



Institute for Water  
and Energy Sciences  
(incl. Climate Change)



**PAN-AFRICAN UNIVERSITY  
INSTITUTE FOR WATER AND ENERGY SCIENCES  
(including CLIMATE CHANGE)**

# **Master Dissertation**

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Presented by

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**TITLE : Assessment and prediction of future Climate Change Impacts and  
Adaptation Strategies for a Hydropower Generation: Case study of Boali  
Hydropower Station (BHS), in the Central African Republic.**

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## **Abstract**

This research provides a comprehensive assessment of the potential impacts of climate change on hydropower generation at the Boali Hydropower Station (BHS) in the Central African Republic and evaluates strategic adaptation measures. Using a combination of observed climate data from 1991 to 2021 and climate projections from three regional climate models ACCESS, CNRM, and MPI under SSP2-4.5 and SSP5-8.5 scenarios, the study reveals a consistent warming trend, annual maximum temperatures rose by 0.1091°C and minimum temperatures by 0.077°C, alongside a decadal reduction in precipitation of approximately 10.7 mm. River inflows into the M'Bali reservoir have declined from 68.5 m<sup>3</sup>/s in 1991 to 62.9 m<sup>3</sup>/s in 2021, resulting in a 0.0153 m<sup>3</sup>/s annual loss, impacting the hydropower potential. Projections indicate further risks under SSP5, with temperature increases reaching up to 6°C and declines in wet-season precipitation, which could reduce electricity generation potential. Despite these risks, the application of the Random Forest model suggests average production could remain around 140 GWh per year under moderate scenarios, extreme conditions could severely disrupt operations. Adaptation strategies such as modernisation of hydropower infrastructure, sediment and water management, deployment of floating photovoltaic systems, and exploration of new hydro and solar sites (e.g., Labaye, Kotto...) are proposed to enhance system resilience. This study offers critical insights for sustainable energy planning in the face of climate change and serves as a foundation for future hydropower research in Central Africa.

# CHAPTER ONE: GENERAL INTRODUCTION

## I.1 Background

The world's energy sector is undergoing a profound transformation, marked by the transition to renewable energy sources and the urgent need to mitigate the effects of climate change. As a mature renewable energy source, hydropower plays a crucial role in this context. However, its potential is strongly influenced by climatic variations, particularly changes in precipitation patterns and temperatures (Qusay Hassan, 2024).

Climate Change refers to a change in the state of climate that can be identified (for example, using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer (IPCC., 2018; UNFCCC., 2011 ). The most noticeable and direct impact of climate change observed in recent years is global warming which is a significant increase in global ambient temperatures. This change may be caused by natural internal processes or external forcings, such as modulation of the solar cycle, volcanic eruptions, and permanent anthropogenic changes particularly, burning of fossil fuels (oil, gas, coal etc.) for energy production, transport and industry, and also the Large-scale deforestation for agriculture, mining and urban expansion. These sectors are the main sources of greenhouse gas (GHG) emissions such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) etc. (IPCC, 2021).

Carbon dioxide and many other greenhouse gases occur naturally in the atmosphere and are important in keeping the earth warm. These GHGs naturally emit trap heat in the atmosphere, upsetting the Earth's radiative balance. Since the industrial revolution, the atmospheric concentration of CO<sub>2</sub> has increased by more than 50% and this trend is expected to continue over the next century which will result into major rise in temperature greater than any time in the past (NOAA, 2022). This increase in greenhouse gases, particularly CO<sub>2</sub>, has caused the global average temperature to rise by approximately 1°C over the past century, now reaching about 15°C from roughly 14°C in the early 20th century. This has led to more extreme weather patterns (NOAA, 2022).

In 2016, the Paris Agreement came into force with the aim of limiting global warming to 2°C above pre-industrial levels (IPCC., 2018). Furthermore, in 2018, the Intergovernmental Panel on Climate Change (IPCC), the united nation body that guides policymakers on climate change

issues, published a landmark report entitled "Special Report on 1.5°C Global Warming". The report demonstrates the importance of limiting global warming to 1.5°C above pre-industrial levels and pathways to achieve this level by reducing greenhouse gas emission (IPCC., 2018).

The effects of climate change are already being felt in many regions through the world, leading to changes in climatic parameters such as temperature, precipitation patterns, wind direction and the increased intensity and frequency of extreme events such as droughts, floods and cyclones (METHO, 2022; Trenberth, 2008; Trenberth et al., 2007). One of the significant sectors already affected by climate change is the energy sector, particularly hydropower generation.

Hydropower, which relies on the flow of water to generate electricity, is directly influenced by changes in precipitation patterns, temperature, and the frequency and intensity of extreme weather events (IPCC, 2021; Wasti et al., 2022). These phenomena have a direct impact on water resources, a key element in hydropower production.

Largely considered as a clean and critical source of renewable energy, Hydropower is accounting for approximately 16% of global electricity production (Dechamps, 2023). However, the dependency of hydropower on water availability makes it particularly vulnerable to climate variability and change. As mentioned above, changes in precipitation patterns, temperature increases, and extreme weather events can significantly influence water flow regimes, reservoir levels, and ultimately, power generation capabilities. That can explain by the fact that a decrease in rainfall pattern can lead to a reduction in available water flows, thus affecting electricity production. Conversely, excessive rainfall can lead to flooding and damage to hydroelectric infrastructure. Additionally, rising temperatures can influence evaporation, glacier melt and aquifer recharge, thus impacting the availability of water for power generation.

Recent studies highlight that climate change can lead to both positive and negative impacts on hydropower potential, depending on regional climatic and hydrological conditions (World Bank, 2020). In some regions, increased precipitation could enhance water availability, whereas in others, prolonged droughts and reduced river flows could diminish hydropower generation capability (World Bank, 2020).

The Central African Republic (CAR), like many other African nations, is highly susceptible to the impacts of climate change. According to the Intergovernmental Panel on Climate Change (IPCC) reports, the region is expected to experience increased temperatures, changes in precipitation patterns, and more frequent extreme weather events like flood, drought etc. (The

World Bank Group, 2021). These changes pose risks to water resources, agriculture, and energy systems, including hydropower.

Located 90 km in northwest of the capital city of Bangui on the Mbali river, the Boali Dam helps to power the hydropower complex, which comprises three units, Boali 1(10MW), Boali 2 (20MW) and Boali 3 Hydropower Stations with hydroelectric generating capacities of 8.75 MW, 20 MW and 10 MW (in project) respectively (AfDB 2020). Boali's Hydropower Stations (BHS) play a pivotal role in the country's energy infrastructure. It supplies a significant portion of the electricity consumed in the capital city of Bangui, and surrounding areas. Given its importance, any changes in the hydropower output due to climate variability could have substantial socio-economic implications on the country.

Research works were done at Boali dam on Mbali river sub-basin, but none was focused on evaluating climate change impact on the hydropower potential of that critical river. This study is therefore aimed to assessing the potential impacts of climate change on the hydrology of Mbali river catchment. Bias corrected RCM temperature and precipitation data set for Mbali sub-basin studies was analysed.

#### Statement of the problem

Climate change poses a significant threat to the socio-economic stability of the Central African Republic (NOAA). The energy sector, particularly hydropower derived from the Boali Dam, is critical for the nation's development and economic stability. Disruptions in water availability due to climate change directly threaten the reliability and efficiency of hydropower generation at the Boali Hydropower Station (BHS) (ENERCA, 2023). With only 15.7% of the population having access to electricity and over 90% relying on wood for heating and cooking, the stability of BHS is paramount (World Bank, 2020). The Intergovernmental Panel on Climate Change (IPCC) reports highlight severe impacts across Africa, yet there is a pressing need for localized studies to understand the specific impacts within the CAR (IPCC, Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems., 2019).

The variability in temperature and precipitation patterns, coupled with an increased frequency of extreme weather events, is expected to alter river flows, potentially leading to both water scarcity and flooding (Aerts, 2012). Such changes can adversely affect the station's power generation capacity and strain the existing infrastructure (National Meteorological Report, 2021). National meteorological reports and studies highlight climate change as a pressing issue

that requires urgent attention (Ministry of Environment CAR, 2021). The impacts of climate change, including altered precipitation patterns, increased frequency of extreme weather events, and variability in river flow, need to be quantified at smaller scales to develop viable strategies for mitigating these challenges (Tabari, 2020).

Given the critical role of BHS in the CAR's electricity supply, it is essential to understand these localized climate impacts and develop targeted adaptation strategies to ensure energy security and sustainable development (Graham et al, 2020). This study aims to bridge the gap in current research by evaluating the potential impacts of climate change on BHS and proposing viable adaptation measures. This will involve detailed climate impact assessments using Shared Socioeconomic Pathways (SSPs) scenarios, which provide a better agreement with observed climate data. These assessments are essential for planning sustainable water resource management and developing robust adaptation strategies.

## **I.2 Main objectives**

The main objective of this research is to exhaustively assess the potential impacts of climate change on the Boali Hydropower Station (BHS) in the Central African Republic, and evaluate adaptation strategies crucial to maximize hydropower generation under climate change scenarios.

### **I.2.1 Specific objectives**

- i) To examine the temperature, and precipitation trends and variability from 1991 to 2021 for M'Bali river basin.
- ii) To analyse the river flow regime of the Mbali River basin from 1991 to 2021 and evaluate its relationship with hydropower generation.
- iii) Assess the potential impact of climate change on Boali Hydropower Station's electricity generation capacity using SSPs and provide adaptation strategies.

Research questions and the working hypothesis

### **I.2.2 Questions:**

This thesis is designed to address the following research questions which were explored throughout the study:

- Q1: What are the seasonal variations trends in temperature and precipitation, within the Mbali river basin from 1991 to 2021?

Q2: What is the seasonal variation trend in water inflows to the Mbali reservoir, from 1991 to 2021?

Q3: What will be the impact of the projected changes in water inflow on the power generation capacity of the BHS?

### **I.3 Working Hypothesis:**

Our study based on the following research hypotheses:

H1: There are seasonal variations in temperature, precipitation, and river flow within the Mbali River basin during the study period (1991-2021).

H2: Climate change will affect the hydrology of the Mbali catchment.

H3: The affected hydrology impacts the hydropower potential of the catchment.

H4: Despite these changes, there are potential adaptation strategies that can help BHS to maintain or increase its electricity generation.

### **I.4 Relevance of your study**

As a crucial water resource in the CAR the Mbali River basin is, supporting livelihoods and hydropower generation. The Boali Dam, located on this river, allows water retention for a continuous supply to two hydropower stations which supply approximately 80% of the national electricity, making it indispensable for the country's energy security and economic stability. Any disruption to this dam could lead to a total blackout in the capital, Bangui (Enerca, 2023) and its surrounding areas.

Currently, under a potential irreversible effects of climate change, Lake M'Bali is experiencing depletion, posing severe risks to local biodiversity and critical electricity supplies (World Bank, 2020). Énergie Centrafricaine (ENERCA) has reported significant reductions in hydropower capacity, highlighting the urgency of understanding and mitigating these impacts (**Radio Ndeke Luka 2024**).

Given these challenges, it is crucial to rigorously monitor water resources, analyse trends, and examine influencing factors. This study aims to assess future climate impacts on the Mbali River's hydroelectric potential and develop resilient adaptation strategies. It highlights the importance of considering climate vulnerability in energy planning and raising awareness about climate change.

## **I.5 Tentative thesis chapter outline**

The manuscript consists of several parts structured into five chapters that we show below: **The first chapter: general introduction**, that includes, the background information's, definition/statement of the problem, the research objectives, research questions, scope of study and limitation. **The second chapter: Literature review**, explores the relevant theories and published research work about climate, climate change trough the world and the overview of current climate and energy situation in Centra African Republic. **The third chapter: Materials and Method**: describes the study area (The Boali hydroelectric dam on the Mbali river in Boali in the Ombella M'poko prefecture), climate and the geography of the area, detailed explanations of the method to be used in the study. **Chapter four: Results and Discussion**: This chapter will implement the various stages from the previous chapter while discussing the results. It will present the analysis of the projected climate change signal in the sub-basin and its impact on the hydrological regime, as well as the assessment of some potential adaptation strategies. **The fifth chapter: Conclusion and Recommendations**, will provide an overall summary and the main conclusions derived from the study and give some recommendations

## CHAPTER TWO: LITERATURE REVIEW

### II.1 Introduction

This chapter reviews existing literature on the impact of climate change on water resources and hydropower generation globally, with a particular focus on the Mbali sub-watershed that supplies the Boali Hydropower Station (BHS) in the Central African Republic (CAR). The BHS is not merely a power source, it serves as a vital lifeline for the region and all of the country. It explores how changes in temperature, precipitation patterns, and extreme weather events affect water availability and hydropower reliability. The goal? This second chapter aims to provide a comprehensive understanding of the current research landscape, highlight gaps in knowledge, and establish the foundation for assessing and developing adaptation strategies to ensure sustainable energy supply in the face of climate change.

### II.2 Definition

#### II.2.1 Climate,

Climate is the set of atmospheric variables existing in a given place over a long period of time. Among the variables that constitute climate are precipitation, atmospheric humidity, temperature, atmospheric pressure, insolation and wind. It should not be confused with weather, because, although the latter is an expression of the same variables, it is considered at an immediate moment and not over a prolonged period of time (Morales, 2022). A particular climate is often referred to by reference to the average values of the variables given above. The extreme values of these variables and the probability of reaching them are also often characterized. However, the climate actually involves the characterization of changes in the climatic variables over short periods of time (daily, monthly and annual). In this case, we speak of the climatic regime or climate variability (Sabo Ago Amina Usman, 2024).

#### II.2.2 Climate variation

Climate variability represents changes in mean status and other statistical climate variables at all temporal and spatial scales other than specific meteorological phenomena (LAOUALI ITANIMOUNE, 2024). In other words, it is the natural variation within and between years of the climate. Climate variability is an inherent feature of the climate that manifests itself in the differences between the long-term statistics of climatic elements (rainfall, temperature, humidity, season duration) calculated for different periods (Roohi, 2024). The variability of the climate is often perceived through the irregularity of climatic parameters in their evolution. According to Leif Christian Stige et al., 2024, Africa is particularly vulnerable to climate

variability in view of its economies largely based on agropastoral production systems that are sensitive to the weather (Leif Christian Stige et al., 2024; Kotir, 2010).

### **II.2.3 Climate Change**

The United Nations Framework Convention on Climate Change (UNFCCC) further characterizes climate change as a long-term shifts or changes in the average temperature or weather patterns that have been observed over an extended period, typically decades to millions of years. This includes alterations in the temperature, precipitation, wind patterns, and other atmospheric conditions on earth. Climate change is influenced by both natural variability and human activities (IPCC, 2023).

Since pre-industrial times, average global temperatures have increased by approximately 1.1°C, with significant warming observed from the late 20th century onward. Due mostly to human activities such the burning of fossil fuels and deforestation, the rate of temperature rise has accelerated, especially since the 1970s (IPCC, 2023). According to recent studies, climate change is causing heatwaves, droughts, and heavy rainfall to occur more frequently and with greater intensity in addition to altering temperatures. With changing precipitation patterns impacting water availability and rising sea levels endangering coastal populations, the effects of climate change are becoming increasingly evident across a range of ecosystems and human systems. The Intergovernmental Panel on Climate Change (IPCC) reports that global temperatures could rise by 1.5°C to 2°C above pre-industrial levels by the end of this century if significant reductions in greenhouse gas emissions are not made (IPCC, 2023).

A large number of observations gives a picture of global warming and other changes in the climate system around the world. These changes can occur naturally, influenced by factors like variations in solar activity or significant volcanic eruptions etc. which release GHG and ash into the atmosphere and can influence climate over long periods. However, since the 1800s, human activities have been the main driver of climate change, primarily due to the burning of fossil fuels such as coal, oil, and gas (Dee et al., 2021; Haque, 2023; Adebayo et al., 2022). Burning fossil fuels generates greenhouse gas emissions that act like a blanket wrapped around the Earth, trapping the sun's heat and raising temperatures and deforestation reduce the Earth's capacity to absorb CO<sub>2</sub> emitted by other activities (Dee et al., 2021).



Figure 1: Causes of climate change (Source: IPCC, 2014)

Human activities, including fossil fuel combustion, deforestation, and land-use changes, have disrupted the atmospheric balance, leading to global warming. The main greenhouse gases involved are carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ), and nitrous oxide ( $\text{N}_2\text{O}$ ) (Adebayo et al., 2022).  $\text{CO}_2$  is the largest contributor, having increased by approximately 35% since industrialization, with significant emissions from electricity generation, transportation, industry, and households (Jagmohan Sharm and al., 2019; Pryck, 2021). Methane, emitted during fossil fuel production and organic waste decay, is much more effective at trapping heat, while nitrous oxide primarily comes from industrial and agricultural activities and has a high global warming potential (Pryck, 2021). Ozone ( $\text{O}_3$ ), formed from organic compounds and sunlight, is a short-lived pollutant that negatively impacts respiratory health in plants and animals (Sumitra Pal Karmakar, 2022).

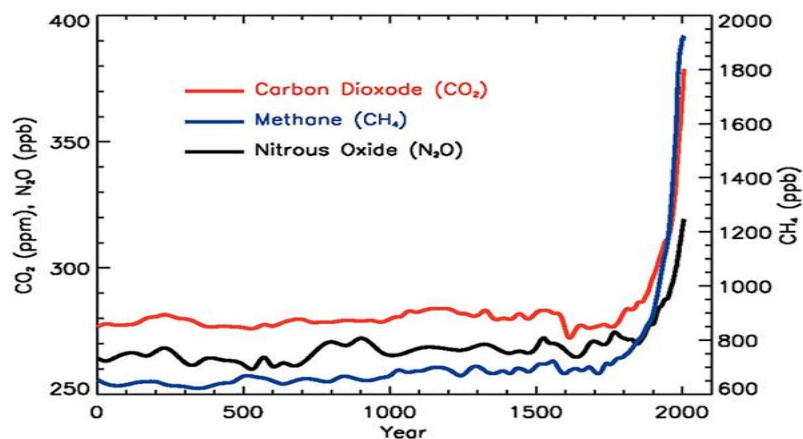


Figure 2: Greenhouse Concentrations Gases from 0 to 2005 (Source: IPCC, 2014)

## **II.3 Climate Change and Its Global Impacts**

The Intergovernmental Panel on Climate Change (IPCC) has established that the warming observed over the past 50 years is predominantly attributable to anthropogenic factors. Global temperatures have risen by approximately 2 degrees Fahrenheit (1 degree Celsius) since the late 19th century, with the last seven years recorded as the warmest on record (IPCC., 2023; Ma, 2020). This warming has induced significant changes across physical and biological systems worldwide, including increased frequency and intensity of heatwaves (Rosenzweig et al., 2008). The incidence of record high temperatures in the United States has risen by 70% since 1950, highlighting the increasing severity of heatwaves (Solomon Hsiang et al., 2017). Additionally, the top 100 meters of the ocean have warmed by about 0.67 degrees Fahrenheit (0.37 degrees Celsius) since 1969, absorbing roughly 90% of the excess heat generated by climate change (IPCC, 2023).

