.8	6.8
SSP585-FF (%)	16.1	28.3	16	10.5	13.4





4. GCM Performance Check Results

- Performance Check at Libanggaun Station for Precipitation

Performance Parameter	Nash-Sutcliffe efficiency (η)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	-0.38	0.02	0.53	0.58	-7.49	0.00
CanESM5	-0.90	-0.27	-0.29	0.42	14.65	0.00
EC-EARTH3	0.10	0.30	0.68	0.66	1.82	0.00
INM-CM4-8	0.32	0.36	0.65	0.64	10.46	0.00
MPI-ESM1-2-hr	0.30	0.32	0.66	0.66	10.30	0.00
NorESM2-MM	0.20	0.32	0.70	0.68	1.23	0.00

- Performance Check at Bijuwartar Station for Precipitation

Performance Parameter	Nash-Sutcliffe efficiency (η)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	-1.51	0.18	0.62	0.68	-50.55	0.00
CanESM5	-1.58	-0.42	-0.30	0.46	-18.77	0.00
EC-EARTH3	-1.36	-0.57	0.72	0.69	-49.85	0.00
INM-CM4-8	-0.05	0.35	0.68	0.70	-25.17	0.00
MPI-ESM1-2-hr	-0.07	0.41	0.70	0.71	-25.51	0.00
NorESM2-MM	-0.66	0.27	0.71	0.68	-36.99	0.00

- Performance Check at Ghorahi Station for Precipitation

Performance Parameter	Nash-Sutcliffe efficiency (η)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	-0.01	0.27	0.68	0.27	-10.09	0
CanESM5	-0.93	-0.74	-0.31	0.36	12.64	0.09
EC-EARTH3	0.44	0.44	0.81	0.75	-0.51	0
INM-CM4-8	0.51	0.55	0.73	0.76	14.07	0.04
MPI-ESM1-2-hr	0.56	0.57	0.78	0.8	8.48	0
NorESM2-MM	0.39	0.45	0.77	0.76	-0.7	0

- Performance Check at Ghorahi Station for Maximum Temperature

Performance Parameter	Nash-Sutcliffe efficiency (η)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**

ACCESS-CM2	0.14	0.85	0.88	0.93	11.99	0
CanESM5	0.09	0.85	0.77	0.92	9.76	0.06
EC-EARTH3	0.23	0.82	0.9	0.91	11.49	0
INM-CM4-8	0.35	0.87	0.92	0.94	10.72	0.06
MPI-ESM1-2-hr	0.21	0.87	0.92	0.94	12.19	-0.01
NorESM2-MM	0.14	0.86	0.89	0.93	12.31	0.07

- Performance Check at Ghorahi Station for Minimum Temperature

Performance Parameter	Nash-Sutcliffe efficiency (η)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	0.81	0.96	0.97	0.98	14.9	0
CanESM5	0.8	0.95	0.95	0.97	12.86	0.05
EC-EARTH3	0.8	0.95	0.97	0.98	14.85	0
INM-CM4-8	0.79	0.96	0.97	0.98	15.49	0.05
MPI-ESM1-2-hr	0.77	0.95	0.97	0.98	16.52	0
NorESM2-MM	0.75	0.96	0.96	0.98	16.92	0.04

- Performance Check at Khanchikot Station for Precipitation

Performance Parameter	Nash-Sutcliffe efficiency (η)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	-0.31	0.20	0.60	0.68	-14.36	0.00
CanESM5	-0.94	-0.36	-0.31	0.26	11.28	0.00
EC-EARTH3	0.28	0.36	0.77	0.71	-5.45	0.00
INM-CM4-8	0.37	0.41	0.68	0.73	5.17	0.00
MPI-ESM1-2-hr	0.42	0.34	0.71	0.68	4.82	0.00
NorESM2-MM	0.28	0.31	0.74	0.69	-3.15	0.00

