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Assessment of Climate Change Impact on Future Water Availability and Irrigation Demand: A Case Study of the Chanda Mohana Irrigation Project, Nepal

BY

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The thesis titled "**Assessment of Climate Change Impact on Future Water Availability and Irrigation Demand: A Case Study of the Chanda Mohana Irrigation Project, Nepal**" prepared and submitted by Sandesh Rai in partial fulfilment of the requirements for the degree of Master of Science (M. Sc.) in Climate Change and Development has been examined by us and is accepted for the award of M. Sc. in Climate Change and Development by Tribhuvan University.

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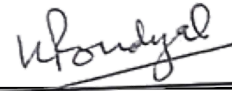
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DECLARATION

I hereby declare that this study titled **“ASSESSMENT OF CLIMATE CHANGE IMPACT ON FUTURE WATER AVAILABILITY AND IRRIGATION DEMAND: A CASE STUDY OF THE CHANDA MOHANA IRRIGATION PROJECT, NEPAL ”** is based on my original research work. Related works on the topic by other researchers have been duly acknowledged. I owe all the liabilities relating to the accuracy and authenticity of the data and any other information included hereunder.

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ABSTRACT

This study assesses the impact of climate change on future water availability and irrigation water demand in the Chanda Mohana Irrigation Project (CMIP), located in the Eastern Region of Nepal. Utilizing observed climatic data (1981–2014) and future projections (2015-2100) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) under SSP245 and SSP585 scenarios, trends in temperature, precipitation. The research employed the empirical methods (WECS/DHM 1990) for the analysis of discharge and CROPWAT 8.0 (Crop Water and Irrigation Requirements Program) is used to estimate Crop Water Requirement and Irrigation Water Requirement. Results shows that climate change causes substantial effects on river discharge of Budhi and Katle rivers along with irrigation water needs for the Chanda Mohana Irrigation Project. The result based on the Multi-Model Ensemble (MME), indicate that maximum temperature increases from 0.66°C to 2.61°C, the minimum temperature increases from 0.97°C to 3.60°C and the variation of precipitation ranges from -33.91 mm to 563.23 mm in the Shared Socioeconomic Pathway (SSP) scenarios of SSP245 and SSP585. According to the findings, the CMIP command area will likely increase precipitation and temperature in the future.

Finding shows that Percentage change for Crop Water Requirement (CWR) ranges from -1.69 % to 20.73 % in two different scenarios compared to historical data from 1990-2014. The Irrigation Water Requirement (IWR) for the command area ranges from 0.018 to 1.84 m³/sec. The SSP585 far-future scenario shows river discharge will significantly increase throughout June-August producing its peak flow of 14.66 m³/s in August. The future river flow is insufficient to meet the IWR in the months of February and March under both SSP245 and SSP585 scenarios.

To address these challenges, the study recommends integrated water resource management strategies, including improved irrigation efficiency, adaptive cropping patterns, and policy measures aimed at enhancing climate resilience. The findings provide vital insights for sustainable agricultural planning and climate-adaptive water management in Chanda Mohana Irrigation Project.

Keywords: Agriculture, Adaptation Strategies, CROPWAT 8.0, Climate Change, CMIP6, Irrigation Water Requirement, WECS/DHM 1990.

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Abbreviations

CC	Climate Change
IPCC	Intergovernmental Panel on Climate Change
FAO	Food and Agriculture Organization of the United Nations
CO ₂	Carbon dioxide
UN	United Nations
GDP	Gross Domestic Product
WECS	Water and Energy Commission Secretariat
CMIP	Chanda Mohana Irrigation Project
GCM	General Circulation Model
CWR	Crop Water Requirement
IWR	Irrigation Water Requirement
CMIP6	Coupled Model Intercomparison Project Phase 6
CWA	Climatic Water Availability
CWD	Crop Water Demand
UNDP	United Nations Development Programme
RCP	Representative Concentration Pathway
SSPs	Shared Socioeconomic Pathways
SWAT	Soil & Water Assessment Tool
SMC	Soil Moisture Constant
DHM	Department of Hydrology and Metrology
NSE	Nash-Sutcliffe efficiency
PBIAS	Percent Bias
RSR	Root Mean Square Deviation Ratio

QM	Quantile Mapping
MME	Multi-Model Ensemble
GIS	Geographic Information System

1. Introduction

1.1 Background

Climate change refers to the changes in statistical properties of earth atmospheric system, usually a decade or a longer duration of time (IPCC, 2007). Reviewed literatures have shown that Climate change is the natural imbalance, for example: increase in the level of carbon dioxide, global temperature, precipitation, and wind pattern) caused by human actions, developmental activities, industrialization, unplanned urbanization and agriculture (Thapa & Chand, 2025). FAO (2015) summarized the major challenges of climate change, including 4°C increment on global temperature by 2080, which is nearly equivalent to the negative effect induced from a 200% increase in the concentration of atmospheric CO₂. In reality, changing climate is one of the greatest challenges and is at the center of the global debate among governments, UN, practitioners, scientists and policy makers (Aruho Tusingwiire et al., 2023). Extreme occurrences including disastrous floods, protracted droughts, intense rainfall, and landslides are occurring more frequently due to climate conditions linked to altered patterns of rain, snowfall, and weather (Ranjan & Mishra, 2023). Climate change has significant impact on the hydrological cycle which is responsible for water availability, circulation and distribution to end-users (Chand et al., 2023).

Experts have stated unequivocally that as developmental activities have increased since the beginning of human life on Earth, greenhouse gas emissions have also increased, and the effects of climate change have become apparent. As a result, by the start of the twenty-first century, unexpected rainfall, prolonged-droughts, water shortages with low quality and water-induced disasters are all become commonplace (Makar et al., 2022; Gabr, 2023). These climate-related calamities pose a threat to life and have an extensive ramification (Aruho Tusingwiire et al., 2023). Scientists warn that if the water crisis increases in the future, it will produce a difficult situation with disastrous results in human civilization (Kumilachew & Hatiye, 2022). Water is essential component for every living being including animals and plants, much like nectar is for agriculture. According to the reports of United Nations, Asian agriculture (crop and livestock), where more than 50 percent of the world's population depends, is the most panicked sector by water problems (Chand et al, 2025). Access of clean water is one of the major constraints for sustainable agriculture development in third-world countries and arid regions where changing climate is becoming an additional risk (Aruho Tusingwiire et al., 2023).

Climate change is causing Nepal to experience a number of negative effects, such as unpredictable rainfall patterns, a significant and rapid temperature rise of more than 0.06

degrees Celsius, an increase in the frequency of extreme events, including severe drought, and rapidly melting glaciers with an average retreat of more than 30 meters per year (Thapa & Chand, 2024; Regmi et al., 2023). Department of Hydrology and Meteorology states that Nepal experienced an increment of annual average temperature by 1.8 degree Celsius between 1975 and 2006. Presently, the rate of temperature rise is estimated to be 0.5 degree Celsius per decade which is notably higher compared (Regmi et al., 2023). The main obstacle to agricultural growth is water, especially in developing and desert areas that are suffering from the effects of climate change (Thapa & Chand, 2024). Various studies indicate that water availability for crop production would be a big challenge due to several factors including (1) increasing temperature, (2) increasing frequency of prolonged droughts, (3) fluctuations in precipitation pattern and (4) increase in water demand from competing industries.

Table 1-1 Major impacts and likelihood of climate change on Nepal's water sector (WECS, 2011).

Phenomenon & direction of trend	Likelihood of future trends based on projections for 21st Century	Projected impact on water resources
Heavy precipitation events: frequency increases over most areas	Very likely	Adverse effects on quality of surface & groundwater, contamination of water supply, water scarcity may be relieved.
Area affected by drought increases	Likely	More widespread water stress
Intense tropical cyclone activity increase	Likely	Power outages causing disruption of public water supply

The sensitivity of characteristics like quality, water availability, and stream flow to temperature and precipitation variations makes quantifying the effects of climate change on water resources a challenging task (WECS, 2011). These changes in water availability during the monsoon, post-monsoon, and pre-monsoon seasons have a direct impact on Nepal's agricultural system, influencing crop production. Table 1-1 indicates the key effects of climate change on water resources in Nepal.

In the developing countries of the world, climate change has become a serious and complicated problem in all sectors for sustainable development. Agriculture, water resources, forest and health are the hardest-hit sector from adverse climatic pattern in Nepal. Water availability, quality, and stream flow have significantly changed across the nation, mostly as a result of changes in weather patterns (temperature and precipitation) (WECS, 2011). Since agriculture contributes a significant portion in Nepal's GDP, its reliance on rainfall and irrigation makes it particularly vulnerable to climate change. Any further decrease in water resources, especially outside of monsoon seasons, will have a severe impact on agricultural output and the livelihoods of the people. Crop water requirement, demand-supply gap and eventually agricultural productivity are connected with climate and climatic behavior (Thapa & Chand, 2024).

Crop water requirement, demand-supply gap and eventually agricultural productivity are connected with climate and climatic behavior (Thapa & Chand, 2024). Agronomic practices and agricultural planning depend on water availability in command area. Irrigation alone has multiplier effect of 20-30% crop production increment. Government of Nepal is designing agricultural projects near to irrigation system so that climate-smart farming could be undertaken. This study will gain a thorough understanding of how climatic dynamics and hydrological processes interact, as well as the skills necessary to create and carry out efficient management plans in an irrigated agricultural system.

1.2 Statement of problem

Water functions as a vital resource which sustains living systems while ecosystems and human civilizations but it represents more than an extractable resource. The Sustainable Development Goals (SDGs) require water as an essential connection to reach their global targets. The resource serves critical functions in health delivery and agriculture production and energy generation and infrastructure development. The fundamental purpose of SDG 6 consists of guaranteeing clean water and sanitation access for everyone as part of basic human rights (Thapa & Chand, 2024). Community access to natural resources benefits both basic need fulfillment and it builds community power and preserves environment biodiversity and facilitates sustainable economic progress and strengthens climate change readiness. The availability, quality, and management of water resources around the world are severely threatened by the increasing effects of climate change. Water supply-demand imbalances with worsening water quality problems become more severe because climate change produces changes in temperature together with disrupted precipitation patterns and unusual weather occurrences (UNEP, 2025). The existing water system vulnerability increases as population numbers rise together

with urban growth and agricultural and industrial operations that drive up water usage (UNESCO, 2025).

In a developing nation like Nepal, Climate Change has become an important concern for water and agricultural sustainability (Regmi et al., 2023). The hydrological regime has been impacted by the climate change, which results in the direct impact on water availability in the river basin. The unpredictable change in climate variables like temperature and precipitation patterns are the result of climate change which directly affect in the hydrology basin. These kinds of change have a direct impact on the water which changes the water supply and the productivity of the agriculture decreases.

Chanda Mohana Irrigation Project (CMIP) is situated in Sunsari district, Koshi province of Nepal. The research has not yet been studied in this area about water availability along with crop and irrigation water requirement and future climate variable projections. More than 20000 beneficiaries form this irrigation project, one of the major contributors to the agro-ecosystems in the middle eastern part of Nepal, does not have adequate research on the effect of climate change on irrigation water availability, which directly affects the water essential for the crops grown across command area. So, to uplift the life of the farmers via modernized agriculture, an effective adaptation strategy should be developed by studying the pattern of climate variables and water availability. This research aims to predict the future temperature and precipitation trends using two emission scenarios in a 25-year time interval: Near Future (2024-2049), Mid Future (2050-2074) and Far Future (2075-2100).

1.3 Significance of study

Global warming, a burning issue affecting the entire global ecology, and its consequence on the river systems of Nepal cannot remain untouched. The high melting of snowlines, glaciers and permafrost in the mountains due to an increase in air temperature as a result of global warming has resulted in an unnatural change in the water availability and water flow across the river networks of the country (Mellander et al., 2007; Singh and Goyal, 2017), and this can turn severe in future global warming trajectories. This makes it highly essential for the systematic exploration of the water availability and effect on irrigation water systems under the future changing climatic scenario.

Policymakers and stakeholders can leverage the insights from this study to gain a comprehensive understanding of the challenges and opportunities associated with water resource management in the context of a changing climate. Additionally, the study evaluated the disparity between crop water requirements and irrigation water demands,

considering the diversion of available water in the river. Furthermore, it identified and assessed the adaptive measures adopted by farmers in response to these changing circumstances. Identifying the gap between water demand and supply plays the vital role in planning adaptation strategies to climate change effects on water resources and to achieve sustainability in agriculture.

Thus, the timely study of the impact of climate change on water availability and irrigation systems on future changing climatic trajectories can help us define the probable risk of climate change in the river network and adopt a thoughtful precaution to minimize damage.

1.4 Objectives

The overall goal of this study is to establish a nexus among crop water requirements, irrigation water requirements and available water in the light of climate change, considering the command area of Chanda Mohana Irrigation Project, Sunsari Nepal.

Specific Objectives: -

- i) To analyze the historical variation of climate parameters (precipitation and temperature) in the study area and project future changes.
- ii) To examine how climate change affects the availability of irrigation water, both in terms of demand and supply.
- iii) To identify adaptive cultivation strategies to address the changing availability of water in response to the impacts of climate change.

1.5 Limitations of the study

The Department of Meteorology stations named Biratnagar Airport (Station No. 1319) and Tarahara (Station No. 1320) maintained daily meteorological records for the (1990–2014) time span. The available records at Biratnagar Airport started in 2020 for wind speed measurements until 2024. The study obtained Crop Coefficient (Kc) values from FAO Irrigation and Drainage Paper No. 56 for CWR estimates. The Crop Water Requirement (CWR) and Irrigation Water Requirement (IWR) projection for the future relied on static climatic elements since observed values indicated no change in sunshine hours, relative humidity, and wind speed. The MME projections provided maximum and minimum temperature data as well as precipitation information.

We could not measure river discharge directly because the Budhi and Katle Rivers lack gauging stations. The 1990 WECS/DHM developed a mathematical formula to estimate

discharge. This study focuses on climate trends and mean annual river discharge and crop water needs but does not integrate significant variables comprising upstream water usage and land use changes and urbanization and natural and anthropogenic changes in water availability.

2. Literature Review

2.1 Climate Change Impacts

Climate change poses a fundamental threat to humanity's existence. Significant climate effects have already been noted across all continents and without substantial, intensified efforts beyond current global measures, even more severe climate consequences are unavoidable, as major scientific reports from 2014 have warned (Romm, 2022). Climate change is one of the most pressing environmental challenges facing by the world today. In this century, climate change has become a critical issue for human societies, leading to uncertainty yet significant shift in rainfall, temperature and other climatic factors. These changes impact surface and groundwater hydrology, environmental sustainability, human health and socio-economics, with altered rainfall posing major agricultural challenges (Chand et al., 2021). Climate change impacts agriculture, biodiversity, forestry and health causing extreme weather, species loss, forest disturbances and economic challenges which required urgent adaptation and mitigation strategies (Abbass et al., 2022).

Climate change intensifies precipitation extremes globally, increasing the frequency and intensity of heavy rainfall events. Regional variations exist, with some areas experiencing decreased precipitation (O'Gorman, 2015). Since 1850, Earth's temperature has increased by an average of 0.11^o Fahrenheit (0.06^o Celsius) per decade, amounting to about 2^o F overall. This warming trend has accelerated significantly since 1982, with the rate of increase now more than three times as fast, at 0.36^o F (0.20^oC) per decade. The year 2023 stands out as the warmest year on record since global temperature records began in 1850, with temperatures 2.120 F (1.18^o C) above the 20th-century average of 57.0^o F (13.9^o C) and 2.43^o F (1.35^o C) above the pre-industrial average. Remarkably, the past decade (2014-2023) has seen the 10 warmest years in recorded history (Lindsey et al., 2020). The raise in atmospheric temperature has led to an increase in the amount of precipitable water vapor, which significantly altered both the seasonal and geographical patterns of precipitation across various regions of the world (Woznicki et al., 2015; Zhou et al., 2010; Wang et al., 2016; UNEP, 2025).

Rudraswamy and Umamahesh (2024) highlight the impact of climate change on water resources in the Tugabhadra basin, predicting increased droughts and variability in streamflow, soil moisture, and evapotranspiration. It emphasizes limited research on CWR and IWR in the Bhadra and TB command areas, particularly using CMIP6 models under SSP245 and SSP585 scenarios. The study aims to fill these gaps and provide insights for policymakers to enhance irrigation planning and reservoir operations in response to climate variability.

Climate change is predicted to have a net detrimental effect on freshwater ecosystems and water supplies in the majority of the world's regions (Solomon et al., 2007). Raising temperatures are thought to lead to higher rates of evapotranspiration, which could significantly boost the Crop water Demand (CWD) and reduce the Climatic Water Availability (CWA). Depending on the type and characteristics of the crop, CWD could increase by as much as 250% by the end of the 21st century (Gondim et al., 2012). In developing regions, the irrigation water requirement (IWR) could raise by 50 % for every degree of global temperature increase. In contrast, in developed regions, this requirement is projected to grow by 16% per degree of warming (Fischer et al., 2007). Due to climate change severe implications in water stress is occurred and results in food security. Climate change alters the availability of renewable water resources by affecting precipitation patterns and runoff timing. Some areas might face water scarcity due to decrease or irregular rainfall, while others might see more rainfall but still with increased evapotranspiration and agricultural water demand. Balancing water availability with agricultural needs is essential as reduced supply can heighten competition among agriculture, industry and domestic use (Fischer et al., 2007).

2.2 Climate Change Impacts in Nepal

Nepal is among the countries most at risk from climate change globally. It is ranked 139th out of 182 nations based on its exposure, sensitivity and capacity to adapt to the adverse impacts of climate change (Amadio et al., 2023). In recent years, Nepal has faced rapid glacier retreat, raising temperatures, erratic rainfall and frequent extreme events like floods and droughts. These climate changes threaten agriculture, tourism, energy and health. Since Nepal is covered with more Mountain regions and are particularly more vulnerable (Karki et al., 2009). Climate change is threatening Nepal's water resources, food security, human habits and tourism sectors seriously. Agriculture is the main source of income for majority of people in Nepal is agriculture and they mainly depend on the monsoon systems and evidence shows that monsoon patterns like rainfall timing, frequency, duration and intensity all may change due to ta climate change (Karki et al., 2009).

Nepal ranked as 142 over 177 countries in Human Development index by UNDP and major contributor to be the lowest ranked country in due to its undeveloped state of agriculture and water resources infrastructure (Watkins, 2008). The different studies reported that Nepal temperature is being increased in which higher altitude more warming is noticed. (Agrawala et al., 2003; Liu and Chen, 2000). By using the GCMs the average temperature rise is 0.5 to 2.0°C by 2030, 1.3 to 3.8°C by 2060 and 1.8 to 5.8°C by 2090 (McSweeney et al., 2008).

According to IPCC, the summer monsoon (June – August) is expected to be more extreme and changeable so more probable frequent rainfall may occur. The future projection of precipitation is in increasing intensity and projected as rainfall changes between -14%-40% by 2030, -40% to 143% by 2060s and -52% to 135% by 2090s (Solomon, 2007; NCVST, 2009). 70% of total population rely on the agriculture for their livelihood and 17% of total land is suitable for the agriculture. The most of the agriculture land is dependent on the rain-fed (60%) and 24% has the access to the irrigation system (HMG, 2001). The hydrology of Nepal is predominantly monsoon-driven and 85% of the rainfall occurs during the four monsoon months of June- September consequently the change in precipitation and runoff produce an issue in dry season and influence the agriculture productivity (Bartlett et al., 2010).

The impact of climate change on irrigation varies depending on the climate scenario (Malek et al., 2018). In the study of “impact of climate change on water resources of the Bheri River Basin, Nepal, the min., maximum temperature, and precipitation are in an increasing trend in two different scenarios (RCPs 4.5 and 8.5) in the three periods of 2020–2044, 2045–2069, and 2070–2099 (Mishra et al., 2018). Adhikari et al., (2022) on ‘The evaluation of climate change impact on hydrologic processes of the mountain river basin’ have found that the future streamflow of the Modi River will increase during the latter time windows (2075–2099), which is greater than mid-future (2050–2074) and near-future (2025–2049).

So, the study in CMIP is necessary to know the impact of climate change in water availability by predicting future climate variables and increase the agriculture productivity and plan for best adaptation strategy to climate change.

2.3 Models essential for predicting future climatic trajectories

Coupling hydrological models with climate models offers significant advantages and challenges in predicting future scenarios under climate change. The main benefit is to improve accuracy in simulating the interactions between climate variables and

hydrological processes essential for effective water resource management. For instance, integrating models such as SWAT, GCMs, and CROPWAT 8.0 allows for more reliable projections of water availability and irrigation needs, as demonstrated in studies of river basin such as the Kankai River Basin in Nepal. Challenges include the necessity for high-quality, localized climate data, inherent uncertainties in model parameters and future scenarios, and the computational demands of coupled models, which can limit their practical applications. Regardless of these hurdles, model coupling remains crucial for understanding and mitigating CC impacts on water resources, supporting informed decision-making for sustainable management (Lamichhane and Mishra, 2022). Therefore, it is very crucial to select an appropriate model for the study of future climatic data.

GCMs are critical for assessing climate impacts on water resources, but their systematic biases require correction before use in hydrological studies. A recent multi-model ensemble approach combining three GCMs and eight hydrological models highlighted that uncertainty in water resource projection stems from both climate and hydrological models. While high-latitude and some mid-latitude regions show consistent changes, variability remains significant in areas like Europe, the Middle East, and southern Africa (Hagemann et al., 2013).

In my study area there is no gauging station available so the methods like hydrological simulation methods like SWAT, WECS/DHM 1990 Method, Nepal Electricity Authority (NEA) 1997 method, General Transportation (GT) Methods, Drainage Area Ratio (DAR) method and DHM 2004 Method are used to simulate the average monthly discharge of the river basin (Marahatta et al., 2021). In this study WECS/DHM 1990 Method is used.

CropWat 8.0 was developed by the FAO, which calculates crop water requirements using the Penman-Monteith method and supports irrigation scheduling and scheme water supply planning, which evaluates irrigation practices and integrates with the ClimWat database for climate data. It is widely used in agricultural planning, water resource management, and research because it aids in optimizing water use and enhancing crop yields. Using atmospheric data, remote sensing, GIS, and CropWat 8.0, we found a 4% increase in irrigation water requirements under current practices and a 13% increase under no-field loss practices in El-Beheira, Egypt, due to climate change (Makar et al., 2022). The research done using CropWat 8.0 along with CMIP-6 GCMs to estimate crop water requirements (CWR) and irrigation water requirements (IWR) for the Bhadra and Tungabhadra command areas projected that CWR and IWR will increase significantly under future climate scenarios, particularly under the SSP-585 scenarios. In CropWat 8.0, the challenges include assumptions of constant climate factors, data quality issues, model

calibration needs, regional variability, complexity of climate scenarios, and integration with other models for comprehensive assessments (Rudraswamy and Umamahesh, 2024).

Yalcin et al. (2023) found that under high-forcing scenarios, SSP585, 9.26, and 22.11% of the total water demand and 20.17 and 38.87% of the total irrigation requirement could not be supplied. The study used the SWAT model to simulate future inflow rates and CropWat 8.0 to estimate crop and irrigation water requirements. Studies integrating SWAT and CropWat 8.0 have provided valuable insights into water availability and irrigation demand. Some studies in the Dhidhessa River Basin demonstrated that SWAT estimated an annual water availability of 9.26 billion cubic meters while CropWat calculated the IWR for crops like maize and sugarcane, indicating a potential irrigation area significantly larger than the current irrigated land, which implies enhancing agricultural productivity in water-scarce regions (Dawit et al., 2020).

2.4 Adaptation Strategies for climate change in Nepal

Climate change risk and vulnerability across Nepal and worldwide need multiple coordinated strategies across different sectors and levels so adaptation to climate change stands as the main development hurdle (Eriksen & Brown, 2011; Regmi & Bhandari, 2013). Human and natural systems use adaptations to handle actual stress from climate-based incidents coupled with hazards while leveraging opportunities from new innovations that target present or predicted circumstances. People cope with undesirable short-term and long-term results while taking advantage of positive circumstances (Regmi & Bhandari, 2013).

Planning, policies, or strategies at the national level that proactively address the possible impact of CC are referred to as strategic adaptation. This involves building infrastructure directly, developing capacity, planning for disaster relief, and a variety of other strategies that make a country more resilient to the possible effects of climate change on ecosystems and people. Planning for strategic adaptation is mostly about water management since the majority of these effects will be felt mainly in water resources, both in developed and developing nations. Therefore, strategic planning will involve focusing on more water-efficient, modern, sustainable farming methods, refocusing efforts on water infrastructure development and rehabilitation through storage and irrigation expansions, and reassessing water management in light of CC's effects (Bartlett et al., 2010; Bates, 2009).

Adaptation strategies are targeted at improving climate change resilience on water resources in Nepal. These may range from incorporating climate change into water management policies to initiatives of community-based adaptation, to upgrading infrastructure in response to climate-induced disasters. Moreover, allowing local institutions and stakeholders to cooperate is necessary to the successful execution of adaptive measures, promoting sustainable use and management of water materials despite a shifting climatic environment. These strategies aim to mitigate risks associated with water scarcity and variability, ultimately supporting the livelihoods of communities dependent on these vital resources (Regmi et al., 2018).

2.5 Soil-water-plant relationship for irrigation requirement dynamics

A coordinated interplay between soil and plant characteristics that integrates water use, retention, and movement for agricultural purposes is known as the soil-water-plant relationship (Michael, 2007; Garg, 2015). Water can be used by plants through their roots thanks to the soil. Depending on the properties of the soil, the rate at which water enters the soil and is retained, moved, and made available to plant roots are physical phenomena (Arora, 2012). Understanding the physical properties of soil is therefore crucial for irrigation water planning and effective management. Important soil characteristics from the perspective of agricultural irrigation are covered in the section that follows.

2.5.1. Properties of soil

The classifications used throughout the world for showing mechanical composition of a soil, also called mine rail fractions are those proposed by the United States Department of Agriculture (USDA) and by the International Soil Science Society shown in Table 2-1.

Table 2-1-Mechanical composition of the soil (adapted from Michael 2007, Garg 2015).

Fraction	Particle diameter	
	USDA	ISSS
Gravel	> 2 mm	> 2 mm
Very coarse sand	1 to 2 mm	-
Coarse sand	0.5 to 1 mm	0.2 to 2 mm
Medium sand	0.25 to 0.5 mm	-
Fine sand	0.1 to 0.25 mm	0.02 to 0.2 mm
Very fine sand	0.05 to 0.1 mm	-
Silt	0.002 to 0.05 mm	0.002 to 0.02 mm
Clay	<0.002 mm	<0.002 mm

2.5.2 Soil texture and structure

Soil texture is a fundamental property of soil that affects how water drains, how much water is stored, and how easy the soil is to work (Rice 2002; Obayomi et al., 2019). In terms of texture, sandy soils are categorized as coarse, loam soils as medium, and clay soils as fine. Water retention, soil water drainage, air circulation, and root growth are all significantly impacted by soil texture (Schaetzl & Anderson, 2005). Soil texture is important because it affects crop production and field management (Alegbeleye et al., 2018). It also influences how susceptible a soil is to erosion. There are 12 main textural classes as presented in Figure 2-1.

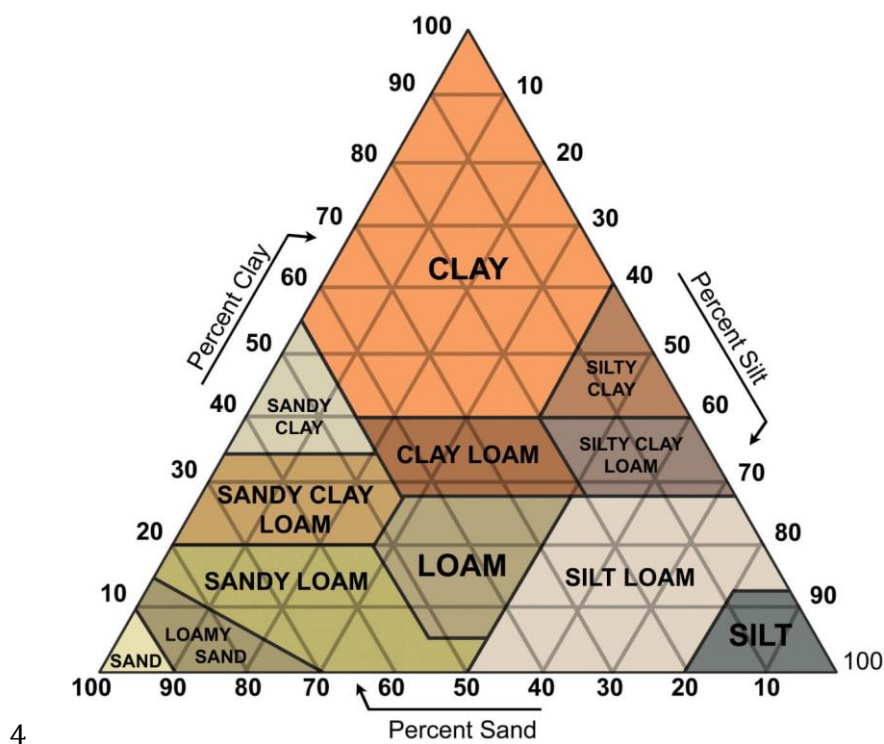


Figure 2-1 Soil textural triangular diagram (adapted from Schaetzl & Anderson, 2005).