Satellite observations indicate a significant decrease in spring snow cover in the Northern Hemisphere, with a decline of approximately 20% since 1967 (Tschudi et al., 2020). Global sea levels have risen by about 8 inches (20 centimeters) over the past century, with the rate of increase nearly doubling from 1.7 mm per year in the 20th century to about 3.3 mm per year in recent decades (Blunden J. et al, 2022; Ma, 2020) . The extent of Arctic Sea ice has decreased by approximately 40% since 1979, indicating significant changes in the Arctic climate (NSIDC, 2023). Collectively, these indicators underscore the multifaceted consequences of climate change, which include rising global temperatures, more frequent and severe weather events (such as hurricanes, droughts, floods, and wildfires), shifts in precipitation patterns, and impacts on ecosystems and biodiversity and the profound impact of climate change on Earth's systems. These changes pose significant risks to human societies, affecting food and water security, health, infrastructure, and economic stability (Loucks, 2021).

## **II.4 Extreme Weather Events and Their Implications**

The frequency and intensity of extreme weather events, including hurricanes, floods, and droughts is significantly increasing by the Climate change. The NOAA reports a 50% rise in the frequency of Category four (4) and five (5) hurricanes since the 1980s, indicating a trend toward more intense storms (NOAA, 2021). Furthermore, the United States (U.S.) Global Change Research Program (2018) notes a twenty percent (20%) increase in extreme precipitation events in the contiguous United States since 1950, contributing to severe flooding incidents, such as the 2021 flooding in the Northeast U.S. that resulted in over \$1 billion in

damages. Drought patterns are also worsening; the Fourth National Climate Assessment (2018) highlights that the western United States is experiencing more frequent and severe droughts, exemplified by the 2012 to 2016 California drought, which caused approximately \$2.7 billion in agricultural losses. Additionally, the increasing frequency of heatwaves poses significant risks to public health, agriculture, and energy systems, underscoring the urgent need for effective strategies to mitigate the impacts of climate change on extreme weather patterns.

### II.5 Overview of climate in Central African Republic

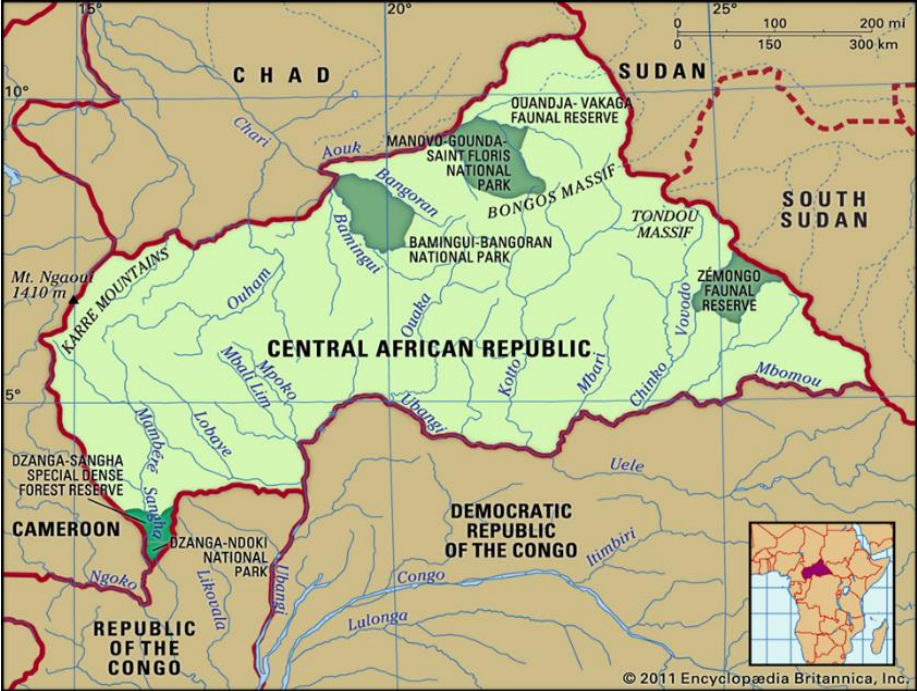
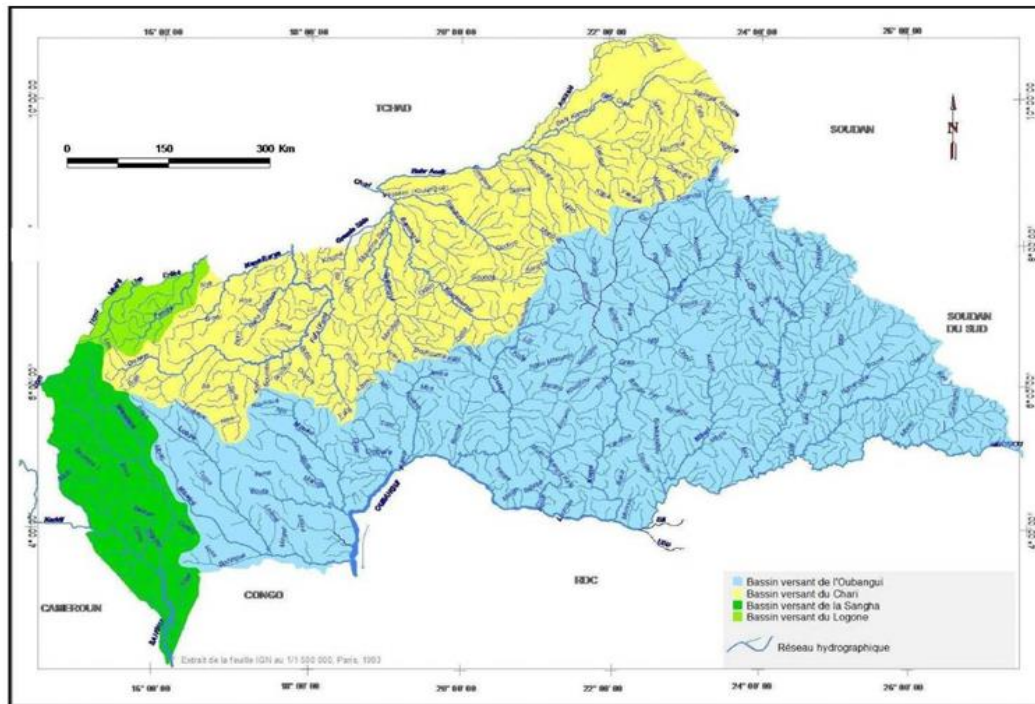


Figure 3: Background of West Africa (Central African Republic Africa Map, 2020) Source: Google Map

A country in the Central African sub-region, the Central African Republic is located in the heart of Africa between latitudes 2°16 and 11°20 North, and longitudes 14°41 and 27°46 East. The country covers an area of 622,984 square Kilometers and is bordered to the north by the Republic of Chad, to the east by the Republic of Sudan and the Republic of South Sudan, to the west by the Republic of Cameroon and to the south by the Democratic Republic of Congo (DRC) and the Republic of Congo. The Central African Republic is landlocked, being more than 1,000 kilometers from the Atlantic Ocean, the Indian Ocean and the Red Sea. From a hydrological point of view (see Figure 1), the territory of the Central African Republic straddles two international river basins: (i) the Lake Chad basin; and (ii) the Congo basin. At national level, the international Lake Chad basin comprises the Chari basin and the Logone basin, while at national level the international Congo basin comprises the Oubangui basin and the Sangha

basin. Sangha basin. The country has a total area of 622 984 square kilometers of which 13,400 square kilometers is occupied by inland water.



Source : Etat des lieux des Services Météorologique et Hydrologique de la République Centrafricaine, août 2014.

Figure 4: Centrale African Republic's river basins

The Central African Republic has four agro-climatic zones. The humid zone is primarily located in the south-western regions, where rainfall is abundant. A significant part of the country falls within the sub-humid zone, including areas like Ombella M'poko and parts of the east, characterized by seasonal rainfall. In the northern regions, the semi-arid zone is prevalent, where rainfall is less consistent and drier periods are more prominent. The arid zone is found in the more extreme northern areas, although it is less prevalent compared to other regions.

## II.6 Hydropower

### II.6.1 Climate Change and Hydropower

A growing body of research emphasizes the vulnerability of hydropower, a crucial renewable energy source, to climate change (SAKOUVOGUI, 2023). In fact, higher concentrations of greenhouse gases in the atmosphere are causing significant changes in our climate, leading to increases in both minimum and maximum temperatures. These changes also affect rainfall patterns, resulting in variability in both distribution and amounts. Such disruptions have serious consequences for the water cycle, impacting precipitation and runoff, which in turn alters the

timing and availability of water resources. Third IPCC Report (2001) emphasizes that global warming is directly influencing water availability. As temperatures rise, evaporation rates increase, creating an imbalance between surface water and the moisture in the atmosphere. Changes in precipitation can negatively affect surface hydrology, contributing to both floods and droughts, which further disrupt regional water systems (GIEC, 2022).

The increased frequency of extreme weather events like severe droughts and intense floods, complicates the operational stability of hydropower infrastructure (GIEC, 2022). These changes in precipitation patterns, temperature fluctuations, and alterations in hydrological cycles directly and indirectly affect river flow, which is essential for hydropower production (Onwudiwe, 2023). Moreover, sedimentation resulting from changing precipitation patterns can reduce storage capacity and hinder hydropower potential.

Existing literature examines these threats across various scales. For example, studies on the impact of climate change on electricity generation in the Amazon basin indicate basin-wide reductions of river discharge (13% and 16%) and hydropower generation (19% and 27%) (Seleshi G. Yalew et al, 2020). In Wales, projections indicate a diminished generation potential for hydropower between 2021 and 2054 (Dallison, 2021). Similar threats have been observed in the Yangtze River in China, the Three Gorges Reservoir, and the Upper Colorado River Basin (Leicheng Guo, 2018; Tan, 2024; Liang, et al., 2022). In North and South America, a decrease in water inflow into reservoirs impacts hydropower potential, as evidenced in Northern Manitoba, Canada, and the Upper Colorado River Basin in the United States (Kim, 2022; Wasti, 2023; Kopytkovskiy, 2015)

In Africa, research in the Eastern Nile Basin highlights concerns about reduced river flows negatively impacting hydropower generation across Ethiopia, Sudan, and Egypt (Abdelkader A et al., 2023; Ahmed Abdelkader, 2023; Keith, 2014). Similar trends have been documented in Kenya, Uganda, and Rwanda, where changing climate patterns threaten hydropower output (Kpewoan, 2022; Omweri, 2024). In West Africa, nations such as Ghana, Ivory Coast, and Nigeria face comparable risks (Salomon Obahoundje et al, 2022) (Boadi & Owusu, 2019; Obahoundje et al., 2022). Research in Southern Africa, particularly in Zambia and Zimbabwe, indicates potential decreases in hydropower generation due to projected changes in precipitation (Abdelkader A et al., 2023; Beharry S.L. et al., 2023; Uamusse, 2020; Blunden J. et al, 2022; Miguel M. Uamusse et al., 2020). Additionally, studies in the Congo basin reveal similar vulnerabilities in the Central African region, including the Democratic Republic of the Congo, Cameroon, and Angola (Lesani S. et al., 2024; Nonki R. M. et al, 2023; Nonki R. M. et al. A. E., 2024; Nonki R. M. et al. L. A., 2019).

## **II.6.2 Localized Research Gaps and Objectives**

In the Central African Republic, recent studies indicate alterations in rainfall patterns, including increased variability and potential shifts in the timing and intensity of precipitation events (Hassan H. B. et al., 2024; Lesani S., 2022; Nguimalet C. R. & Orange D., 2013; Nguimalet, 2010; Orange D. et al., 1997). These changes threaten to disrupt river inflows, consequently impacting the availability of water resources for hydropower generation (Radio Ndeke Luka, 2024). However, a critical knowledge gap exists regarding the specific impacts on the Boali Hydropower Station (BHS) located on the Mbali River. This study aims to address this gap by assessing the vulnerability of BHS to climate change (Shrestha et al., 2021) and evaluating adaptation strategies such as energy mix diversification, improved reservoir management, and infrastructure development. By conducting this research, valuable insights will be provided for policymakers, energy planners, and BHS operators to maximize hydropower generation and ensure a climate-resilient energy future for the Central African Republic. This work aligns with current trends in hydropower research, which emphasize the importance of localized assessments and adaptation plans to sustain this vital renewable energy source in a changing climate. The literature review serves as a concise overview of recent research on climate change impacts and adaptation strategies specifically related to hydropower generation across the African continent.

## **II.7 Overview of Shared Socioeconomic Pathways (SSPs)**

The Shared Socioeconomic Pathways (SSPs) represent a framework developed by the scientific community to examine potential future trajectories of socioeconomic development, technological change, and climate policy responses. Unlike Representative Concentration Pathways (RCPs) which focus specifically on greenhouse gas concentration trajectories, SSPs provide narratives describing alternative societal developments and their implications for both climate change mitigation and adaptation (O'Neill et al., 2017).

## **II.8 The Five Core SSP Scenarios**

**SSP1 - Sustainability (Green Road) :** This pathway envisions a future characterised by strong international cooperation, rapid transition to renewable energy systems, and comprehensive sustainable development policies. Significant investments in education, healthcare and clean technologies promote balanced economic growth alongside reduced inequality. Mitigation challenges are relatively low as emissions decline sharply, potentially aligning with ambitious

targets such as RCP 2.6. However, this scenario requires substantial political commitment globally and fundamental shifts in consumption patterns (Riahi et al., 2017).

**SSP2 - Middle of the Road:** Following historical trends, this moderate pathway features gradual technological and economic progress without major systemic changes. Inequality persists while climate policies are implemented unevenly across regions. Emissions stabilise slowly, roughly corresponding to RCP 4.5. Although plausible, this trajectory carries significant risks as insufficient mitigation action may complicate long-term adaptation to climate impacts (Kriegler et al., 2017).

**SSP3 - Regional Rivalry (Fragmented World):** This pessimistic scenario depicts a fragmented international order where geopolitical tensions and nationalism hinder cooperation. Limited investment in infrastructure and innovation exacerbates inequality. High emissions pathways (RCP 7.0-8.5) emerge alongside severe mitigation and adaptation challenges. Vulnerable populations face heightened risks of food insecurity, conflict and climate-related disasters (O'Neill et al., 2017).

**SSP4 - Inequality (Divided Societies):** Marked by extreme socioeconomic disparities, this pathway features technological advances benefiting only privileged elites while marginalised groups experience worsening living conditions and climate vulnerability. Emission patterns vary regionally, with low mitigation challenges for wealthy enclaves but severe adaptation difficulties elsewhere, highlighting risks of societal polarisation in climate responses (Riahi et al., 2017).

**SSP5 - Fossil-Fuelled Development:** Prioritising rapid economic growth through fossil fuel dependence and high-tech innovation, this scenario achieves improved living standards but at the cost of very high emissions (RCP 8.5). While accumulated wealth enables some adaptive capacity, extreme mitigation challenges and potential long-term climate impacts threaten this resilience (Kriegler et al., 2017).

## Conclusion

The SSP framework provides valuable analytical tools for anticipating diverse climate-society interactions. When combined with RCPs, these scenarios enable integrated assessment of mitigation and adaptation strategies under varying socioeconomic conditions, supporting more robust policy development amidst uncertainty (O'Neill et al., 2020).

# CHAPTER THREE: MATERIALS AND METHOD

## III.1 Study Area

### III.1.1 Location

The Boali Hydroelectric Plant (BHS), located in the M'Bali River basin in the Central African Republic, has been selected as a case study to evaluate the impacts of climate change on hydropower production. The M'Bali watershed is situated between 4.0° N and 4.5° N latitude and 18.5° E and 19.0° E longitude, approximately 90 km northwest of the capital, Bangui, in the Ombella-Mpoko prefecture. This basin covers about 1% of the total area of the Central African Republic, encompassing approximately 62,000 km<sup>2</sup>. The M'Bali River flows for around 150 kilometres from the high plateaus, passing through Yaloké, Bossembélé, and reaching Boali, where the hydroelectric facilities are located. The river continues its course until it meets the M'pama River, then flows into the M'poko River before eventually joining the Ubangi River.

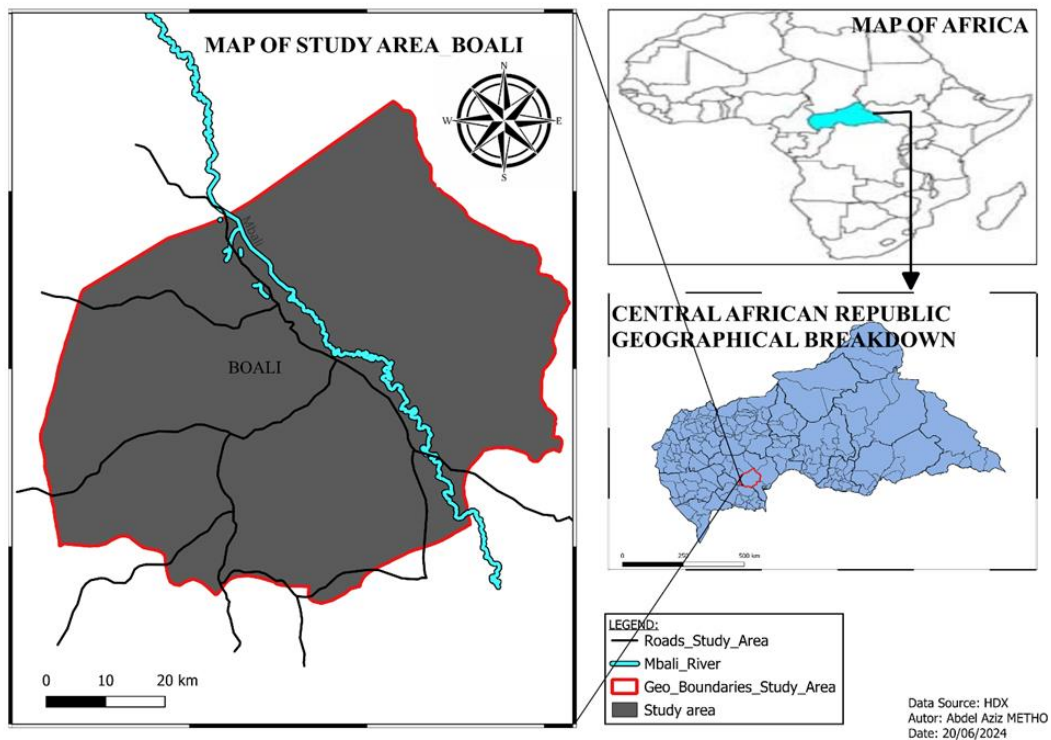


Figure 5: Study Area

This set of hydroelectric facilities includes the Boali dam, with a capacity of 250 million m<sup>3</sup>, as well as two hydropower plants: Boali II (20 MW) and Boali I (10 MW), which are situated successively downstream of the dam. This infrastructure serves to regulate the river's flow, allowing the two plants to maintain their operational units during the dry season when demand is high (from November to April) by utilizing water stored during the rainy season (from May

to October). Although the dam is designed to mitigate the impacts of flow variations caused by climatic fluctuations, prolonged droughts or extreme weather conditions may still compromise its ability to meet energy demands.