- Performance Check at Khanchikot Station for Maximum Temperature

Performance Parameter	Nash-Sutcliffe efficiency (η)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	-0.88	0.60	0.78	0.79	-22.10	0.00
CanESM5	-1.42	0.65	0.75	0.81	-25.27	0.06
EC-EARTH3	-0.98	0.56	0.77	0.76	-22.88	0.00
INM-CM4-8	-1.07	0.62	0.80	0.80	-23.99	0.06
MPI-ESM1-2-hr	-5.33	0.64	0.81	0.81	-45.52	0.00
NorESM2-MM	-0.82	0.60	0.78	0.79	-21.85	0.07

- Performance Check at Khanchikot Station for Minimum Temperature

Performance Parameter	Nash-Sutcliffe efficiency (η)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	0.62	0.87	0.93	0.93	-16.45	0.01
CanESM5	0.57	0.87	0.93	0.93	-18.69	0.05
EC-EARTH3	0.60	0.86	0.93	0.93	-16.86	-0.01
INM-CM4-8	0.63	0.88	0.94	0.94	-15.67	0.05
MPI-ESM1-2-hr	0.65	0.87	0.94	0.93	-14.47	0.00
NorESM2-MM	0.65	0.87	0.93	0.93	-14.44	0.05

- Performance Check at Musikot Station for Maximum Temperature

Performance Parameter	Nash-Sutcliffe efficiency (η)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	0.41	0.79	0.88	0.89	9.07	0.00
CanESM5	0.37	0.80	0.82	0.90	6.88	0.07
EC-EARTH3	0.41	0.73	0.87	0.86	8.42	0.01
INM-CM4-8	0.50	0.79	0.89	0.89	7.81	0.06
MPI-ESM1-2-hr	0.39	0.76	0.88	0.88	9.19	0.00
NorESM2-MM	0.40	0.80	0.88	0.90	9.35	0.07

- Performance Check at Musikot Station for MinimumTemperature

Performance Parameter	Nash-Sutcliffe efficiency (η)		Coefficient of Determination (R^2)		Percentage of BIAS (PBIAS)	
Model	**Before BC**	**After BC**	**Before BC**	**After BC**	**Before BC**	**After BC**
ACCESS-CM2	0.75	0.86	0.93	0.93	10.71	-0.01
CanESM5	0.79	0.86	0.93	0.93	8.38	0.04
EC-EARTH3	0.66	0.83	0.93	0.91	-17.61	-0.65
INM-CM4-8	0.74	0.86	0.93	0.93	11.73	0.06
MPI-ESM1-2-hr	0.69	0.84	0.91	0.92	12.89	0.00
NorESM2-MM	0.73	0.86	0.93	0.93	12.94	0.04

5. GCM Model Rank at Different Station

- Ghorahi station GCM Ranking

Rank	GCM	Nash-Sutcliffe efficiency (η)	Coefficient of Determination (R^2)
1	**MPI-ESM1-2-hr**	0.80	0.90
2	**INM-CM4-8**	0.79	0.89
3	**NorESM2-MM**	0.76	0.89
4	**EC-EARTH3**	0.74	0.88
5	**ACCESS-CM2**	0.69	0.88
6	**CanESM5**	0.35	0.75

- Khanchikot station GCM Ranking

Rank	GCM	Nash-Sutcliffe efficiency (η)	Coefficient of Determination (R^2)
1	**INM-CM4-8**	0.64	0.82
2	**MPI-ESM1-2-hr**	0.62	0.81
3	**NorESM2-MM**	0.59	0.80
4	**EC-EARTH3**	0.59	0.80
5	**ACCESS-CM2**	0.56	0.80
6	**CanESM5**	0.38	0.67

- Musikot station GCM Ranking

Rank	GCM	Nash-Sutcliffe efficiency (η)	Coefficient of Determination (R^2)
1	**MPI-ESM1-2-hr**	0.80	0.90
2	**INM-CM4-8**	0.79	0.89
3	**NorESM2-MM**	0.76	0.89
4	**EC-EARTH3**	0.74	0.88
5	**ACCESS-CM2**	0.69	0.88
6	**CanESM5**	0.35	0.75