Soil structure refers to the way sand, silt and clay arrange themselves according to Scherer et al. (2017). Among fundamental elements for successful crop cultivation stand porosity and hydraulic conductivity as well as infiltration and water holding capacity whose development depends on soil structure (Leuther et al., 2019). Scientific methods of soil structure management include controlled irrigation and the application of proper fertilizers together with optimal tillage practices at suitable SMC levels (Hillel, 2004; Patra et al., 2019).

2.5.3 Bulk density and porosity

As shown in Figure 2-2, soil is a three-phase system made up of solid, liquid, and gas. Given its impact on the soil's hydraulic conductivity and water-holding capacity, bulk density is a crucial physical characteristic. For instance, the hydraulic conductivity value drops to the point where drainage may become challenging when the bulk density of clay or loamy subsoil surpasses 1.7 g/cm^3 (Michael, 2007).

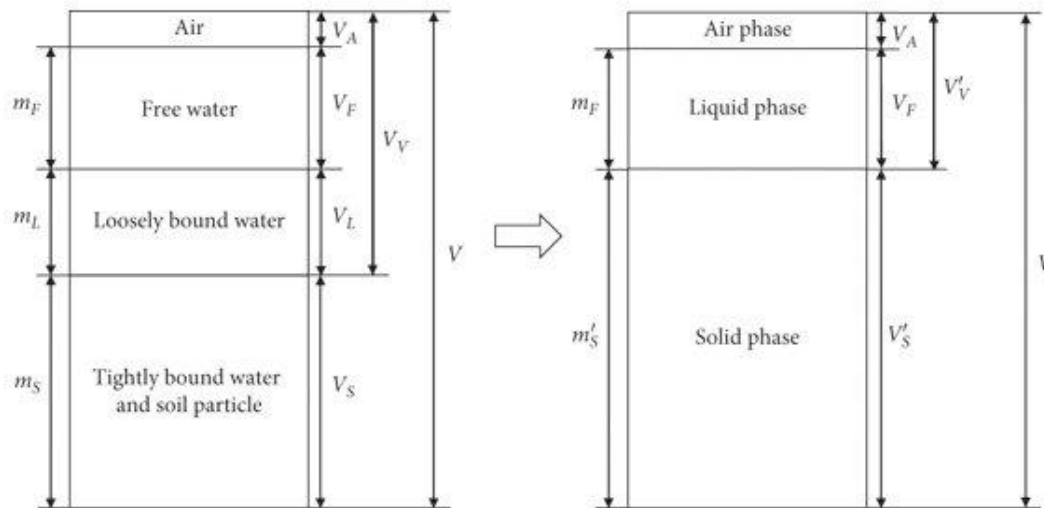


Figure 2-2-Schematic diagram of soil as a three-phase system (adapted from Zhang et al., 2020).

For example, when the bulk density of clay or loamy subsoil exceed 1.7 g/cm^3 , the hydraulic conductivity value becomes so less that drainage might become difficult (Michael, 2007).

Porosity (n) is an index of the relative volume of pores and can be defined as the ratio of the volume of pores (voids) to the total soil volume. The textural and structural properties of the soil affect the porosity value (Garg, 2015). For instance, clay soil often has porosity between 40% and 60%, but sandy soil typically has porosity between 35% and 50%. It suggests that the porosity increases with the fineness of the individual soil particles.

2.5.4 Soil moisture constants

Certain moisture values, such as field capacity (FC), saturation capacity (SC), ultimate wilting point (UWP), and permanent wilting point (PWP), are crucial for the usage and application of water in agricultural production (Haghverdi

et al., 2019). Using a hypothetical soil column, Figure 2-3 provides the relative locations of these particular moisture contents.

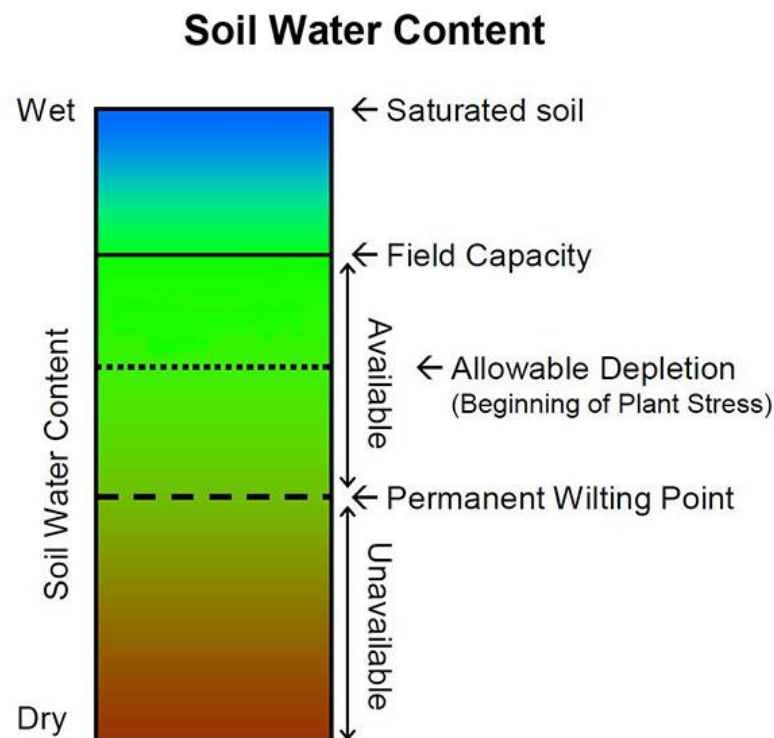


Figure 2-3-Representation of a typical soil moisture constants (Haghverdi et al., 2019).

The soil is said to be saturated (SC) when all of its pores are filled with water. A few days after the soil is saturated and the gravitational water's downward movement has slowed significantly, FC is the SMC (Xu et al., 2019). It is the quantity of water or soil moisture that remains in the soil after surplus water has evaporated and the moisture content has stabilized (Garg, 2015). One to three days after the soil has been completely soaked by irrigation or rain, this condition typically occurs (Xu et al., 2019).

At FC, water fills the micropores, air fills the big soil pores, and further drainage is extremely slow. PWP is the SMC at which a plant will wilt without water because it can't get enough moisture to meet CWR. UWP is the SMC at which the plants die and the wilting is complete (Arora, 2012). Available water (AW) is the term used to describe soil moisture between FC and PWP. It is a predictor of crop output and the amount of moisture available for plant usage (Wong & Asseng, 2006). The management permitted deficit is the maximum soil water deficit or the amount of water held in the root zone that is readily accessible to the plant.

The groups of soil texture with the range of water holding capabilities are shown in table no 3. The root system of a mature plant that will be cultivated is used to determine the

total amount of water that is accessible for a given soil depth when designing an irrigation system. In comparison to other soil types, Table 2-2 shows that sandy soil has lower field capacity, PWP, and accessible water. Sandy soil should require frequent watering to meet crop water needs.

Table 2-2-Water status and available water holding capacity in different soil textures (adapted from Michael, 2007).

Texture	FC (%)	PWP (%)	AW
Sandy	3-5	1-3	2-4
Sandy loam	5-17	3-8	4-11
Silt loam	12-19	6-10	6-13
Clay loam	15-30	7-16	10-18
Clay	25-40	12-20	16-30

Note: FC and PWP are expressed in dry basis; Available water in cm/m soil.

2.5.5 Crop water requirement and irrigation efficiency

The estimation of crop water requirements (CWR) is fundamental planning in any irrigation project. CWR is the amount of water needed to compensate for a crop's water losses, and is calculated to prevent water stress and to allow crops to grow without water limitations. Evapotranspiration (ET) and consumptive usage (C_n) losses, irrigation water application losses (unavoidable losses), and the amount of water needed for special operations like leaching, transplanting, and soil preparation are all included in the water demand (Michael, 2007). Mathematically,

$$CWR = ET \text{ or } C_w + \text{application losses} + \text{special needs.}$$

Michael (2007) explains CWR calculation by stating "Water requirement is; therefore, a demand and the supply would consist of contributions from any of the sources of water, the major source being the irrigation water (IR), Effective Rainfall (ER), and soil profile contributions (S), including that from shallow water tables." The numerical calculation of water requirement shows the following expression:

$$CWR = IR + ER + S$$

An irrigation requirement for a field crop measures all necessary water requirements minus rainfall effectiveness and soil contribution. Therefore, we can describe it as:

$$IR = WR - (ER + S)$$

The irrigation needs of a farming operation rely on crop water requirement and cultivation area and the water lost through farm water systems leakage. The total irrigation need for an outlet command area consists of both farm holding water needs and water losses inside the conveyance and distribution systems. The irrigation needs of individual farm holdings as well as the losses in the distribution and transportation networks are included in the irrigation requirements of an outlet command region.

The analysis by Koch et al., (2011) demonstrates how climate change in the Jordan River region would diminish crop yields from irrigated areas which would boost the necessity to expand irrigated land as per A1B forecasts. The researchers used LandSHIFT to develop a local version that measured how climate change affects irrigation land requirements at a constant farm output level. According to their results the expansion of irrigation area amounts to 25% due to climate change while various climate projections generate only slight differences in simulated irrigation area demands. The study demonstrates that increased crop demand would need a 71% growth in irrigated land areas.

2.5.6 Effective rainfall

In the simplest sense, effective rainfall means utilizable or useful rainfall. Effective rainfall is the amount of rain that is available for plants to use, and is also known as useful rainfall. It's a key concept in agriculture because it helps farmers decide how much water their crops need (Garg, 2015). The time, rate, or quantity of rainfall does not always indicate its use or desirability. It's possible that some of it will be inevitably wasted, while others might even be harmful. The amount of effective rainfall varies as much as the total rainfall. The user receives and stores the beneficial component of rainfall, while the undesired portions must be quickly removed or transmitted. Effective rainfall in dryland agriculture is that which can be saved for the next crop when the land is kept fallow. An individual farmer views effective rainfall as the amount that helps him manage the crops that are grown on his property. Water that escapes the field through runoff or deep percolation outside of the crop's root zone is useless. Also, Effective rainfall is important because it helps farmers decide how much water their crops need. This helps them ensure that their crops have enough water to grow and develop.

FAO (2022a) states that some rainwater runs off as runoff over the soil surface and some percolates beneath the plant's root zone. The plants are unable to use this runoff and deep percolation water. Stated differently, a portion of the rainfall is ineffective. The plants can use the leftover portion, which is kept in the root zone. The so-called effective rainfall is the portion that remains. The effectiveness of field investigation areas depends on three

main groups of factors: climate variables (air temperature, wind speed, and relative humidity), rainfall conditions (amount, intensity, distribution of rainfall and frequency) and soil characteristics (soil structure, slope of the land, the depth of the root zone and irrigation) together with recent irrigation practices.

When evaluating effective rainfall, it requires measurements of rainfall and irrigation alongside surface runoff losses and percolation losses outside the root zone and crop uptake of soil moisture for evapotranspiration. The required information about crop plant rooting depths comes from FAO (2022). Effective rainfall measurements occur directly or indirectly in both individual and integrated conditions.

2.6 Chanda Mohana Irrigation Project

Chanda Mohana Irrigation Project (CMIS) was constructed in year 2000 to irrigate Eighteen Hundred (1800) hectares, Eastern Main Canal System as 1000 ha. and Western Main Canal system as 800 ha., of command area of the then Rajganj, Aamduwa, Sahebganj and Sinuwari and Amihebella VDCs (Village Development Committees), at present: - Barju Rural Municipality in the east and Dewangunj Rural Municipality in the west, located at the Southern part of Sunsari district. OPEC Fund for International Development supported the construction of this headwork system through the international contractor known as China Henan International Economic Technical Cooperation Corporation, China (CMIP, 2025). The construction site of the headwork exists where Budhi Khola meets Katle Khola. The existing east head regulator was originally located at the same spot as the confluence points of Budhi (right side stream), Katle (left side stream), and Jala Khola. The Jala Khola is being redirected eastward from the headwork construction, where it meets two streams downstream. The command area is located between the tail ends of Shankarpur branch and Sitagunj branch canals of Sunsari Morang Irrigation Project (SMIP). Both of the aforementioned canals are unable to provide sufficient and dependable water to their tail ends because of the high demand for agricultural water in the head reach of the corresponding SMIP branch.

According to a JICA report "The Feasibility Study on the Sunsari River Irrigation Project" this project provides water for irrigation across 1000 hectares in Sitagunj (the eastern side) and 1200 hectares in Shankarpur (the western side). The salient features of CMIP are:

- | | | |
|----|-------------------------|----------------------------------|
| 1. | Province | : Province 1 |
| 2. | District | : Sunsari |
| 3. | Village | : Barju and Dewangunj Gaunpalika |
| 4. | Number of Beneficiaries | : 20000 |

5.	Command Area	
	Eastern	: 1000 Ha.
	Western	: 800 Ha.
6.	Name of Source	: Budhi and Katle River
7.	High Flood Discharge	: 500 cumes
8.	Catchment Area at H/W Site	: 120 sq.km.
9.	Type of Diversion structure	: Barrage cum Bridge (65 m clear span)
10.	Length of Main Canals	
	Eastern	: 7.474 km
	Western	: 7.980 km
11.	Idle length of Main canal	
	Eastern	: 1.981 km
	Western	: 4.000 km
12.	Number of branch canals	
	Eastern	: 12 nos. (Total Length 15.107 Km)
	Western	: 7 nos. (Total Length 7.225 Km)
13.	No. of structures	
	Main Canal including Access Road and Afflux bund	: 90 nos.
	Branch Canal	: 187 nos.
14.	Total Initial Estimated Cost (including contingencies)	: NRs 17,57,15,727.00
15.	Date of commencement	: FY 1995/96
16.	Due date of completion	: FY 2002/2003
17.	Internal Rate of Return (IRR)	: 10.4%
18.	Irrigation Service Fee (ISF, 20777-78)	: NRs. 750/ Ha.

3. STUDY AREA AND DATA

3.1 Study area

The Chanda Mohana Irrigation (CMIP) Project is located in the Eastern Part of Nepal with in the Sunsari District, Koshi Province. It was constructed in year 2000 to irrigate 1800 hectares, Eastern Main Canal System as 1000 ha. and Western Main Canal System as 800 ha. which covers Barju Rural Municipality in the east and Dewangunj Rural Municipality in the west, in the Southern part of Sunsari District. The headworks is located in the latitude of 25°29'03.65"N and longitude of 87°09' 49.35" E. The command area of CMIP covers an area between 26°24'29.221"N to 26°28'34.049"N and 87°8'45.532" E to 87°12'25.76" E. The beneficiaries from this irrigation project are 20000 household. The

source of CMIP is Budhi (right side stream) and Katle (left side stream). The average annual Precipitation is 1804.99 mm. The daily temperature ranges from 2°C to 42°C.

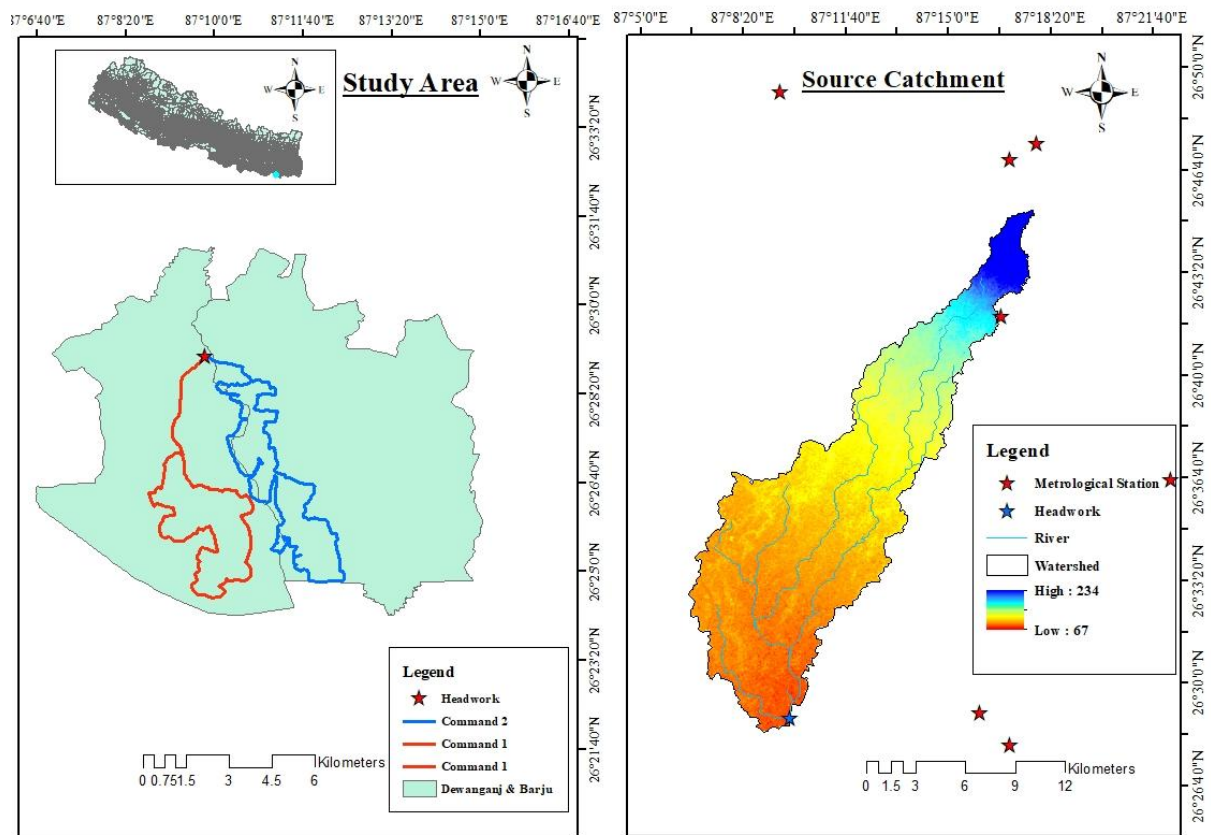


Figure 3-1- Study Area (CMIP with its Headwork and Command Area)

The Eastern Main Canal (EMC) and the Western Main Canal (WMC) are the two primary canals in this project. The EMC off leads to the nearby region from the headworks' left side. Twelve branches in all take off to irrigate a command area of 1000 hectares. The 800-hectare command area is irrigated by the WMC off-takes on the right. Numerous offshoot canals can be found on its eastern side, and three on its western side.

3.2 Data Collection

3.2.1 Metrological Data

The observed historical data like daily precipitation, maximum temperature, minimum temperature, wind speed and relative humidity data was collected from the Department of Hydrology and Metrology (DHM), Babar mahal for the period of (1990-2014). The Tarahara data is collected from the Office of Hydrology and Metrology (Dharan) for period (1990-2014). Table 3-1 shows the details about the Metrological Station that had been used in this research.

Table 3-1- Metrological Station details used in this study.

Station Index	Name	District	Lat. (°)	Long. (°)	Altitude (m)	Metrological Parameter	Date
1319	Biratnagar Airport	Morang	26.48397	87.26701	72	Precipitation	1990-2014
						Max. & Min. Temperature	1990-2014
						Sunshine Hours	1990-2014
						Wind Speed	2020-2024
						Relative Humidity	1990-2014
1320	Tarahara	Sunsari	26.69882	87.27874	120	Precipitation	1990-2014

3.2.2 Crop Data & Soli data

The crop coefficient (K_c), yield response factor (K_y) and root zone depth for the study area were sourced from FAO irrigation and drainage paper number 56. The soil data necessary for the CROPWAT 8.0 are collected from FAO database.

To obtain details on cropping patterns, crop colanders (including sowing and harvesting dates) and the types of crops cultivated in different seasons, data were gathered from the Irrigation Management Office in Biratnagar and by questionnaires with the farmer and field visit.

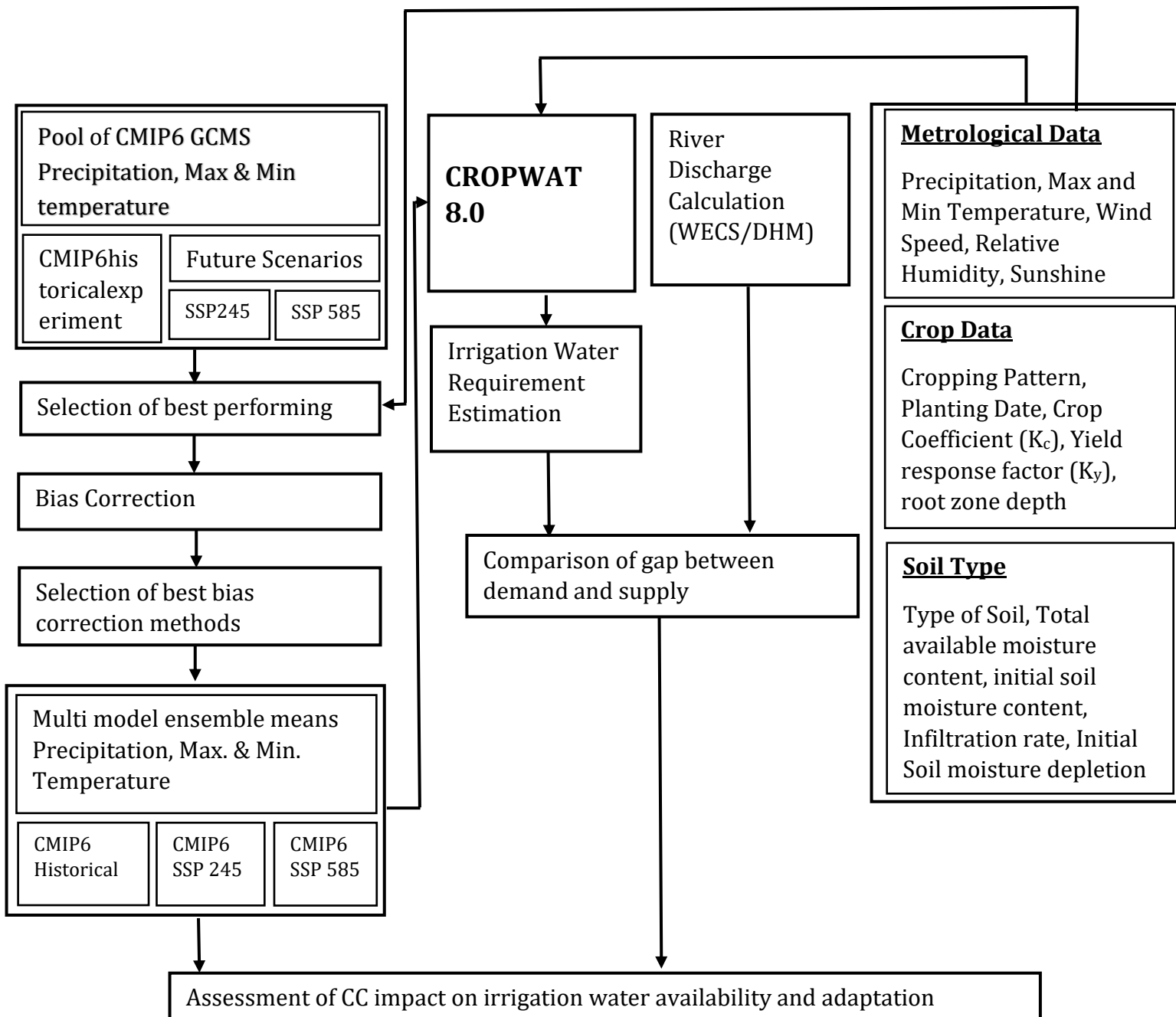
4. METHODOLOGIES

4.1 Research approach and Design

Selection of Best-Performing GCMs and bias-correction based on the performance metrics such as the Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE) and percent bias (PBIAS) were performed. The best four GCMs are multi-ensemble by taking two scenarios SSP245 and SSP585. The future period is divided into 3 timelines of 25 years interval: Near Future (2025-2049), Mid Future (2050-2074) and Far Future (2075-2100). The hydrological station does not exist in the basin (ungauged basins) so the WECS/DHM 1990 Methods was used to predict the future monthly flow of Chanda Mohana Irrigation Project. After that the CROPWAT 8.0 is utilized to estimate crop water requirements and irrigation water requirement, taking into account the projected changes in temperature and precipitation and lastly the data is analyzed including flow duration curves and irrigation requirement. Analyzing the water balance was reveal the discrepancies between water supply and demand, pushing irrigation managers and

farmers to develop effective strategies for managing irrigation water and adapting to changing conditions.

Figure 4-1- Flowchart Showing the Process



4.2 Selection of Best GCMs

The latest CMIP 6 GCMs were used for the research. CMIP6-GCMs model outputs were collected from World Climate Research Programme (WCRP) website

(<https://esgfnode.llnl.gov/search/cmip6/>). Using the pool of 10 GCMs (Lamichhane et al., 2022) shown in the table below, the best 4 GCMs for each climatic variable's precipitation, max temperature and mean temperature were selected. Every GCMs have its own strength and shortcoming; some will be more effective in the tropical area and some in mountainous area. So, it was very important to select the model that work best in our study area. The GCMs for two scenarios SSP245 and SSP585 was selected using the performance metrics (i.e., RMSE, R², PBIAS and NSE) comparing with the observed historical data. The equation used for ranking is shown below 1,2,3 and 4.

Table 4-1- Information on CMIP6 models used in this study, including model name, institutions and atmospheric resolution.

S. No	Model	Institution	Resolution
1	BCC-CSM2-MR	Beijing Climate Center, Beijing	1.125 ^o x 1.125 ^o
2	ACCESS-CM2	Commonwealth Scientific and Industrial Research Organisation (CSIRO) and ACCESS (Australian Research Council Centre of Excellence for Climate System Science).	1.125 ^o x 1.875 ^o
3	MRI-ESM2-0	Meteorological Research Institute, Ibaraki, Japan	1.125 ^o x 1.125 ^o
4	ACCESS-ESM1-5	Commonwealth Scientific and Industrial Research Organisation (CSIRO) and ACCESS (Australian Research Council Centre of Excellence for Climate System Science)	1.125 ^o x 1.875 ^o
5	NorESM2-MM	Norwegian Climate Center, Norway	2.5 ^o x 1.89 ^o
6	CMCC-CM2-SR5		
7	MPI-ESM1-2-LR	Max Planck Institute for Meteorology (MPI-M), Germany	0.94 ^o x 0.94 ^o
8	MIROC6	Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Kanagawa	1.4 ^o x 1.4 ^o
9	INM.INM-CM4-8	Institute for Numerical Mathematics, Russia	2 ^o x 1.5 ^o
10	INM-CM5-0	Institute for Numerical Mathematics, Russia	2 ^o x 1.5 ^o
11	GFDL-ESM4	Geophysical Fluid Dynamics Laboratory, USA	1 ^o x 1 ^o
12	NESM3	Nanjing University of Information Science and Technology Earth System Model version3	1.25 ^o x 1.25 ^o

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \dots\dots\dots 1$$

$$NSE = \frac{\sum_{i=1}^n (O_i - \bar{O})^2 - \sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \dots\dots\dots 2$$

$$R^2 = \frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (P_i - \bar{P})^2}} \dots\dots\dots 3$$

$$PBIAS = \frac{\sum_{i=1}^n (O_i - P_i) \times 100}{\sum_{i=1}^n O_i} \dots\dots\dots 4$$

Table 4-2-Performance Evaluation Criteria of Historical Raw GCMs (Moriassi et al., 2007)

Performance rating	NSE	RMSE	PBIAS	R ²	Rating
Very good	0.75<NSE<=1.0	0.0<RMSE<=0.50	PBIAS< 10	75<R2<100	5
Good	0.55< NSE<=0.75	0.50<RMSE<=0.6	10<=PBIAS	65<R2<75	4
Satisfactory	0.40<NSE<=0.55	0.60<RMSE<=0.70	15<=PBIAS<25	50<R2<65	3
Unsatisfactory	0.25<NSE<=0.40	0.70<RMSE<=0.80	25<=PBIAS	40<R2<50	2
Poor	NSE<=0.25	RMSE>0.80	PBIAS>=35	R2<40	1

The best performing GCMs must have more NSE (or NSE near to 1), less RMSE (or near to 0) and less PBIAS (less than 10).

4.3 Selection of Bias Correction

Most of the climate change research need bias correction techniques as an important method for Regional Climate Model (RCM) outputs (Ines et al., 2006). The process of bias correction realigns simulated data using observed data while resolving systematic biases (Reiter et al., 2016). Bias Correction data correction methods need to maintain climate alterations present in original data sets but they function based on the premise that future observational-statistical connections with past simulations will remain stable (Ngai et al., 2017). A successful bias correction method remains fundamental for eliminating systematic errors which occur within climate models. This adjustment methods enhances model data agreement with actual observations (Lamichhane et al., 2024).