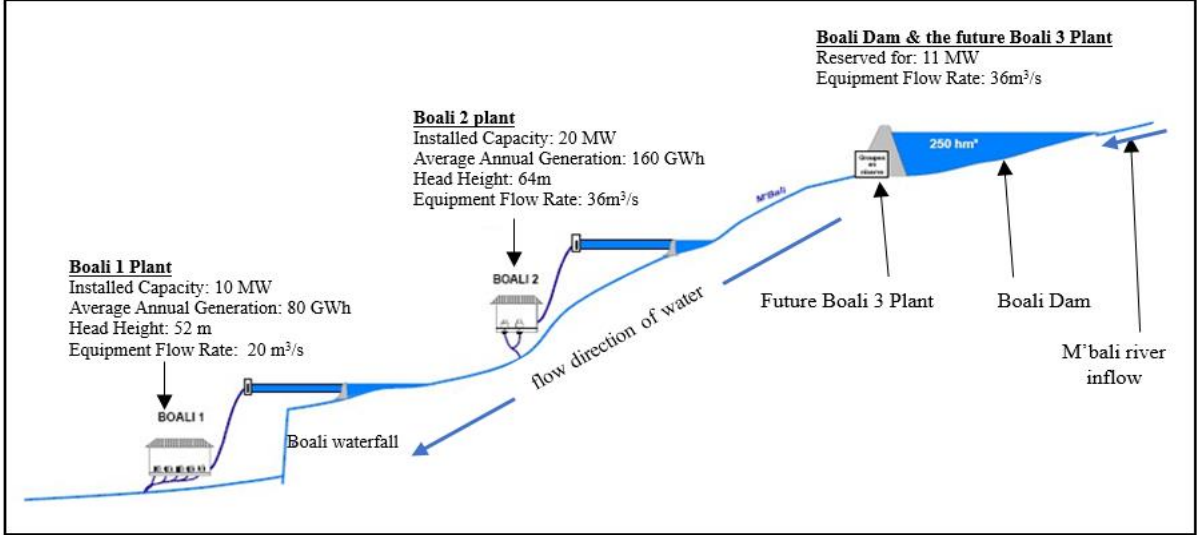


Figure 6: Boali Hydropower Station Configuration

**III.1.2 Location of Gauge and Meteorological Stations**

In this study utilized gauge and meteorological stations located within and near the catchment area. Given the diverse topographic features of the region, stations were selected across various elevations to ensure accurate and representative data. Additionally, stations were strategically positioned in different directions.

The catchment area includes several tributaries that feed into the main M'bali River. A gauge station is situated at the outlet of the catchment to monitor the stream flow of the river.

Table 1: Information about meteorological stations

| N° | Station    | Latitude | Longitude | Type      |
|----|------------|----------|-----------|-----------|
| 1  | Ubangui    | 04°22'N  | 18°35'E   | Hydrology |
| 2  | Boali      | 04°88'N, | 18°03'E   | Synoptic  |
| 3  | Bossembélé |          |           | Synoptic  |
| 4  | Yaloké     |          |           | Agro      |

### III.1.3 Elevation

The topographic features of the region impact runoff generation and velocity, as well as rainfall patterns and temperature. The elevation of the watershed was determined using QGIS version 3.34.6, based on a 30 m x 30 m resolution DEM of the study area downloaded from STRM. Higher elevations are observed in the northern part of the watershed, as well as in the extreme west and southwest. In contrast, the lowest elevations are found at Lake M'Bali in the southern part of the watershed, near the structure of the Boali Dam, which delineates our study area. Large portions of the watershed are situated below the average elevation.

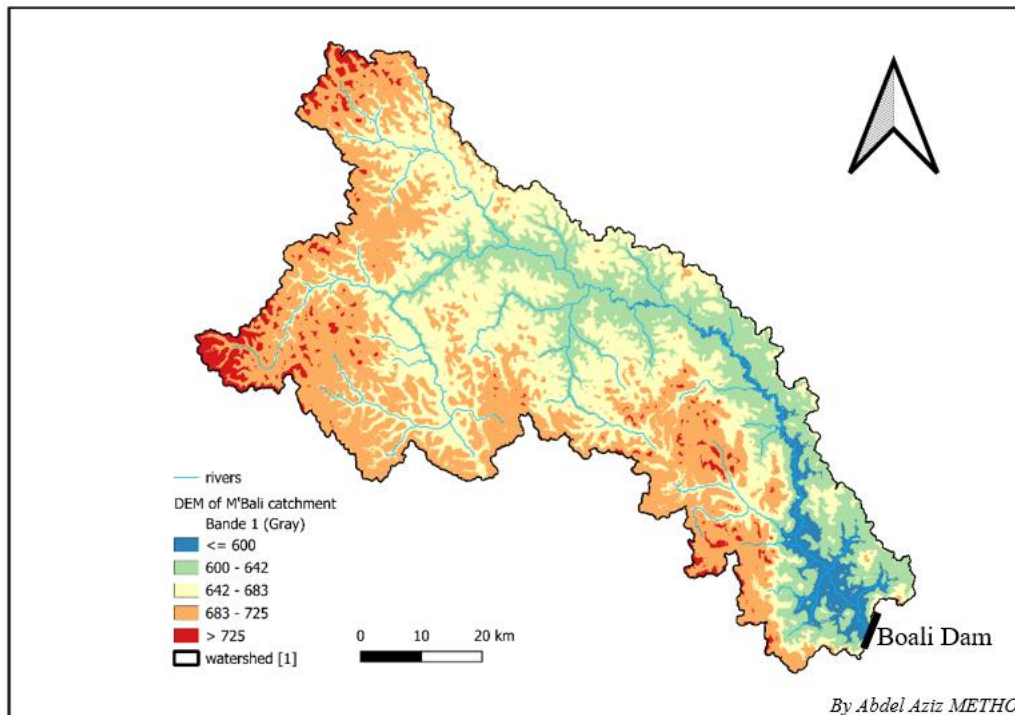


Figure 7 :Elevation information of the M'Bali catchment (study area)

### III.1.4 Soil Types

Soil type is a significant factor influencing runoff generation and velocity, serving as an input parameter for modelling the SWAT (Soil and Water Assessment Tool) to simulate river discharge. As part of the Ubangi basin, which varies in elevation and slope, the catchment features diverse soil types. Predominantly underlain by ancient Precambrian rocks, the M'Bali benefits from geological stability that influences hydrological dynamics. The primary soil types are Plinthic Ferralsols in the north-west and Orthic Ferralsols in the south-east. Plinthic Ferralsols or (Plinthosols) have a significant plinthite layer that hardens when dry, often found in flood-prone areas, impacting water resource management. Conversely, Orthic Ferralsols are well-drained, highly weathered tropical soils rich in iron and aluminium oxides, affecting water retention and drainage patterns crucial for hydropower operations. Both soil types are

susceptible to erosion, highlighting the need for sustainable management practices to protect water quality and quantity.

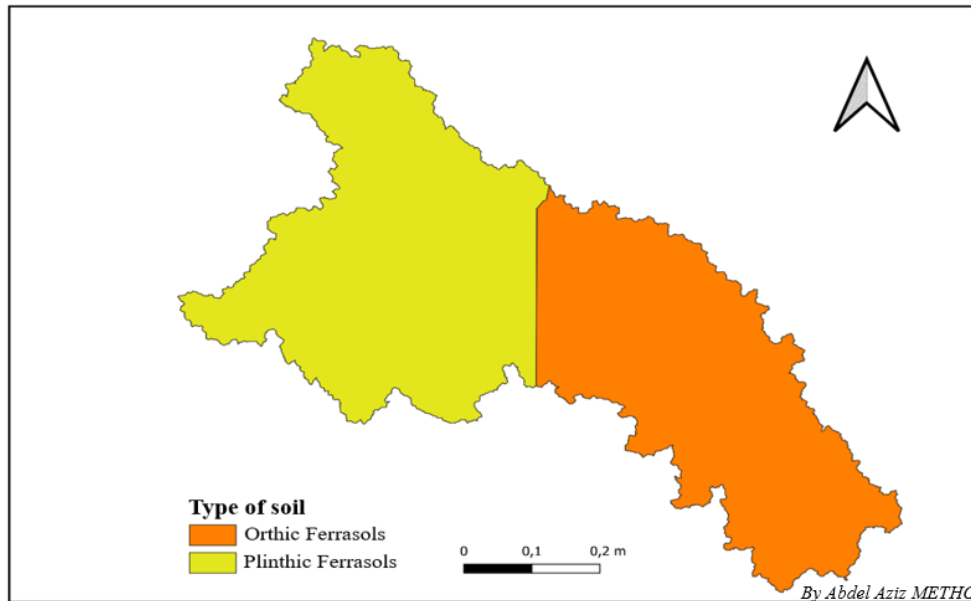


Figure 8: Major soil types in the study area (M'Bali catchment)

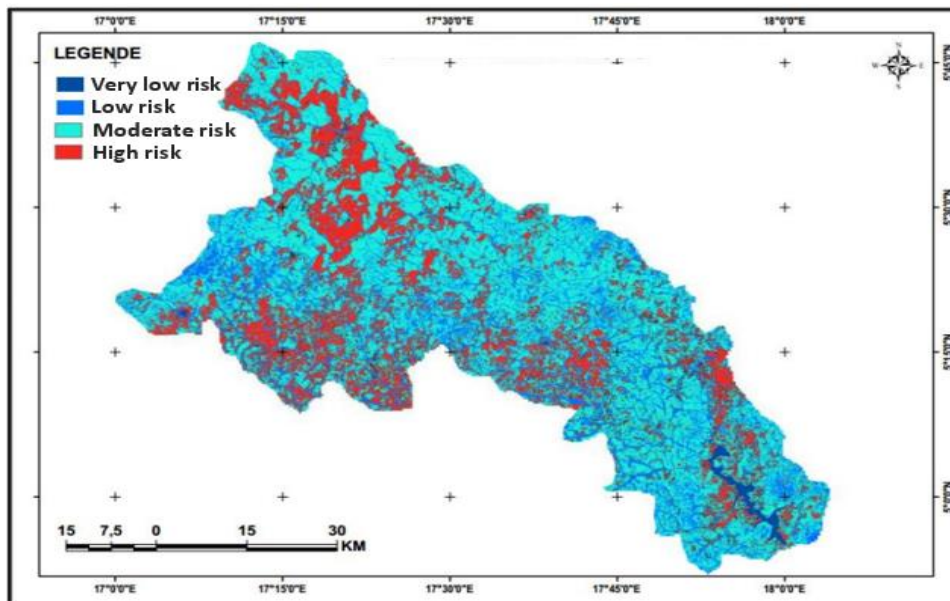


Figure 9: Map of the soil erosion hazard of the Mbali watershed controlled by the dam. Beto (2012)

### III.1.5 Land Use Land Cover

Land use (LULC) significantly influences runoff and water quality within watershed areas. The LULC map indicates that forest cover is the dominant type, playing a vital role in regulating the water cycle and reducing soil erosion. While agricultural zones exist, their impact is relatively minor compared to that of forests. Additionally, urbanisation, characterised by impervious surfaces, exacerbates runoff and diminishes groundwater recharge. Changes in land

use, such as deforestation, have direct implications for hydrology, highlighting the need for sustainable land management practices.

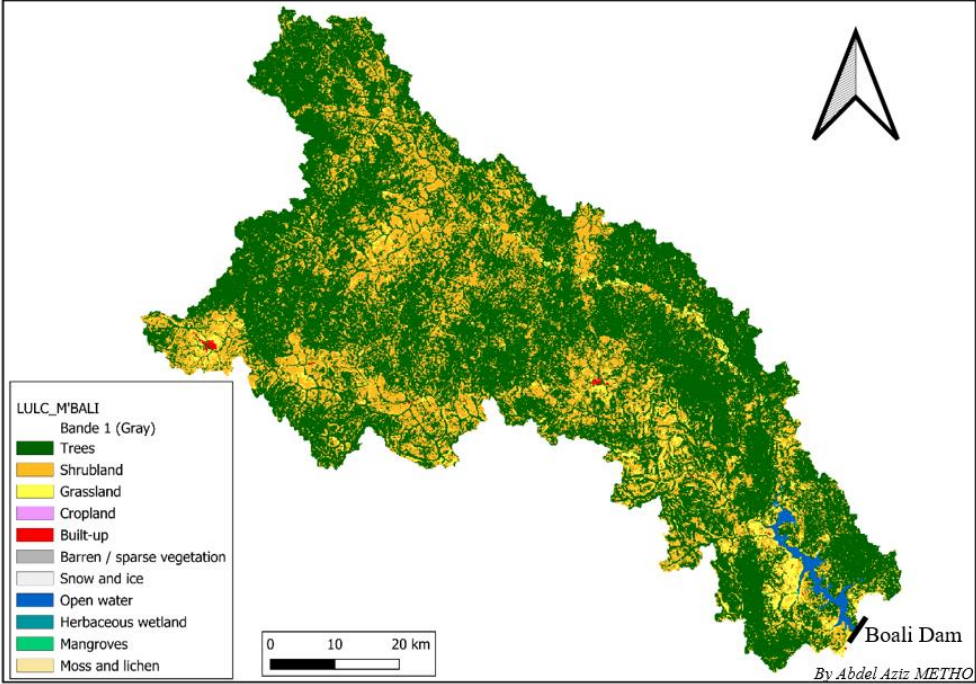


Figure 10: LULC map of Mbali from 2021

**III.1.6 Climate**

The climate of the Central African Republic is primarily influenced by the seasonal migration of the Intertropical Convergence Zone (ITCZ), its associated atmospheric circulation, and the country's diverse topographic features. The ITCZ's movement, which follows the position of the sun relative to Earth, brings varying weather patterns across the region.

This climate can be classified based on altitude and temperature into several distinct zones. The Equatorial Climate Zone experiences high temperatures and heavy rainfall throughout the year, with cities such as Bangui and Berberati falling within this zone. The Tropical Savanna Climate Zone is characterized by distinct wet and dry seasons with hot temperatures year-round, encompassing cities like Bambari and Bria. The Semi-Arid Climate Zone, found in the northern parts of the country, has a short rainy season and a long dry season with high temperatures. Additionally, the Mountain Climate Zone, found at higher elevations, experiences cooler temperatures and higher rainfall, including areas in the western most part of the country such as the prefectures of Nana-Mambéré and Ouham-Pendé. Reformulate.

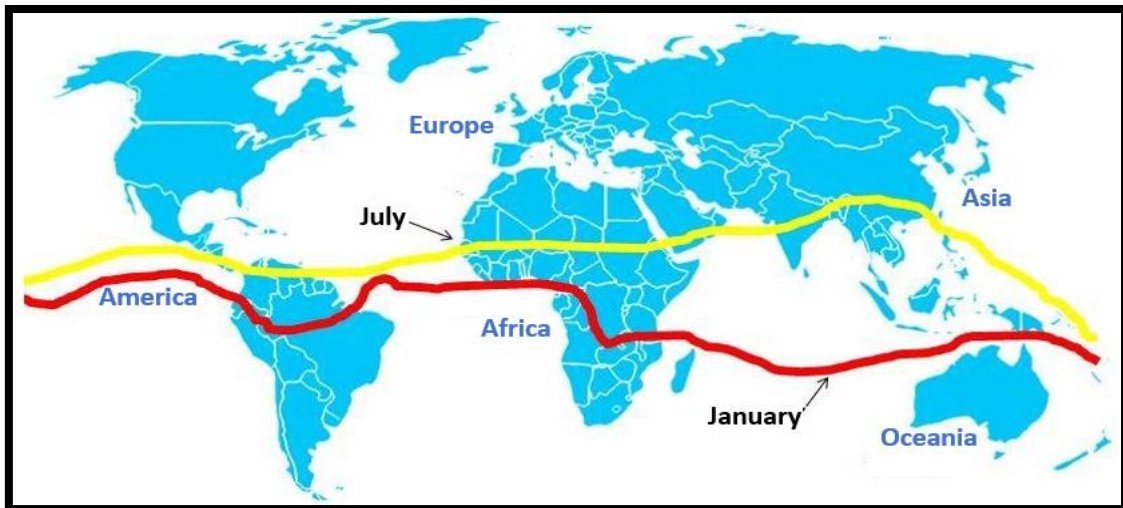


Figure 11: Annual position of the ITCZ. Source NASA

The majority of the Ombella Mpoko prefecture falls under the Tropical Savanna Climate Zone, characterized by distinct wet and dry seasons and warm temperatures. Some parts of the study area fall under the Equatorial Climate Zone, experiencing high temperatures and heavy rainfall throughout the year. According to the classification, the prevailing climate in this region is categorized as “Aw”. The higher elevations in the region may experience conditions similar to the Mountain Climate Zone, with cooler temperatures and higher rainfall (MARKU SKOTTEK et al., 2006; Beck H. E. et al., 2018).

### III.1.6.1.a Temperature

Temperature varies with elevation. Lower elevation areas tend to be temperate, while higher elevations are typically tropical or cold regions (CONWAY, 2000).