Appendix B: Reservoir Physical and Other Necessary Data

- Height-Area-Volume Table for Naumure Reservoir

SN	Elevation (m)	Dam height (m)	Surface Area (m^2)	Surface Area (Mm^2)	volume (m^3)	volume (Mm^3)
1	362	0	2428.71	0	0	0
2	363	1	18677.1	0.02	9280.3	0.01
3	364	2	45857.31	0.05	40547	0.04
4	365	3	56408.79	0.06	82308.79	0.08
5	370	8	149235.9	0.15	546701.2	0.55
6	375	13	291968.2	0.29	1629940	1.63
7	380	18	373660.5	0.37	3289819	3.29
8	385	23	481691.9	0.48	5422492	5.42
9	390	28	666834.2	0.67	8281290	8.28
10	395	33	845078.5	0.85	12052285	12.05
11	400	38	1088693	1.09	16873875	16.87
12	405	43	1461430	1.46	23226359	23.23
13	410	48	1867714	1.87	31528482	31.53
14	415	53	2330334	2.33	42002297	42
15	420	58	2861160	2.86	54958358	54.96
16	425	63	3391786	3.39	70571925	70.57
17	430	68	3907464	3.91	88804850	88.8
18	435	73	4406248	4.41	1.1E+08	109.58
19	440	78	4988765	4.99	1.33E+08	133.05
20	445	83	5670782	5.67	1.6E+08	159.68
21	450	88	6307135	6.31	1.9E+08	189.61
22	455	93	6931647	6.93	2.23E+08	222.7
23	460	98	7712556	7.71	2.59E+08	259.29
24	465	103	8549906	8.55	3E+08	299.93
25	470	108	9204372	9.2	3.44E+08	344.3
26	475	113	9881501	9.88	3.92E+08	392.01
27	480	118	10601263	10.6	4.43E+08	443.21
28	485	123	11397503	11.4	4.98E+08	498.2
29	490	128	12130132	12.13	5.57E+08	557
30	495	133	12924703	12.92	6.2E+08	619.63
31	500	138	13766894	13.77	6.86E+08	686.35
32	505	143	14693310	14.69	7.57E+08	757.49
33	510	148	15505278	15.51	8.33E+08	832.97
34	515	153	16286585	16.29	9.12E+08	912.45
35	520	158	17253040	17.25	9.96E+08	996.28
36	524	162	18032678	18.03	1.07E+09	1066.85
37	525	163	18227588	18.23	1.08E+09	1084.98
38	530	168	19202589	19.2	1.18E+09	1178.54
39	531	169	19397589	19.4	1.2E+09	1197.26
40	535	173	20177590	20.18	1.27E+09	1272.11
41	540	178	21152592	21.15	1.37E+09	1365.67

- Monthly Irrigation Demand at Kapilvastu Irrigation Project

Month	Kapilvastu Irrigation Demand (Mm³)
Jan	35.03
Feb	45.34
Mar	57.96
Apr	52.82
May	48.69
Jun	47.38
Jul	82.12
Aug	58.6
Sep	60
Oct	106.09
Nov	32.48
Dec	20.49
Total	**647**

- Modified Rule Curve Elevation

Month	Present Rule	Rule Curve-1	Rule Curve-2	Rule Curve-3	Rule Curve-4	Rule Curve-5	Rule Curve-6	Rule Curve-7	Rule Curve-8
Jan	516.69	513	517	519	516	516	512	516.5	513
Feb	511.17	507	511	514	511.5	509	502	511	506
Mar	502.51	498	500	505	501	502	490	500	498
Apr	492.33	488	490	495	491	494	479	490	490
May	480.78	480	478	482	479	478	473.21	478	477
Jun	473.21	473.21	473.21	473.21	473.21	473.21	477	473.21	473.21
Jul	484.64	487.64	487	493	491	489	498	493	488
Aug	510.54	513.54	506	515	511	505	515	510	508
Sep	524	524	518	524	523	520	522	524	520
Oct	522.59	521.5	524	523	524	524	524	523	524
Nov	521.12	519	523	522	522	523	522.5	521	523.5
Dec	519.95	517	521	521	520.5	521	520.5	519.5	522.5
Jan	516.69	513	517	519	516	516	512	516.5	513