The Quantile Mapping (QM) bias correction method utilizes 13 statistical transformation functions available in the Qmap package in R. The present study utilized 13 varieties of QM bias correction techniques for adjusting precipitation in GCMs together with 9 other techniques applied for maximum and minimum temperature adjustment. These functions include:

- Bernoulli Exponential
- Bernoulli Gamma
- Bernoulli Weibull

- Bernoulli Log-normal
- Exponential Asymptote
- Exponential Asymptote x0
- Linear Transformation
- Power Transformation
- Power x0 Transformation
- Scale Transformation
- Non-parametric Quantile Mapping
- Non-parametric Robust Quantile Mapping
- Smoothing Spline

The assessment of these bias correction approaches used as many as four selected GCMs to evaluate their performance through four recognized performance matrices. The overall research focused on applying the different bias correction methods to four selected GCMs with subsequent performance evaluation using established criteria, including RSR and R² and PBIAS and NSE shown in table no 6.

The bias-correction methods had been ranked using the performance metrics (i.e., RSR, R², PBIAS and NSE) using equation 1,2,3 and 4.

The bias-corrected yearly precipitation and maximum and minimum temperatures for the baseline period (1990-2014) from selected General Circulation Models (GCMs) were compared with observed data from the Department of Hydrology and Metrology (DHM).

4.3 Multi-Model Ensemble

The difference research done by merging climate models through multi model ensemble builds a strong foundation for detailed prediction about the upcoming climate variability. This approach intensifies prediction accuracy and reduce the uncertainties of the individual models. The predictive ability of ensemble means obtains greater power than individual models because bias cancellation occurs during output averaging. Several climate models become more reliable when their individual biases merge and negate each other (Tebaldi & Knutti, 2007).

The best 4 GCMs from the pool of 10 GCMs were used to generate the Multi-Model Ensemble (MME) of historical experiment and future scenarios (SSP 245 & SSP585) averaging the best 4 GCMs after the bias correction.

Simple Mean = $\frac{1}{n} \sum_{j=1}^n GCM_j$ 5

The calculation incorporates the term n representing GCM numbers selected for MME creation with a value of four in this analysis. The analysis used four GCM simulations as well as the numbering system of GCMj to represent the climate variable data in this study. The data represent (i.e., precipitation, maximum temperature and minimum temperature) which results from simulations of GCMs.

4.4 Calculation of River Discharge

WECS/DHM 1990 Method:

The Water and Energy Commission Secretariat (WECS) and Department of Hydrology and Metrology (DHM) proposed a method called WECS/DHM 1990 Methods to calculate the discharge of ungauged rivers. The equation is given below

$$Q_{\text{mean}}(\text{m}^3/\text{s}) = C \times (\text{Basin Area})^{A_1} \times (\text{Basin Area below 5000+1})^{A_2} \times (\text{Mean Monsoon Precipitation}) \dots\dots\dots 6$$

Where, C, A1, A2 are A3 are coefficients whose values are given

In this method whole Nepal is consider as one hydrological region and is appropriate for any catchment whose area is greater than equal to 100 km² (Subedi et al., 2022; Basnet & Acharya, 2019). The catchment area of the Budhi and Katle Khola (by taking outlet point at the headwork site), the Geographic Information System (GIS) tool shall be used.

Table 4-3- Values of Various coefficients for WECS/DHM (1990) Method

Month	C	A ₁	A ₂	A ₃
January	0.0142	0.0000	0.9777	0.0000
February	0.0122	0.0000	0.9766	0.0000
March	0.0100	0.0000	0.9948	0.0000
April	0.0080	0.0000	1.0435	0.0000
May	0.0084	0.0000	1.0898	0.0000
June	0.0069	0.9968	0.0000	0.2610
July	0.0212	0.0000	1.0093	0.2523
August	0.0255	0.0000	0.9963	0.2620
September	0.0168	0.0000	0.9894	0.2878
October	0.0097	0.0000	0.9880	0.2508
November	0.0018	0.9605	0.0000	0.3910
December	0.0015	0.9605	0.0000	0.3607

Source: <https://lib.icimod.org/record/4202>

4.5 Calculation of Crop Water Requirement and Irrigation Requirement:

CROPWAT is a decision support tool developed by the Land and Water Development Division which calculates crop water requirements and irrigation requirement from climate and crop data (Smith, 1992; FAO). The required data like metrological data, soil data and crop data for the calculation of CWR are collected from DHM, FAO database and from questionnaires to the farmers and stakeholders respectively. These extensive inputs enable accurate calculations of the crop water requirement and irrigation water requirements for the command area.

For the calculation of crop water requirements Penman-Monteith equation 9 is used and monthly data on reference evapotranspiration (ET_o) and rainfall are required. There are different methods to calculate the ET_o like Fixed Percentage, Dependable rain (FAO/AGLW formula), Empirical formula, USDA soil conservation service and rainfall not considered in irrigation calculation (effective rainfall=0) but in this study USDA soil conservation service methods is used, similar to the study previously used in Kamala Basin (Dawadi et al., 2022).

$$P_{eff} = (P * (125 - 0.2 * 3 * P)) / 125 \text{ for } P \leq 250/3 \text{ mm} \dots\dots\dots 7$$

$$P_{eff} = 125/3 + 0.1 * P \quad \text{for } P > 250/3 \text{ mm} \dots\dots\dots 8$$

P= Precipitation

$$ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \dots\dots\dots 9$$

$$ET_c = ET_o \times K_c \dots\dots\dots 10$$

ET_c =Crop water Requirement

ET_o =reference crop evapotranspiration

K_c = Crop Coefficient

For the calculation of irrigation water requirement below equation is used.

$$IR = ET_c - ER \dots\dots\dots 11$$

IR= irrigation water requirement

ER=effective rain (useful rainfall for plant (Adnan et al., 2009))

4.6 Calculation of gap between demand and supply:

To analyze the gap between water demand and supply, it's crucial to calculate the monthly IWR for the crops of command area and compare it with the available water supply or river discharge obtained from the WECS/DHM 1990 Method of Budhi and Katle rivers. This will help identify any excesses or deficits in water availability on a monthly basis. By examining the water balance, water managers can detect shortages or surpluses and make informed decisions on water management practices and adaptation strategies to mitigate climate change effects.

Excess/deficit water for irrigation= monthly river discharge – monthly irrigation water requirement.

5. Results and discussion

5.1 Selection of GCM from the pool of raw GCM

The CMIP6 GCMs were analyzed against observed data to evaluate how well they replicated the observations and were rated using performance metrics. In the pool of 10 GCMs for the precipitation the four best GCMs for this study are BCC-CSM2-MR, ACCESS-CM2, MRI-ESM2-0 and ACCESS-ESM1-5. For temperature max, 6 GCMs pool were taken and the best 4 GCMs are MIROC6, GFDL-ESM4, INM-INM-CM4-8 and ACCESS-ESM1-5. For minimum temperature, within 6 GCMs pool the best GCMs for study area are MIROC6, MRI-ESM2-0, ACCESS-ESM1-5 and INM-CM5-0. Since, INM.INM-CM4-8 also include in the top 4 for minimum temperature but the ssp585 data are only available for 2064 year so, in place of this GCM INM-CM5-0 is used. The MRI-ESM2-0 GCM rank 3rd while performing performance matrix but it has result up to 2064 only so we exclude this GCM and other top rank GCMs are used further for bias-correction.

The research identifies BCC-CSM2-MR together with ACCESS-CM2 and MRI-ESM2-0 and ACCESS-ESM1-5 as the best models to conduct precipitation event projections. Among the models used for maximum temperature predictions MIROC6 is most reliable alongside GFDL-ESM4 and INM-CM4-8 and INM-CM5-0. The Chanda Mohana Irrigation Project can rely on MIROC6 and MRI-ESM2-0 with ACCESS-ESM1-5 and INM-CM5-0 as the most suitable models for predicting future minimum temperatures.

Table 5-1:- Performance Rating of CMIP6 GCMs.

Precipitation	Rating	Maximum Temperature	Rating	Minimum Temperature	Rating
BCC-CSM2-MR	2.25	MIROC6	3.5	MIROC6	5
ACCESS-CM2	2	GFDL-ESM4	3	MRI-ESM2-0	5
MRI-ESM2-0	1.75	MRI-ESM2-0	2.75	ACCESS-ESM1-5	5
ACCESS-ESM1-5	1.5	INM.INM-CM4-8	2.5	INM.INM-CM4-8	4.25
NorESM2-MM	1.5	INM-CM5-0	2.25	INM-CM5-0	4
CMCC-CM2-SR5	1.5	ACCESS-ESM1-5	2.25	NESM3	2.25
MPI-ESM1-2-LR	1.5	NESM3	2	MPI-ESM1-2-LR	2
MIROC6	1.25	MPI-ESM1-2-LR	1.75		
INM.INM-CM4-8	1.25				
INM-CM5-0	1.25				

5.2 Bias Correction Method Selection

For the bias correction, 13 bias correction methods were used for precipitation and 9 bias methods were used for maximum and minimum temperature. The bias- correction methods analyzed against observed data to evaluate how well they replicated. The result shows that the bias-corrected GCM data are more uniformity with the observed data than the raw GCM data as shown in figure below. The results from this present study showed that the best bias correction methods are (a) non-parametric quantile mapping using robust empirical quantiles-linear for precipitation, (b) Parametric Transformation function-power for maximum temperature and (c) Parameter Transformation function-linear for minimum temperature. There are other methods also which have same value but methods which have been used in other study have been picked for further shown in table 5-2.

Using the 13 bias-correction for precipitation the most effective methods are non-parametric quantile mapping using empirical quantiles-tricub, non-parametric quantile mapping using robust empirical quantiles-linear and non-parametric quantile mapping using robust empirical quantiles-tricub. In most of the paper the best methods are Bernoulli Weibull for precipitation which was different from my study (Subedi et al., 2024; Raila et al., 2022). Out of best three methods non-parametric quantile mapping using robust empirical quantiles-linear bias correction methods is used. There are four best bias correction methods for maximum temperature as by QM bias correction in R studio. Out of four Non-parametric quantile mapping using robust empirical quantiles-linear this method is used in this study similar to the study done by Subedi et al., 2024. As result for minimum temperature most of the bias methods is good to use but Quantile

Table 5-2:- Performance rating of the bias correction methods

Bias Correction Methods	Rating		
	Precipitation	Maximum Temperature	Minimum Temperature
Bernoulli Exponential	1.5625		
Bernoulli Gamma	2.125		
Bernoulli Weibull	2.1875		
Bernoulli Log-normal	1.75		
Non-parametric quantile mapping using empirical quantiles-linear	2.3125	4.6875	5
Non-parametric quantile mapping using empirical quantiles-tricub	2.375	4.75	5
Parameter Transformation function-exponential asymptote	1.75	4.625	5
Parameter Transformation function-linear	2.25	4.5625	5
Parametric Transformation function-power	2.25	4.6875	4.875
Parametric Transformation function-scale	1.875	3.9375	5
Non-parametric quantile mapping using robust empirical quantiles-linear	2.375	4.75	5
Non-parametric quantile mapping using robust empirical quantiles-tricub	2.375	4.75	5
Quantile mapping using a smoothing spline	2.25	4.75	5

mapping using a smoothing spline is used for the study as the previous study shows these methods is good for minimum temperature (Lamichhane et al., 2024).

Comparison of Observed, Raw and Bias Corrected Model Data of Precipitation for 4 GCMs (1990-2014).

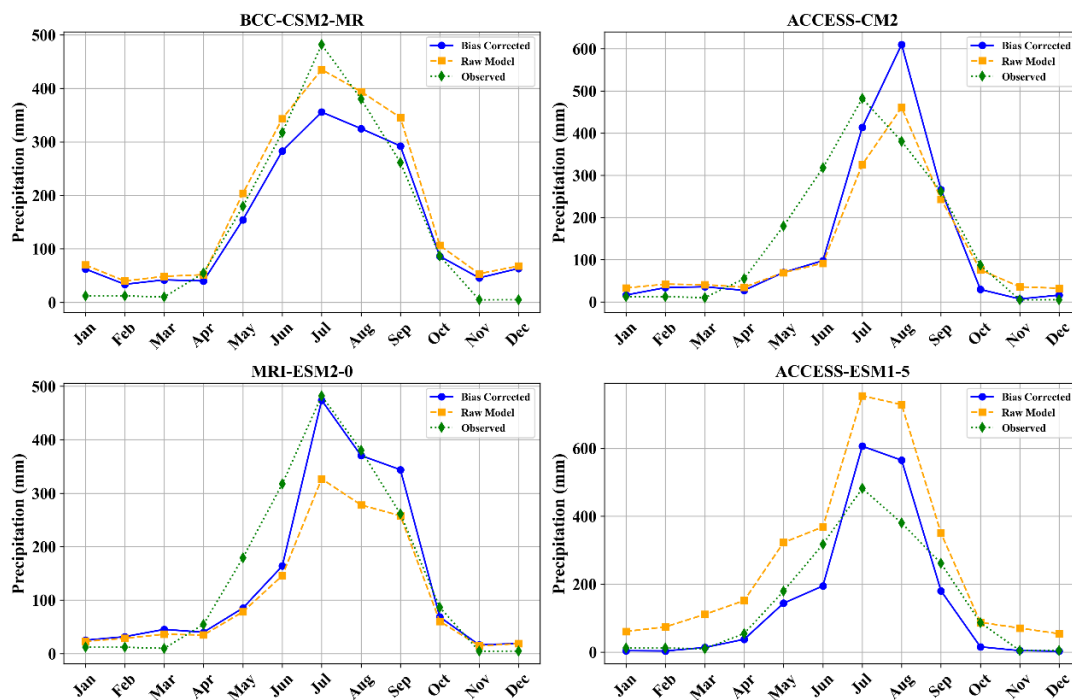


Figure 5-1-Differences between raw and bias-corrected and observed average monthly precipitation for four selected GCMs (BCC-CSM2-MR, ACCESS-CM2, MRI-ESM2-0 and ACCESS-ESM1-5)

The figure 5-1, 5-2 and 5-3 shows that the bias correction methods significantly reduce the difference between the raw and actual observed climatic variables which reduces the forecasting errors. The increased reliability of climate models through this enhancement allows them to serve better in hydrological analysis.

The above figure shows that the bias correction methods significantly reduce the difference between the raw and actual observed climatic variables which reduces the forecasting errors. The increased reliability of climate models through this enhancement allows them to serve better in hydrological analysis.

These techniques demonstrate their value best in streamflow analysis because accurate climate inputs are essential for this method. Revised climate data sources generated through this method enable better predictions about future water availability which helps both sustainable water resource management and agriculture planning.

Comparison of Observed, Raw and Bias Corrected Model Data of Minimum Temperature for 4 GCMs (1990-2014).

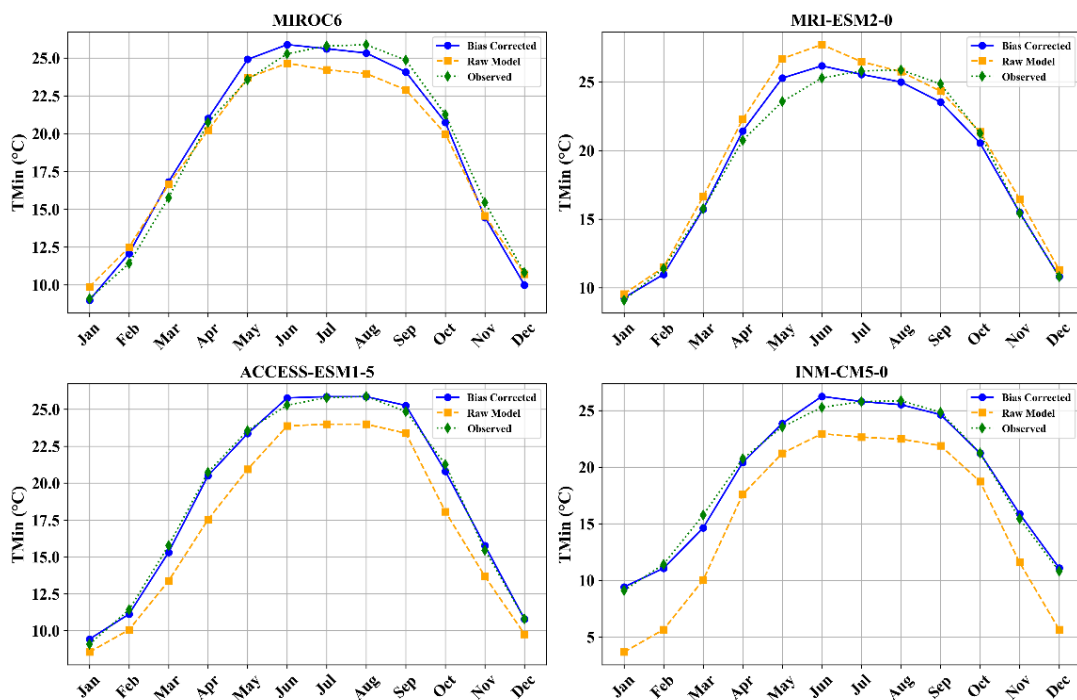


Figure 5-2-Figure 4-Differences between raw and bias-corrected and observed Average Monthly Minimum Temperature for four selected GCMs (MIROC6, MRI-ESM2-0, ACCESS-ESM1-5 and INM-CM5 -0)

Comparison of Observed, Raw and Bias Corrected Model Data of Maximum Temperature for 4 GCMs (1990-2014).

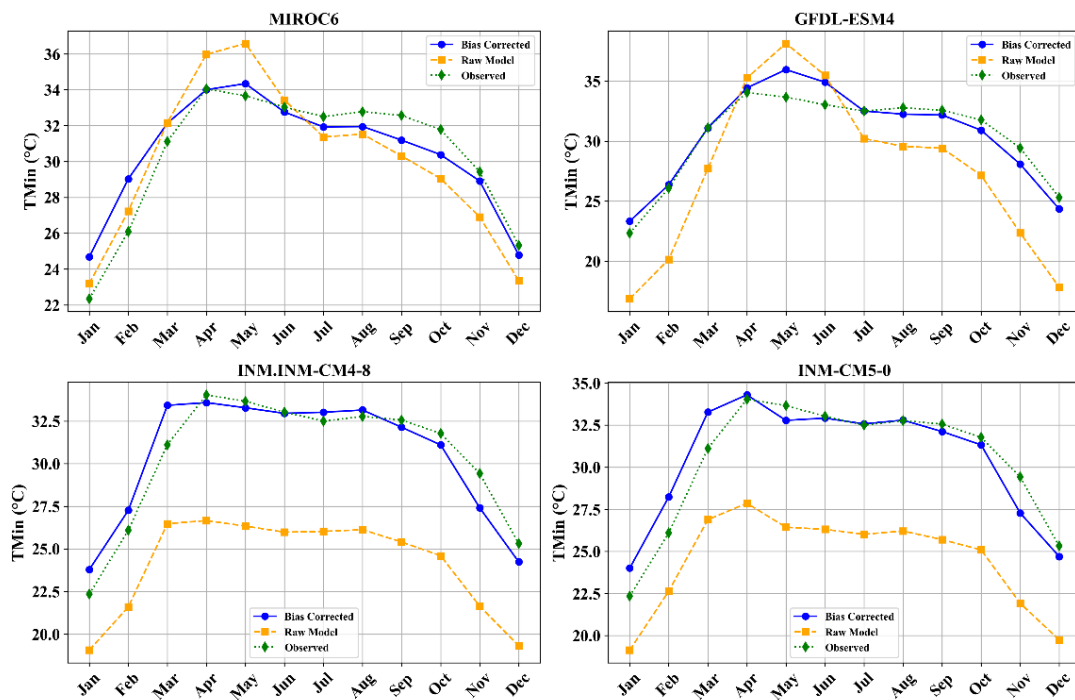


Figure 5-3-Differences between raw and bias-corrected and observed Average Monthly Maximum Temperature for four selected GCMs (MIROC6, GFDL-ESM4, INM.INM-CM4-8 and INM-CM5-0).

5.3 Formation of Multi-Model Ensemble (MME) and Projected Trend of Climatic Variables

The combination of various climate models known as multi-model ensembles (MMEs) outperforms single models at tracking precipitation and temperature changes (Samouly et al., 2018; Iqbal et al., 2020). The selection of suitable model quantity stands as a critical factor because MMEs featuring weak performers will show marked distinctions from ensembles containing only strong performers (Aadhar & Mishra, 2020). There exists no absolute criterion for choosing the correct number of GCMs for reducing climate projection uncertainties but using three to ten best-performing models stands as the standard practice (Ahmed et al., 2019; Pandey et al., 2020). This research employed four GCMs which maintained the highest ranks to build ensemble predictions for various climate variables. Researchers developed daily time series by relying on the CMIP6 historical experiment and SSP245 and SSP585 future emission scenarios.

5.3.1 Future Projection of Precipitation

The future projection is divided into 3-time frame near (2025-2049), mid (2050-2074) and far (2075-2100). The figure 10 and 11 shows the all best GCMs for precipitation and MME annual average precipitation in scenarios ssp245 and ssp585. The future trend in

ssp585 is in increasing order than ssp245. The observed annual precipitation for baseline 1990-2014 is in the range of between 829.70 (1994) to 2676.50 mm (1998). The near, mid and far future annual precipitation for scenarios ssp245 is range from 1460.56 mm (2028) to 2187.64 mm (2027), 1561.92 mm (2071) to 2534.90 mm (2062) and 1392.00 mm (2087) to 2449.49 mm (2082) respectively.

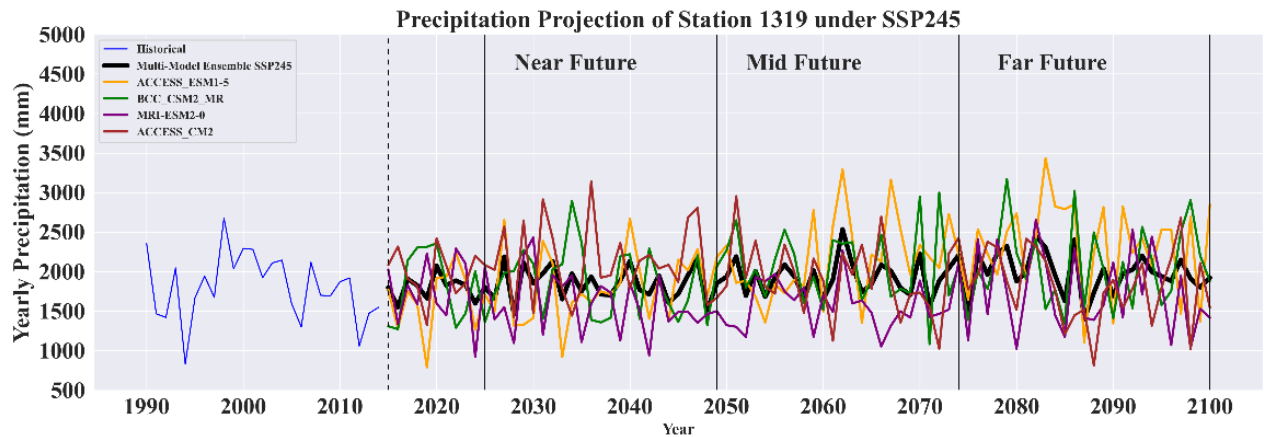


Figure 5-4- Baseline (1990-2014) and future (Near, Mid, and Far Future) annual average Precipitation at Biratnagar Airport Station (1319) under SSP245 scenarios.

The figure 5-4 shows the future trends of precipitation for scenarios ssp585. The annual precipitation of near, mid and far future under ssp585 scenarios ranges from 1409.81 mm (2033) to 2184.60 mm (2042), 1529.02 mm (2063) to 2657.11 mm (2064) and 1738.79 mm (2096) to 3479.65 mm (2092) respectively. This shows that the precipitation is increasing with time in the study area.

Table 5-3- Projected annual observed and future precipitation in three different time periods of Biratnagar Airport.

Observed Precipitation (mm)	1804.99 mm			
		Near Future (2025-2049)	Mid-Future (2050-2074)	Far-Future (2075-2100)
SSP 245		1846.22mm	1936.19mm	1980.29mm
SSP585		1771.08mm	2127.53mm	2368.22mm

The table no. 5-3 shows the annual Precipitation for observed time period (1990-2014), near future, mid and far future. The difference between observed annual Precipitation with near, mid and far future for SSP245 is 41.23 mm, 131.2 mm and 175.3 mm respectively, which is in gradually increasing order. For SSP585 the difference is -33.91 mm, 322.54 mm and 563.23 mm for near, mid and far future respectively. In SSP585 near future time period the precipitation is in decreasing trend remaining other all shows the increasing order.

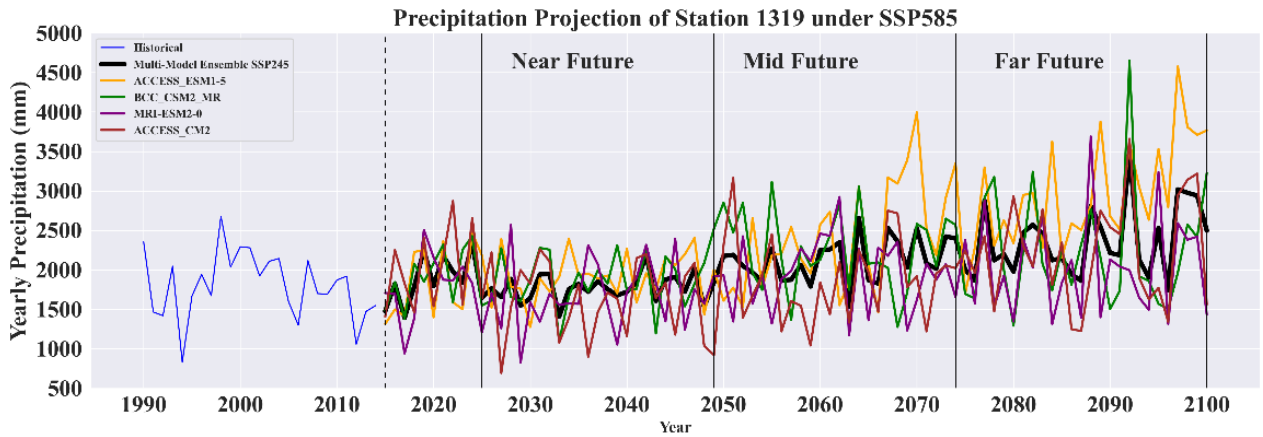


Figure 5-5-Baseline (1990-2014) and future (Near, Mid, and Far Future) annual average Precipitation at Biratnagar Airport Station (1319) under SSP585 scenarios.

The future precipitation of Tarahara Station (index no. 1320) for two different scenarios ssp245 and ssp585 for three different time period near (2025-2049), mid (2050-2074) and far (2075-2100) is shown in figure no. 5-4 and 5-5. The four GCMs have been selected from 10 GCMs of table no. 8 using 4 performance metrics equations 1,2,3 and 4. The best four GCMs are BCC-CSM2-MR (1.75), INM.INM-CM4-8 (1.5), INM-CM5-0 (1.5) and ACCESS-CM2 (1.5). Thirteen Bias-correction methods for precipitation was used same as table no 5-2 in which Bernoulli Gamma methods is best for Tarahara Station (2.125 overall value).

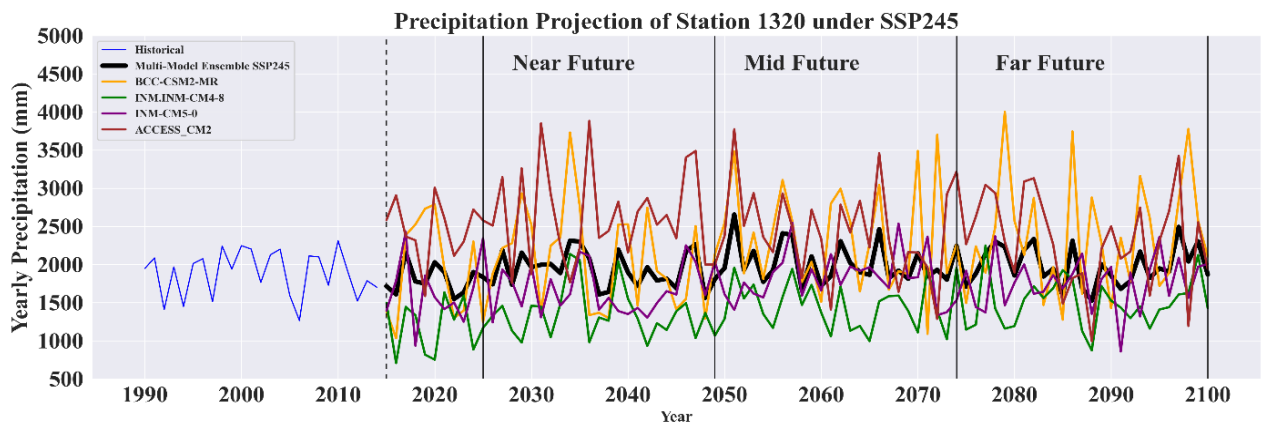


Figure 5-6-Baseline (1990-2014) and future (Near, Mid, and Far Future) annual average Precipitation at Tarahara Station (1320) under SSP245 scenarios.

Table 5-4-Projected annual observed and future precipitation in three different time periods of Tarahara.