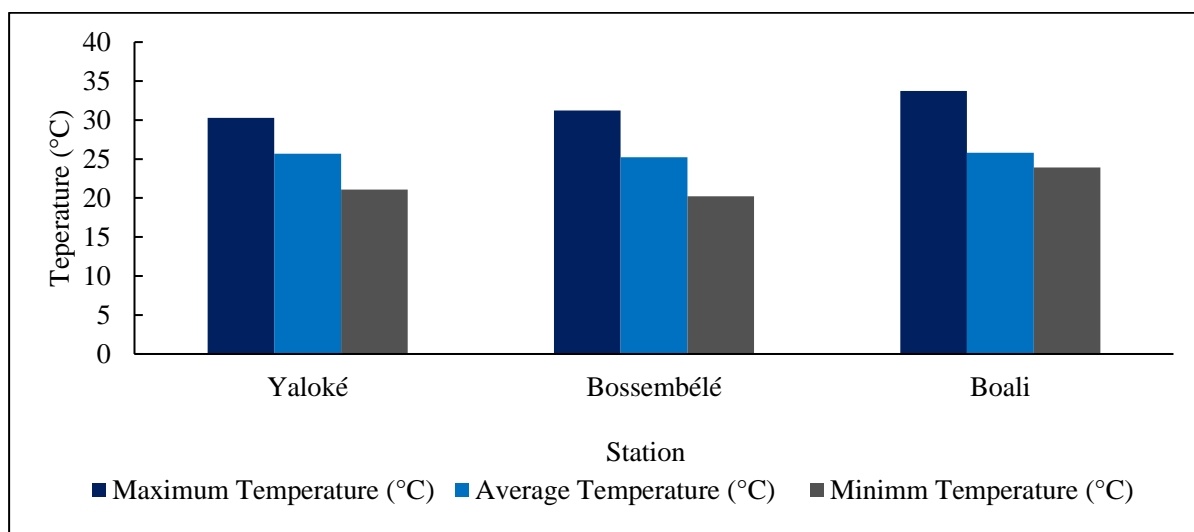


Figure 12: Mean daily observed maximum and minimum temperature data (1991-2021)

The findings from this thesis align with Conway's results. Stations at higher elevations recorded the lowest temperatures, whereas those at lower elevations recorded the highest minimum and maximum temperatures (refer to Table 1 for station elevations). On average, temperature decreases by 5.8°C for every 1000 meters of elevation (CONWAY, 2000).

The differences in minimum temperatures between the stations are lower than those in maximum temperatures. This indicates that the spatial variability of maximum temperatures is higher than that of minimum temperatures. All stations recorded their highest temperatures in February and March. The lowest temperatures were observed in July and August. For minimum temperatures, the highest values were recorded in May and July, while the lowest occurred in December, November, and January.

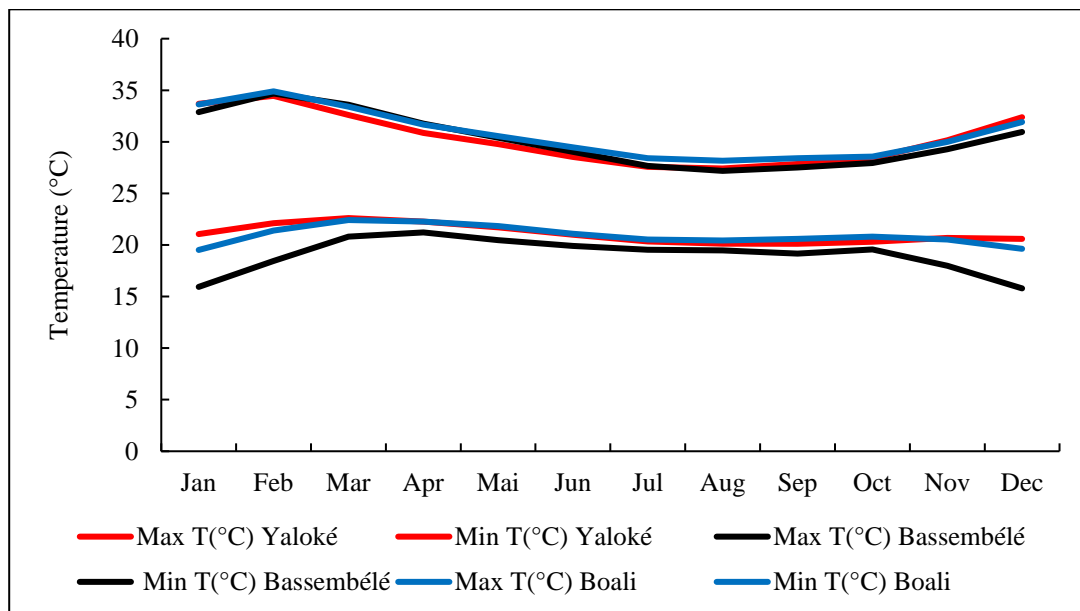


Figure 13: Mean monthly maximum and minimum temperature data

The region maintains warm temperatures throughout the year, with an average annual temperature of approximately 26.4°C. The hottest months typically occur between February and April, where temperatures can rise above 30°C. Conversely, the cooler months, from June to August, still experience warm temperatures, rarely dropping below 20°C.

### III.1.6.1.b Rainfall

Rainfall also in the M'bali region is varies spatially, temporally and highly seasonal. Areas located in lower elevations receive less rainfall, while regions at higher elevations tend to experience greater amounts of precipitation (CONWAY, 2000).

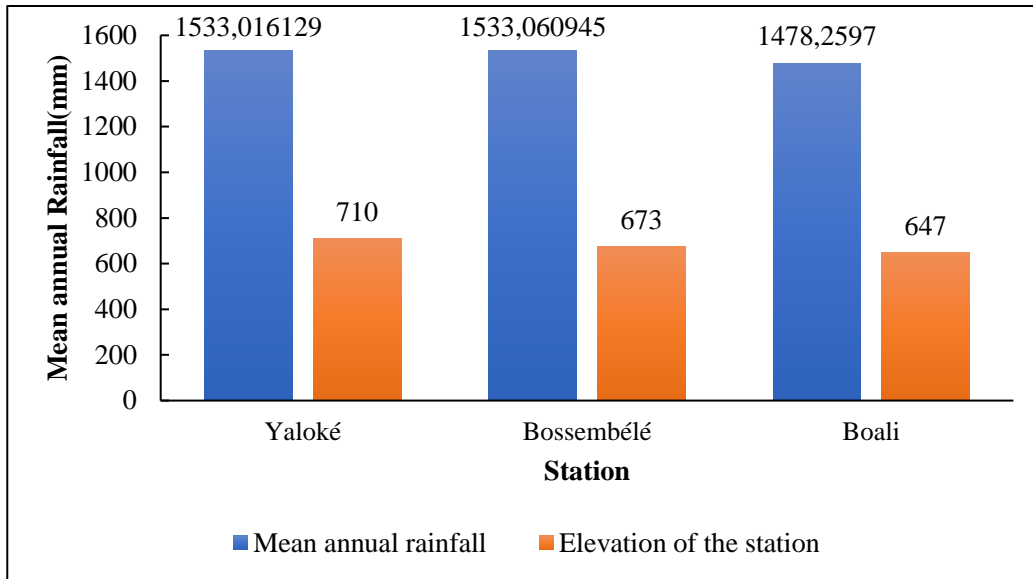


Figure 14: Mean annual rainfall and elevation of stations

Looking at Figure 11, it's clear that the rainfall at the stations isn't related to their elevation. For example, the rainfall in Yaloké does not differ significantly from that in Bossembélé, nor from that in Boali, despite an elevation difference of about 100 metres.

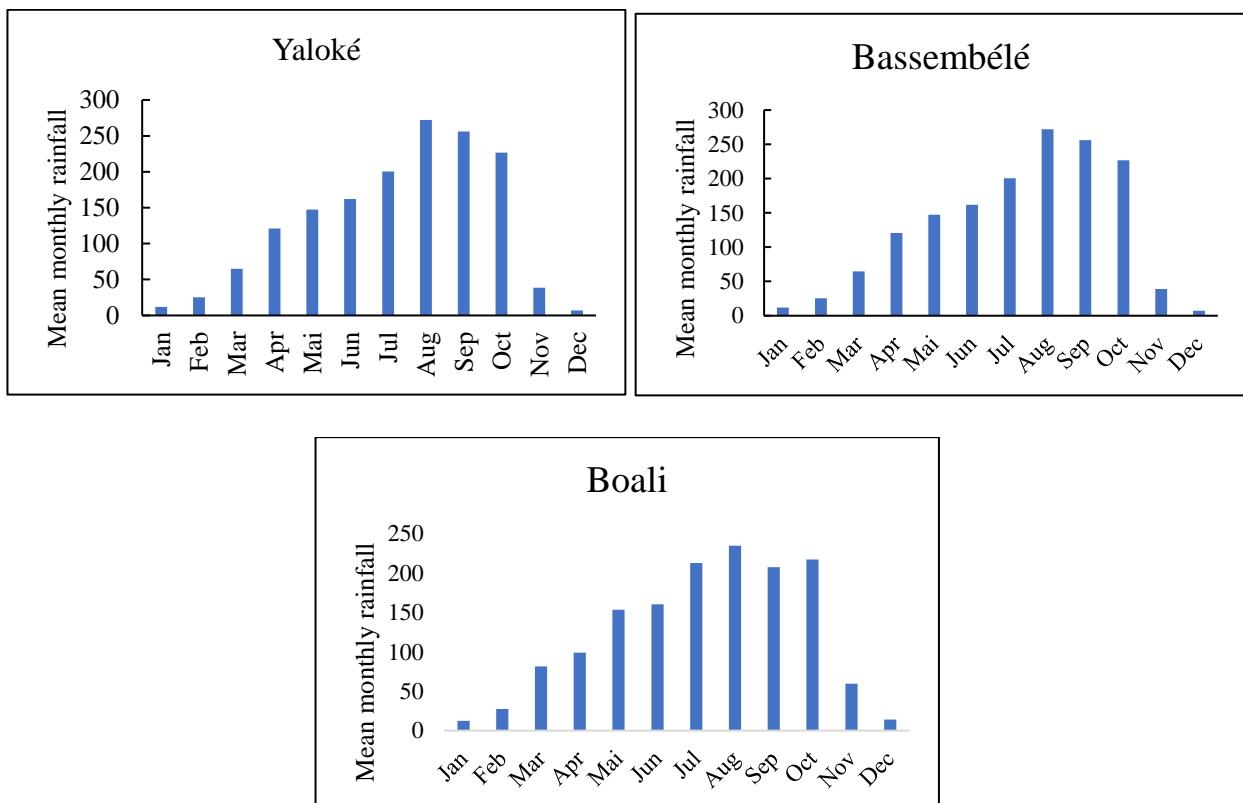


Figure 15: Distribution of mean monthly rainfall in different stations on the study area

This can be attributed to other factors such as temperature, wind speed, and direction.

Most part of the country receives a substantial amount of rainfall during the summer, particularly in July and August, according to reports from Central African meteorological studies. The average monthly rainfall distribution also shows a peak in August, indicating a variability in rainfall within the specific basin.

Studies conducted in the M'Bali sub-basin and the Ubangi basins, carried out by Conway (2000), Kebede et al. (2006), Sutcliffe and Parks (1999), and Tarekegn and Tadege (2005), indicate that the hydrological year of the studied areas is characterised by a main rainy season (summer) from June to September, during which 70% to 90% of the annual total rainfall occurs.

**III.1.6.1.c Seasonal Variations**

The M'Bali region, like much of the Central African Republic, experiences a transitional tropical climate, marked by distinct wet and dry seasons. The wet season, spanning from April to October with peak rainfall between July and September, averages around 1500 mm annually.

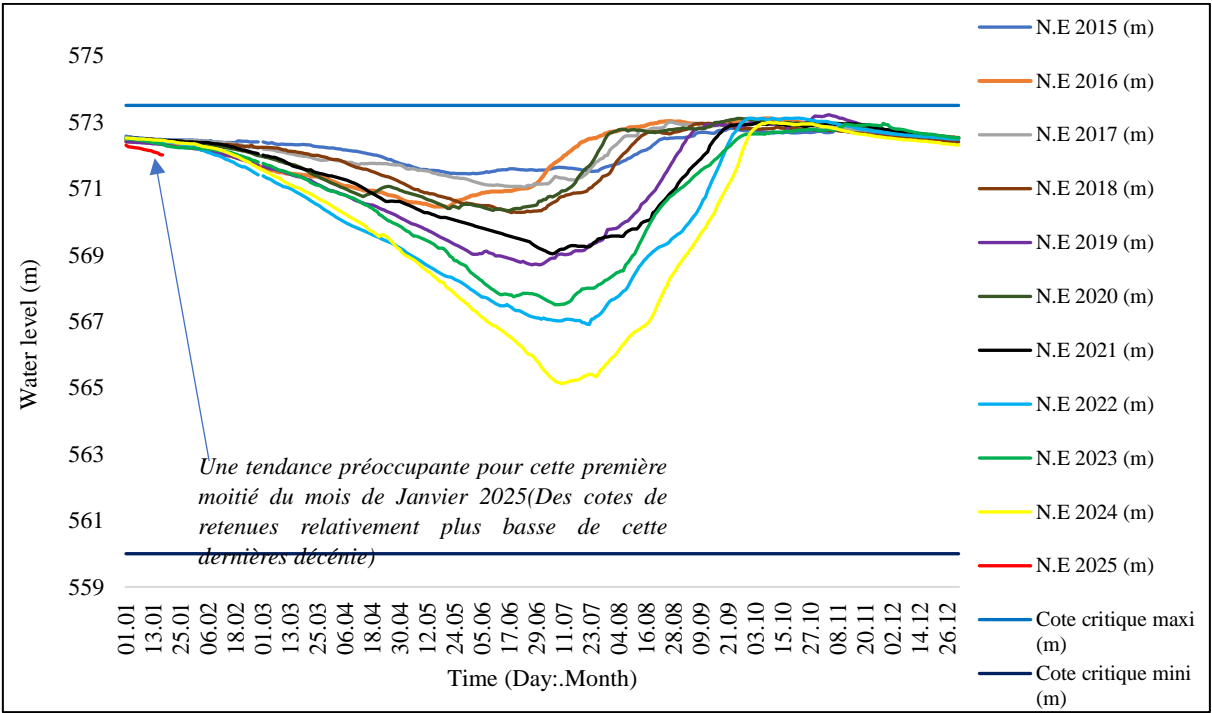


Figure 16: Observed water level variations between 2015 and 2025 demonstrate in Boali Dam

This period supports lush vegetation and replenishes water resources, which are crucial for agriculture and the supply of Lake M'bali, essential for the country’s hydroelectric production. Conversely, the dry season, from November to March, is characterised by a sharp decrease in precipitation and a rise in temperatures that can reach 34°C in some areas, leading to increased water stress and potentially compromising hydroelectric production due to the lake's lower

levels as is 2024 (See Fig. below). The region has experienced a concerning increase in the severity of dry seasons over the past decades, with temperatures consistently nearing 34.6°C, critically impacting reservoir levels. Compounding this issue, the General Directorate of Meteorology forecasts temperatures potentially reaching 35.6°C in 2025, posing a significant risk to future water resource availability.

**III.1.7 River Discharge Information**

The M'bali River, located in the Ombella Mpoko prefecture of the Central African Republic, plays a crucial role in the region's hydrology and ecology. River discharge, which refers to the volume of water flowing through the river per unit of time, is a key parameter for understanding the river's behavior and its impact on the surrounding environment. In line with the recommendations of Gordon et al. (1992), the initial step in river flow data analysis involved a quick visual inspection of the time series data to identify major errors such as incorrect flow peaks, missing records, and constant flows. The average daily flow of the M’Bali River was approximately 70,79m<sup>3</sup>/s

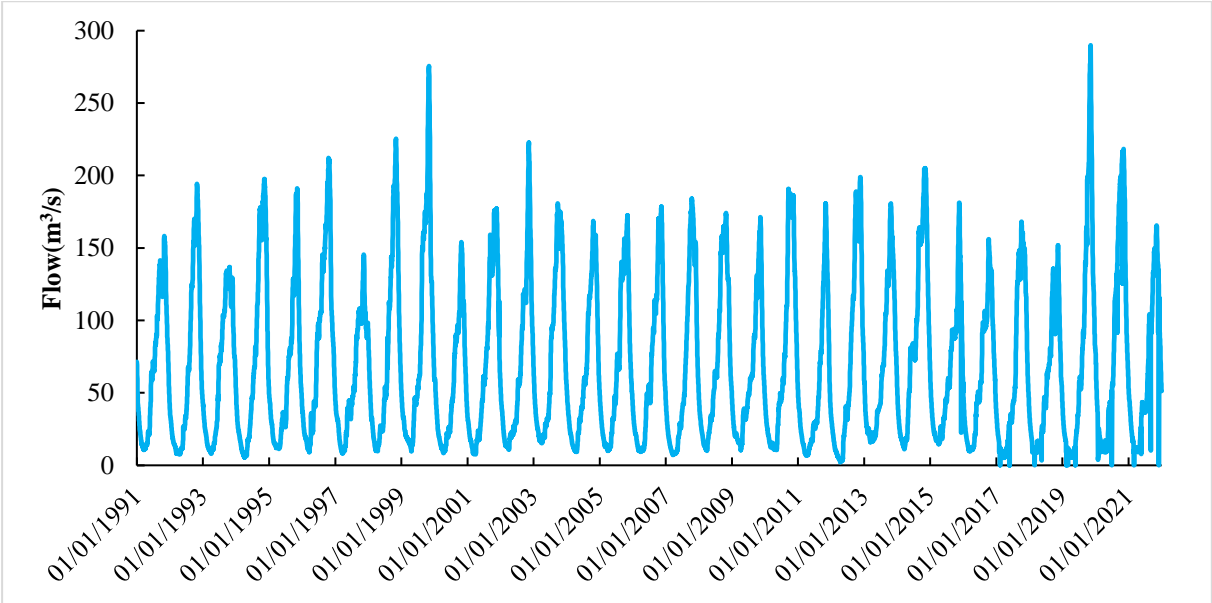


Figure 17: Daily stream flow of M'Bali River in Boali

The stream flow is directly influenced by the amount of precipitation received. The hydrological regime of the M'bali River is characterised by a significant increase in mean monthly flow from August, reaching its peak between September and November, in accordance with the wet season. Although the highest precipitation is recorded between August and October across all observation stations, the peak flow is slightly delayed. This temporal lag, attributable to hydrological response time, can be explained by a delay in the transfer of rainwater to the river network, as well as by the gradual reduction in water loss through infiltration and deep percolation during the season, which contributes to increased flow at the end of the season.