Observed Precipitation (mm)	1888.74 mm			
		Near Future (2025-2049)	Mid-Future (2050-2074)	Far-Future (2075-2100)
SSP 245	1895.60 mm	2016.27 mm	1978.05 mm	
SSP585	1804.91 mm	2103.88 mm	2337.05 mm	

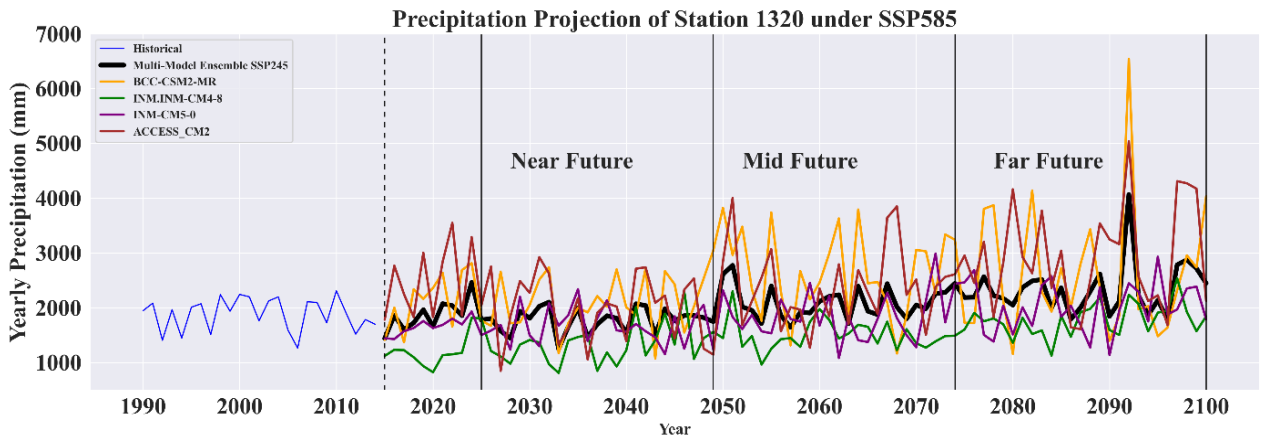


Figure 5-7-Baseline (1990-2014) and future (Near, Mid, and Far Future) annual average Precipitation at Tarahara Station (1320) under SSP585 scenarios.

The observed average annual precipitation of Tarahara Station is 1888.74 mm. For the scenarios ssp245 the future precipitation is 1895.60, 2016.27 and 1978.05 mm for near, mid and far time period which shows the difference of 6.86mm, 127.53 mm and 89.31 mm respectively. For the scenarios ssp585 the future precipitation is 1804.91, 2103.88 and 2337.05 mm for near, mid and far time period which shows the difference of -83.83 mm, 215.14 mm and 448.31 mm respectively. The table no 5-4 shows the details of annual average precipitation.

5.3.2 Future Projection of Minimum Temperature

The figure 5-8 and 5-9 shows the future trend of average annual minimum temperature of 4 best GCMs and MME of four GCMs and observed baseline year. The figure shows that there is an increasing trend in minimum temperature in both scenarios. For minimum temperature, the increase was less under the ssp245 scenario in compare to the ssp585 scenario.

The observed annual average minimum temperature of station 1319 ranges from 18.31°C (1991) to 19.88°C (2010). The future annual average minimum temperature according to MME in three different period near, mid and far ranges from 19.74°C (2031) to 20.68°C (2049), 20.16°C (2050) to 21.14°C (2064) and 20.53°C (2077) to 21.49°C (2098) respectively.

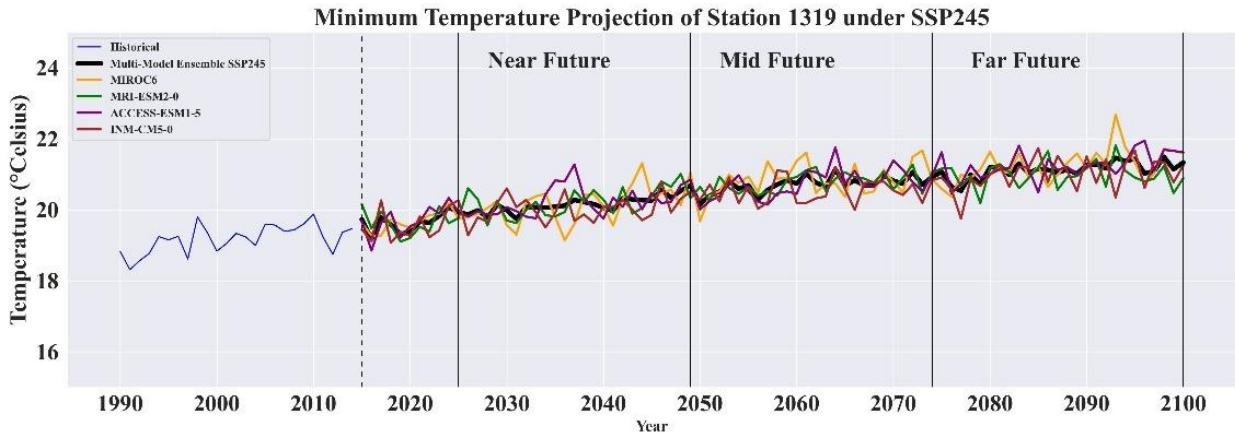


Figure 5-8-Baseline (1990-2014) and future (Near, Mid, and Far Future) annual average Minimum Temperature at Biratnagar Airport Station (1319) under SSP245 scenarios.

According to the MME future prediction for ssp585 the annual average minimum temperature for 3 different time period near, mid and far ranges from 19.67°C (2028) to 20.82°C (2047), 20.95°C (2052) to 22.54°C (2073) and 21.92°C (2078) to 23.75°C (2098).

Table 5-5-Projected annual observed and future minimum temperature in three different time periods of Biratnagar Airport.

Observed Min. Temperature (°C)	19.18°C			
		Near Future (2025-2049)	Mid-Future (2050-2074)	Far-Future (2075-2100)
SSP 245		20.15°C	20.72°C	21.12°C
SSP585		20.28°C	21.53°C	22.78°C

The table no. 5-5 shows the annual average of Minimum temperature for observed time period (1990-2014), near future, mid and far future. The difference between observed

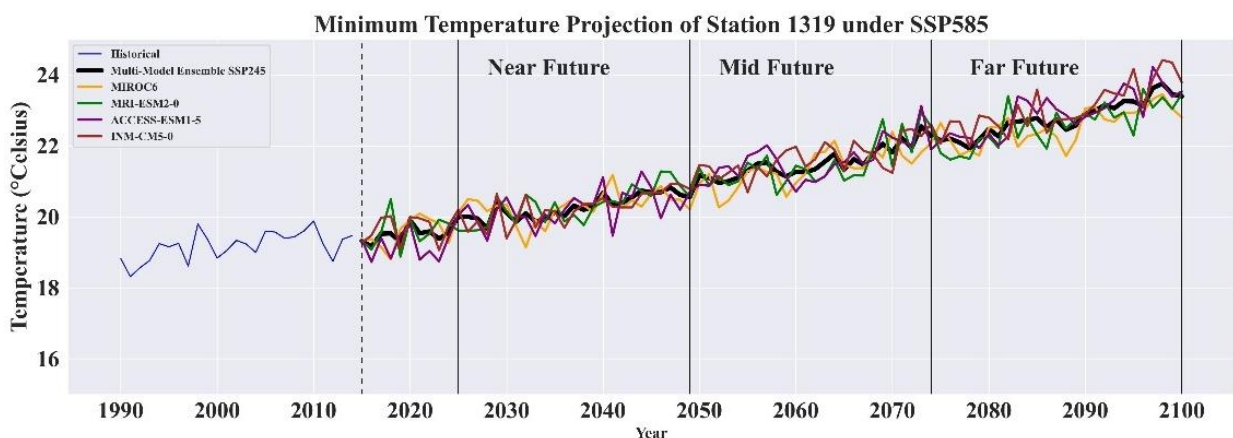


Figure 5-9-Baseline (1990-2014) and future (Near, Mid, and Far Future) annual average Minimum Temperature at Biratnagar Airport Station (1319) under SSP585 scenarios.

The table no. 5-5 shows the annual average of Minimum temperature for observed time period (1990-2014), near future, mid and far future. The difference between observed annual average minimum temperature with near, mid and far future for SSP245 is 0.97°C, 1.54°C and 1.94°C respectively, which is in gradually increasing order. For SSP585 the difference is 1.1°C, 2.35°C and 3.6°C for near, mid and far future respectively.

5.3.3 Future Projection of Maximum Temperature

The figure 5-10 and 5-11 shows the future trend of average annual maximum temperature of 4 best GCMs and MME of four GCMs and observed baseline year. The figure shows that there is an increasing trend in maximum temperature in both scenarios. For maximum temperature, the increase was less under the ssp245 scenario in compare to the ssp585 scenario.

The observed annual average minimum temperature of station 1319 ranges from 29.55°C (1990) to 31.13°C (2012). The future annual average minimum temperature according to MME under ssp245 scenario in three different period near, mid and far ranges from 30.58°C (2040) to 31.66°C (2045), 31.16°C (2050) to 31.98°C (2064) and 31.54°C (2077) to 32.57°C (2098) respectively.

According to the MME future projection for ssp585 the annual average maximum temperature for 3 different time period near, mid and far ranges from 30.73°C (2032) to 31.68°C (2043), 31.59°C (2050) to 32.78°C (2070) and 32.26°C (2076) to 33.54°C (2099).

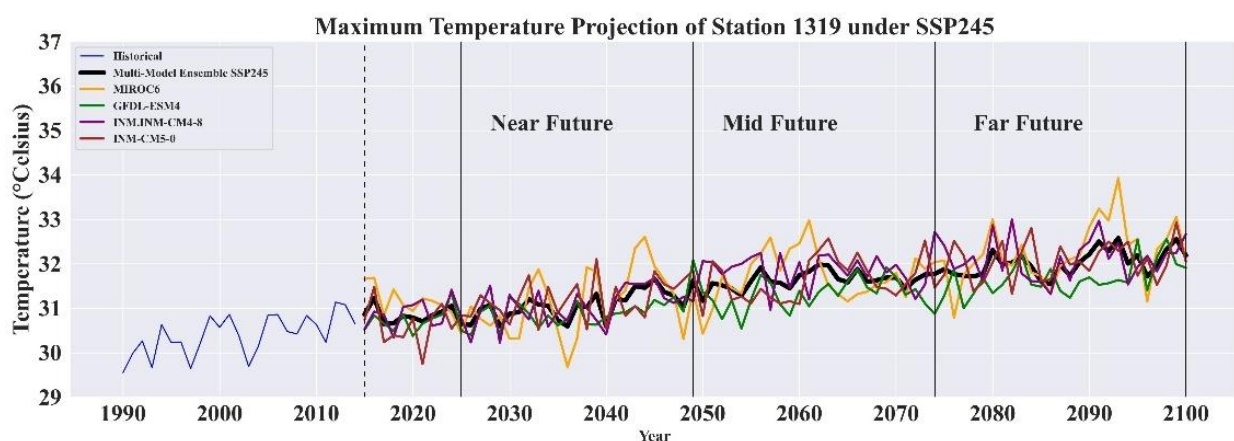


Figure 5-10-Baseline (1990-2014) and future (Near, Mid, and Far Future) annual average Maximum Temperature at Biratnagar Airport Station (1319) under SSP245 scenarios.

Table 5-6-Projected annual observed and future maximum temperature in three different time periods of Biratnagar Airport.

Observed Max. Temperature (°C)	30.40°C			
		Near Future (2025-2049)	Mid-Future (2050-2074)	Far-Future (2075-2100)
SSP 245		31.06°C	31.64°C	32.03°C
SSP585		31.21°C	32.14°C	33.01°C

The table no. 5-6 shows the annual average of Maximum temperature for observed time period (1990-2014), near future, mid and far future. The difference between observed annual average maximum temperature with near, mid and far future for SSP245 is 0.66°C, 1.24°C and 1.63°C respectively, which is in gradually increasing order. For SSP585 the

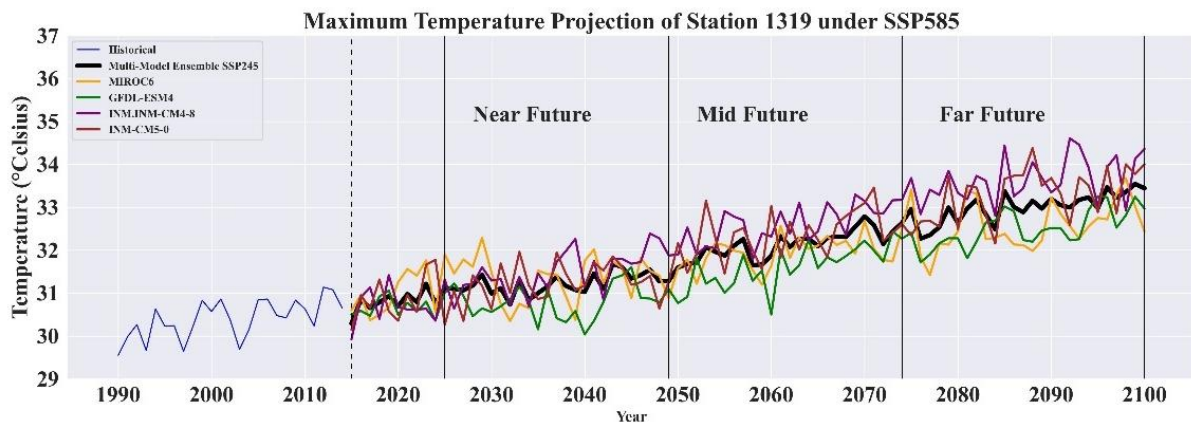


Figure 5-11- Baseline (1990-2014) and future (Near, Mid, and Far Future) annual average Maximum Temperature at Biratnagar Airport Station (1319) under SSP585 scenarios.

difference is 0.81°C, 1.74°C and 2.61°C for near, mid and far future respectively. In SSP585 the maximum temperature is also in increasing order but a little bit more increasing order than SSP245 scenarios.

The total change in projected monthly maximum temperature, precipitation and minimum temperature at Biratnagar airport station with the observed annual maximum temperature, minimum temperature and precipitation is illustrated in the figure below.

5.4 Monthly Change in Climate Variable

5.4.1 Change in Minimum Temperature

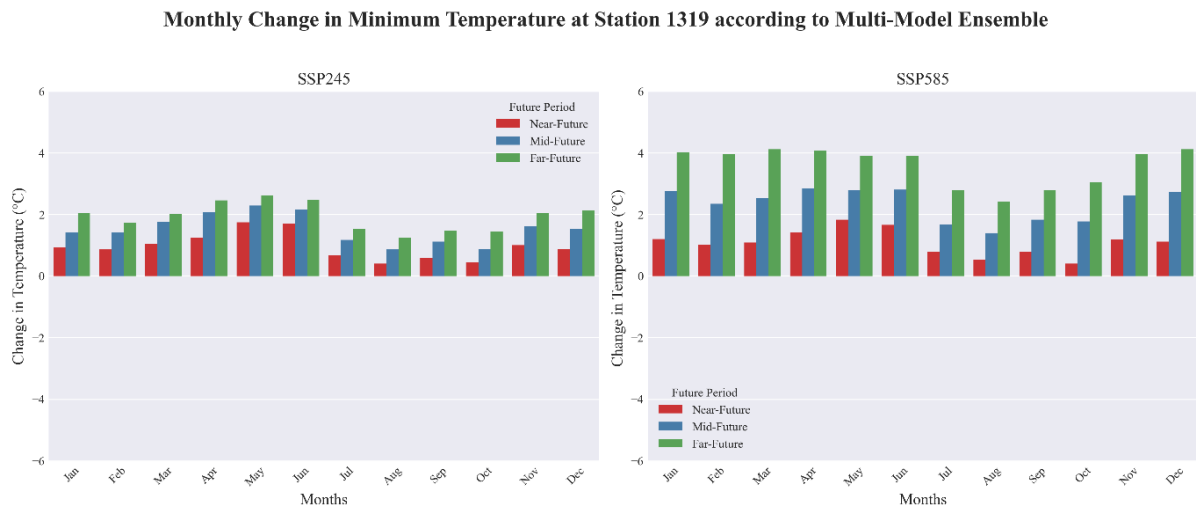


Figure 5-12-Monthly Changes in Minimum Temperature under the SSP245 and SSP585 scenarios.

The monthly change in minimum temperature in both scenarios with observed monthly temperature is projected in figure no 5-12. In comparison to SSP245, SSP585 exhibits much higher temperature increases in every month.

Table 5-7-Projected Monthly Change (°C) in future Minimum Temperature.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline (°C)		9.09	11.4	15.7	20.7	23.5	25.2	25.7	25.8	24.8	21.2	15.4	10.8
		1	6	3	6	8	9	7	5	5	4	1	
SSP245	NF	0.93	0.87	1.05	1.25	1.75	1.70	0.68	0.41	0.59	0.44	1.01	0.88
	MF	1.43	1.42	1.76	2.07	2.29	2.17	1.18	0.87	1.12	0.89	1.62	1.54
	FF	2.04	1.74	2.02	2.46	2.62	2.48	1.53	1.24	1.48	1.45	2.04	2.13
SSP585	NF	1.2	1.02	1.09	1.43	1.83	1.66	0.80	0.54	0.79	0.41	1.19	1.12
	MF	2.76	2.35	2.53	2.85	2.80	2.81	1.68	1.40	1.83	1.78	2.62	2.73
	FF	4.03	3.96	4.12	4.08	3.92	3.91	2.80	2.42	2.80	3.05	3.97	4.12

The changes for ssp245 in three different time period ranges from 0.41°C to 1.75°C in near future 0.87°C to 2.29°C in mid future and 1.24°C to 2.62°C for far future.

The changes for SSP585 in three different time period ranges from 0.41°C to 1.83°C in near future, 1.4°C to 2.85°C in mid future and 2.42°C to 4.12°C in far future. The monthly change with the average observed minimum temperature is shown in table 5-7 above with the baseline average minimum temperature.

5.4.2 Change in Maximum Temperature

Monthly Change in Maximum Temperature at Station 1319 according to Multi-Model Ensemble



Figure 5-13- Monthly Change in Maximum Temperature under the SSP245 and SSP585 scenarios.

The monthly change in maximum temperature in both scenarios with observed monthly temperature is projected in figure no 5-13. In comparison to SSP245, SSP585 exhibits much higher temperature increases in every month. The changes for ssp245 in three different time period ranges from -0.86°C to 2.49°C in near future, -0.36°C to 3.41°C in mid future and 0.04°C to 3.89°C for far future.

Table 5-8-Projected Monthly Change (°C) in future Maximum Temperature.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline(°C)	22.3	26.0	31.1	34.0	33.6	33.0	32.5	32.7	32.5	31.7	29.4	25.3
	4	9	1	4	6	3	0	8	7	8	3	2
SSP245												
NF										-	-	-
MF	2.47	2.49	1.79	0.33	0.78	0.90	0.49	0.33	0	0.45	0.86	0.17
FF	3.41	3.35	2.22	0.79	1.34	1.37	0.89	0.59	0.36	0.09	0.36	0.91
SSP585												
NF	2.74	2.59	1.72	0.23	1.18	0.87	0.64	0.39	0.17	0.16	0.71	0.18
MF	4.35	3.94	2.94	0.95	1.61	1.63	1.37	1.07	0.89	0.64	0.18	1.40
FF	5.57	5.00	3.91	1.85	2.38	2.41	1.80	1.61	1.49	1.42	1.28	2.69

The changes for SSP585 in three different time period ranges from -0.71°C to 2.74°C in near future, 0.18°C to 4.35°C in mid future and 1.28°C to 5.57°C in far future. In both scenarios the highest increase in maximum temperature is in the month of January and the lowest change is in months of November. The monthly change with the average observed maximum temperature is shown in table 5-8 below. Table 5-8 indicated that there was an increment in the monthly maximum temperature (Tmax). The most

significant increase in Tmax was observed during January, with a value of 0.1409 °C. The finding of this study is convergent with Mikhalchuk, et al. (2023) and Ramachandra & Shivamurthy (2023) at global level and WECS (2011) and Shrestha, et al. (2019) in regional level.

5.4.3 Change in Precipitation

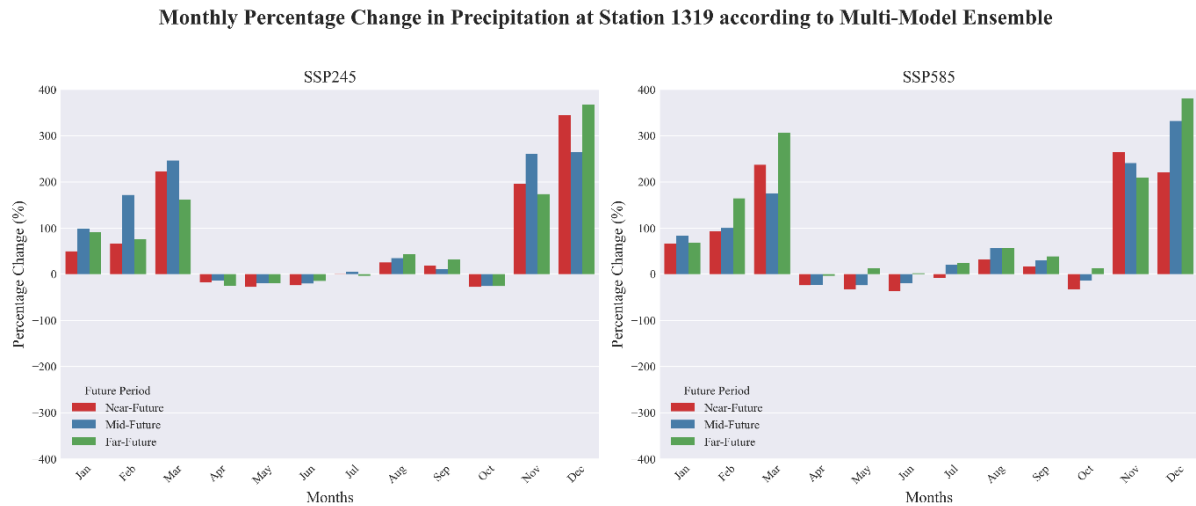


Figure 5-14- Monthly Change in Precipitation under the SSP245 and SSP585 scenarios.

Table 5-9-Projected Monthly Percentage Change (%) in future Precipitation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation (mm)	11.9	11.9	9.88	54.7	179.	317.	482.	380.	261.	86.6	4.61	4.83
	4	5	4	1	33	41	08	08	45	8	6	2
SSP245												
NF				-	-	-	-			-		
MF	49.7	65.7	222.	17.3	27.9	23.9	-	25.2	18.8	28.0	196.	343.
FF	2	4	13	2	2	2	1.18	6	5	1	19	72
SSP585												
NF				-	-	-	-			-		
MF	99.0	171.	246.	13.8	19.7	20.7		34.5	10.2	26.2	260.	264.
FF	7	67	31	4	9	4	4.86	1	4	7	33	93
	90.4	75.8	161.	24.5	19.0	14.7	-	43.3	31.8	26.0	173.	366.
	9	0	55	9	2	5	3.54	0	3	6	53	82
SSP585												
NF				-	-	-	-			-		
MF	65.6	92.3	236.	23.9	33.2	37.1	-	31.2	17.1	33.8	264.	220.
FF	8	7	70	7	8	4	8.84	3	5	4	93	31
	82.8	99.4	174.	22.6	24.2	19.7	20.3	55.7	29.5	13.9	240.	332.
	9	6	38	6	4	9	1	7	7	8	54	02
	68.2	164.	306.	-	13.5		24.9	57.1	38.1	13.6	209.	380.
	0	19	50	3.60	0	1.94	2	1	4	0	14	83

The monthly percentage change in precipitation in both scenarios with observed monthly precipitation is projected in figure no 5-14. The month December has the highest

percentage of precipitation change. The percentage changes for ssp245 in three different time period ranges from -28.01 to 343.72% in near future, -26.27 to 264.93% in mid future and -26.06 to 366.82% for far future.

The changes for SSP585 in three different time period ranges from -37.14 to 264.93% in near future, -24.24 to 332.02% in mid future and -3.60 to 380.83% in far future. The monthly percentage change with the monthly observed precipitation is shown in table 5-9 below.

5.5 Crop Water Requirement and Irrigation Water Requirement

Since, there is no cropping calendar prepared by the CMIP office and the farmers of CMIP command area so the questionnaire was prepared to collect the data. Cropping pattern and cropping calendar were known by interviewing with Prime Minister Agriculture Modernization Project (PMAMP) agriculture officer, Sunsari, Krishi Gyan Kendra officer, Biratnagar, Water users Committee of CMIP, the farmers and CMIP staffs.

The table 5-11 represent the cropping calendar of the CMIP command area and table 5-10 represent the cropping pattern of the CMIP command area. The total area covered by rice 1500 ha., wheat 650 ha., Maize 700 ha., sugarcane 300 ha. and potato 45 ha. including both east and west command area.

Table 5-10-Cropping Patterns of the CMIP command area.

Cropping Patterns		
	Eastern Command Area	Western Command Area
<i>Rice</i>	700	800
<i>Wheat</i>	150	500
<i>Maize</i>	500	200
<i>Sugarcane</i>	300	0
<i>Potato</i>	20	25
Total area	1000	800

The table no. 5-11 shows the cropping calendar of Chanda Mohana Irrigation Area command area which shows different 3 stage of crops sowing, Mid-season and harvesting in color red, blue and purple. Rice is grown in mid of June and harvested in the mid of October, maize is grown in the starting of January to end of April, wheat is grown in mid of December to the mid of April, sugarcane is grown all the year and potatoes are grown in mid of October to the end of February.

Several weather patterns along with the type of cultivated crop determine what quantity of water the crop requires (Chand et al., 2021).

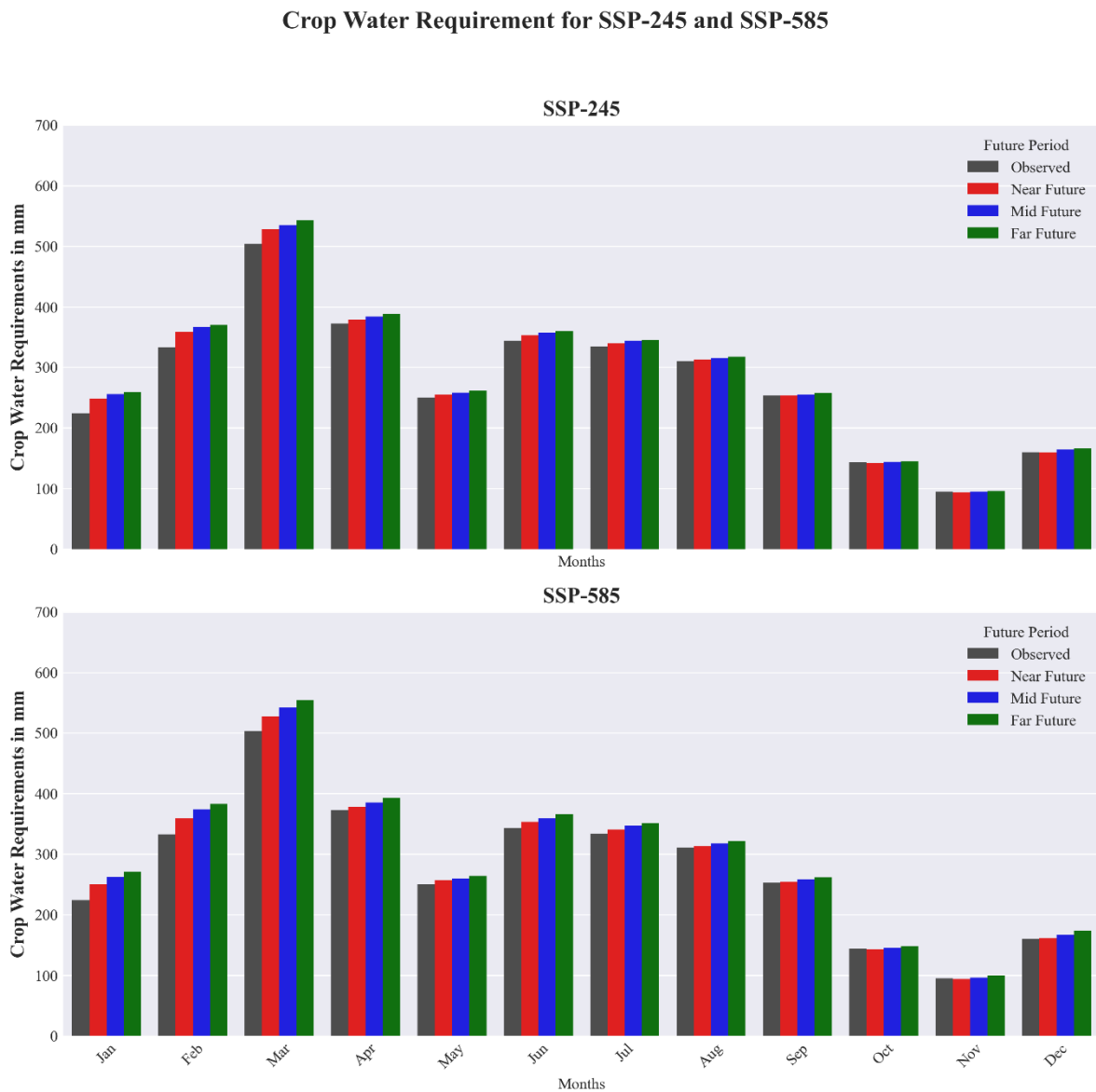


Figure 5-15-CWR of Chanda Mohana Irrigation Project (observed, near, mid and far) time period.

According to FAO standards the necessary water requirement for rice during its growth period can vary between 450-700 mm. The estimated rice crop water requirement for CMIP falls away between 713 mm to 749.7 mm since the climate of Biratnagar is hot, dry and windy. The FAO recommended wheat (450-650 mm) and maize (500-800 mm) and potato (500-700 mm) water requirement levels diverge from the measured study values that range between 376-419 mm, 374.2-420.1 mm, and 284.3-318.1 mm respectively. The low wheat and maize crop water need in this region are explained by chilly climate conditions merged with humid atmospheric conditions and surplus rotting soil moisture

during sowing season. FAO's recommended sugarcane water requirements between 1500 and 2500 mm matches our study findings because sugarcane in our research consumed between 1574.6 and 1680 mm because the crop-growing climate remains moderate thus following the FAO recommendations.

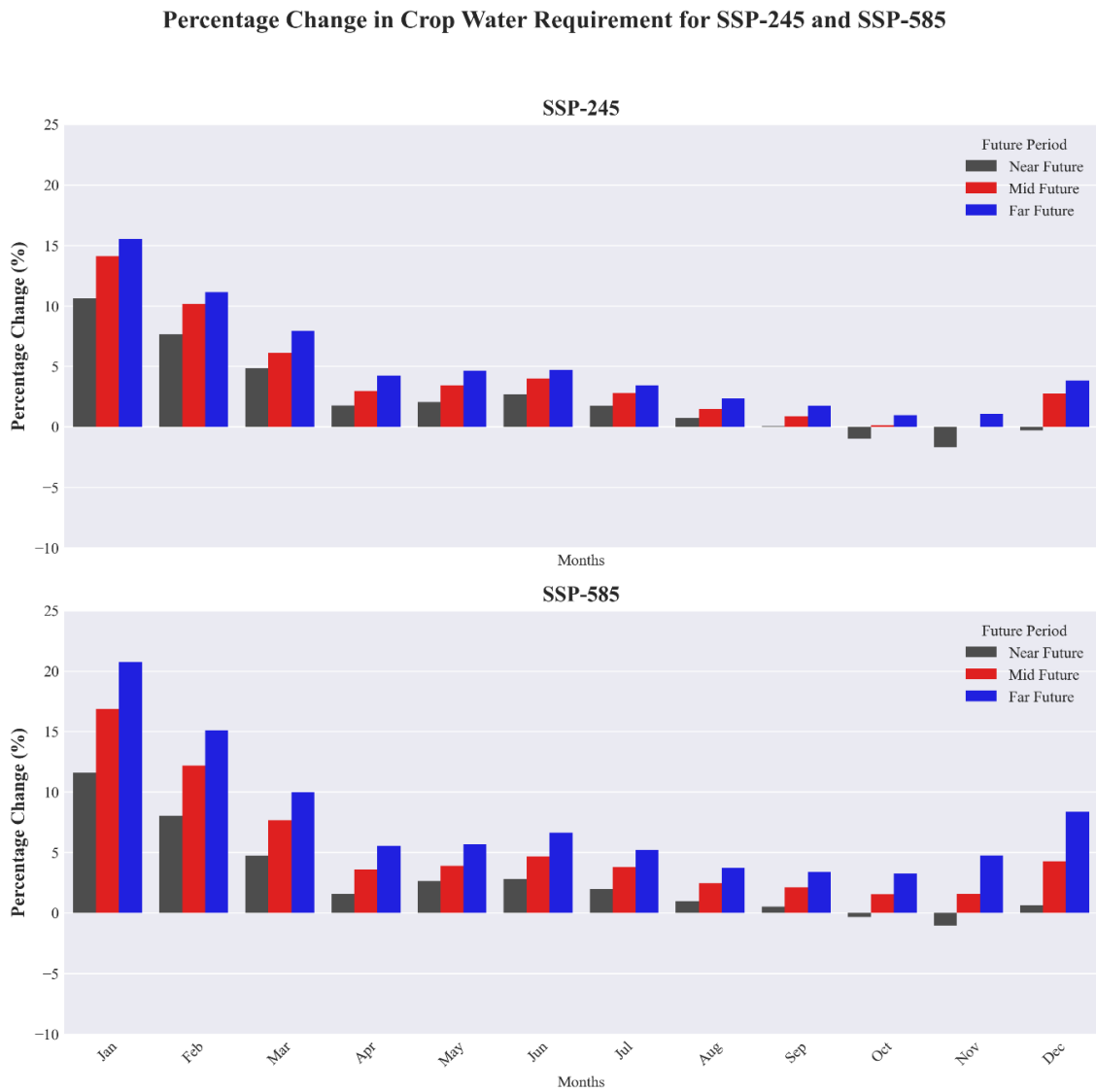


Figure 5-16-Percentage Change of CWR in three different period with observed CWR.

The crop water requirement toward the future period is increased for all months except for October, November and December in Near Future. The first two months (January and February) have a much bigger percentage change in crop water requirements than the other months because of the higher percentage rise in the CMIP command area's maximum and lowest temperatures during those months. In the near future, SSP245's agricultural water requirements will rise to 10.61079 percent in January and fall to -1.689 percent in November. In other time period for ssp245 the percentage change for CWR is in increasing 15.56% in January. In mid future period (2050-2074) the % change

in CWR is zero in the month of November. For ssp585 the percentage of CWR increases up to 20.73% in January month and decreases up to -1.06% in November. According to the research, the NF, MF, and FF have higher agricultural water requirements as the maximum and minimum temperatures are rising in the near, mid, and far future (Figure 5-16).

5.5.2 Irrigation Water Requirement (IWR)

Irrigation Water Requirement for Observed, SSP-245 and SSP-585

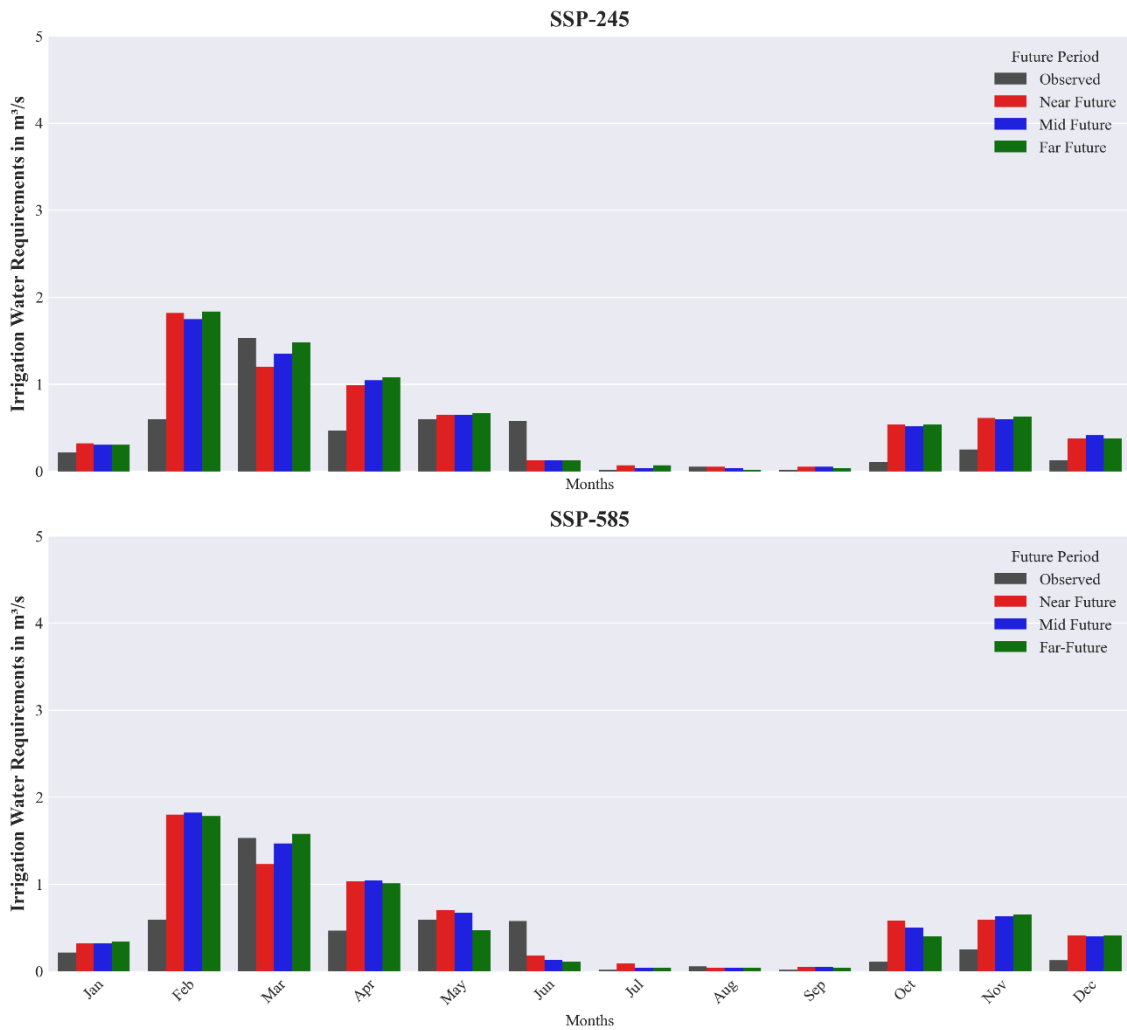


Figure 5-17-IWR of Chanda Mohana Irrigation Project (observed, near, mid and far) time period.

The current water requirements for irrigation at CMIP command area receive representation through the figure no. 5-17 above. The irrigation water requirements ascended in both timeframes in scenarios while staying above the observed IWR numbers. The weather conditions significantly influence the amount of water crops require for irrigation. The amount of precipitation and timing and evapotranspiration need combine to form the basic determinants for irrigation requirements. The high

irrigation requirement develops when there is insufficient precipitation or enhanced evapotranspiration demand. The precipitation pattern at CMIP (Biratnagar Airport station) indicates an upward trend matched by increasing temperatures. There appears to be a precipitation shortage when compared to crop evapotranspiration needs. The highest IWR is 1.836 m³/sec (Feb, SSP245 Far) and the lowest IWR were 0.018 m³/sec (July, SSP585 near & August, SSP245 far).

A figure 5-18 displays the IWR percentage changes based on observed time and projected future periods including near, mid and far. According to ssp585 scenario the irrigation water demand decreases toward future periods in three months March, June and August. The increased in CWR is fully meet by increased precipitation. Effective rainfall has a significant impact on the amount of water needed for irrigation. The rise in effective rainfall during these months is the reason for the decrease in the need for irrigation water. Remaining other 9 months, the irrigation water requirement is increased. The crop water requirement during those months also increased. But, precipitation in November and December months also increased. The higher agricultural water requirements could not be satisfied by the extra precipitation. As a result, the need for irrigation water also rises.

The irrigation water demand evaluations within the near future span of ssp245 indicate a range between -78.13% in June to 400% (October) %, for mid future period range from -78.12 (June)- 383.33 (October) % and for far future range from -78.125(June) to 400% (October). The October months show the maximum irrigation water need among all time periods under study. The month of October needs the highest amount of irrigation water because the precipitation declines and both maximum and minimum temperature rise during this period. During March the irrigation water requirement dropped because precipitation levels in this month progressively increased. August receives decreasing water demand since the meteorological data indicates a rising precipitation trend in this month compared to observed values.

The IWR presents the highest % change during October since the month shows declining precipitation patterns which the above figure 5-14 and table no 5-9 display. The growing water requirements of the crops are completely fulfilled by higher precipitation amounts. Effective rainfall determines the majority of irrigation water needs. These months

experience decreased irrigation water requirements because effective rainfall increases throughout the period.



Figure 5-18-Percentage Change of IWR in three different period with observed IWR.

5.6 WECS/DHM Methods

The WECS/DHM, 1990 performed the estimation of monthly river discharge. A complete hydrological analysis with this method demands details on the catchment area and altitude distribution together with catchment monsoon wetness index data. Hydrological experts determined the monsoon wetness index for the Budhi and Katle River catchment during each year between 1990 to 2014. A monsoon precipitation index existed as a reference point based on average monsoon precipitation data measurements taken at Tarahara meteorological station. A study of the Budhi and Katle River catchment area

detected this area to be 112 km² using ARCGIS ARC Hydro (Kaini et al., 2011). Table 5-12 shows the results of annual flow from WECS/DHM method:

Table 5-12-Total annual mean monthly flow by WECS/DHM Method (m³/s).

Year	Annual Flow, m ³ /s
1990	55.47
1991	57.50
1992	50.90
1993	53.67
1994	49.85
1995	52.95
1996	57.32
1997	49.53
1998	57.05
1999	54.69
2000	52.42
2001	54.64
2002	52.95
2003	52.82
2004	55.23
2005	52.35
2006	47.43
2007	54.21
2008	53.87
2009	50.70
2010	56.63
2011	50.63
2012	48.70
2013	52.80
2014	49.96

The increasing trend of precipitation over future periods contributes to a rise in river flow. The result shows that present (1990-2014) average annual river discharge estimated to be 52.97 m³/s and future river discharge available will be 54.58 m³/s (increase by 3.04%), 55.23 m³/s (increase by 4.27%) and 54.99 m³/s (increase by 3.81%) under ssp245 in three different time period near (2025-2049), mid (2050-2074) and far (2075-2100) respectively and 53.53 m³/s(increase by 1.06%), 56.03 m³/s(increase by

5.78%) and 56.73 m³/s (increase by 7.10%) for ssp585 scenarios in three different time period. These estimated values of river discharge based on projected annual rainfall for the near, mid, and far future can be found in Table 5-13.

Table 5-13-Projected future average annual river discharge of Budhi & Katle River.

River Discharge (1990-2014)	52.97 m³/s		
	<i>Near Future (2025-2049)</i>	<i>Mid-Future (2050-2074)</i>	<i>Far-Future (2075-2100)</i>
SSP 245	54.58 m³/s	55.23 m³/s	54.99 m³/s
SSP585	53.52 m³/s	56.03 m³/s	56.73 m³/s

The figure 5-19 shows the monthly discharge calculated from WECS/DHM 1990 methods for observed time period (1990-2014) and discharge under two different scenarios SSP245 and SSP585 in three different time period near (2025-2049), mid (2050-2074) and far (2075-2100).

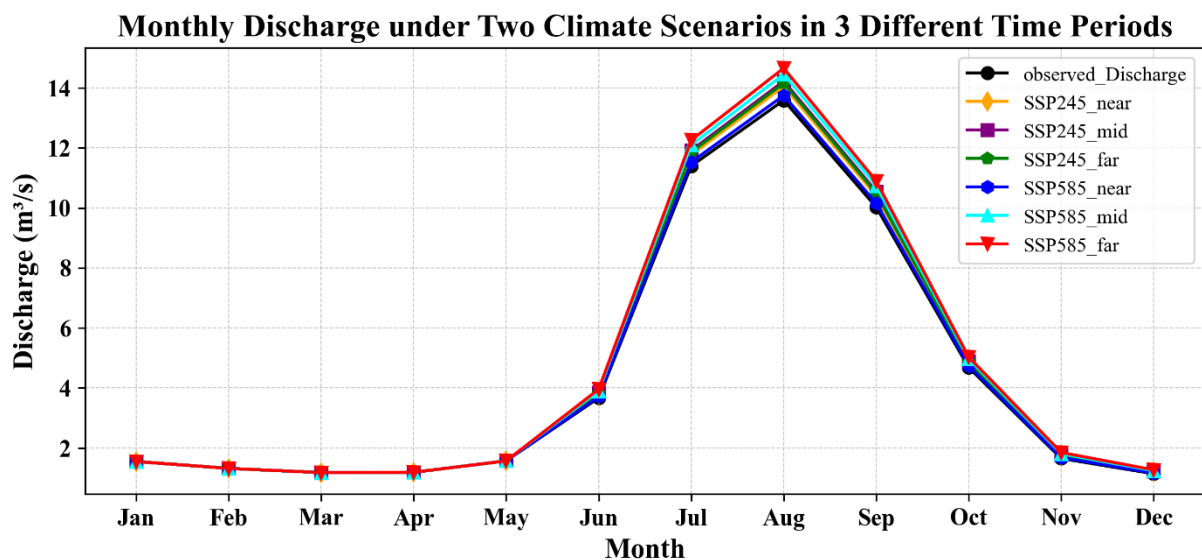


Figure 5-19-Comparison of Monthly Discharge between observed (1990–2014) and Projected Discharge of Two Different Scenarios in three Different Time Frame.

The results shows that the discharge values are similar between the observed and predicted periods for 2 different scenarios in 3 time period from January to May. In August, the river discharge reached its peak at 14.66 m³/sec (SSP585 Far), while in December, it reached its lowest point at 1.14 m³/sec (Observed). The discharge is in increasing trend for month Jun-August. The finding of this study is convergent with Dawadi et al., 2022 and Lamichhane et al, 2022 that the discharge is maximum its June to October. The table 5-14 shows the discharge of two different scenarios in three different time period near, mid and far future with observed baseline period.

Table 5-14- Discharge of two different scenarios in the different time period.

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed	1.55	1.32	1.18	1.19	1.57	3.67	11.40	13.59	10.03	4.68	1.65	1.14
SSP245 Near	1.55	1.32	1.18	1.19	1.57	3.79	11.77	14.05	10.40	4.83	1.73	1.20
SSP245 Mid	1.55	1.32	1.18	1.19	1.57	3.84	11.92	14.23	10.55	4.89	1.77	1.22
SSP245 Far	1.55	1.32	1.18	1.19	1.57	3.82	11.86	14.16	10.49	4.87	1.76	1.21
SSP585 Near	1.55	1.32	1.18	1.19	1.57	3.71	11.53	13.75	10.16	4.73	1.68	1.16
SSP585 Mid	1.55	1.32	1.18	1.19	1.57	3.90	12.10	14.46	10.74	4.97	1.81	1.24
SSP585 Far	1.55	1.32	1.18	1.19	1.57	3.96	12.26	14.66	10.90	5.03	1.85	1.27

5.7 Calculation of water balance

The major objective to calculating water balance in this study was to estimate the gap between demand and supply of water. The figure 5-20 shows Monthly Average River Discharge vs. Monthly Irrigation Water Requirement for the observed period (1990-2014). The discharge is highest at August 13.59m³/second lowest at December 1.14 m³/sec.

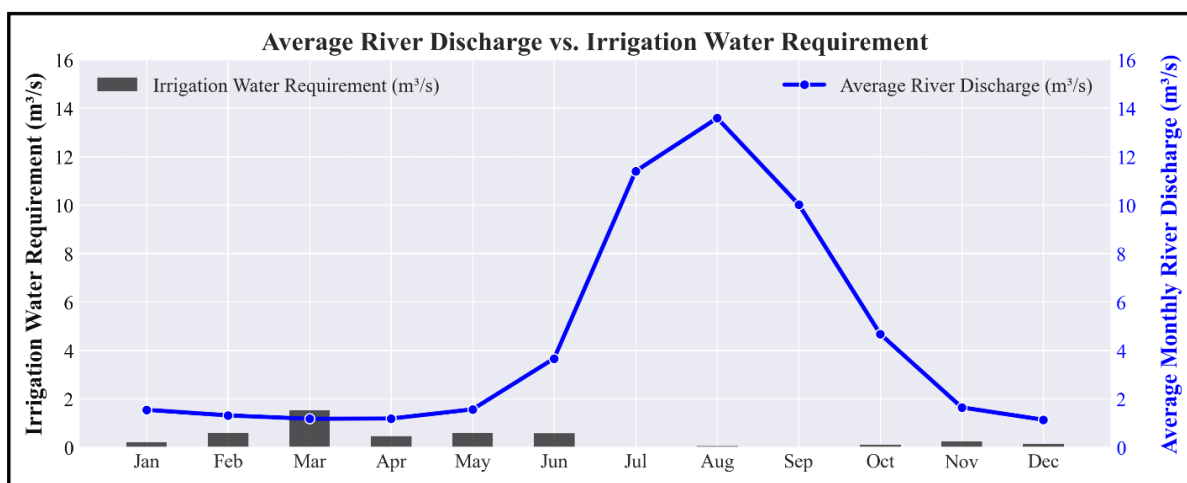


Figure 5-20-Average River discharge vs. irrigation requirement (Observed Period)

The table 5-15 shows that is water available from the river is enough to fulfill the Irrigation Water Requirement of Chanda Mohana Irrigation Project (CMIP) command area. In the observed time period, the water is deficit in March month with a value of 0.35 m³/sec.

Table 5-15-Calculation of gap between demand and supply (excess/deficit water for irrigation).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average River Discharge (m ³ /sec)	1.55	1.32	1.18	1.19	1.57	3.67	11.40	13.59	10.03	4.68	1.65	1.14
Irrigation water requirement (m ³ /sec)	0.22	0.59	1.53	0.47	0.59	0.58	0.02	0.05	0.02	0.11	0.25	0.13
Water Balance (m ³ /sec)	1.33	0.73	-	0.72	0.98	3.09	11.38	13.54	10.01	4.57	1.40	1.01

The figure 5-21 shows Monthly Average River Discharge vs. Monthly Irrigation Water Requirement for the near period (2025-2049) under SSP245. The discharge is highest at August 14.05 m³/second lowest at December 1.2 m³/sec.

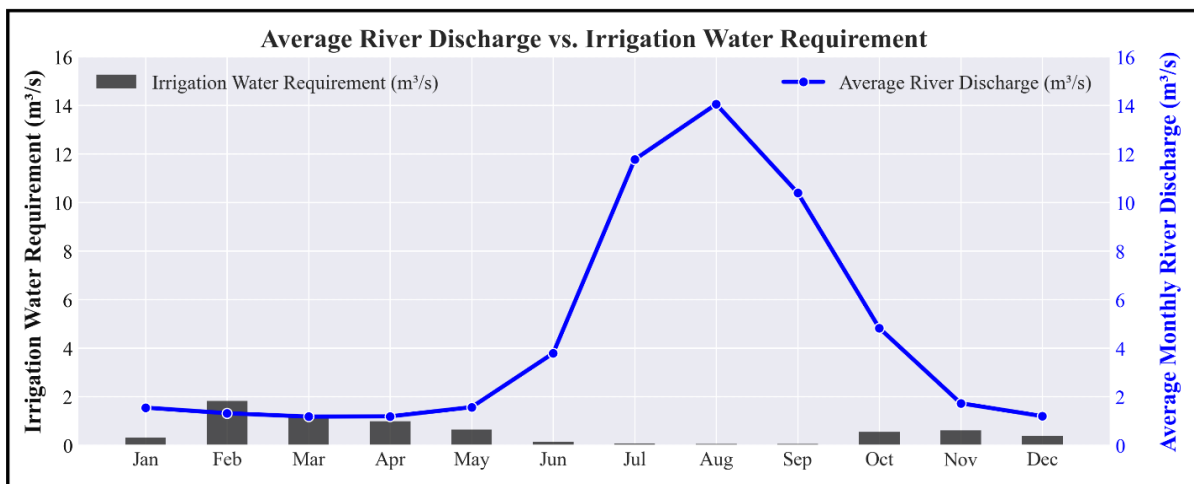


Figure 5-21-Average River discharge vs. irrigation requirement (SSP245-Near).

Table 5-16-Calculation of gap between demand & Supply (SSP245-Near).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average River Discharge (m ³ /sec)	1.55	1.32	1.18	1.19	1.57	3.79	11.77	14.05	10.40	4.83	1.73	1.20
Irrigation water requirement (m ³ /sec)	0.32	1.82	1.20	0.99	0.65	0.13	0.07	0.05	0.05	0.54	0.61	0.38
Water Balance (m ³ /sec)	1.23	-	-	0.20	0.92	3.66	11.70	14.00	10.35	4.29	1.12	0.82

In the case of the near future under ssp245 scenarios, a water deficit is seen in February and March. The amount of water deficit is 0.498 m³/sec and 0.02 m³/sec assuming that there will be present cropping pattern in future which is shown in table no. 5-16.

The figure 5-22 shows Monthly Average River Discharge vs. Monthly Irrigation Water Requirement for the mid period (2050-2074) under SSP245. The discharge is highest at August 14.23 m³/second lowest at December 1.22 m³/sec.

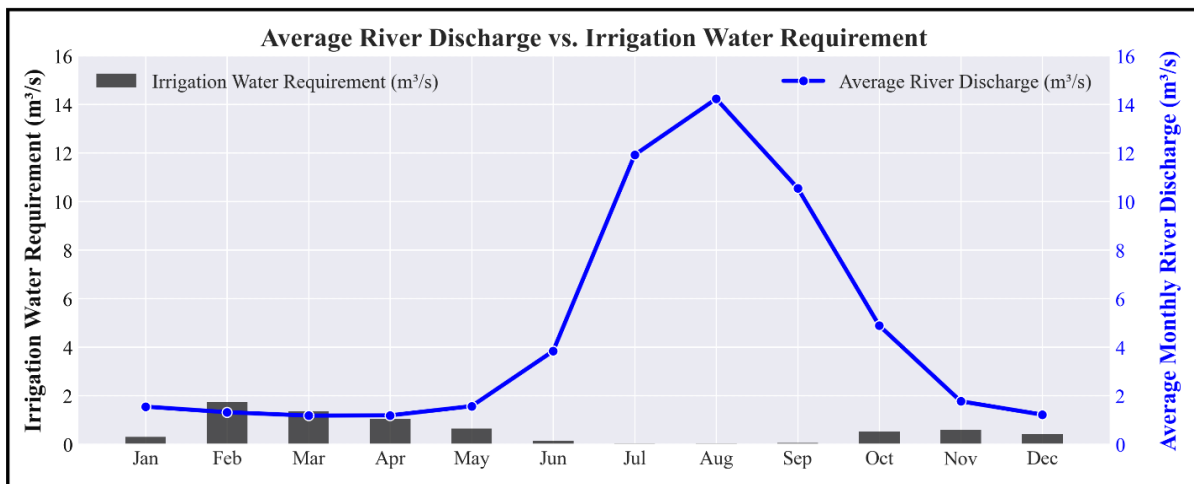


Figure 5-22-Average River discharge vs. irrigation requirement (SSP245-Mid).

In the case of the mid future under ssp245 scenarios, a water deficit is seen in February and March. The amount of water deficit is 0.43 m³/sec and 0.17 m³/sec assuming that there will be present cropping pattern in future which is shown in table no. 5-17.

Table 5-17-Calculation of gap between demand & Supply (SSP245-Mid).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average River Discharge (m ³ /sec)	1.55	1.32	1.18	1.19	1.57	3.84	11.92	14.23	10.55	4.89	1.77	1.22
Irrigation water requirement (m ³ /sec)	0.31	1.75	1.35	1.04	0.65	0.13	0.04	0.04	0.05	0.52	0.59	0.41
Water Balance (m ³ /sec)	1.24	0.43	0.17	0.15	0.92	3.71	11.88	14.19	10.50	4.37	1.18	0.81

The figure 5-23 shows Monthly Average River Discharge vs. Monthly Irrigation Water Requirement for the far period (2075-2100) under SSP245. The discharge is highest at August 14.16 m³/second lowest at December 1.21 m³/sec.

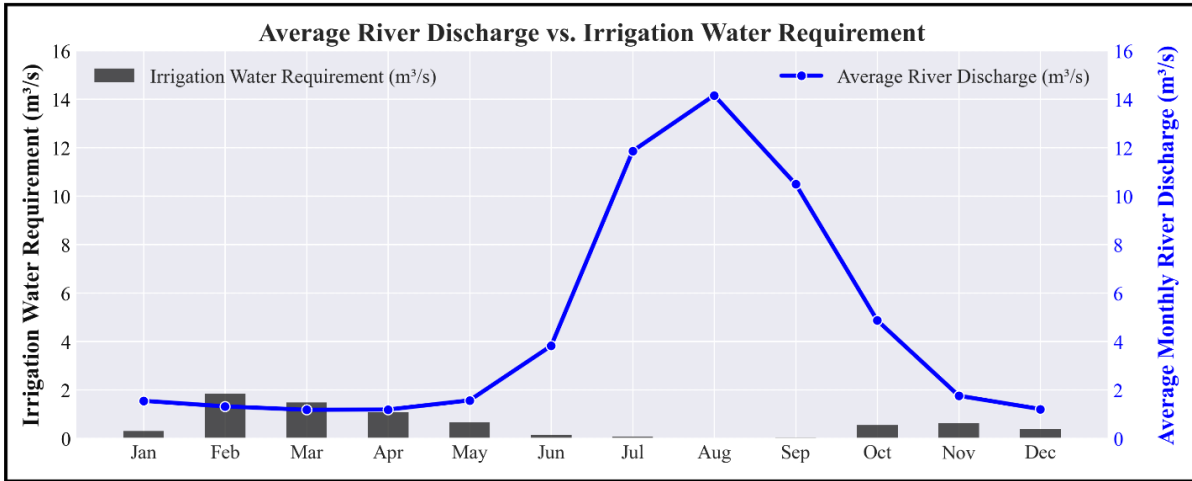


Figure 5-23-Average River discharge vs. irrigation requirement (SSP245-Far).