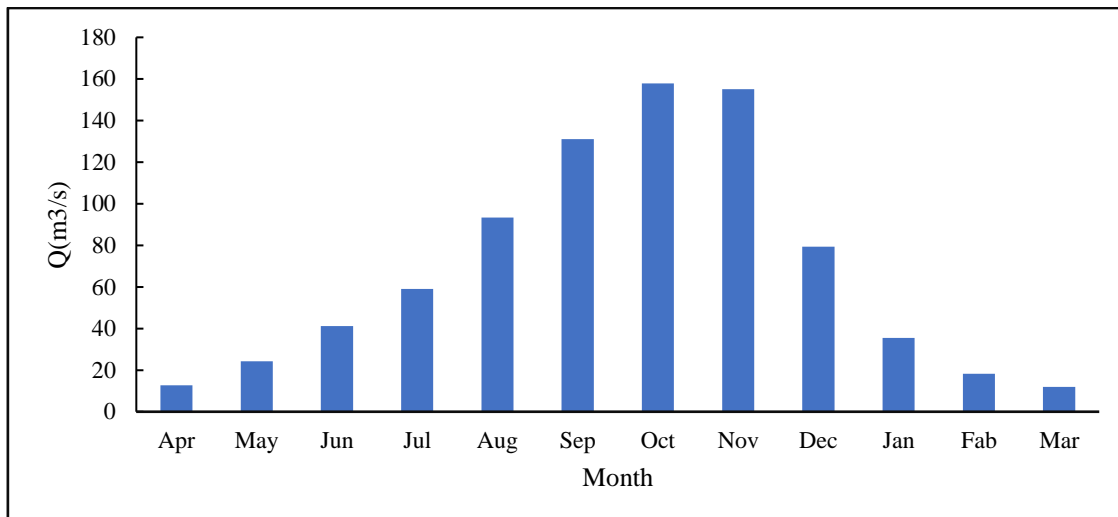


Figure 18: Monthly average discharge of M'Bali River

Indeed, the soil's water retention capacity plays a crucial role in this phenomenon, as soil saturated at the beginning of the season can limit subsequent infiltration, leading to increased runoff to the river, which results in high flows in August. It is also crucial to note that the period from July to August coincides with the recharge of the dam's reservoir, highlighting the importance of hydrological processes in the region's water resource management and their direct impact on the lake level and, by extension, on hydroelectric power generation.

## III.2 . Methodology and data availability

### III.2.1 General Methodology of the Study

This study aims to assess the potential impacts of climate change on hydroelectric production within the Southern Hydrographic Basin (BHS) through a rigorous methodological approach that combines numerical analysis with field investigations. The adopted methodology is based on three main pillars: climate data processing, analysis of hydro-climatic trends, and complementary field investigations.

For the collection and processing of climate data, we utilised outputs from regional climate models (RCMs) and global climate models (GCMs) concerning daily precipitation and temperature. A crucial step of bias correction was applied to enhance the reliability of the climate projections. The processed data facilitated the establishment of projections for three key time horizons: the mid-century (2026-2050), the third quarter of the century (2041-2075), and the end of the century (2076-2099). Two representative climate scenarios were selected for analysis: SSP2-4.5 (intermediate scenario) and SSP5-8.5 (high emissions scenario).

The analysis of climatic and hydrological trends relied on robust statistical methods. Mann-Kendall tests and linear regressions were employed to identify significant trends in precipitation and temperature data.

Complementing this numerical approach, comprehensive field investigations were conducted. Several missions were undertaken to collect in situ data, including flow measurements and local observations of climate change impacts. Interviews with dam managers and local communities provided valuable insights into hydrological changes. These field data were contrasted with an extensive literature review, encompassing an analysis of previous technical reports, hydrological studies, and local meteorological archives.

This methodology presents several advantages, as well as certain limitations. The integration of numerical and field approaches allows for cross-validation of results, while the selection of scenarios covers a realistic range of possible climate developments. However, some uncertainties persist, particularly concerning the modelling of precipitation in tropical regions and the occasionally limited availability of high-quality historical hydrological data. These factors will be considered in the interpretation of results and the final recommendations for adaptation strategies.

### **III.3 Assessment of Precipitation and Temperature Trends**

The analysis of precipitation and temperature trends involved the collection of rainfall and temperature data from 1991 to 2021 across three sites within the study area. For temperature, the minimum, maximum, and average monthly and annual temperatures were computed and plotted over time, enabling the observation and analysis of the resulting trends. Similarly, the mean monthly and annual precipitation data gathered from various rainfall stations in the area were plotted against time to assess the precipitation trends. These trends in both precipitation and temperature served as indicators of climate change in the M'bali River basin.

### **III.4 Analysis of the M'Bali River Flow Regime**

The natural flow of a river exhibits variations across different time scales, including hours, days, seasons, years, and decades. To accurately characterise the flow pattern of a river, it is typically necessary to gather extensive observational data from a streamflow gauge over many years. For this study, 31 years of discharge data for the M'Bali river were sourced from the General Meteorological Directorate(DGM) in Bangui.

The analysis focused on changes in flow throughout this 31-year period, with discharge trends

being plotted accordingly. To assess the variations in the river flow regime over these three decades, the study period was segmented into three 10-year intervals, starting from 1991 and concluding in 2021. The flow regimes of various streams within the watershed were identified, allowing for the establishment of a general trend in streamflow over the study duration. Additionally, the average flow and the minimum peak flow were calculated. The QGIS software was utilized for the analysis of catchment characteristics.

**III.5 Relationship Between River Flow Regime and Hydropower Production**

As mentioned above, data on hydropower production from 2010 to 2017, along with reservoir levels from 1991 to 2021, were obtained from ENERCA. A trend in hydropower production over this period was also established. Changes in water resource availability were converted and linked to variations in hydropower output. Runoff is regarded as the primary limiting factor for hydropower generation. Generally, runoff is defined as the difference between precipitation and evaporation over extended periods.

The analysis methodology is based on the understanding that hydropower generation is a function of flow (Q, in m<sup>3</sup>/s), head (H, in m), and efficiencies.

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot H \dots \dots \dots 3.1$$

where:

*P = Power generated (in watts), η = System efficiency, ρ = Density of water (in kg/m<sup>3</sup>), g = Acceleration due to gravity (in m/s<sup>2</sup>), Q = Flow rate (in m<sup>3</sup>/s), H = Head (in meters)*

It is assumed that future changes in water resources will significantly affect hydropower generation, with flow being the most variable element. The approach posits that the current hydropower generation capacity is primarily constrained by water availability. The key assumption is that a persistent reduction in water supply will lead to a corresponding decrease in hydropower output, and vice versa, provided that the existing systems can be upgraded.

In this context, changes in annual and monthly mean flows serve as the main indicators of hydropower generation. A relationship will subsequently be established between hydropower output and trends in stream flow.

Assuming that changes in water resources will affect future hydropower output, the most variable factor will be the flow. This approach suggests that the current hydropower production system may be constrained by water availability. The main assumption is that if water supply

persistently decreases, the output of hydropower systems will also decline on a long term, and vice versa, provided that existing systems can be upgraded. In this context, variations in annual and monthly mean flows are considered key indicators of hydropower generation. Consequently, a relationship will be established between hydropower production and river flow trends.

### **III.5.1 Discharge Versus Hydropower Generation Analysis**

Hydropower technology enables the conversion of approximately 90% of the kinetic energy from flowing water into electricity. To produce one kilowatt of electricity, a flow rate of about 4000 litres per second is required, assuming a vertical elevation difference of 100 meters. Since hydropower generation necessitates a continuous water flow with minimal sedimentation, the construction of large dams is often essential, particularly on rivers that experience significant flow fluctuations. The reservoirs formed by damming rivers help regulate the river flow and also act as sediment settling tanks. Additionally, building a dam across a river alters the downstream flow regime and impacts water quality.

Generally, high amounts of precipitation in an area leads to high stream flow rates and consequently higher hydropower generation since the reservoirs will be constantly full of water, and therefore the channel flow and the power production will be positively correlated. However, deviations from these expectations do occur and are usually attributed to changing climate and activities upstream the dam, including land use practices, that lead to poor vegetation cover and hence accelerated runoff or reduced flows due to diversion of water to other point uses such as irrigation.

### **III.6 Assessment of Future Climate Scenarios and Their Implications for Hydropower Generation**

Future climate conditions in the M'Bali River basin were analyzed using SSP2 (Middle of the Road) and SSP5 (Fossil-Fueled Development) scenarios. These scenarios provide quantitative assessments of climate change impacts, representing plausible future conditions based on different socioeconomic and emission pathways (Andrea J. Ray, 2007; Qin D. et al., 2007).

Key factors such as soil properties, land use, and slope characteristics were examined to understand their role in hydrological responses under changing climate conditions. The study evaluates how projected shifts in precipitation and temperature under SSP2 and SSP5 may influence water availability and hydropower generation potential in the basin.

General Circulation Models (GCMs) are currently the most advanced tools for simulating the response of the global climate system to changes in atmospheric composition. Generally, a GCM serves as a numerical representation of atmospheric phenomena across the Earth, incorporating various fluid dynamics, chemical, and even biological equations (Andrea J. Ray, 2007). GCMs are run using different climate change scenarios and yield outputs in the form of annual and seasonal averages, which help identify likely changes in precipitation, temperature, and runoff resulting from these scenarios.

Climate models and scenarios were selected to produce projections of future climate change in the study area. Relevant models and scenarios were identified through a literature review. These models were then employed to create future climate ensembles based on emission scenarios from the Special Report on Emission Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC). According to Mango et al. (2010), GCMs predict climate change, and thus, downscaling approaches should be applied when assessing the climate impacts on smaller basins. Downscaling is a method that connects large-scale atmospheric predictor variables with local or site-specific meteorological data (Mango et al., 2010). Consequently, future climate projections must be spatially downscaled from low-resolution GCMs to a scale suitable for watershed-level analysis.

### **III.6.1 Data Acquisition**

#### **III.6.1.1 Historical Climate Data**

The requisite meteorological data encompassed precipitation, maximum and minimum temperatures, wind speed, relative humidity, and solar radiation. Primary data were sourced from the General Directorate of Meteorology and the Agency for the Safety of Air Navigation in Africa and Madagascar, located in Bangui. This data was instrumental in the Microsoft Excel and in the correction of biases within the projected datasets.

However, only the Bossembélé and Boali stations, situated mid-stream and downstream of the watershed, respectively, provided data of sufficient quality and quantity. Reliance on data from these two incomplete stations did not adequately represent the topographical diversity of the study area. To mitigate this limitation, supplementary data were acquired through NASA Power, an online platform that offers access to high-resolution climatic and environmental datasets.

Bossembélé and Boali were the sole primary stations that provided information on wind, relative humidity, and sunshine hours. The selection of representative meteorological stations was contingent upon the availability of essential climatic variables, the duration of the recording

period, the distance from the watershed, as well as the chosen reference period for analysing both the current and future climate, in conjunction with the duration of historical model outputs.

Furthermore, none of the selected stations possessed a complete dataset. Among them, only Bossembélé and Boali supplied reference temperature and precipitation data from 1991 to 2021. Relying exclusively on these two stations failed to deliver a comprehensive representation of the entire area due to the aforementioned topographical diversity. Consequently, to reduce uncertainties in future streamflow projections, it became imperative to diversify the selected stations and the RCM data. As a result, the average aerial precipitation method was employed to generate precipitation data for the Yaloké station, which has only been collecting precipitation data since 1991. Additionally, information on daily temperatures (maximum and minimum) for the Yaloké region, considered as the upstream station for our study area, was sourced from international institution such as the NASA Power. These data were also extracted from online databases, including ERA5 Land, due to the absence of synoptic stations in this area.

*Table 2: Data availability for this study*

| Station    | Climate data |      |                             | Data availability |
|------------|--------------|------|-----------------------------|-------------------|
|            | RF           | Temp | Wind, RH,<br>Sunshine hours | Year              |
| Boali      | X            | X    | X                           | 1991-2021         |
| Bossembélé | X            | X    | X                           | 1991-2021         |
| Yaloké     | X            | -    | -                           | 1991-2020         |

*RF: Rainfall; Temp: Temperature; RH: Relative Humidity*

*Rainfall and temperature data from 1991 to 2021 were utilised for SWAT modelling, while data from 1986 to 2010 were employed as the baseline period for streamflow generation.*

### **III.6.1.2 Spatial Data**

The hydrological analysis utilizes three key spatial datasets: (1) A 30m-resolution Digital Elevation Model (DEM) from the online tool provided by the United States Geological Survey (USGS Earth Explorer) (<https://earthexplorer.usgs.gov/>) for watershed delineation and terrain analysis, (2) Similarly, the land use map with a resolution of 10 meters for the year 2021 was obtained from the European Space Agency (ESA World Cover) website at (<https://viewer.esa-worldcover.org/>) for characterizing surface conditions, and (3) The FAO

Soil Database Program (<https://www.fao.org/soils-portal/en/>) was utilized to acquire the FAO's 1:5,000,000 scale soil data for hydrological properties. Following the downloads, all these data were processed using QGIS version 3.34.6 to generate the maps corresponding to our study area:

- Watershed boundaries and sub-basin divisions
- Drainage networks and flow accumulation patterns
- Composite land-soil units for hydrological characterization

**III.6.1.3 Hydrological Data**

Daily streamflow records (1991-2021) were reconstructed for the M'Bali outlet using:

- Stage-discharge relationships from Bangui station
- Hydrological scaling methods accounting for catchment area differences
- Cross-validation with precipitation-runoff correlations
- 

**III.6.1.4 Hydrological Data:**

Due to the absence of daily flow data (covering our study period from 1991 to 2021) at the outlet of the M'Bali, we reconstructed these data (the daily flows) using measurements from the hydrological station in Bangui. This reconstruction is based on the assumption that the specific discharge remains constant between the study area and Bangui, in accordance with the following formula (Cyriaque-Rufin Nguimalet' et al., 2022).

$$q = Q * \left(\frac{a}{A}\right)^{1,8} \dots \dots \dots 3.1$$

where:

- *q*: Discharge (or flow) of the sub-basin, expressed in cubic meters per second (m<sup>3</sup>/s).
- *Q*: Observed discharge of the main catchment, also expressed in cubic meters per second (m<sup>3</sup>/s).
- *A*: Area of the main catchment, expressed in square kilometers (km<sup>2</sup>).
- *a*: Area of the sub-basin, expressed in square kilometers (km<sup>2</sup>).

This formula is used to estimate the discharge of a sub-basin based on the discharge of a larger basin, taking into account the difference in surface area between the two.

**III.6.1.5 Boali Hydropower Station Data:**

Historical power generation data (e.g., Megawatt-hours) and the technical specifications of the Boali Hydropower Station like the daily water level in the reservoir from 1991 to 2021 were

acquired from the Boali Hydropower Station Authority and In the Directorate of Production and Transport (DPT) of Central African Energy in Bangui (ENECA) at Bangui respectively.

### **III.6.2 Data Quality Verification**

Research conducted by engineers, climatologists, and hydrologists on the impacts of climate change on water resources, as well as their development and management, primarily relies on meteorological and hydrological data. Certain essential data, at an acceptable level, may be lost for various reasons, such as instrument malfunctions or the absence of recordings due to different circumstances. Therefore, filling in missing data should be an integral part of the research process. However, obtaining accurate results is not solely dependent on the completion of missing data. Numerous errors can also occur in the recorded data during the processes of reading, coding, management, and so forth. According to hydrological principles, the data used for frequency analysis and hydrological modelling must be stationary, consistent, homogeneous, and free from trends ([Gebremichael, 2014](#)) A quality check of the data was conducted for precipitation, temperature, and streamflow data based on their availability.

#### **III.6.2.1 Filling Missing Data**

The occurrence of missing data in climate and hydrology is common and poses significant challenges, as it can introduce bias into study results. Regardless of how well a system is designed, the professionalism of the recorder, or the accuracy of the measuring instruments, gaps in meteorological and hydrological data can still arise. It is essential to fill in these missing data when conducting analyses of hydrological basins that require continuous time series data ([Goosse H. et al., 2010](#))

The main issue lies in determining how to handle the missing data, as it is impossible to recover the actual values that are absent. Researchers in hydrology and related fields often face the dilemma of selecting appropriate techniques for managing these gaps. Missing data can adversely affect the validity and reliability of results ([McKnight P. E. et al., 2007](#)). Furthermore, employing inaccurate methods for filling in missing data can also lead to problems concerning the accuracy of outcomes. To conduct effective analyses and simulations using long time series data, it is crucial to address this issue with an accepted method for filling in missing data.

Various methods are employed to fill in missing values, depending on the extent of the missing data. Common techniques include the arithmetic mean, normal ratio, regression, and distance

power methods. The choice of an appropriate method depends on several factors, such as simplicity, the length of the missing data, and accuracy. When missing data exceeds 10% at monitoring stations, the normal ratio method, which is familiar to users, is often utilized for this study. The relevant equation is:

$$P_X = \frac{N_x}{n} \left( \frac{P_1}{N_1} + \frac{P_2}{N_2} + \frac{P_3}{N_3} + \dots + \frac{P_n}{N_n} \right) \dots\dots\dots 3.2$$

*Where:  $P_x$  : value of missing data and  $N_x$  : normal precipitation of station in question ;  $P_1$ ,  $P_2$ ,  $P_3$  and  $P_n$  : recorded precipitation values of the nearest stations 1, 2, 3 and nth stations, respectively, for an observation station; and  $N_1$ ,  $N_2$ ,  $N_3$  and  $N_n$  are normal precipitation of 1, 2,3 and nth stations, respectively.*

Missing rainfall and temperature data were filled based on the data availability.

**III.6.2.2 Data Homogeneity and Consistency Test**

Conducting a homogeneity test is highly recommended to ensure reliable results. For various reasons, data from stations and gauges may exhibit heterogeneity. It is crucial to statistically assess the quality and reliability of the data used in modelling hydrological processes and water resource management. The outcome of this test results in a "decision": either the null hypothesis ( $H_0$ ) is rejected, indicating data heterogeneity, or it is accepted, signifying data homogeneity. Rejecting the null hypothesis implies acceptance of the alternative hypothesis, which suggests a change in the data at some point or heterogeneity within the time series. In this regard, Pettitt's test, developed by Alexandersson in 1986 to detect changes in rainfall data series, was utilized. The rainfall, temperature, and streamflow data were subjected to a homogeneity analysis based on the available data.

Moreover, it is essential that time series of hydro-meteorological data are consistent, particularly when periodic data are proportional to an appropriate simultaneous time series (Ruml M. et al., 2012) Double mass curve analysis is regarded as a fundamental tool for checking the consistency of hydrological and meteorological data records. In this study, the consistency of rainfall data was carefully examined.

**III.6.2.3 Trend Test of Hydro-Meteorological Data**

The non-parametric tests established by Mann (1945) and Kendall (1970) were employed to investigate whether trends exist in the data intended for this analysis. As the calculated p-value exceeds the significance level of  $\alpha = 0.05$ , we cannot reject the null hypothesis ( $H_0$ ). The outcome of the test leads to a decision: either  $H_0$  is accepted or rejected. Rejecting  $H_0$  implies

accepting the alternative hypothesis, indicating the presence of a trend in the time series data (Arun M. et al., 2012).

The p-value is computed using either an exact one-tailed or two-tailed method. Each data point is compared with all subsequent values. If a later value is higher than an earlier one, the statistic S is increased by 1. Conversely, if a later value is lower than an earlier one, S is decreased by 1. The final value of S is determined by the net result of these increases and decreases.