In the case of the far future under ssp245 scenarios, a water deficit is seen in February and March. The amount of water deficit is 0.52 m³/sec and 0.30 m³/sec assuming that there will be present cropping pattern in future which is shown in table no. 5-18.

Table 5-18-Calculation of gap between demand & Supply (SSP245-Far).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average River Discharge (m ³ /sec)	1.55	1.32	1.18	1.19	1.57	3.82	11.86	14.16	10.49	4.87	1.76	1.21
Irrigation water requirement (m ³ /sec)	0.31	1.84	1.48	1.08	0.67	0.13	0.07	0.02	0.04	0.54	0.63	0.38
Water Balance (m ³ /sec)	1.24	-0.52	-0.30	0.11	0.9	3.69	11.79	14.14	10.45	4.33	1.13	0.83

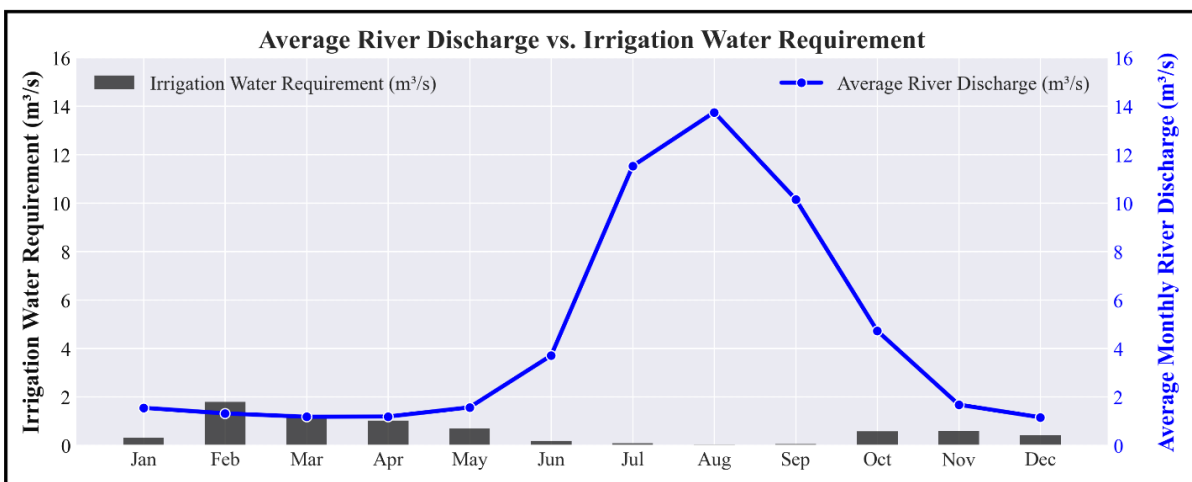


Figure 5-24-Average River discharge vs. irrigation requirement (SSP585-Near).

The figure 5-24 shows Monthly Average River Discharge vs. Monthly Irrigation Water Requirement for the near period (2025-2049) under SSP585. The discharge is highest at August 13.75 m³/second lowest at December 1.16 m³/sec.

In the case of the near future under ssp585 scenarios, a water deficit is seen in February and March. The amount of water deficit is 0.48 m³/sec and 0.05 m³/sec assuming that there will be present cropping pattern in future which is shown in table no. 5-19.

Table 5-19-Calculation of gap between demand & Supply (SSP585-Near).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average River Discharge (m ³ /sec)	1.55	1.32	1.18	1.19	1.57	3.71	11.53	13.75	10.16	4.73	1.68	1.16
Irrigation water requirement (m ³ /sec)	0.32	1.80	1.23	1.03	0.70	0.18	0.09	0.04	0.05	0.58	0.59	0.41
Water Balance (m ³ /sec)	1.23	0.48	0.05	0.16	0.87	3.53	11.44	13.71	10.11	4.15	1.09	0.75

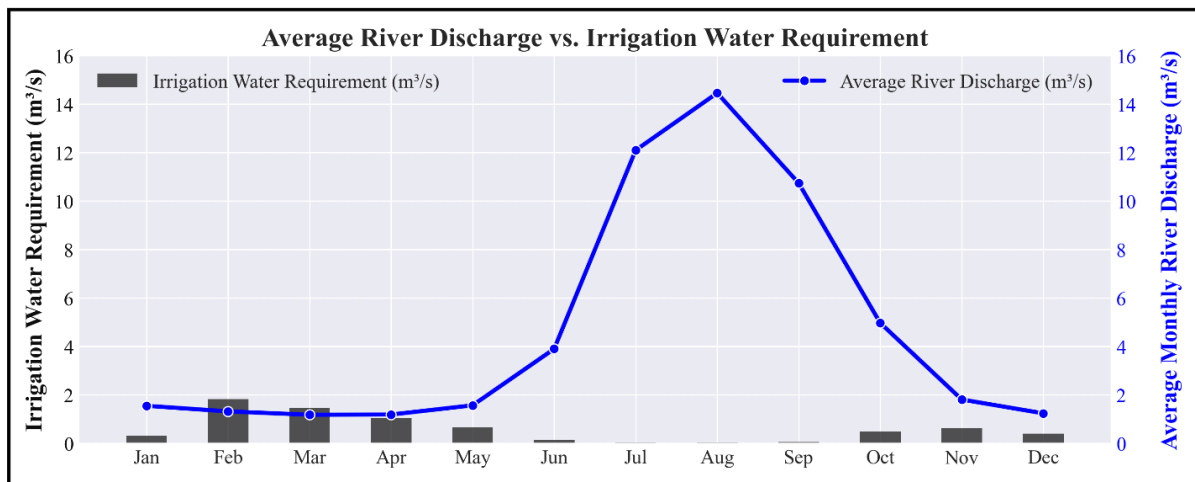


Figure 5-25-Average River discharge vs. irrigation requirement (SSP585-Mid).

The figure 5-25 shows the comparison between monthly average river discharge and monthly irrigation water requirements during the distant period 2050-2074 under

SSP585. The discharge shows its highest monthly value of 14.46 m³/sec during August while March records its minimum discharge of 1.18 m³/sec.

The ssp585 scenario project water deficit during both February and March in the mid-term period. The present cultivation system found in Table no. 5-20 results in water deficits of 0.50 m³/sec and 0.29 m³/sec based on projections.

Table 5-20-Calculation of gap between demand & Supply (SSP585-Mid).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average River Discharge (m ³ /sec)	1.55	1.32	1.18	1.19	1.57	3.90	12.10	14.46	10.74	4.97	1.81	1.24
Irrigation water requirement (m ³ /sec)	0.32	1.82	1.47	1.04	0.67	0.13	0.04	0.04	0.05	0.50	0.63	0.40
Water Balance (m ³ /sec)	1.23	0.50	0.29	0.15	0.90	3.77	12.06	14.42	10.69	4.47	1.18	0.84

The figure 5-26 shows the comparison between monthly average river discharge and monthly irrigation water requirements during the distant period 2075-2100 under SSP585. The discharge shows its highest monthly value of 14.66 m³/sec during August while March records its minimum discharge of 1.18 m³/sec.

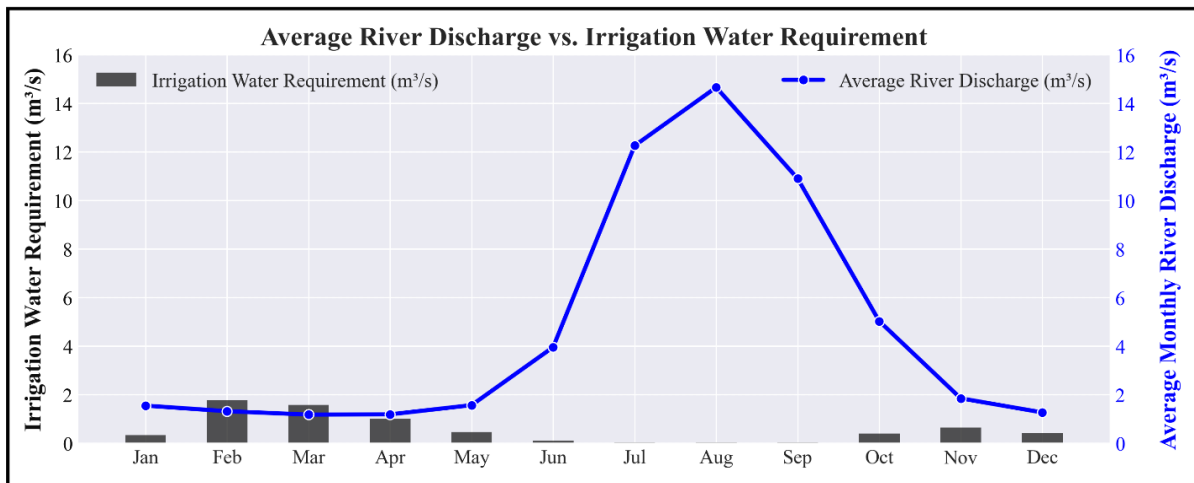


Figure 5-26-Average River discharge vs. irrigation requirement (SSP585-Far).

The ssp585 scenario project water deficit during both February and March in the far-term period. The present cultivation system found in Table no. 5-21 results in water deficits of 0.46 m³/sec and 0.40 m³/sec based on projections.

Table 5-21-Calculation of gap between demand & Supply (SSP585-Far).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average River Discharge (m ³ /sec)	1.55	1.32	1.18	1.19	1.57	3.96	12.26	14.66	10.90	5.03	1.85	1.27
Irrigation water requirement (m ³ /sec)	0.34	1.78	1.58	1.01	0.47	0.11	0.04	0.04	0.04	0.40	0.65	0.41
Water Balance (m ³ /sec)	1.21	-	-	0.18	1.10	3.85	12.22	14.62	10.86	4.63	1.20	0.86

The study area experiences water scarcity in only one month which is March at present. Future water deficits extending to two months between February and March will affect the chosen crop pattern of rice, wheat, maize, sugarcane and potatoes based on their common crop water needs up to 2100 AD. SSP245 Far experiences the largest water shortage between the months of 0.52 m³/sec. The water supplies surplus the demands for both SSP245 and SSP585 during the three distinctive time periods (near, mid, and far) in every month except March and February. The maximum water deficits will occur during the months of February and March. The water requirement is lower in January April together with May, June, August, September, October and December yet there is still surplus water available during these months. Water levels are at their highest point between July through September. The finding of this study is convergent with Dawadi et al., 2022; Lamichhane et al., 2022 and Mishra et al., 2021 had the water deficit in first five months (Jan- May). In my study Feb and March had water deficit and other month April have less excess water than others. The availability of water supply throughout seasons creates the biggest challenge for water management since demands for water do not match with natural supply cycles. The study area should focus on resolving its water shortage by implementing a water storage plan to stock monsoon rains which will help during dry seasons. Research by Khan et al. (2014) shows that stored monsoonal flow fills can solve water shortage problems in the Ganges Basin for dry season uses.

5.8 Adaptation Strategy

Based on existing practices and results of this study, following adaptation measures are recommended to manage climate change effects on study area:

5.8.1 Irrigation automation with water saving irrigation strategies

The goal of irrigation science is to provide a uniform water supply on the farm to satisfy crop water requirements at right times using different methods depending on

topography, water sources and economics (Thapa & Chand, 2024). Studies have been undertaken to correlate irrigation application methods to crop yield and sustainable economic return per unit of water (Jha et al., 2019). The major irrigation methods commonly applied are micro irrigation, sub-surface, and surface. Among them, drip irrigation is a relatively new micro-irrigation initiative that minimizes losses due to evaporation, deep percolation, and surface runoff. Compared to other irrigation techniques, a well-designed drip system is said to have a water application efficiency of 90% or greater (Qu et al., 2020). In addition to being the most efficient, drip irrigation improves the quality of agricultural output (Chand & Bimali, 2023).

The concept of drip irrigation dates to ancient times, but modern drip irrigation systems emerged in the mid-20th century. An Israeli engineer, Simcha Blass, invented contemporary drip irrigation system in the 1950s after noticing a tree thrived with a minor leak in a water line, prompting him to design slow but regular watering techniques. By the 1960s, Blass and his team at Netafim invented the first commercially viable drip irrigation system, employing plastic emitters to efficiently distribute water to plant roots and prevent losses. Over the decades, drip irrigation has evolved with advancements in materials, emitters, and integration with automation technologies. A review by Lakhari et al., (2024) examines Precision Irrigation Water-Saving systems (PISs) as a potential way to improve agricultural sustainability in the face of climate change and lessen global water scarcity. It emphasizes the creation, application, and advantages of PISs in raising crop output, lowering environmental effects, and increasing water usage efficiency.

Automation has revolutionized various industries by introducing advanced technologies to enhance efficiency, reduce human intervention, and optimize resource utilization. Digital agriculture is a pioneering technology that contributes to meeting the growing demand for food security worldwide (Abiri et al., 2023). Automation enables remote communication between equipment and wireless networks, enabling remote commands and service provision in agriculture and extending the capabilities of current computer networks (Silva et al., 2020). Efficient irrigation practices, such as drip or precision irrigation, as well as automation systems, are essential for sustainable agriculture because they preserve water, save energy, increase crop production, and reduce environmental impact (Ray & Majumder, 2024). Automation in precision irrigation reduces water wastage, fertilizer use, and energy use by allowing real-time adjustment of crop requirements. This reduces water wastage, labor costs, and environmental impacts, resulting in healthier plants and improved crop yields (Kumar et al., 2023).

5.8.2 Rainwater harvesting

Worldwide, precipitation patterns have begun to shift as a result of global warming, affecting the world's primary water source—the sky rainfall. In many places of the world, this has resulted in indicators of increased dryness and decreased rainfall. Rainfall is a significant source of water for human life, and the fear of a decrease in its supply is leading to a water crisis. Rainwater harvesting has been widely used to sustain freshwater resources worldwide (Rahman, 2017). It increases water availability, maintains the groundwater table, and improves groundwater quality by diluting pollutants like arsenic, fluoride, phosphate, nitrate, etc. In Nepal, rainwater harvesting is traditionally stored in a tank, pond, lake, etc. Rainwater is collected to provide year-round water for crop and fodder production and livestock. Rainwater harvesting fits nicely into the adaptation strategy for Nepali agriculture in the context of climate change. The government is encouraging and promoting the installation of rainwater tanks everywhere (Amos et al., 2020). Studies have indicated that domestic rainwater systems can meet 12 to 100% of drinking water demand depending on environmental conditions (Tamaddun et al., 2018).

5.8.3 Watershed Management

Watershed management is the study of the relevant characteristics of a watershed to sustainably distribute its resources to sustain and enhance watershed functions that affect the flora, fauna, and human communities within the watershed's boundaries. Water problems cannot be addressed sustainably if the overall approach starting from the watershed is not considered in planning and implementation (Hoekstra et al., 2018). Watershed management conserves and efficiently manages surface and groundwater resources, especially in watershed areas. Storage for groundwater recharge through various methods like recharge wells, tanks, check dams, etc., is prioritized to prevent runoff. The main objective of watershed management is to balance the utilization of natural resources and their demands on various end users. The achievement of watershed development mainly depends on the participation of local communities.

5.8.4 Controlling water quality

According to Michael, 2003, of the several factors influencing irrigation water quality, the generally accepted criteria for judging the quality are: a) bicarbonate and boron contents b) relative proportions of cations as expressed by SAR, and c) total salt concentration. The author indicated the suitability of an irrigation water (SIW) as defined by equation 12.

$$\text{SIW} = f(\text{QSPCD}) \dots\dots\dots 12$$

Q = quality of irrigation water, S = soil type, P = salt tolerance characteristics of the plant, C = climate, and D = drainage characteristics of the soil

The finer the soil texture, the more salt builds up when irrigating with low-quality water. Therefore, it is crucial to use irrigation techniques that limit the salt in the root zone. In order to do this, the frequency and volume of irrigation should be controlled to meet the CWR and the leaching requirement.

5.8.5 Conjunctive use

Conjunctive water use is a strategy that involves the coordinated management of both surface water and groundwater resources to maximize overall water availability and reliability, especially during periods of scarcity. Farmers in the study area have adopted conjunctive use as an effective strategy to combat water scarcity. In response to the water scarcity challenge, some farmers have come together to collectively fund the construction of deep tube wells, while others have individually established private tube wells. Despite the notably higher costs associated with tube well operation, construction, and maintenance compared to using economical canal water, this practice has become essential due to the lack of water availability in both the source and canal. By embracing conjunctive use, farmers have been able to cultivate high-valued cash crops using groundwater from tube wells. This adaptation strategy not only minimizes the impact of water scarcity on agriculture but also contributes to sustaining livelihoods through the cultivation of profitable crops.

5.8.6 Water management plan

This study recommends to prepare a water management plan including operation, repair and maintenance plan of the irrigation system, agriculture with crop calendar, introduction of climate-resistant crop varieties and climate-smart agriculture so that adverse effects of changing climate could be minimized. When water supplies are few and expensive, the two quick fixes for sustainable agricultural development are investigating alternative water sources and putting effective irrigation management techniques into place. In the absence of an optimum water management plan, sustainable agricultural development could not be achieved.

5.8.7 Nexus among Crop Water Requirement, Irrigation Water Requirement and Water Availability

The interrelationship among crop water requirements, irrigation water requirements and available water is directly influenced by climate change. As temperature and

precipitation patterns shift due to climate variability, the amount of water that crops require for optimal growth can increase, while the timing and quantity of available water resources may become more unpredictable. This dynamic affects the irrigation water requirement, which serves as the critical link between crop demand and water supply. In periods of insufficient rainfall or heightened evapotranspiration—both of which are expected to become more pronounced with climate change—the gap between crop water needs and natural water availability widens, placing greater pressure on irrigation systems. Therefore, climate change acts as a key driver in shaping not only the individual components of this nexus but also their interactions, underscoring the necessity for adaptive water management and resilient agricultural practices in regions like the Chanda Mohana Irrigation Project.

6. Conclusion and Recommendations

6.1 Conclusion

This research investigated how climate change affects future conditions of the Budhi and Katle Rivers together with CMIP command area irrigation water requirements. Historical climate patterns were studied to foretell future temperature and rainfall modifications for assessing agriculture-related water availability under SSP245 and SSP585 project spanning multiple time points, implementing WECS/DHM methodology. The study analyzed multiple approaches for addressing water scarcity problems caused by climate change while recording these strategies to be implemented in the study area.

Based on the results and discussions, the major conclusion of this study relative to research objectives are:

- a) **Objective 1:** To analyze the historical variation of climate parameters (precipitation and temperature) in the study area and project future changes
The research identified BCC-CSM2-MR together with ACCESS-CM2 and MRI-ESM2-0 and ACCESS-ESM1-5 as the best models to conduct precipitation event projections. Among the models used for maximum temperature predictions MIROC6 is found to be most reliable. The Chanda Mohana Irrigation Project has to rely on MIROC6 and MRI-ESM2-0 with ACCESS-ESM1-5 and INM-CM5-0 as the most suitable models for predicting future minimum temperatures. The analysis at Biratnagar Airport Station (1319) determined non-parametric quantile mapping using robust empirical quantiles-linear as the optimal technique to adjust precipitation data from 13 bias correction methods for four GCMs. At Tarahara Station (1320) researchers selected the Bernoulli Gamma Method as the

best bias correction technique for precipitation. The SSP245 along with SSP585 indicated that temperature extremes will experience substantial growth by the future period. Under SSP585 the temperature increase will exceed the rate predicted by SSP245. Both SSP245 and SSP585 lead to enhanced precipitation patterns but SSP585 produces higher amounts of precipitation when compared to SSP245. Under SSP585 conditions the projections, minimum temperature shows a higher expected rise which will amount to 1.10°C in the near future then 2.35°C in the mid-future and will finish at 3.60°C in the far future. The findings for projected precipitation show increasing uncertainty as time progresses forward. The projected precipitation in near future is increased up to 2.28 %, 7.27% in mid future and 9.71% in far future.

- b) **Objective 2:** To examine how climate change affects the availability of irrigation water, both in terms of demand and supply.

Future modeling estimates showed a decrease of irrigation water requirements during the months of March, May and August across SSP245 as well as SSP585 simulation scenarios. At different periods from July to September the irrigation water requirement demonstrates its minimum value because of enhanced precipitation levels. The highest irrigation water requirements for all scenarios appear in February and March indicating water management needs to be effective at this time period. Irrigation in the CMIP command area depends heavily on the Budhi and Katle Rivers which fail to generate enough water to fulfill needs during non-monsoon and post-monsoon times due to changing climate patterns. The projections for river discharge growth from 3.04% to 4.27% under SSP245 and 1.06% to 7.10% under SSP585 show limited improvement due to the fact that more than 80% of rainfall happens during the monsoon season thus creating persistent dry-season water shortages. The future flow of Budhi and Katle Khola is not sufficient to meet the irrigation water demand in February and March months in near future under both ssp245 and ssp585 scenarios. The maximum deficit occurring in February (0.52 m³/sec, SSP245-Far) and the lowest water deficit in month of March (0.02 m³/sec, SSP245-Near). Highest water excess is at the Month of July to September. By storing the extra monsoonal flow, this extra water might be used throughout the dry season, thus reducing the research area's water scarcity.

- c) **Objective 3:** To identify adaptive cultivation strategies to address the changing availability of water in response to the impacts of climate change.

The demand for effective water management strategies needs to increase because agricultural operations must resist escalating environmental stress. The effective use of water becomes more efficient through the combination of drip and precision

irrigation systems with automated systems. The management of rainwater and watersheds acts as fundamental methods for growing water resources. The quality maintenance of irrigation water combined with surface and groundwater integration becomes a solution for dealing with water scarcity challenges. A complete water management strategy needs to implement climate-smart agriculture together with crop planning and personnel maintenance for systems. The implemented adaptive strategies create more food security and rural stability and successful livelihoods. Sustainable agricultural practices require revolutionary approaches to water resource management.

6.2 Recommendation for Further Study

This study solely relies on climatic parameters such as precipitation and temperature to estimate river water availability. Therefore, it is imperative to include other critical factors like upstream water usage, land use changes, and urbanization in the analysis. Conducting a hydrological analysis in the study area is essential to precisely assess the influence of changing rainfall and temperature patterns on river discharge for greater accuracy. The thesis can be useful for prediction future crop yields for wheat, rice, potatoes, maize and sugarcane in CMIP command area.

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APPENDICES

ANNEX I-Precipitation (mm) Data of Biratnagar Airport (1319) Station from DHM (1990-2014)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1990	0	16.1	15.1	108.7	312.8	467.1	601.6	509.5	300.8	22.5	0	0	2354.20
1991	34.6	4	22.4	50.9	108.4	162.5	285.3	290	410.7	70.1	0	26.1	1465
1992	2	2.6	0	1.7	186.7	147.2	396.4	201.4	189.3	290.6	0.1	1.4	1419.40
1993	21.1	1	34.6	91.3	130.4	307.499	357.1	699	346.399	48.5	8.9	0	2045.79
1994	28.3	31.2	8.9	2.9	80.7	165.3	122.8	224.8	160.2	0.9	3.4	0.3	829.70
1995	4.1	14.9	1.8	0	46.8	561.7	308.3	252.9	371	17.9	70.4	16.8	1666.60
1996	41.4	57.9	0.2	1.6	201.3	220	659	541.4	149.5	70.4	0	0	1942.70
1997	11.7	2	6.4	62.1	180.8	242.999	476	228.4	380.4	16.6	0.3	65.3	1672.99
1998	1.3	4.1	29	71.2	47.6	260.5	1225.2	733.4	276.7	22.2	5.3	0	2676.50
1999	0	0	0	29.5	176.8	317.9	534.9	501.1	202	272.9	1	0	2036.10
2000	0	8.9	0.2	102.5	307.4	569.2	558	342.8	382.4	21	0	0	2292.40
2001	2.4	0	1.4	76.9	228.5	296.4	206.1	383.6	509.6	560.8	13.8	0	2279.50
2002	38.4	3.2	4	90.8	168.8	216.6	1000.1	306.7	87.2	6.7	0	0	1922.50
2003	20	30.8	30.6	140.8	141.6	324.1	787.2	168.1	317.7	138.6	0.4	8.3	2108.20
2004	39.6	1.4	4.3	133.5	211.9	224	876.1	249.2	365.5	38.4	0	0	2143.90
2005	38.5	13.5	25.3	23.5	112	381.1	276.9	572.7	94.4	57.6	0	0	1595.50
2006	0	0	5.5	45.2	221.5	149.2	356.8	132.6	280	105.5	1.1	2.6	1300
2007	0	55	2.8	24.9	240	309.7	392.2	672.6	417.7	1.6	0.9	0	2117.40
2008	0.1	2.6	35.6	44.6	142.3	372.5	369.4	434.2	248.8	49.9	0	0	1700
2009	0	0	4.4	17	460.3	296.4	280.1	455.8	58	117.1	0.6	0	1689.70
2010	0	0	0	33.3	136.2	409	564	443.7	254.7	29.2	0	0	1870.10
2011	5.8	9.1	8.1	107.7	242.3	377.6	467.299	430.1	250.1	12.3	9.2	0	1919.59
2012	8.5	0	0	64.3	113.3	227.199	353	92.5	159.1	40.1	0	0	1057.99
2013	0	13.3	6.5	31.2	82.7	502.3	466.3	205.2	65.4	98.5	0	0	1471.40
2014	0.8	27.2	0	11.7	202.2	427.4	132	430.4	258.7	57.1	0	0	1547.50

ANNEX I-Precipitation (mm) Data of Tarahara (1319) Station from DHM (1990-2014)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1990	0	35.5	9.7	89.8	298.5	391.5	364.1	431.7	316.6	11.5	0	0	1948.9
1991	64.5	5	35.8	57.4	111.3	394.7	322	474.9	556.8	51.5	0	12.3	2086.2
1992	0.5	4.3	0	5.5	206.1	137.4	549.8	176.7	181.1	126	1.2	20.2	1408.8
1993	4.5	27.3	131.9	85.5	343	410.5	562.3	192.9	142.9	9.8	0	58	1968.6
1994	38.3	1	41.2	189.4	208.2	274.3	400.3	275.6	6	10	0	5.5	1449.8
1995	20.8	6.8	0	92.8	510.8	437	356.5	294.4	147.6	83.2	24.8	38	2012.7
1996	14.8	0	9.3	147.2	169.5	1134	367.7	161.5	61.7	0	0	10.4	2076.1
1997	15.2	86.3	88.7	93.7	252.9	294.3	258.4	362.2	15.2	0	46.6	0	1513.5
1998	4.6	53.6	87.8	91.4	284.7	677.7	438.8	391.1	184.6	27.6	0	0	2241.9
1999	0	0	53.9	233	233	603.6	456	225.4	131.3	0	1.6	1.6	1939.4
2000	7.2	0.5	114	307.1	601.2	339.5	496.2	273.3	74.8	33	0	0	2246.8
2001	0	4.4	55	267.1	317.7	396.8	411.3	425.8	177.5	69.4	0	76.8	2201.8
2002	4.2	14.9	72.7	251.8	166.3	919.3	171.1	119.1	26.5	0	0	19	1764.9
2003	33.9	83.3	135.2	83.1	484.2	616.5	240.1	198.4	168.1	0	39.4	45.6	2127.8
2004	0	6.4	121.2	268.6	298.5	857.4	89.8	402.2	127.3	0	0	29.6	2201
2005	8.5	54.7	70.8	76.2	205.3	356.4	649.1	120	52.5	0	0	0	1593.5
2006	0	7.6	64.5	161.3	256.5	278.6	76.3	308.7	108.1	2.5	0	1	1265.1
2007	103.4	0	88.3	215.4	284.8	650.3	291.8	354.3	68.7	15.9	0	38.9	2111.8
2008	9.4	91.7	56.9	210.5	402.5	595.8	425	308.1	0	0	0	0	2099.9
2009	0	22.8	4.4	338.5	333.8	335.2	533.8	88	70.2	0.5	0.6	0	1727.8
2010	0	0	50.4	181.3	408.6	686	555.3	289.3	109.9	28.3	0	3.8	2312.9
2011	5.7	11.1	98.5	149	570.2	411.5	360.9	196	53.2	46.4	1	5	1908.5
2012	0.3	10.9	89.3	273.4	282.3	394	193.9	215.5	61.6	0	0	0	1521.2
2013	19.8	10.5	90.4	207.6	236.4	648.4	237.8	173.8	161.5	1.2	0	0	1787.4
2014	28.9	1.6	45.1	178.1	474.4	252	404.9	221.3	86.8	0	2.7	6.5	1702.3

ANNEX II-Minimum Temperature (°C) Data of Biratnagar Airport (1319) Station from DHM (1990-2014)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tmin Average
1990	10.36	12.32	14.62	19.83	22.89	25.35	25.51	25.67	24.78	20.12	14.36	9.76	18.83
1991	8.28	10.93	15.64	19.77	22.97	24.03	24.66	25.06	24.41	20.57	13.01	9.97	18.31
1992	8.57	9.33	15.54	20.43	22.33	25.30	25.39	25.81	25.04	21.14	14.17	9.48	18.57
1993	8.76	12.21	13.29	18.52	23.03	24.68	25.91	25.51	24.39	21.15	16.62	10.83	18.77
1994	10.43	10.89	16.97	20.30	24.49	25.81	26.46	26.15	24.85	20.20	14.42	9.44	19.25
1995	7.53	11.05	14.94	20.11	25.86	25.75	25.73	25.69	24.42	21.12	15.90	11.29	19.15
1996	9.75	12.42	17.30	20.25	23.61	24.78	25.60	25.90	25.23	21.21	15.05	9.76	19.25
1997	7.89	9.85	15.15	19.11	22.92	24.71	25.90	26.08	24.52	19.26	15.73	11.71	18.61
1998	9.34	11.39	14.91	20.35	24.60	26.70	25.85	25.91	25.10	23.39	18.24	11.34	19.80
1999	8.89	12.68	15.20	23.31	23.71	25.22	25.23	25.03	24.32	21.67	15.68	11.16	19.36
2000	9.18	8.93	14.29	19.87	23.85	25.13	25.71	25.87	24.37	21.81	17.10	9.64	18.84
2001	8.11	11.10	14.53	20.36	23.04	25.35	26.32	26.10	24.80	21.38	16.27	10.83	19.05
2002	9.87	12.00	16.08	20.50	23.52	25.08	25.16	25.92	24.69	21.38	15.80	11.61	19.34
2003	8.47	12.58	16.29	21.10	22.65	24.89	25.77	26.37	25.20	22.04	15.44	9.67	19.23
2004	8.47	10.37	17.18	21.26	23.65	24.93	25.12	26.04	24.74	20.29	14.37	11.27	19.00
2005	9.74	12.65	17.99	20.96	23.21	25.45	25.91	25.95	25.70	21.67	14.91	10.59	19.59
2006	9.33	14.37	15.33	20.70	23.72	25.52	26.33	26.31	24.84	21.20	15.97	11.02	19.57
2007	8.15	12.75	15.17	21.62	24.20	25.25	26.10	25.94	24.49	22.40	16.36	10.01	19.40
2008	9.70	9.63	17.35	21.75	22.87	25.27	25.72	25.38	24.72	21.11	15.72	13.65	19.43
2009	11.08	12.04	15.63	22.62	23.15	25.47	26.29	25.89	25.36	21.09	15.20	11.05	19.60
2010	9.25	10.77	18.16	23.23	24.17	25.58	26.01	26.35	25.25	22.25	17.08	9.97	19.88
2011	8.84	11.49	15.82	20.77	23.35	25.19	25.32	25.79	24.83	21.74	15.44	11.68	19.22
2012	8.92	10.38	13.96	20.41	23.47	25.61	26.18	26.31	24.97	20.14	13.40	10.97	18.75
2013	7.68	12.10	16.84	21.11	23.72	26.03	26.02	25.77	25.17	21.85	14.34	11.36	19.37
2014	10.59	11.40	15.88	20.11	24.06	24.87	26.48	25.94	25.00	21.17	15.51	12.09	19.47

ANNEX III-Maximum Temperature (°C) Data of Biratnagar Airport (1319) Station from DHM (1990-2014)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tmax Average
1990	23.07	24.81	28.58	31.62	31.63	32.12	31.37	32.46	31.71	30.57	30.63	25.85	29.55
1991	22.73	27.11	31.30	33.77	32.71	32.14	32.03	32.09	31.45	31.73	28.42	24.24	29.98
1992	23.12	23.65	31.60	36.37	33.00	33.76	32.14	32.44	32.68	31.00	29.07	24.09	30.25
1993	20.00	26.09	29.55	32.46	31.99	32.34	32.76	31.53	31.71	31.70	28.96	26.74	29.66
1994	23.60	24.44	30.23	34.82	35.78	33.00	33.67	32.99	32.73	31.28	29.09	25.53	30.63
1995	22.63	24.96	30.45	35.85	36.73	31.66	31.51	32.46	31.17	31.45	29.13	24.42	30.22
1996	21.68	25.96	30.95	35.83	32.66	32.41	31.90	32.23	32.71	31.31	29.14	26.02	30.23
1997	22.68	24.21	30.60	31.17	33.72	33.26	32.46	32.90	32.09	30.74	28.83	22.76	29.64
1998	20.39	26.34	28.76	32.85	35.17	34.63	31.35	31.53	32.52	32.46	30.13	26.40	30.22
1999	23.24	28.77	33.03	35.54	33.27	33.33	31.81	31.50	32.00	31.20	29.64	26.67	30.83
2000	22.59	25.05	30.82	33.91	33.00	32.87	32.99	33.21	31.95	33.23	29.87	27.11	30.56
2001	23.63	27.66	32.66	34.99	33.02	33.12	33.69	33.80	32.40	31.39	29.36	24.49	30.86
2002	23.82	26.94	31.44	31.73	32.76	32.89	31.99	32.76	32.73	31.85	30.09	25.42	30.38
2003	19.98	24.93	29.02	32.55	32.78	32.43	32.47	33.74	32.33	31.47	28.56	25.79	29.69
2004	21.33	26.76	31.73	31.78	32.91	32.78	31.32	33.55	32.52	31.34	29.50	26.16	30.14
2005	23.05	26.63	31.42	34.00	33.53	34.13	32.83	32.88	34.13	31.33	28.99	27.03	30.84
2006	23.07	28.56	32.10	34.01	33.40	33.24	33.22	33.83	32.14	32.83	28.10	25.73	30.86
2007	22.27	24.68	30.10	33.56	35.21	32.91	31.78	33.14	32.11	32.58	30.93	26.14	30.48
2008	24.12	25.37	31.25	34.29	33.58	32.60	33.00	31.57	32.81	31.93	29.71	24.76	30.42
2009	23.27	27.64	32.19	35.36	33.46	33.55	32.86	32.29	33.83	32.02	28.92	24.59	30.83
2010	20.34	26.66	33.06	35.63	33.57	33.14	32.52	32.76	32.42	31.93	29.72	25.75	30.64
2011	20.91	26.93	31.45	33.09	32.67	33.02	32.71	33.12	32.69	32.66	29.09	24.37	30.23
2012	22.04	26.48	31.58	34.65	36.66	33.80	33.28	34.29	34.31	32.62	30.03	23.75	31.13
2013	22.28	28.09	32.64	34.93	33.85	33.05	33.18	33.23	34.35	31.68	30.35	25.26	31.08
2014	22.72	24.16	31.31	36.33	34.48	33.61	33.67	33.12	32.63	32.10	29.50	23.90	30.66

ANNEX IV: Relative Humidity (%) Data of Biratnagar Airport Station from DHM (1990-2014)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	RH Average
1990	83.12	72.04	57.51	56.53	72.45	81.08	84.24	79.95	81.67	72.94	65.36	72.08	73.28
1991	75.01	65.71	53.63	48.19	66.06	77.21	80.12	80.88	83.76	76.03	72.27	76.68	71.35
1992	78.49	68.77	47.22	41.08	67.40	71.50	79.59	84.35	81.09	78.63	72.83	79.66	70.94
1993	85.89	71.30	53.48	53.96	69.11	77.06	79.90	84.75	81.01	76.14	78.84	72.74	73.71
1994	80.92	73.59	60.85	46.29	60.83	76.96	76.29	78.47	78.58	74.75	70.87	73.59	71.01
1995	74.44	70.49	55.81	39.27	62.08	82.28	83.10	80.71	84.70	79.26	77.11	84.73	73.05
1996	85.28	75.36	56.85	40.78	70.99	76.22	83.34	80.47	79.52	76.78	74.57	72.74	72.78
1997	75.42	66.67	54.42	58.62	63.11	73.75	80.63	79.74	82.21	73.55	71.91	81.24	71.82
1998	82.05	68.64	59.74	61.24	65.10	77.52	87.81	87.54	83.95	79.96	77.75	78.34	75.87
1999	78.15	71.14	46.77	59.35	71.12	79.25	83.63	84.75	82.85	81.93	76.56	77.19	74.42
2000	80.41	70.18	53.45	56.95	74.02	80.89	81.41	82.79	84.52	76.44	79.94	78.97	75.02
2001	80.10	74.32	53.22	51.61	69.74	78.84	80.28	81.46	83.94	79.99	77.78	82.44	74.49
2002	78.24	72.95	58.42	64.33	68.64	77.18	85.22	80.58	78.40	75.14	69.46	79.85	74.06
2003	87.48	76.34	70.88	64.62	67.44	81.13	83.32	79.71	83.61	81.03	79.88	78.07	77.81
2004	84.95	72.14	62.73	66.37	70.34	79.68	86.13	82.21	83.05	76.86	72.53	76.58	76.16
2005	80.65	73.93	62.30	56.75	66.62	74.64	83.20	85.03	83.54	84.59	78.50	78.41	75.72
2006	86.67	77.25	52.77	57.66	69.23	80.23	82.00	78.34	83.25	74.69	80.05	80.42	75.20
2007	81.45	79.38	60.89	64.19	66.30	80.47	85.82	83.08	84.79	79.62	74.45	78.70	76.58
2008	79.58	72.29	66.87	60.62	69.67	80.78	84.55	86.02	83.46	77.16	73.68	85.87	76.76
2009	85.61	70.66	56.10	61.09	71.17	79.21	81.72	85.56	80.18	76.13	72.63	81.69	75.20
2010	85.16	70.83	61.04	62.26	70.63	79.56	83.85	84.05	83.98	80.21	77.59	77.10	76.41
2011	83.90	72.27	56.21	59.91	74.24	80.44	85.82	82.12	83.71	82.04	81.04	84.25	77.21
2012	81.97	73.24	54.95	61.39	67.19	80.46	86.00	82.55	84.01	80.37	76.48	86.61	76.29
2013	81.30	73.65	62.14	61.15	73.33	81.82	85.38	84.18	81.45	84.60	81.16	82.92	77.80
2014	88.42	79.18	65.86	53.21	67.90	81.54	82.25	86.42	89.06	87.13	86.87	91.05	79.94
Monthly Average	81.79	72.49	57.76	56.30	68.64	78.79	83.02	82.63	82.81	78.64	76.00	79.68	

ANNEX V: Wind Speed (km/day) Data of Biratnagar Airport Station from DHM (2020-2024)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	RH Average
2020	92.63	72.75	153.70	218.46	81.73	173.79	161.23	186.68	144.75	73.70	82.53	83.52	127.12
2021	122.83	135.25	198.15	259.87	245.76	295.06	241.63	175.50	186.09	133.01	66.38	92.34	179.44
2022	162.02	186.68	199.87	358.84	310.28	299.28	257.51	265.25	203.28	129.90	94.82	123.88	215.96
2023	149.40	147.95	225.39	301.01	264.36	324.47	246.61	188.69	198.31	122.73	75.86	103.81	195.79
2024	132.20	147.75	229.41	262.54	309.99	357.36	322.61	320.02	251.87	230.55	125.94	105.82	233.29
Monthly Average	131.81	137.68	201.31	280.15	242.42	289.99	245.92	227.23	196.86	137.98	89.10	101.87	

ANNEX X: Annual Discharge Data of Budhi & Katle River (1990-2014)

$$Q_{\text{mean}} (\text{month}) = C \times (\text{Basin Area})^{A1} \times (\text{Basin Area below 5000+1})^{A2} \times (\text{Mean Monsoon Precipitation})^{A3}$$

Year	Q _{monthly}												Q _{mean} (m ³ /s)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1990	1.55	1.32	1.18	1.19	1.57	3.86	11.97	14.30	10.61	4.91	1.78	1.23	55.47
1991	1.55	1.32	1.18	1.19	1.57	4.01	12.44	14.88	11.08	5.10	1.89	1.29	57.50
1992	1.55	1.32	1.18	1.19	1.57	3.51	10.92	13.00	9.55	4.49	1.54	1.07	50.90
1993	1.55	1.32	1.18	1.19	1.57	3.72	11.56	13.79	10.19	4.75	1.69	1.17	53.67
1994	1.55	1.32	1.18	1.19	1.57	3.43	10.68	12.70	9.31	4.39	1.49	1.04	49.85
1995	1.55	1.32	1.18	1.19	1.57	3.67	11.39	13.58	10.02	4.68	1.65	1.14	52.95
1996	1.55	1.32	1.18	1.19	1.57	4.00	12.39	14.82	11.03	5.09	1.88	1.29	57.32
1997	1.55	1.32	1.18	1.19	1.57	3.41	10.61	12.61	9.24	4.36	1.48	1.03	49.53
1998	1.55	1.32	1.18	1.19	1.57	3.98	12.33	14.75	10.97	5.06	1.86	1.28	57.05
1999	1.55	1.32	1.18	1.19	1.57	3.80	11.79	14.08	10.42	4.84	1.74	1.20	54.69
2000	1.55	1.32	1.18	1.19	1.57	3.63	11.27	13.43	9.90	4.63	1.62	1.12	52.42
2001	1.55	1.32	1.18	1.19	1.57	3.80	11.78	14.06	10.41	4.84	1.74	1.20	54.64
2002	1.55	1.32	1.18	1.19	1.57	3.67	11.39	13.58	10.02	4.68	1.65	1.14	52.95
2003	1.55	1.32	1.18	1.19	1.57	3.66	11.36	13.55	9.99	4.67	1.64	1.14	52.82
2004	1.55	1.32	1.18	1.19	1.57	3.84	11.92	14.23	10.55	4.89	1.77	1.22	55.23
2005	1.55	1.32	1.18	1.19	1.57	3.62	11.26	13.41	9.89	4.62	1.62	1.12	52.35
2006	1.55	1.32	1.18	1.19	1.57	3.24	10.12	12.01	8.75	4.16	1.37	0.96	47.43
2007	1.55	1.32	1.18	1.19	1.57	3.76	11.68	13.94	10.31	4.80	1.71	1.18	54.21
2008	1.55	1.32	1.18	1.19	1.57	3.74	11.60	13.84	10.23	4.76	1.70	1.17	53.87
2009	1.55	1.32	1.18	1.19	1.57	3.49	10.87	12.94	9.50	4.47	1.53	1.07	50.70
2010	1.55	1.32	1.18	1.19	1.57	3.95	12.24	14.63	10.87	5.02	1.84	1.26	56.63
2011	1.55	1.32	1.18	1.19	1.57	3.49	10.86	12.92	9.49	4.46	1.53	1.07	50.63
2012	1.55	1.32	1.18	1.19	1.57	3.34	10.41	12.37	9.04	4.28	1.43	1.00	48.70
2013	1.55	1.32	1.18	1.19	1.57	3.66	11.36	13.54	9.99	4.66	1.64	1.14	52.80
2014	1.55	1.32	1.18	1.19	1.57	3.44	10.70	12.73	9.33	4.40	1.50	1.04	49.96

ANNEX VI: Sunshine Hour (hrs) Data of Biratnagar Airport Station from DHM (1990-2014)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	S Average
1990	5.57	6.90	8.98	8.66	8.26	6.50	4.55	6.72	6.13	7.58	9.08	7.36	7.19
1991	7.26	8.46	8.86	8.58	8.41	5.24	5.25	5.15	5.08	8.40	8.19	6.00	7.06
1992	6.85	7.74	8.66	9.11	8.92	8.19	5.88	7.09	8.77	7.41	7.05	8.67	7.86
1993	2.85	6.52	8.92	8.57	9.46	7.85	6.70	6.65	6.65	8.03	8.59	8.58	7.45
1994	6.55	7.73	8.34	5.40	0.00	0.00	0.00	0.00	0.00	3.48	6.84	8.75	3.90
1995	8.00	9.56	8.75	5.25	6.65	6.87	7.67	9.09	6.20	6.50	7.41	9.02	7.58
1996	9.08	8.75	8.07	3.41	5.95	4.96	6.08	7.30	8.71	7.00	6.38	8.63	7.03
1997	9.46	8.54	6.13	5.06	5.29	6.05	6.88	6.77	7.64	6.45	6.84	7.93	6.91
1998	9.17	8.36	6.82	7.90	5.95	4.54	6.01	8.38	6.11	7.57	6.81	6.80	7.03
1999	7.46	7.58	7.34	4.74	4.21	7.95	6.84	7.86	7.61	4.12	5.33	8.66	6.64
2000	8.84	8.14	6.55	4.37	6.74	7.01	6.14	6.46	7.28	6.54	6.79	8.32	6.93
2001	9.21	8.57	8.32	4.80	6.02	6.04	6.41	8.88	8.26	4.82	6.60	8.00	7.16
2002	7.80	9.10	6.18	4.65	8.05	5.32	8.31	6.16	7.00	4.30	5.20	8.02	6.67
2003	8.12	5.83	4.10	5.34	4.35	7.44	8.30	7.08	5.70	6.35	7.20	8.85	6.56
2004	7.51	6.12	4.98	5.44	6.00	7.78	5.20	4.51	7.82	7.94	8.79	7.27	6.61
2005	5.73	4.40	4.79	7.17	7.89	5.77	3.63	5.34	7.57	7.11	7.36	6.54	6.11
2006	3.94	6.12	4.36	6.11	7.40	6.92	5.53	6.37	8.22	7.79	6.84	3.53	6.08
2007	4.16	5.64	5.80	6.35	6.44	5.07	7.03	8.93	9.54	7.10	5.83	5.86	6.48
2008	5.68	8.05	8.66	3.85	5.55	7.52	8.32	8.23	6.35	6.07	7.09	5.99	6.78
2009	6.80	4.35	6.55	8.95	8.97	7.11	5.20	6.52	8.01	5.52	6.08	5.95	6.68
2010	7.49	7.01	6.24	4.84	6.67	5.71	5.94	6.53	8.10	6.24	8.19	6.31	6.60
2011	3.71	4.86	6.38	7.58	5.57	4.17	6.61	7.07	7.44	6.54	5.43	4.22	5.80
2012	7.40	2.63	8.76	8.27	5.53	2.38	7.25	7.20	7.88	6.19	3.70	5.15	6.05
2013	4.09	6.55	7.54	8.69	7.42	5.05	7.90	7.98	7.54	6.81	4.01	6.00	6.63
2014	6.61	6.05	8.27	8.95	6.71	4.44	6.15	7.70	7.86	9.75	5.53	5.72	6.99
Monthly Average	6.77	6.94	7.13	6.48	6.50	5.84	6.15	6.80	7.10	6.63	6.69	7.05	

Table: - List of Farmers involved in Questionnaires

S. No	Name of Participants	S. No	Name of Participants
	Head of East Side		Head of West Side
1	Indra Dev Chaudhary (VC 3, Chairman)	1	Bijay Kumar Meheta
2	Surya Narayan Pandit	2	Dev Narayan Meheta (VC 2, Chairman)
3	Shiva Lal Pandit	3	Rama Nand Meheta
4	Shital Pandit	4	Log Narayan Pandit
5	Sovan Yadav	5	Ashok Kumar Pandit
6	Darpi Narayan Roy	6	Mahananda Yadhav
7	Mural Narayan Meheta (Barju 5, Ward member)	7	Manoj Kumar Meheta
8	Jay Prakash Yadhav	8	Devi Lal Meheta
9	Sudim Lal Yadav	9	Jagadish Yadhav
	Middle of East Side		Middle of West Side
1	Ashok Mehata (VC-4, Chairman)	1	Bijyanath Meheta
2	Ram Charan Sharma	2	Santosh Mandal
3	Mukesh Kumar Yadav	3	Ranjan Yadav
4	Manik Chandra Chaudhary	4	Biplen Kumar Yadav
5	Dev Saran Sharma	5	Budhan Chaudhary
6	Manoj Sharma	6	Umesh Yadhav
7	Dip Narayan Chaudhary	7	Shyam Kumar Bharadhar
8	Sanichar Mehata	8	Bechan Chaudhary
9	Kishor Kumar Chaudhary		
	Tail of East Side		Tail of West Side
1	Jag Narayan Bahardar (VC-11, Chairman)	1	Ganesh Mehata (VC-6, Chairman)
2	Deva Nand Chaudhary	2	Pankaj Yadav
3	Ramdev Chaudhary	3	Mahesh Meheta
4	Shatrughan Chaudhary	4	Binod Kumar Yadhav
5	Bhagwal Bahardar	5	Jagadish Meheta
6	Indreswor Chaudhary	6	Ramdev Meheta
7	Babulal Chaudhary	7	Dev Narayan Mehta
8	Badri Narayan Chaudhary	8	Hari Narayan Meheta
9	Sudip Lal Pandit	9	Jiten Bahardar
10	Jay Mala Devi Chaudhary	10	Pahudy Bahardar
11	Danalal Chaudhary	11	Shyam Sundar Yadhav
12	Pannalal Chaudhary	12	Jadaulal Yadhav
13	Satyendra Chaudhary		

List of Participants involved in Key Information Interview (KII)

S. No.	Name of Participants
1	Er. Raman Parajuli (Acting office head CMIP)
2	Neel Kamal Singh (Senior Agriculture Extension Officer, Krishi Gyan Kendra, Biratnagar)
3	Prabin Shrestha (Information Officer, Krishi Gyan Kendra, Biratnagar)

4	Sachindra Upadhya (Agriculture Officer, PMAMP)
5	Ramita Kumari Singh (Sub-engineer, CMIP)
6	Arjun Meheta (Office Assistant, CMIP)
7	Kishwor Kumar Chaudhary (WUC Chairman, CMIP)
8	Prabhu Narayan Pandit (East Gate Operator, CMIP)
9	Umesh Prasad Yadhav (West Gate Operator, CMIP)

Questionnaires for Farmers

1) Farmers Profile

- a) Name:
- b) Age:
- c) Gender:
- d) Education Level:
- e) Address:
- f) Representing: head, middle or tail end of irrigation system

2) Farming system: Open or Greenhouse or Both

3) Farm Details

- a) Land holding Capacity: _____ Hectors
- b) Land Ownership Types: Owned (), Leased(), Sharecropped()
- c) How many years have you been farming in this area? _____ years

Current Cropping Pattern

4) What are the primary crops you grow in your fields? (List by season):

- a) Summer (Monsoon): _____
- b) Winter: _____
- c) Spring (if applicable): _____

5) In how many areas does this crop are grown?

6) What cropping system do you follow?

- a) Mono-cropping
- b) Crop Rotation
- c) Intercropping
- d) Mixed cropping

7) What is the average yield for each crop?

- a) Crop 1: _____ kg/hectare
- b) Crop 2: _____ kg/hectare
- c) Crop 3: _____ kg/hectare
- d) Crop 4: _____ kg/hectare
- e) Crop 5: _____ kg/hectare
- f) Crop 6: _____ kg/hectare
- g) Crop 7: _____ kg/hectare
- h) Crop 7: _____ kg/hectare

- 8) What are your main reasons for selecting these crops? (Check all that apply):
- a) Traditional practices
 - b) Market demand
 - c) Soil Condition
 - d) Water availability
 - e) Government recommendations
 - f) Resilience to pests/diseases
 - g) Recommendation of Agriculture Experts like Agriculture Engineers
- 9) How much of your total land is allocated to each crop?
- a) Crop 1: _____ hectares
 - b) Crop 2: _____ hectares
 - c) Crop 1: _____ hectares
 - d) Crop 2: _____ hectares
 - e) Crop 1: _____ hectares
 - f) Crop 2: _____ hectares
 - g) Crop 1: _____ hectares
 - h) Crop 1: _____ hectares
 - i) Crop 2: _____ hectares
- 10) Agricultural machineries used:
- a) Land preparation: tractor, plough, mini tiller, power tiller.....
 - b) Leveling: laser land leveler, wooden leveler,.
 - c) Planting/ seeding: rice transplanter, corn planter, seed drill, manual.....
 - d) Weeding: weeder, manual,.....
 - e) Harvesting: Combines, reaper, manual,.....
 - f) Threshing: Thresher, animal power, manual...
 - g) Transportation: Cart, vehicle, manual,....
- 11) Chemical fertilizer used
- a) Chemical (Urea, DAP, Potash)
 - b) Organic fertilizer
 - c) Farmyard manure
 - d) Cow dung
- 12) Seed Used
- a) Own Home-based
 - b) Agroveter
 - c) Community seed bank
 - d) Nearby Indian market

Seasonal Cropping Calendar

- 13) What is the planting and harvesting times for your main crops?
- a) Crop 1: Planting _____; Harvesting _____
 - b) Crop 2: Planting _____; Harvesting _____
 - c) Crop 1: Planting _____; Harvesting _____
 - d) Crop 2: Planting _____; Harvesting _____
 - e) Crop 1: Planting _____; Harvesting _____
 - f) Crop 2: Planting _____; Harvesting _____
 - g) Crop 1: Planting _____; Harvesting _____
 - h) Crop 2: Planting _____; Harvesting _____
 - i) Crop 1: Planting _____; Harvesting _____

- 14) Are there any gaps between harvest and new planting for your land?
 a. Yes _____(____Months)
 b. No _____
- 15) Do you prepare crop calendar for agriculture? Yes or No
- 16) Do you prepare business plan for your farming? Yes or No
- 17) Have you got training about crop calendar preparation and or business plan?
- 18) If yes, from GO or INGO?
- 19) Do you use the same land for multiple crops in a year (e.g., relay cropping or successive cropping)?

- a) Yes
- b) No

Irrigation and Water Use

- 20) What irrigation methods do you use for your crops?
 a) Surface irrigation
 b) Drip Irrigation
 c) Sprinkler Irrigation
 d) Rainfed only
- 21) What is the source of irrigation water?
 a) Surface (River, stream....)
 b) Groundwater
 c) Conjunctive use of a and b
 d) Rainwater
- 22) How often do you irrigate your fields during each growing season?
 a) Crop 1: _____ times per week
 b) Crop 2: _____ times per week
- 23) Is water availability consistent throughout the year?
 a) Yes
 b) No (which Month: _____)
- 24) What are the strategies you had adapted to tackle the condition of water scarcity?
- 25) Is the depletion of water at Source due to Climate change or any other reason?
 c) Yes
 d) No
- 26) If yes, then what are its consequences?
- 27) Do you have practice of conjunctive water use in irrigation? Yes or No
- 28) Do you have irrigation scheduling? Yes or No

29) Do you have irrigation repair & maintenance plan? Yes or No

30) Have you got training about irrigation management?

a) If yes, from Government or Non-Government

Factors Affecting Cropping Decisions

31) What factors have influenced your cropping decisions in recent years? (Rank the importance):

- a) Climate Change (rainfall, temperature) _____
- b) Market prices _____
- c) Availability of labor _____
- d) Access to credit _____
- e) Government subsidies or schemes _____
- f) Input costs (fertilizer, seeds etc.) _____
- g) Suggestion by the experts like Agriculture Engineers _____
- h) Existence of pest and diseases _____

32) What crops do you think will be most viable in this region in the future?

33) Are there crops you plan to stop growing due to climate or water-related challenges? Why?

34) Are there crops you would consider growing if the conditions (e.g., water availability, temperature) change?

Climate change

- 1) Have you heard about climate change?
- 2) If yes, do you have any adaptation strategies below?
 - a) Drought resistant crop varieties
 - b) Greenhouse farming
 - c) Conservation agriculture
 - d) Climate-resilient agriculture machineries
- 3) Can you say the major effect of climate change on agriculture?
- 4) Can you say the major effect of climate change on freshwater resources?
- 5) Have you got training/awareness program about climate change management?
- 6) If yes, GoN or Non-governmental organizations?

KII for WUC (Water User Committee)

- 1. How has the water availability in River/IS changed over time, and what effects or repercussions have these changes had?
- 2. How did the people who used water from the Chanda Mohana Irrigation Canal alter their farming methods and practices? (Changes in crop types and cultivars,

variations in crop sequences, and an attempt to depict the spatial variations by irrigation system head, middle, and tail).

3. How have the aforementioned modifications affected the demand for irrigation water and/or farmers' reliance on irrigation?
4. What have been the driving forces behind the farmers' adaptation of the changes?
5. What steps are they taking to adjust to these shifts in irrigation water supply and scarcity?

KII (Key Informant Interview) for Office Staff

1. Has the amount of water available in the source changed noticeably? How and why have these modifications emerged over time? What effects have these modifications had on the canal's irrigation services?
2. How have farmers been handling the scarcity if the aforementioned developments have resulted in limitations on the irrigation supply that is accessible to them? How has the farmers' reliance on groundwater risen as a result of the canal's growing water scarcity?
3. What are the present adaptive strategies practiced by farmer to mitigate the water scarcity problem for irrigated agriculture?

ANNEX XIV: List of Photos



KII with Senior Agriculture Extension Officer, Krishi Gyan Kendra, Biratnagar.



KII with Information Officer Krishi Gyan Kendra, Biratnagar.