Mann-Kendall S Statistics is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{Sign}(x_j - x_i) \dots \dots \dots 3.3$$

$$\text{Sign}(x_j - x_i) = \begin{cases} 1 & \text{if } x_j - x_i > 1 \\ 0 & \text{if } x_j - x_i = 1 \\ -1 & \text{if } x_j - x_i < 1 \end{cases}$$

A positive and negative value of S indicates an upward and downward trend respectively (Arun M. et al., 2012).

Variance of the data is computing by using the following formula.

$$E(S) = 0, \text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(i-1)(2i+5)}{18} \dots \dots \dots 3.4$$

Where:  $t_i$  is considered as number of ties up to sample  $i$ .

We used Addinsoft's XLSTAT2016 and Python as software for performing statistical Mann-Kendall test for this study.

### III.6.3 General Circulation Models (GCM)

The data from GCMs are based on relatively coarse information regarding the atmosphere, oceans, and land surfaces (Scher et al, 2019). Due to the use of these imprecise data, the model outputs are also not very detailed. However, to accurately project future climate changes, it is essential to utilise higher resolution data or model results. The use of GCM data impacts the accuracy of climate predictions at local or catchment levels. The precision of GCMs has improved from their first generation to the current fifth generation. Downscaling techniques are commonly employed to correct errors in the model data. This approach allows for the extraction of fine-scale information from GCM or RCM outputs, as well as smaller-scale climate results that arise from the interaction between global climate and local physiographic features (Randall, 2000).

### III.6.4 Climate Change Scenario Projection Data

The data for the Shared Socioeconomic Pathways SSP2-4.5 and SSP5-8.5, which include maximum and minimum temperatures as well as mean precipitation and Evapotranspiration for future periods (2022-2099), were sourced from the Copernicus data portal. This NetCDF data was derived from several General Circulation Models (GCMs), including ACCESS-CM2, CNRM-ESM2-1, and MPI-ESM1-2-LR, and was utilised for this study. These NetCDF data were extracted using Arcmap software. To ensure that these SSPs data matched the specific scale of the M'Bali region, statistical downscaling techniques were employed using Microsoft Excel. This approach allowed for a more accurate representation of climate variables pertinent to the local context.

**III.6.5 Bias Correction**

Although the climate change projection dataset for the M'Bali Basin offers a finer resolution, it is essential to perform further bias correction using observed data from the nearest meteorological stations. Discrepancies have been noted when comparing historical model data with observed values. This requirement arises from the high spatial variability of climate variables, particularly precipitation, which necessitates adjustment to achieve reliable results. Consequently, the precipitation and temperature data were downscaled to the station level through bias correction methods. (Sorbe et al., 2023).

Various techniques exist for bias correction in hydrological studies, including linear scaling, power transformation, variance scaling, and quantile mapping. For this study, the corrected precipitation and temperature values, denoted as  $P_{corrected}$  and  $T_{corrected}$ , are obtained by applying the Delta Change Relative (DCR) adjustment to the model's projections. Using the DCR formula, the corrected values are calculated as follows (Teutschbein, 2012):

$$P_{corrected} = P_{RCM} * \left( 1 + \frac{P_{RCM} - P_{observed}}{P_{observed}} \right) \dots\dots\dots 3.7$$

$$T_{corrected} = T_{RCM} * \left( 1 + \frac{T_{RCM} - T_{observed}}{T_{observed}} \right) \dots\dots\dots 3.7$$

*Where:  $P_{RCM}$  and  $T_{RCM}$  are the model's projected values for precipitation and temperature.  $P_{observed}$  and  $T_{observed}$  are the observed values for precipitation and temperature from the nearest meteorological stations.*

These corrected values are then used in further analysis, ensuring that the projections better align with actual observed conditions.

### III.7 The Random Forest Model

The Random Forest model, developed by Breiman (2001), is a robust and widely used ensemble machine learning algorithm recognised for its superior predictive performance and ability to manage complex, non-linear relationships between variables. In hydrological and climatic studies, the Random Forest model is especially beneficial due to its resilience against overfitting, high accuracy, and inherent capacity to handle numerous predictor variables and their interactions simultaneously (Tyrallis et al., 2019). This makes it particularly suitable for forecasting hydropower generation under varying climate conditions, as demonstrated in multiple hydrological modelling studies (Chen et al., 2021). Its capability to provide insights through variable importance measures further enhances the interpretability of complex environmental datasets, contributing significantly to informed decision-making processes in climate change adaptation planning (Prasad et al., 2020).

### III.8 Impacts of Climate Change on electricity generation at the Boali Hydropower Station

To assess the potential impacts of climate change on electricity generation at the Boali Hydroelectric Power Plant, a methodology incorporating climate model data, the Random Forest algorithm, and socio-economic scenarios was used. Key variables included temperature (Tmax, Tmin), precipitation (Prec), evapotranspiration (ETp), and electricity generation (Elec Gen) as the dependent variable. The Random Forest algorithm was selected for its ability to model complex, non-linear relationships. The dataset was pre-processed through data cleaning and feature scaling, then divided into training (80%) and test (20%) sets. After training, future conditions were projected under SSP2 and SSP5 scenarios from 2022 to 2099. Model performance was assessed using Mean Squared Error (MSE) and R<sup>2</sup>. However, a major challenge was the insufficient electricity production data, which limited the accuracy of the model. Despite this, the methodology provided useful insights into the potential impacts of climate change, highlighting the need for more comprehensive data in future studies.

### III.9 Materials Used

Table 3: Material used for this study

| No | Tools       | Purpose                                                                                        |
|----|-------------|------------------------------------------------------------------------------------------------|
| 1  | QGIS 3.34.6 | Geo-referencing, rectification, and other various spatial analysis                             |
| 2  | XLSTAT2016  | For data quality testing (Homogeneity test and trend analysis) of meteorological and flow data |

|   |                     |                                                                                                                                              |
|---|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| 3 | Google Earth Pro.   | Helps to cross check the recorded coordinates of the metrological and gauge stations, to cross check the land use features of the study area |
| 4 | Microsoft Word      | used to Write and insert biography and references                                                                                            |
| 5 | Python              |                                                                                                                                              |
|   | Random Forest Model |                                                                                                                                              |
|   | Microsoft Excel     | For downscaling and Bias Corrections                                                                                                         |

## CHAPTER FOUR: RESULTS AND DISCUSSION

### IV.1 Temperature and Precipitation Trends from 1991 to 2021

This section examines key climate change indicators and their effects on hydropower generation, specifically focusing on the Boali Dam reservoir. The table below summarizes data on the maximum, minimum, and mean annual temperatures within the catchment area, measured in degrees Celsius, along with the average annual rainfall intensity expressed in millimetres. Additionally, it includes the inflow to the reservoir from upstream rivers, quantified in cubic metres per second. These metrics provide a comprehensive overview of climatic trends over a 31-year period and their relevance to hydropower production.

*Table 4: Hydrometeorological data of M'Bali catchment*

| Year | Annual Mean Minimum Temperature (°C) | Annual Mean Maximum Temperature (°C) | Annual Mean Temperature (°C) | Annual total Precipitation (mm) | Mean Annual Discharge (m3/s) |
|------|--------------------------------------|--------------------------------------|------------------------------|---------------------------------|------------------------------|
| 1991 | 19,2                                 | 31,3                                 | 25,3                         | 1508,0                          | 68,5                         |
| 1992 | 18,1                                 | 31,2                                 | 24,7                         | 1444,6                          | 66,0                         |
| 1993 | 18,7                                 | 28,7                                 | 23,7                         | 1571,5                          | 63,6                         |
| 1994 | 19,0                                 | 31,5                                 | 25,2                         | 1499,5                          | 74,2                         |
| 1995 | 18,7                                 | 31,7                                 | 25,2                         | 1588,2                          | 61,7                         |
| 1996 | 19,2                                 | 31,5                                 | 25,3                         | 1547,5                          | 84,1                         |
| 1997 | 19,0                                 | 31,2                                 | 25,1                         | 1480,3                          | 58,5                         |
| 1998 | 19,7                                 | 32,3                                 | 26,0                         | 1759,7                          | 77,4                         |
| 1999 | 19,2                                 | 31,1                                 | 25,2                         | 1784,6                          | 85,1                         |
| 2000 | 18,8                                 | 32,0                                 | 25,4                         | 1231,2                          | 55,0                         |
| 2001 | 18,9                                 | 31,6                                 | 25,3                         | 1482,0                          | 71,5                         |
| 2002 | 18,9                                 | 31,8                                 | 25,3                         | 1333,5                          | 68,4                         |

|      |      |      |      |        |      |
|------|------|------|------|--------|------|
| 2003 | 19,4 | 31,5 | 25,5 | 1495,7 | 76,6 |
| 2004 | 19,1 | 31,7 | 25,4 | 1379,9 | 65,4 |
| 2005 | 19,4 | 31,8 | 25,6 | 1497,9 | 66,0 |
| 2006 | 17,7 | 31,6 | 24,6 | 1570,6 | 65,3 |
| 2007 | 18,0 | 31,8 | 24,9 | 1576,0 | 65,3 |
| 2008 | 18,8 | 31,4 | 25,1 | 1425,4 | 72,0 |
| 2009 | 19,9 | 31,5 | 25,7 | 1486,6 | 61,2 |
| 2010 | 20,0 | 31,5 | 25,7 | 1739,4 | 73,2 |
| 2011 | 19,0 | 31,0 | 25,0 | 1507,8 | 52,2 |
| 2012 | 20,0 | 30,8 | 25,4 | 1592,4 | 69,3 |
| 2013 | 20,9 | 32,1 | 26,5 | 1721,7 | 69,7 |
| 2014 | 20,4 | 32,6 | 26,5 | 1436,9 | 87,8 |
| 2015 | 19,4 | 32,6 | 26,0 | 1411,9 | 60,8 |
| 2016 | 21,9 | 34,7 | 28,3 | 1561,9 | 60,6 |
| 2017 | 20,7 | 34,7 | 27,7 | 1520,7 | 62,9 |
| 2018 | 20,9 | 32,6 | 26,8 | 1354,0 | 57,4 |
| 2019 | 20,7 | 34,7 | 27,7 | 1560,3 | 84,4 |
| 2020 | 20,6 | 34,8 | 27,7 | 1284,4 | 82,2 |
| 2021 | 20,9 | 34,9 | 27,9 | 1618,6 | 62,9 |

#### IV.1.1 Temperature Trends

Over the past thirty years, both monthly and annual average temperatures in the M'Bali catchment have shown an upward trend. According to Table 4.1, the trends in annual maximum and minimum temperatures indicate increases of 0,1091°C and 0,077°C, respectively, between 1991 and 2021 (see Figures 4.1 and 4.2).

Table 4.1 also reveals a decadal increase in the mean annual temperature of 0,0929°C, as illustrated in Figure 3.3. If this trend continues, it is anticipated that there could be a rise of 0,9~1°C in average temperatures over the next 100 years. The increase in temperatures within the M'Bali catchment is a complex phenomenon resulting from both natural processes and human activities.

It is important to emphasize that this rise in temperatures will inevitably lead to higher surface evaporation rates, thereby reducing the availability of surface water and altering soil moisture levels. According to research by Arnel and Reynard (1993), potential evapotranspiration simulations suggest that temperature increases alone could result in an over 10% rise in evapotranspiration in England and Wales by 2050 (Singh et al., 2023).

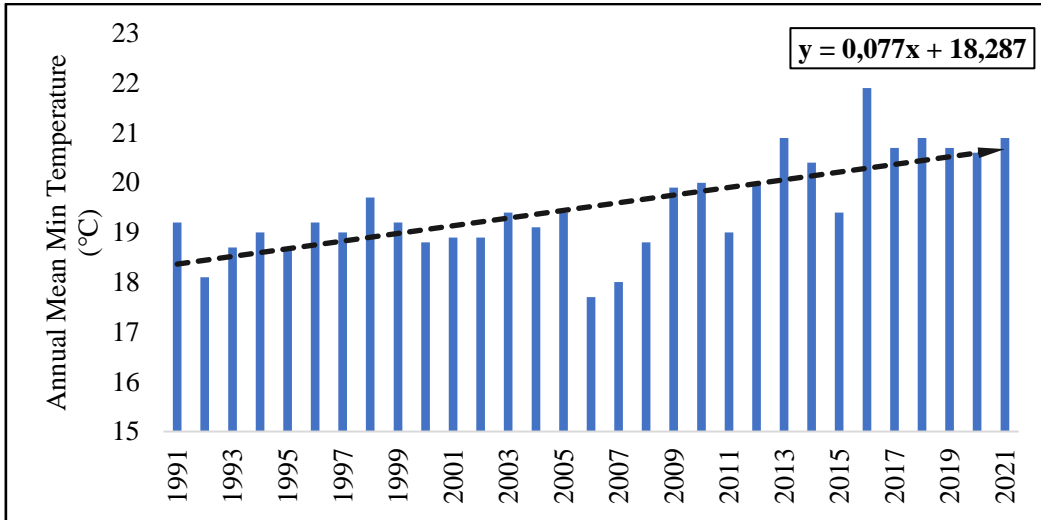


Figure 19 : Annual Mean Minimum Temperatures in M'Bali catchment

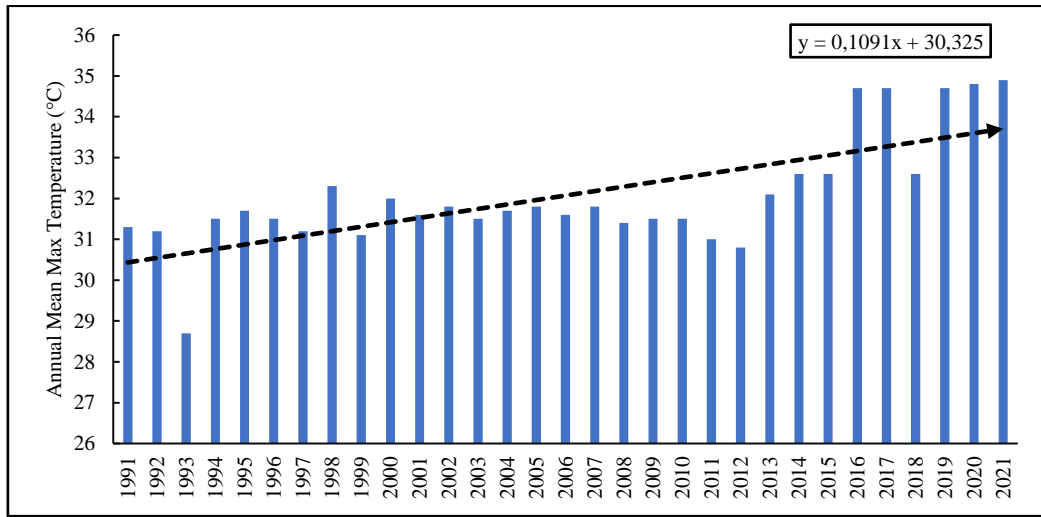


Figure 20: Annual Mean Maximum Temperatures in M'Bali Catchment

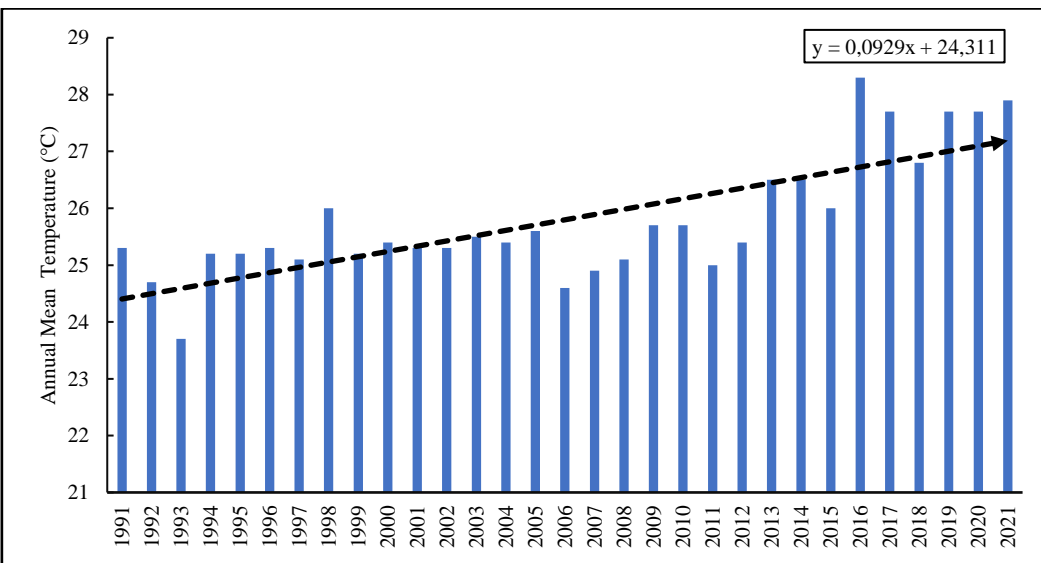


Figure 21: Mean Annual Temperatures in M'Bali Catchment

### IV.1.2 Precipitation Trends

The intensity and distribution of precipitation play a crucial role in the hydrology of a catchment area. Records of average annual precipitation for the M'Bali basin, derived from weather stations in Yaloké, Bossembélé, and Boali, indicate a consistent and gradual decline in rainfall from 1991 to 2021. This decrease in precipitation affects both river flows and the levels and volumes of the Boali reservoir, particularly during the dry periods that occur from November to March.

The driest months are December, January, and February, with average monthly rainfall of approximately 7, 11, and 25 mm, respectively. In contrast, August, September, and October are the wettest months, featuring average monthly precipitation of around 272-, 256- and 226-mm. Graphical analysis reveals a negative trend of 1,07mm, suggesting a decadal decrease in precipitation of about 10,7 mm. Although the decline in precipitation is gradual, the high variability poses challenges for rivers to maintain a stable and economically viable hydroelectric power generation.

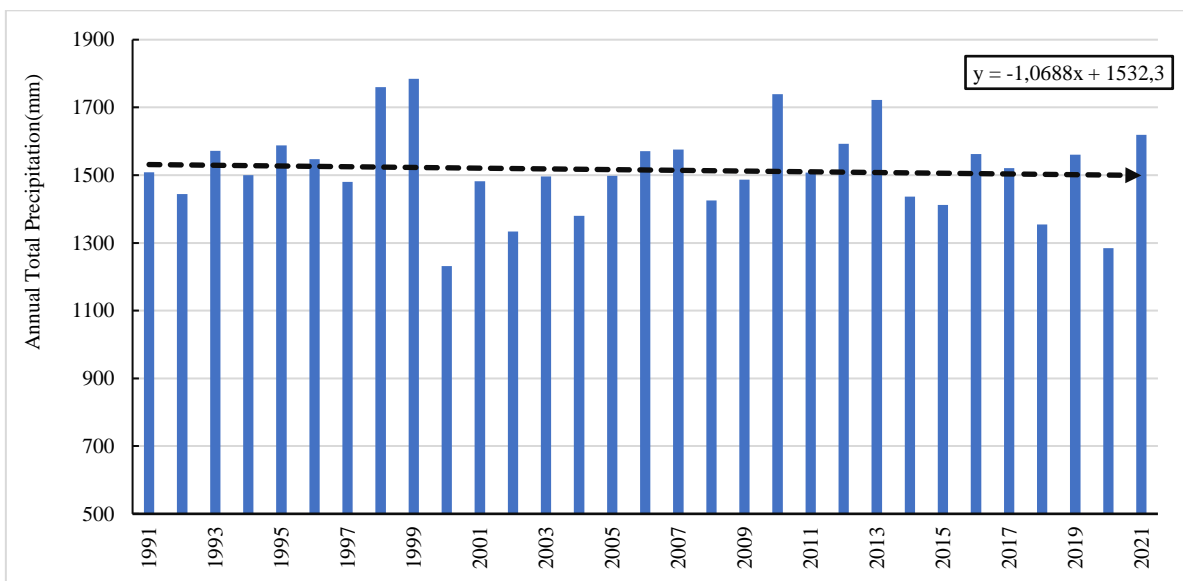


Figure 22: Total annual rainfall intensity in the Mbali catchment

The ongoing reduction in precipitation, coupled with rising temperatures in the basin, leads to increasingly complex hydrological processes. Elevated temperatures have resulted in increased evapotranspiration rates, exacerbating the severity of dry periods and consequently leading to even lower river flows.

### IV.2 Flow Regime of the M'Bali

The stream flow response to rainfall depends on the catchment attributes that include the physiographic, underlying geology, vegetation cover and rainfall amount, intensity, and frequency. The interaction between these attributes and the nature of the response are variable in space and time and induce complexity, which cannot yet be predicted in hydrology (Nzango J. ..., 2018; Nzango C. , 2019; Berhanu, 2015). To better understand this complexity in river flow responses within a catchment, it is possible to classify watercourses based on their similar flow characteristics.

The temporal pattern of a river’s flow over a given period constitutes its flow regime, which is essential for the health of aquatic and riparian ecosystems. This regime describes the average seasonal behaviour of flows and reflects the climatic and physiographic conditions of the catchment. Variations in the regularity of seasonal patterns indicate diversity in flow regimes, which may change in response to climatic conditions.

For the analysis of the flow regime, the observation period was divided into three classes to examine fluctuations: the first class includes flow data from 1991 to 2001, the second from 2002 to 2012, and the last from 2013 to 2021. The flow regimes for these periods were analyzed, and any observed changes were noted.

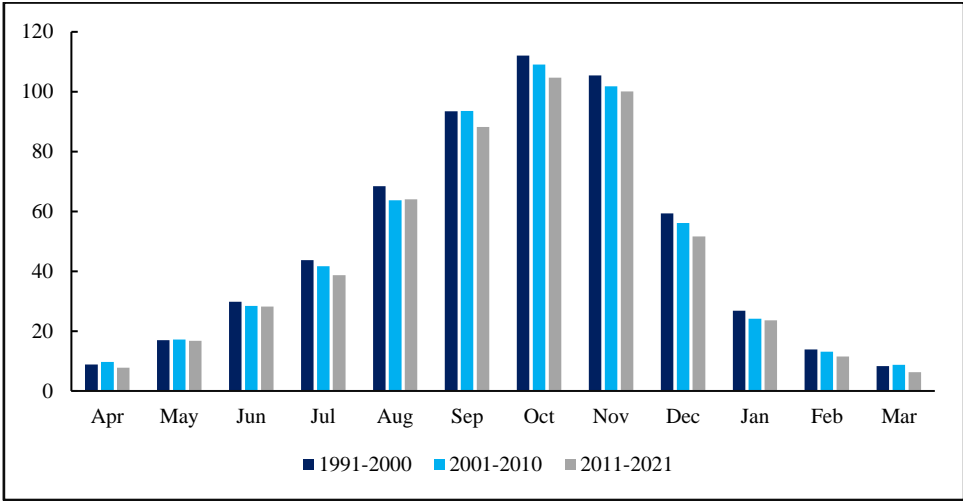


Figure 23: M'Bali River flow regime at Bossembélé

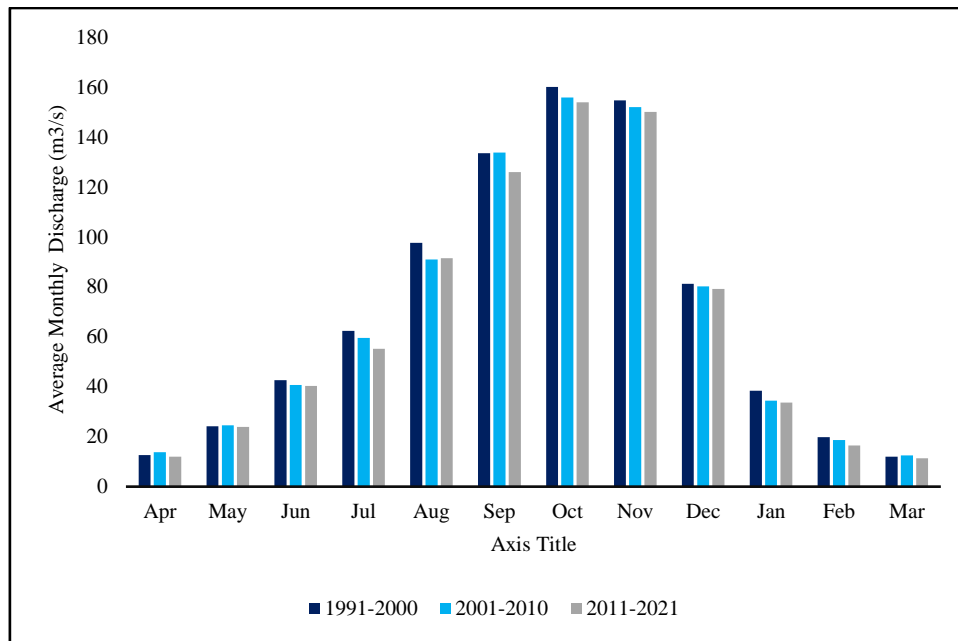


Figure 24: M'Bali River flow regime at Boali

There has been a gradual decline in river discharge over the 30-year study period, as illustrated in Figure 4.5. The peak discharge, which occurs in October, has consistently decreased over the years. In the first decade (1991-2000), the peak flow reached 112,1 m<sup>3</sup>/s in the M'Bali River at Bossembélé, which was followed by a drop to 109,04 m<sup>3</sup>/s in the next decade (2001-2010), and finally to 104,7 m<sup>3</sup>/s in the last decade ending in 2021.

Similarly, a decrease in discharge has also been observed at the entrance of the Boali dam during the same timeframe. Figure 4.6 reflects this trend, showing a reduction from 160,2 m<sup>3</sup>/s in the first decade to 155,9 m<sup>3</sup>/s in the following decade, ultimately reaching 104 m<sup>3</sup>/s in the last decade.

The fluctuations observed in the flow of the Mbali River after its regulation have also had consequences on the hydrological calendar of the river. Similar to the Ubangi, the initial hydrological calendar of the Mbali was typically spread from April to March. Consequently, the hydrological calendar has been slightly modified following the establishment of the Boali dam. It is increasingly distributed between May and April. The month of May now marks the resumption of flow in the Mbali, whereas this resumption previously occurred in April. Likewise, April now signifies the end of the recession, which used to take place in March. Finally, the peak flood in October is increasingly less pronounced in the river since its regulation (see Figure 4.5 et 4.6). This peak has now become variable, occurring between September, October, and November (Nzango., 2019.).

The decline in the streamflow over the years is basically due to decline in the amount of water flowing through the river channels, the reduction in the river flow can be attributed to decreasing amounts of precipitation and also the gradually increasing temperatures from the year 1991 to 2021 as shown in Figure 4.4 and 4.3 respectively, which can be attributed to climate change.

### IV.3 Impact of River Flow Regime on Hydropower Generation

For efficient and sustainable hydropower generation, water availability is an essential component. Changes in the river flow regime in a catchment can affect the amount of water available in the hydropower generating reservoirs which can in turn have an impact on the hydropower plants operation and electricity generation.

#### IV.3.1 Inflow Trends of the Boali Reservoir

The data regarding the inflows to the Boali reservoir were calculated based on the flow rates of the Ubangi River, obtained from the Meteorological General Directorate (MGD) authorities to estimate the inflow to the dam in cubic meters per second. The inflow rates are determined based on daily dam levels. Trend analysis indicates that the inflow rates to the dam show a steady decline (see Figure 4.7).

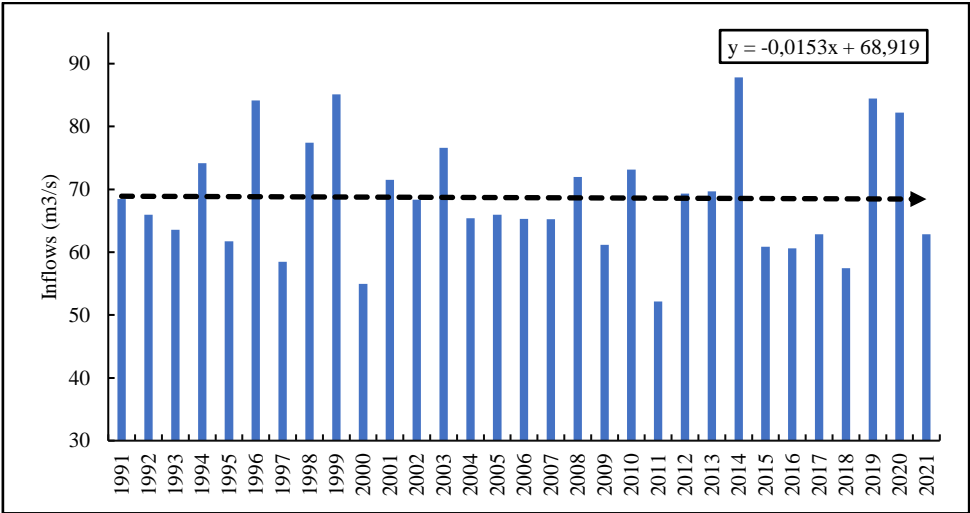


Figure 25: Boali reservoir inflows

The construction and filling of the Boali dam has led to the creation of a lake covering an area of approximately 25,000 km<sup>2</sup>, constituting the sole reservoir of the hydroelectric production system in the Central African Republic. The primary objectives of this reservoir are to store water to regulate flow, allowing the downstream hydroelectric plants, Boali 1 and Boali 2, to maintain their operations during the dry season when demand is high—a function it continues

to perform to this day. The second function involves hydroelectric production with a capacity of 11 MW, which has not yet been realised.

Similar to precipitation trends in the catchment area, inflows to the Boali reservoir indicate a decreasing trend. This decline can largely be attributed to the reduced flow of rivers contributing to the reservoir's recharge, as shown in Figure 4.5 for the flows at Bossembélé. Average annual inflows to the dam are decreasing at a rate of 0,0153 m<sup>3</sup>/s per year, according to the trend line equation  $y = -0,0153x + 68,919$ . This means that inflows into the reservoir are decreasing by 0,0153 m<sup>3</sup>/s each year. Over a 30-year period, inflows to the reservoir have decreased by 0,456 m<sup>3</sup>/s.

According to Figure 4.6, the lowest inflow rates are on the rise, with the years 2000, 2011, and 2018 recording the lowest inflows at 55,0 m<sup>3</sup>/s, 52,2 m<sup>3</sup>/s, and 57,4 m<sup>3</sup>/s respectively. The highest and lowest inflows in the last two decades occurred in 2014 and 2011 respectively, indicating an increase in extreme weather events such as droughts and floods. The year 2011 recorded the lowest inflow level at 52,2 m<sup>3</sup>/s, a year when the operation of the Boali plants was deficient, and reservoir water levels dropped to concerning levels.

The primary causes of inflow variations are fluctuations between periods of scarce and abundant rainfall, high evapotranspiration rates, and increasing temperatures in the catchment area. The reduction in inflows to the reservoir directly threatens the operation of the Boali hydroelectric station, as this reservoir plays a regulatory role for the downstream plants.

#### **IV.3.2 Boali dam reservoir levels**

Daily data on the reservoir level of the dam has been collected from ENERCA from 1991 to 2024. According to the obtained data, the average annual levels of the reservoir are about 571,3 meters above sea level (m a.s.l.). At this level, the dam operates at its optimal capacity. The minimum water level required for energy production is 560 m a.s.l. Generally, the reservoir levels fluctuate between a critical maximum height of 573,50 m a.s.l. (the highest level) and a critical minimum height of 560 m a.s.l (the lowest). However, the water level has dropped to its lowest recorded value of 572 m a.s.l. and 568,1 in 2001, 2009, and 2024 due to severe drought conditions.

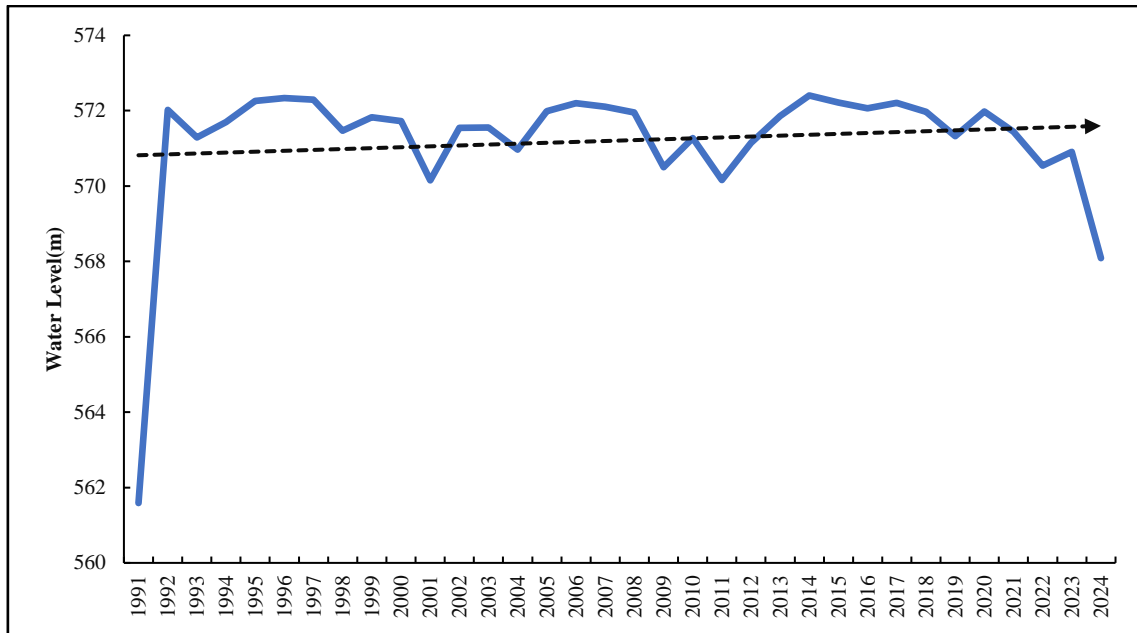


Figure 26: Boali reservoir levels

According to the configuration of the Boali hydroelectric facility (see Figure 2.2), the dam is located at the highest altitude upstream of the two production plants. This positioning allows it to fully serve its function as a regulator of river flow. However, this structure, which forms a lake with a capacity of 250 million m<sup>3</sup> and is never subject to any drainage, acts as a sediment accumulation basin, resulting from a mixture of exogenous and endogenous materials.

A study conducted by Nzango in 2019 estimated the accumulation rate to be 0,8 cm/year. This trapping effect could compromise the long-term storage capacity of the reservoir and, consequently, hydroelectric production (Nzango., 2019.). The filling of the reservoir's bottom leads to an increase in water surface area, which in turn raises the evaporation rate due to rising temperatures. Indeed, the shallower a reservoir is, the higher the evaporation rate, making water management even more challenging.

As a result, any decrease in the dam's level negatively impacts electricity production, particularly during dry seasons when water inflows are minimal. A decline in the flow of rivers in the M'Bali catchment has led to reduced inflows into the Boali dam reservoir over the 30-year study period, resulting in lower reservoir levels. As illustrated in Figure 4.7, the years with the lowest inflows to the dam also experienced the lowest levels. This decline can be attributed to fluctuations observed in rainfall and temperature patterns (see Figures 4.2 and 4.4) caused by climate change.

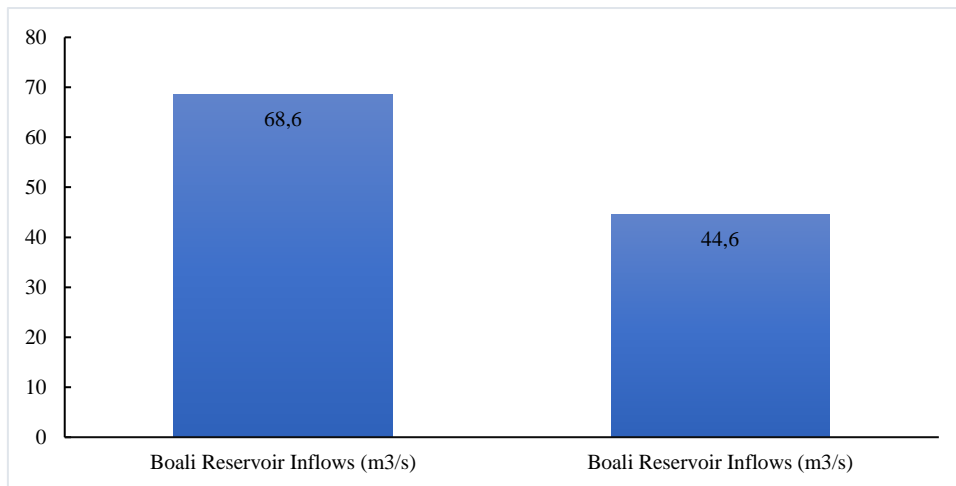


Figure 27: Boali Dam inflow and outflow

Moreover, Figure 4.9 illustrates that, out of an average inflow of  $68 \text{ m}^3/\text{s}$  into the dam, only an average of  $44,6 \text{ m}^3/\text{s}$  is released downstream to operate the Boali 2 and Boali 1 plants. This indicates that the dam discharges only about 65% of the water entering its reservoir. This situation, combined with sedimentation at the bottom of the reservoir, is one of the primary reasons for the observed trends in water levels, linked to the decreasing inflow and precipitation in the catchment.