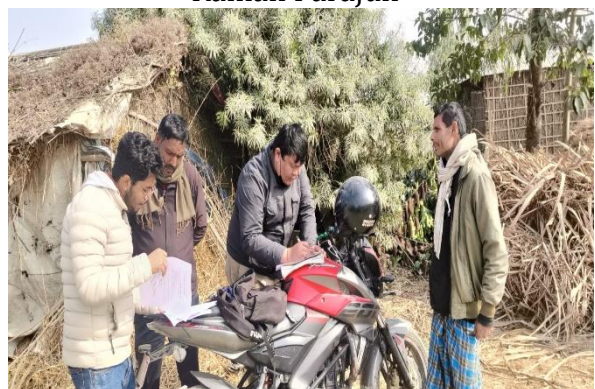
KII with Agricultural Officer, PMAMP Sunsari.



KII with Acting office head CMIP, Er. Raman Parajuli



Interviewing with farmers of West command area.



Interviewing with farmers in East Command area.



Interview with farmers in East Command Area.



Interviewing with farmers in East command area.



Gate Operator of East command area.



Interviewing with farmers in the East Command area.



KII with the WUC chairman, CMIP



Photo with Er. Bibhushan Subedi in Headwork of CMIP who helped me in Data collection.



WUC office, CMIP.



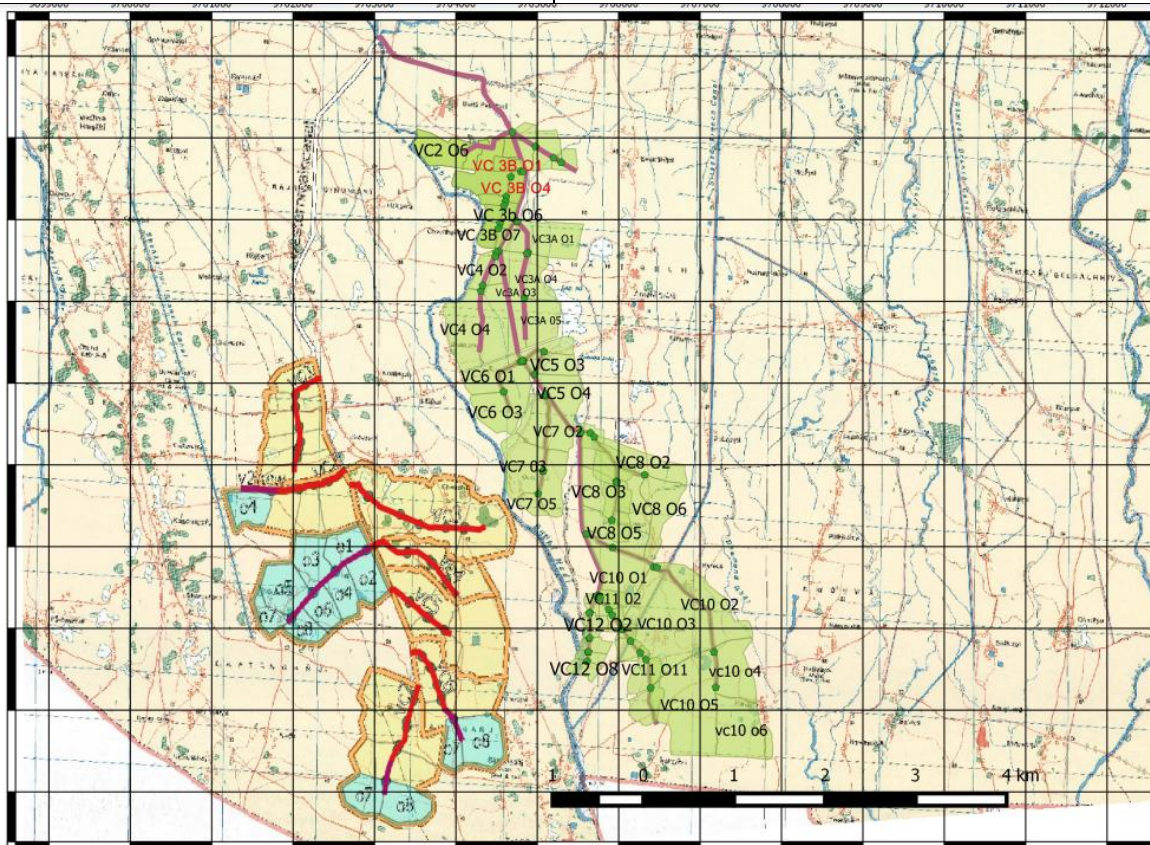
CMIP Headworks.



Gate operator west command area.



Interviewing with farmers in West Command Area.



Layout of East and West Command Area of Chanda Mohana Irrigation Project



त्रिभुवन विश्वविद्यालय
Tribhuvan University
इन्जिनियरिङ्ग अध्ययन संस्थान
Institute of Engineering
थापाथली क्याम्पस
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गोश्वारा पो. नं. २८०, थापाथली, काठमाडौं
फोन: ०१-५३३९७६६

Date: April 21, 2025

To Whom It May Concern:

This is to certify that the paper titled “**Climate change and future projection of crop water requirements: a case study of Chanda Mohana Irrigation Project, Nepal**” (Submission# 351) submitted by **Sandesh Rai** as the first author, which had been accepted for presentation after the peer-review process, has successfully been presented at the 16th IOE Graduate Conference held during April 18 - 20, 2025. Kindly note that the final revision of the papers and publication process of the conference proceedings is still underway and hence inclusion of the accepted manuscript in the conference proceedings is contingent upon timely response to further edits during the publication process.



Dr. Raj Kumar Chaulagain,
Convener,
16th IOE Graduate Conference



“How crop water requirements are projected to change with climate change in Chandra Mohan Irrigation Project in Nepal?”

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Abstract

This study focuses on knowing the future crop water requirements under two climate scenarios ssp245 and ssp585 for the Chanda Mohana Irrigation Project in Sunsari, Nepal. The ACCESS-ESM1-5 CMIP6 GCM had been used, the research applies bias correction methods to decrease the uncertainties and CROPWAT 8.0 model to find the future water requirement of crops. This study covers three time periods: near-future (2025-2049), mid future (2050-2074) and far future (2075-2100). The findings show the increasing trend in both precipitation and temperature, with raising max temperature by 0.5°C more in ssp585 as compared to ssp245. According to CROPWAT 8.0, the crop water requirement until the observed date (1990-2014). March month has a highest requirement and December has the lowest crop water requirement. The percentage change of Crop Water Requirement from the baseline line to near, mid and far future for ssp245 are 7.48%, 8.10% and 15.15% respectively and the % change of Crop Water Requirement from baseline to near, mid and far future for ssp585 are 8.07%, 11.47% and 19.39% respectively. This change underscores the importance of implementing climate – adaptive irrigation planning strategies to ensure agricultural productivity in the region.

Keywords

ACCESS-ESM1-5; Agriculture; Chanda Mohana Irrigation Project; Climate change; Crop water requirement

1. Introduction

Climate change refers to the changes in statistical properties of earth atmospheric system, usually a decade or a longer duration of time [1]. Reviewed literatures have shown that Climate change is the natural imbalance, for example: increase in the level of carbon dioxide, global temperature, precipitation, and wind pattern) caused by human actions, developmental activities, industrialization, unplanned urbanization and agriculture ([2][3][4]. FAO (2015) summarized the major challenges of climate change, including an increasing in 4°C global temperature by 2080, which is similar to the adverse effect induced from a 200% increase in the atmospheric concentration of CO₂. In reality, changing climate is one of the biggest problem and is at the center of the global debate among policy makers, scientist, government, practitioners and UN [5]. Climatic uncertainty linked with new pattern of weather, snowfall and rains are causing a greater frequency of extreme events, such as prolonged devastating floods, drought, landslides and high intensity rainfall [6].

Climate change has significant impact on the hydrological cycle which is responsible for water availability, circulation and distribution to end-users [7]. Experts have stated unequivocally that as developmental activities have increased since the beginning of human life on Earth, greenhouse gas emissions have also increased, and the effects of climate change have become apparent. As a result, by the start of the twenty-first century, unexpected rainfall, prolonged-droughts, water shortages with low quality and water-induced disasters

are all become commonplace [8][9][5]. These climate-related calamities pose a threat to life and have an extensive ramification [5]. Scientists warn that if the water crisis increases in the future, it will produce a difficult situation with disastrous results in human civilization [9]. Access of clean water is one of the major constraints for sustainable agriculture development in third-world countries and arid regions where changing climate is becoming an additional risk [10].

Country of Himalaya Nepal is evidence of climate change including fast melting glaciers with an average retreat of over 30 meters per year, a rise in temperature of more than 0.06-degree Celsius, increased frequency of extreme events including severe drought and unpredictable rainfall patterns [11]. Department of Hydrology and Meteorology states that Nepal experienced an increment of annual average temperature by 1.8 degree Celsius between 1975 and 2006. Presently, the rate of temperature rise is estimated to be 0.5 degree Celsius per decade which is notably higher compared [11]. Water is the main limiting factor for agricultural growth, especially in arid and developing regions that are facing negative effects due to climate change [2]. Various studies shows that water availability for production of crops would be a big barrier due to several factors including (1) increasing temperature, (2) fluctuations in precipitation pattern, (3) increasing frequency of prolonged droughts and (4) increase in water demand from competing industries. In the developing countries of the world, climate change has become a serious and complicated problem in all sectors for sustainable development. Agriculture, water resources, forest

and health are the hardest-hit sector from adverse climatic pattern in Nepal. Water availability, quality, and stream flow have significantly changed across the nation, mostly as a result of changes in weather patterns (temperature and precipitation) [12]. Crop water requirement, demand-supply gap and eventually agricultural productivity are connected with climate and climatic behavior [2].

The sensitivity of characteristics like water availability, quality, and stream flow to temperature and precipitation variations makes quantifying the effects of climate change on water resources a challenging task [12]. These changes in water availability during the monsoon, pre-monsoon, and post-monsoon seasons have a direct impact on Nepal's agricultural system, influencing crop production. Crop water requirement, demand-supply gap and eventually agricultural productivity are connected with climate and climatic behavior [2]. Agronomic practices and agricultural planning depend on the availability of water in the command area. Irrigation alone has multiplier effect of 20-30% crop production increment. The government of Nepal is designing agricultural projects close to the irrigation system so that climate-smart farming could be carried out. This research targets to gap the knowledge deficit through study of climate change effects on crop water requirements in Chanda Mohana Irrigation Project. The analysis focuses on CMIP command areas under SSP-245 and SSP-585 scenarios in 3 different period near-future (2025-2049), mid-future (2050-2074) and far-future (2075-2100) through the outputs produced by GCM. The Future changes in CWR demonstrate significant importance for policy decisions because they reveal important information for future planning.

2. Study Area and Data

2.1 Study Area

The Chanda Mohana Irrigation (CMIP) Project is located in the Eastern Part of Nepal with in the Sunsari District, Koshi Province. It was constructed in year 2000 to irrigate 1800 hectares, Eastern Main Canal System as 1000 ha. and Western Main Canal System as 800 ha, which covers Barju Rural Municipality in the east and west part is covered by Dewanganj Rural Municipality, in the Southern part of Sunsari District. The headworks is located in the latitude of 25°29'03.65"N and longitude of 87°09' 49.35" E. The command area of CMIP covers an area between 26°24'29.221"N to 26°28'34.049"N and 87°8'45.532" E to 87°12'25.76" E. The beneficiaries from this irrigation project are 20000 household. The source of CMIP is Budhi (right side stream) and Katle (left side stream).

2.2 Data Collection

2.2.1 Metrological data

The wind speed, daily minimum temperature, maximum temperature, and precipitation of Biratnagar Airport are collected from Department of Hydrology and Meteorology (DHM), Kathmandu for the time period of 1990-2014. The relative humidity, solar radiation, sunshine hour data is used from the CLIMWAT 2.0 . The details of meteorological station are shown in table no 1.

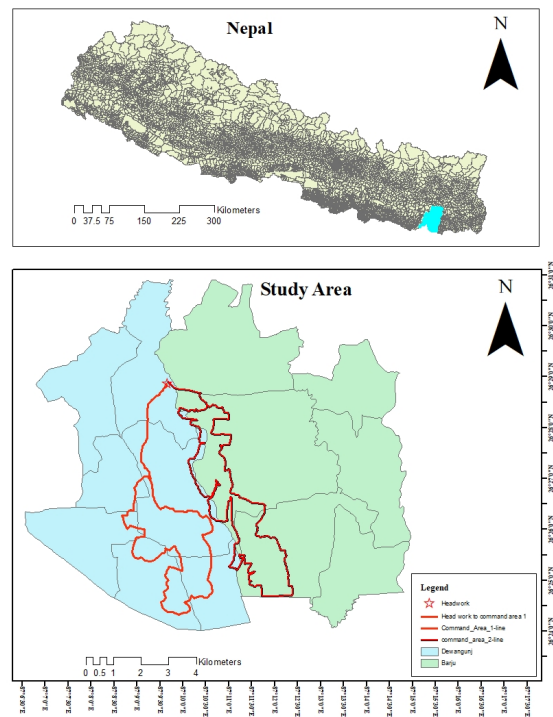


Figure 1: Location Map of Study Area (Chanda Mohana Irrigation Project, Sunsari)

Table 1: Metrological Station Details of Study Area

S.N.	Station	Index No.	District	Latitude	Longitude	Elevation
1.	Biratnagar Airport	1319	Morang	26.48397	87.26701	72 m

2.2.2 Soil Data and Crop Data

The FAO Irrigation and Drainage Paper No. 56 provided data on soil characteristics, crop coefficients (K_c), yield response factors (K_y) and root zone depths for the study area. Cropping pattern details and crop calendars were obtained from the CIMP office and through interviewing with farmers in the command area.

2.2.3 Collection of Climate Data

ACCESS-ESM1-5 GCM is one of the most widely used GCM for climate Projection which has been ranked as top GCM for all climate variable projection precipitation, max. and min. temperature [13, 14]. The ACCESS-ESM1-5 General Circulation Model of CMIP6 is obtained from World Climate Research Programme at <https://esgnode.llnl.gov/search/cmip6/>. ACCESS-ESM1-5 belongs to the institutions known as CSIRO and ACCESS (Australian Research Council Centre of Excellence for Climate System Science) and operates at 1.25 x 1.875 resolution.

3. Methodology

3.1 Future Climate Projection

3.1.1 Downscaling GCM

The GCM were downscaled using the latitude and longitude of metrological station (Biratnagar Airport).

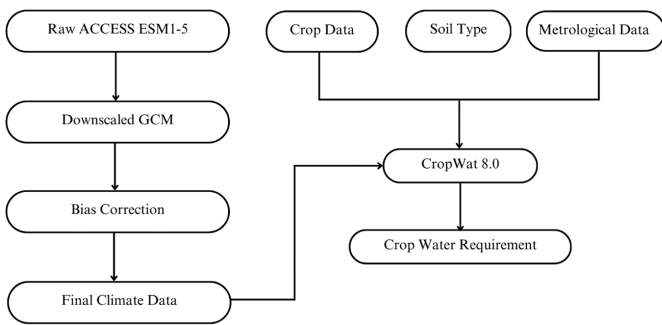


Figure 2: Methodological Flowchart

3.1.2 Bias-Correction

The forecasting of climate model data for rainfall and max and min. temperature fails to match the observed data. The difference in data between observed values and raw data leads to inaccurate future process calculations. The correction of biases happens through model output modifications to achieve better alignment between simulated data and observations from the control period. Climate model predictions gain higher levels of dependability through this process which produces more reliable future climate impact assessments [15]. The Qmap package in R contains 13 statistical transformation functions for bias correction of precipitation data and 9 statistical functions for bias correction of max. temperature and min. temperature data [16]. Bias-correction method Bernoulli Weibull method was used for precipitation and Linear Transformation method was used for max. and min. temperature [13].

3.2 CropWat model

The Land and Water Development Division of Food and Agriculture Organization (FAO) through its CROPWAT program produces a decision support tool that computes both Crop Water Requirement (CWR) and Irrigation Water Requirement (IWR). The Penman-Monteith Methods served as the basis to calculate reference evapotranspiration (ET_0) as per Allen et. al [17]. The product of ET_0 with K_c results in Crop evapotranspiration (ET_c) as shown in below equation. The estimation of CWR requires calculating ET_c for five distinct growth phases including the initial period and crop development stage as well flowering and grain formation and ripening stages.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

$$ET = K_c \times ET_0$$

u_2 : Wind speed at 2 m height (m/s)

K_c : Crop coefficient specific to the crop and growth stage.

G : Soil heat flux density ($MJm^{-2}day^{-1}$)

Δ : Slope of the vapor pressure-temperature curve ($kPa \text{ } ^\circ C^{-1}$)

e_a : Actual vapor pressure (kPa)

R_n : Net radiation at the crop surface ($MJ m^{-2}day^{-1}$)

T : Mean air temperature ($^\circ C$)

e_s : Saturation vapor pressure (kPa)

γ : Psychrometric constant ($kPa \text{ } ^\circ C^{-1}$)

4. Result and Discussion

4.1 Bias-Correction

Comparison of Observed, Raw and Bias Corrected Model Data of Precipitation for station 1319 from 1990-2014

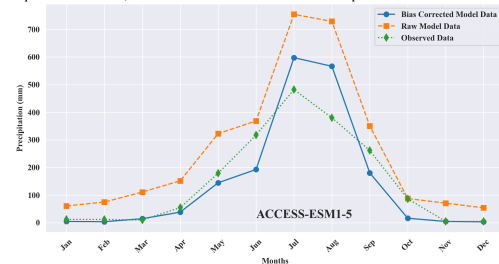


Figure 3: A graph illustrating the comparison of observed average monthly precipitation with both raw model outputs and bias corrected data (1990-2014) for ACCESS-ESM1-5 Model.

In this study, bias correction method used are Bernoulli Weibull method for precipitation and linear transformation method for max. and min. temperature. The previous study had showed that the methods used are best for bias-correction [13] in the Eastern part of Nepal.

Comparison of Observed, Raw and Bias Corrected Model Data of Maximum Temperature for station 1319 from 1990-2014

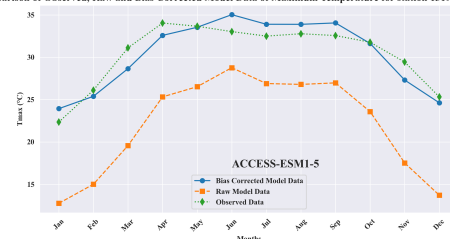


Figure 4: A graph illustrating the comparison of observed average monthly Maximum Temperature with both raw model outputs and bias-corrected data for the period (1990–2014), for the ACCESS-ESM1-5 model.

Using the bias correction methods, the variations in raw and observed data has in reduced as seen in the figure 3,4 and 5. Bias correction is essential for improving the reliability of climate forecasts by reducing systematic errors in climate model outputs. Climate models often differ from observed historical data when simulating variables like temperature and precipitation. Bias correction techniques adjust these outputs to better match observed data, ensuring that both historical simulations and future projections are more accurate.

4.2 Future Projection

The observed period is from 1990 -2014 and the future period is divided in 3 period near future from 2025-2049, mid future period from 2050-2074 and far future period from 2075 to 2100 in this study.

Comparison of Observed, Raw and Bias Corrected Model Data of Minimum Temperature for station 1319 from 1990-2014

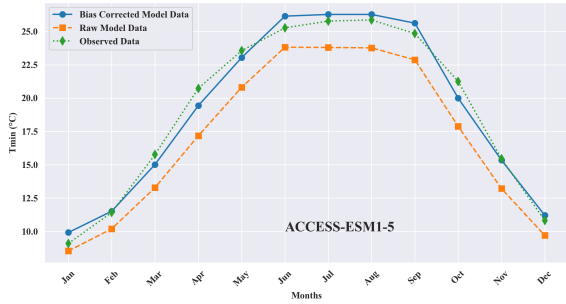


Figure 5: Figure 5:-A graph illustrating the comparison of observed average monthly Minimum Temperature with both raw model outputs and bias-corrected data for the period (1990–2014), for the ACCESS-ESM1-5 model.

4.2.1 Precipitation

The figure 6 shows the future trend of precipitation up to 2100. The figure shows that in ssp585 scenarios is more in increasing trend than the ssp245. The average yearly precipitation of observe time (1990-2014) is 1804.99 mm per year. The average yearly precipitation of ssp245 scenarios is 1812.87 mm for near future (2025-2049), 2159.10mm for mid-future (2050-2074) and 2321.59 mm for far-future (2075-2100). Difference from near future to observed baseline yearly average precipitation is 7.88 mm, from mid-future 354.11 mm and from far-future is 516.61 mm. The precipitation is in increasing trend for ssp245. The yearly average precipitation for ssp585 scenarios is 1911.89mm for near future, 2427.42mm for mid-future and 2979.81mm for near future. The difference with observed yearly average precipitation are 106.91mm, 622.44mm and 1174.82mm for near, mid and far future respectively.

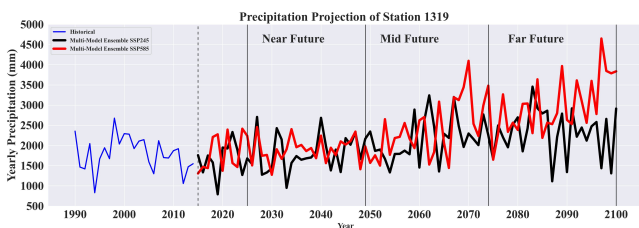


Figure 6: Future Precipitation Trend of station 1319 under both ssp245 and ssp585 scenarios in 3 different time period near future (2025-2049), mid-future (2050-2074) and far-future (2075-2100).

4.2.2 Maximum Temperature

The trend of ssp585 is in increasing trend as compared to ssp245 as shown in the figure 7 below. The baseline (1990-2014) yearly average temperature is 30.4°C. The average yearly temperature for ssp245 for future period from (2025-2100) is 31.65°C and the average yearly temperature for ssp585 for future period from (2025-2100) is 32.15°C. The difference from yearly average observed maximum temperature to ssp245 and ssp585 are 1.25°C and 1.75°C respectively and difference between ssp245 and ssp585 are 0.5°C.

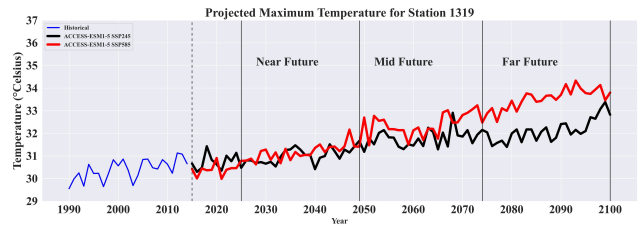


Figure 7: Future Maximum Temperature Trend of station 1319 under both ssp245 and ssp585 scenarios in 3 different time period near future (2025-2049), mid-future (2050-2074) and far-future (2075-2100).

4.2.3 Minimum Temperature

The baseline period (1990-2014) yearly average min. temperature is 19.19°C. The average yearly temperature for ssp245 and ssp585 for time period 2025-2100 are 20.59°C and 21.29°C respectively. The difference between observed yearly average temperature (1990-2014) to yearly average temperature of ssp245 and ssp585 (2025-2100) are 1.4°C and 2.1°C respectively. The difference between ssp245 and ssp585 is 0.7°C. The temperature raise for ssp245 is less than ssp585.

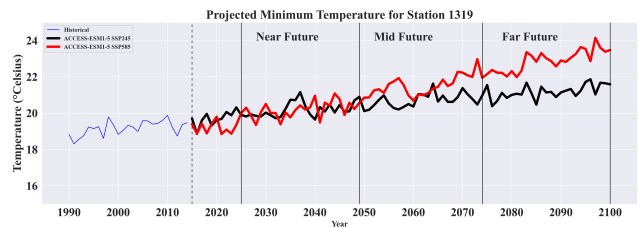


Figure 8: Future Minimum Temperature Trend of station 1319 under both ssp245 and ssp585 scenarios in 3 different time period near future (2025-2049), mid-future (2050-2074) and far-future (2075-2100).

4.3 Crop Water Requirement (CWR)

The command area of Chanda Mohana Irrigation Project has a total command area in which rice 1500, wheat 650, Maize 700, sugarcane 300 and potato at 45 hatters. This was obtained from the office of Chanda Mohana Irrigation Project Office, Water Uses Committee and interviewing the farmers. The rice, maize, wheat, sugarcane and potatoes are planted on June, December, December, October and October respectively with the harvesting time on october, April, April, February and March respectively for 5 crops which was found from the investigation with farmers, WUCs and CMIP officers.

The March month have a great crop water requirement and December has the lowest crop water requirement. The highest crop water requirement is 1082.4 mm and lowest CWR is 226.32 mm. March has the highest crop water requirement due to 3 (maize, wheat and sugarcane) crop development stage in same months. Lowest CWR on December due to only sugarcane and Wheat initial stage have been grown in this month.

Figure 10 shows the percentage change in CWR between baseline year (1990-2014) and different future period near (2025-2049), mid (2050-2074) and far future (2075-2100) in two different scenarios ssp245 and ssp585. The highest

Crop Water Requirement for Observed, SSP-245 and SSP-585

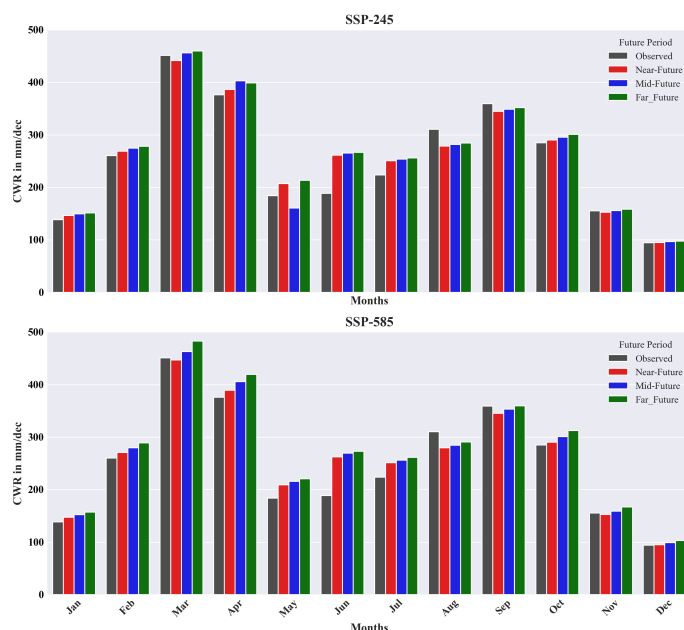


Figure 9: Monthly average of Crop Water Requirement of baseline, near, mid and far.

change is in June for both scenarios. For ssp245 in 3 different future periods are 44.37 %, 46.58 % and 53.02 % respectively for near, mid and far future. For ssp585 in 3 different period 44.98%, 48.68% and 56.81% respectively for near, mid and far future. The percentage change of CWR from the baseline line to near, mid and far future for ssp245 are 7.48%, 8.10% and 15.15% respectively and the % change of CWR from baseline to near, mid and far future for ssp585 are 8.07% to 19.39% respectively.

5. Conclusions

Using ACCESS-ESM1-5 GCM under 2 scenarios was projected, bias correction was done after the downscaling of the GCMs. The ssp585 is 0.5°C more than ssp245 max temperature. Every variable temperature and precipitation both are in increasing trend. The Chanda Mohana Irrigation Project shows varying crop water requirements (CWR) across months and future climate scenarios. March has the highest CWR (1082.4 mm) due to the growth stages of maize, wheat, and sugarcane, while December has the lowest (226.32 mm). Future projections under SSP245 and SSP585 indicate a significant CWR increase, especially in June. The highest change is observed under SSP585. Compared to the baseline (1990-2014), SSP245 shows a CWR increase of 7.48% to 15.15%, while SSP585 shows 8.07% to 19.39% in near, mid, and far future periods. These findings highlight climate change's impact on irrigation demands, particularly in later decades. Adaptive water management strategies are crucial to ensure sustainable agricultural productivity in the command area.

Percentage Change in Crop Water Requirement for SSP-245 and SSP-585

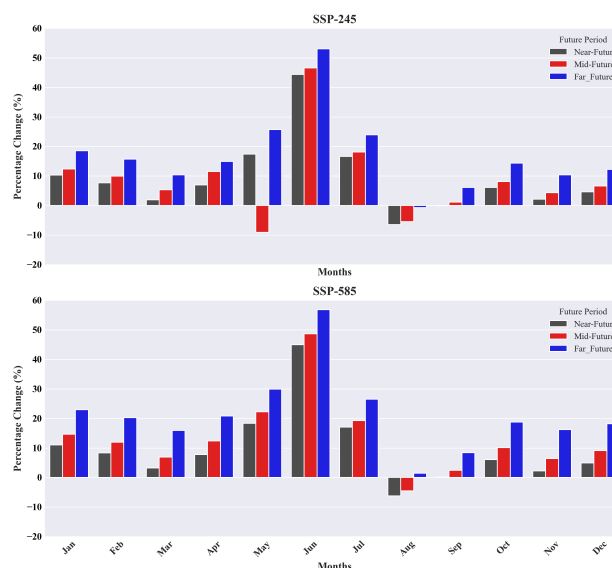


Figure 10: Crop Water Requirement Change with baseline.

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