### IV.3.3 The Potential Evapotranspiration

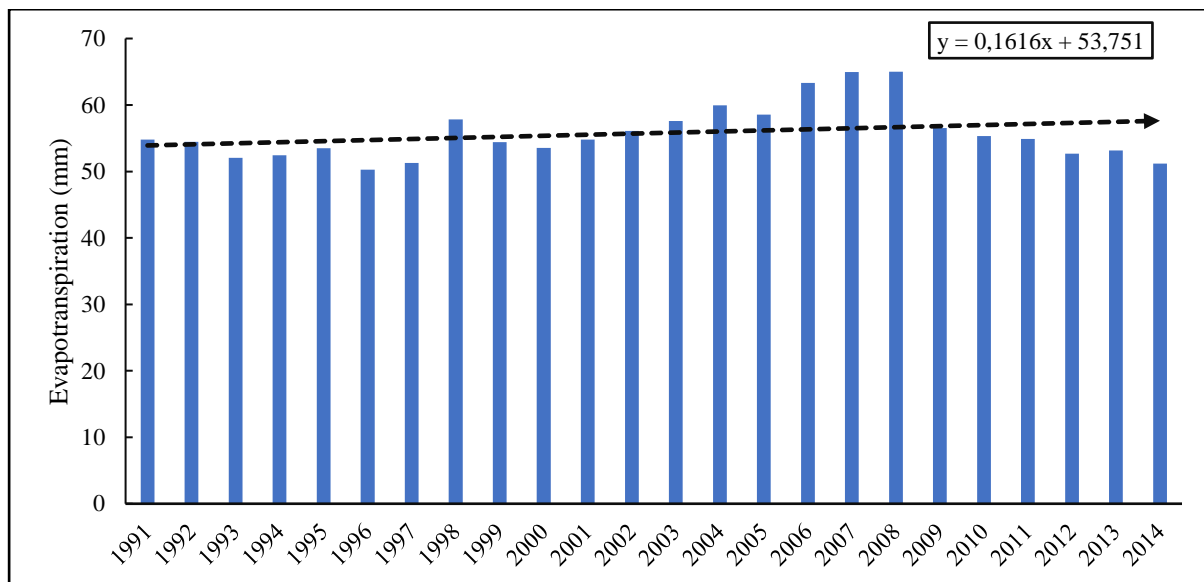


Figure 28: Potential evapotranspiration in M'Bali catchment

the figure displays the trend of evapotranspiration (in mm) from 1991 to 2014, with a linear trend line illustrating the overall change. The data shows annual fluctuations in evapotranspiration, with the highest values recorded in 2007 and 2008, and the lowest in 1992 and 1993. Despite these variations, the overall trend is an upward shift, as indicated by the positive slope of the trend line (0.1616). This

suggests that evapotranspiration has been gradually increasing over the study period. The equation of the trend line ( $y = 0.1616x + 53.751$ ) indicates that evapotranspiration increased at an average rate of 0.1616 mm per year, with the intercept value of 53.751 mm representing the estimated evapotranspiration for the base year (1991), assuming this trend continued backward. This increase in evapotranspiration could be attributed to shifting climatic conditions, such as rising temperatures or changes in precipitation patterns, both of which could directly impact the water balance and consequently hydropower generation in BHS. The results emphasize the need for a thorough understanding of evapotranspiration trends, as these changes may have significant implications for water resource management and hydropower generation, especially in regions already experiencing water availability challenges due to climate change.

**IV.4 Relationship between Boali dam inflows and water levels**

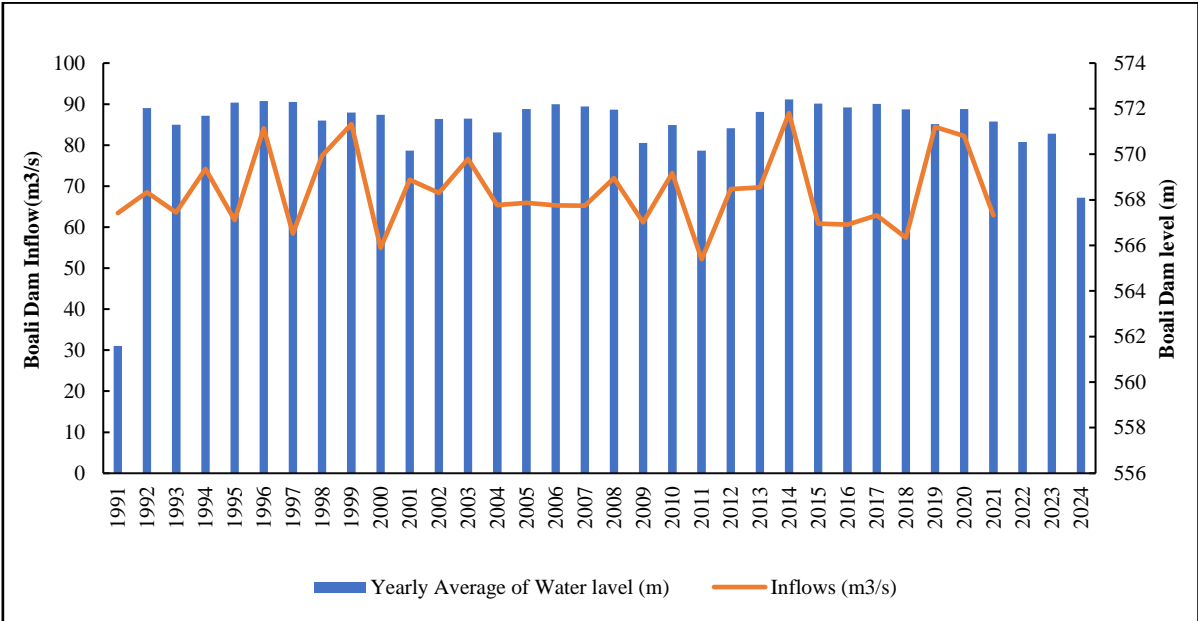


Figure 29: Relationship between Boali dam inflows and water levels

Water is essential for hydropower generation; therefore, a decrease in water levels in the Boali dam will directly impact energy production. The Boali dam is crucial to the Boali hydroelectric project as it regulates water inflows to the mini-dams that supply the power plants. Consequently, a decline in water levels at the Boali dam will affect all downstream mini-hydropower stations along the M'Bali River.

Figure 4.8 illustrates the trend in hydropower production within the framework of the two plants, Boali 1 and Boali 2. There has been a noticeable downward trend in hydropower generation from 1990 to 2010, as depicted in the graph. The driest years, specifically 1999-2000 and 2009, recorded the lowest levels of hydropower output. During these periods,

hydropower generation was even halted for several months due to reservoir levels falling below threshold values. The figure also demonstrates a clear correlation between stream flow, dam water levels, and hydropower generation, highlighting the interdependence of these factors, which is relevant for my master's thesis.

### IV.5 Hydropower generation trend

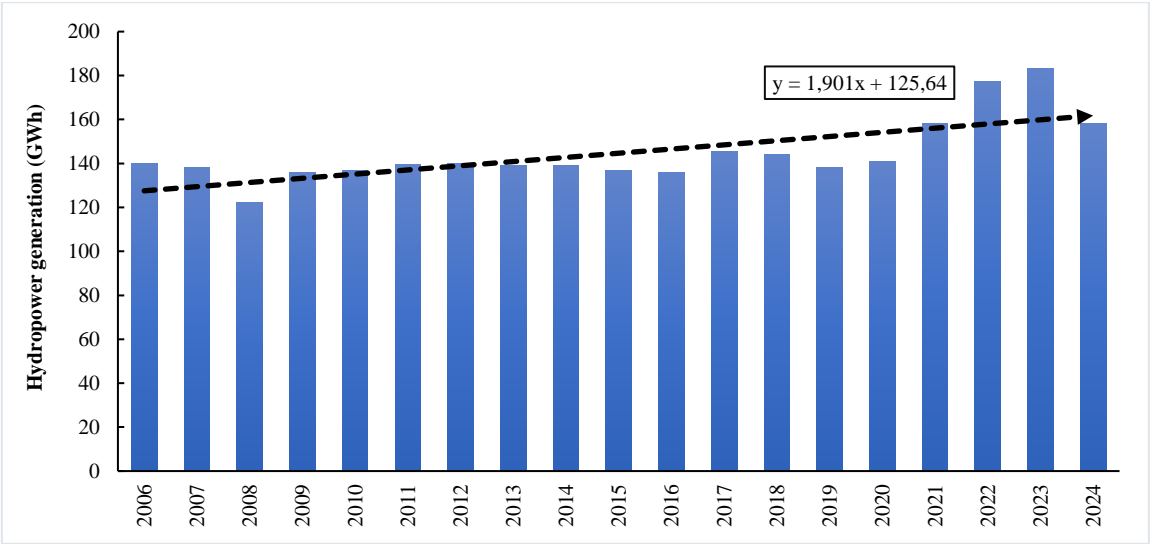


Figure 30: Hydropower generation trend in the Boali Hydropower Complex (BHC)

The effects of climate change on water resources and, consequently, on hydropower generation present a complex relationship that necessitates thorough analysis to evaluate the extent of climate-related events on the sustainability of hydropower resources as a significantly reliable source of renewable energy in the Central African Republic. The observed decrease in precipitation and the increase in temperatures have led to declining inflow rates in the Boali dam, as shown in Figure 4.7. This trend would typically suggest a decrease in hydropower production over the years. However, contrary to expectations, the annual production data reveals a noteworthy upward trend.

This increase can be attributed to the recent expansion project, which involved the installation of two 5 MW hydroelectric generators at the Boali 2 plant, raising the total capacity of the hydropower complex from 28,75 MW to 38,75 MW in 2021. Additionally, this extension required an increase in the outflow rate to accommodate the operation of the two new generators.

Furthermore, rising temperatures are likely to exert significant pressure on the floral biodiversity of the catchment areas, potentially leaving the soil bare and vulnerable to erosion agents. Increased erosion rates in the catchment will lead to sediment deposition in the dams,

thereby reducing the storage capacity of the reservoirs and diminishing the overall operational efficiency of the hydropower systems.

### IV.6 Relationship between hydropower generation and water inflow

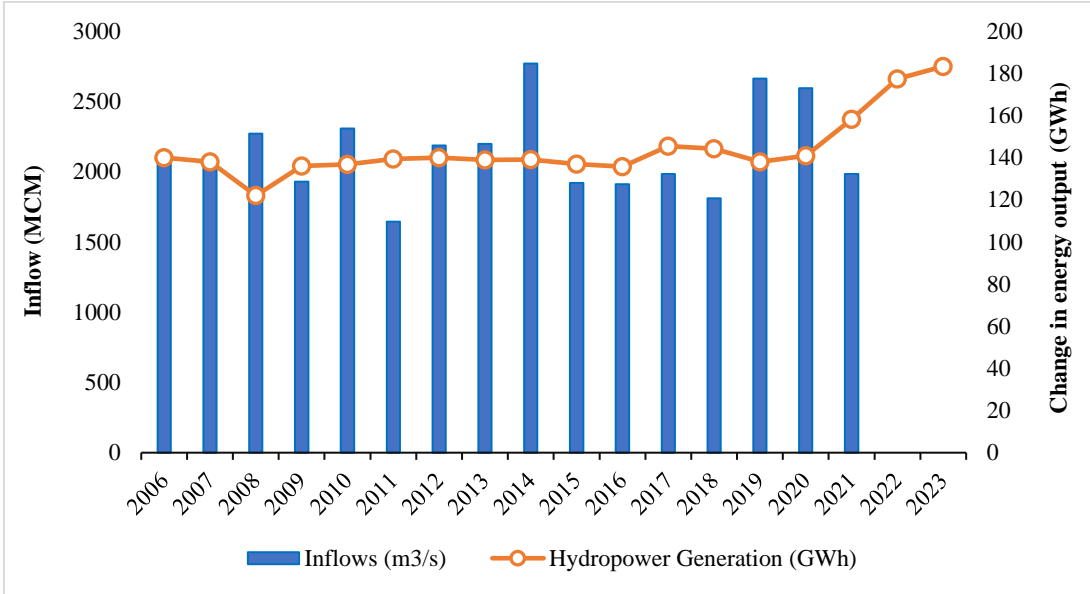


Figure 31: Changes in energy output relative to Boali dam reservoir inflows

Figure 4.12 illustrates the relationship between annual inflows into reservoirs, expressed in millions of cubic metres (MCM), and variations in annual energy output. A clear correlation exists between the volume of inflows into the dams, linked to precipitation levels, and fluctuations in energy production.

Although the inflows observed in the reservoirs in 2008, 2014, 2019, and 2020 were relatively high, the variations in energy production were not significantly affected for several reasons:

- + **Regulation of Water Resources:** The Boali Dam is designed to regulate water flow, storing water during periods of heavy rainfall and releasing it gradually. Water management officials optimize hydropower production by considering both drought and flood periods. According to figure 4.9, the downstream flow remains relatively constant throughout the year, representing approximately 65% of the incoming flow. Consequently, even if the volume of water entering the dam fluctuates, electricity production remains stable, following the trend of the downstream flow.
- + **Influence of Mini Dams Downstream:** Furthermore, the presence of mini dams downstream also plays a crucial role in water management, particularly when these structures have a certain retention capacity or are used to optimize production during

peak demand periods. This can help mitigate the variability in electricity production upstream.

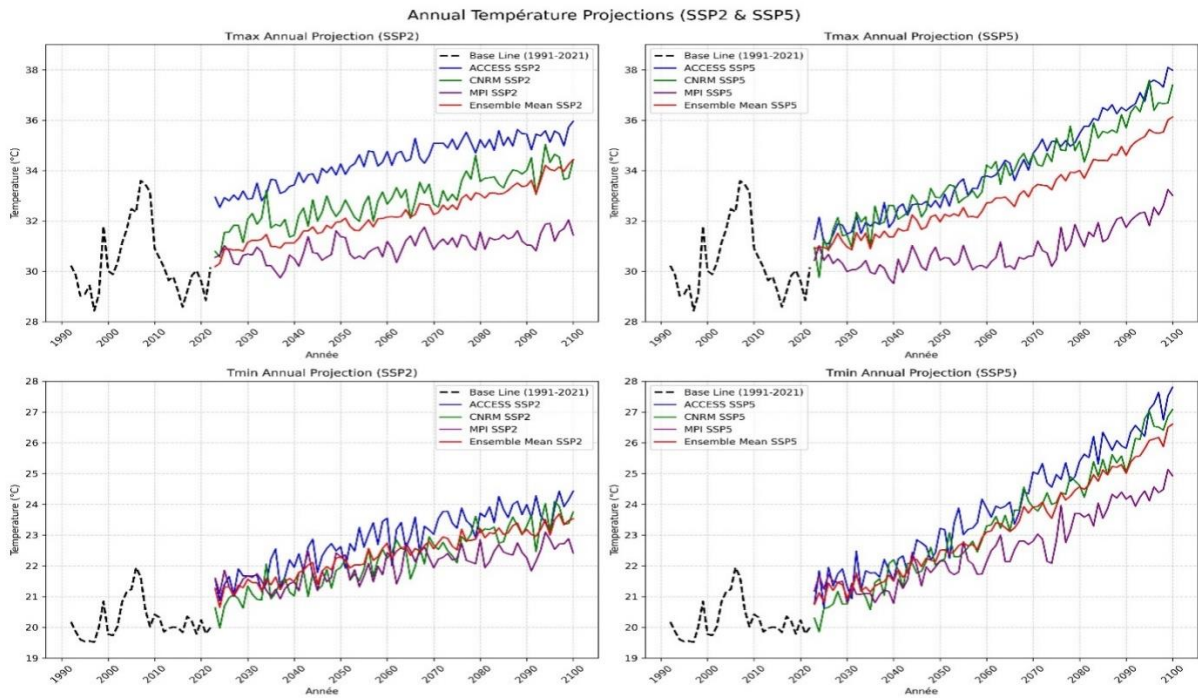
These factors highlight the importance of integrated and adaptive water resource management to ensure the sustainability of hydropower production in the context of climate change.

## IV.7 Future RCMs Projection under SSP2 and SSP5

### IV.7.1 Analysis of the projected temperature and precipitation

#### 🚦 Temperature

The projections of maximum and minimum temperatures under the SSP2-4.5 and SSP5-8.5 scenarios for the Bossembélé station, derived from various regional climate models (RCMs), indicate a rising trend until the end of the 21st century.



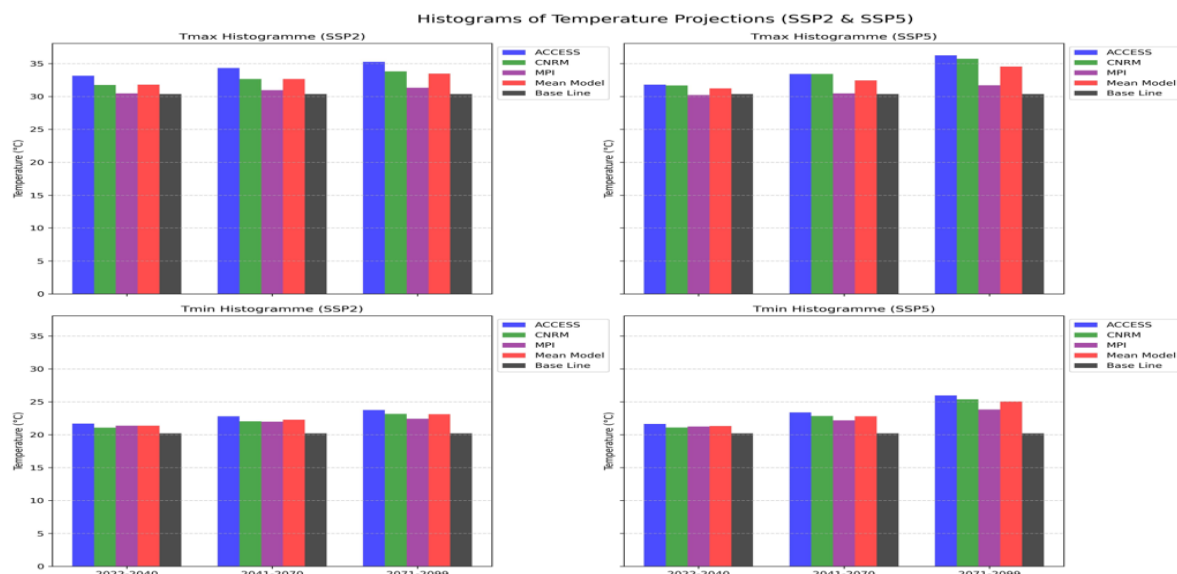


Figure 32: Maximum and minimum temperature projected under SSP2-4.5 and SSP5-8.5 scenario from 2026 to 2099 for Bossembelé station

The baseline maximum temperature is observed to range between 28 and 34 °C, which is projected to range between 29 and 36 °C under the SSP2 scenario and between 29 and 39 °C under the SSP5 scenario, respectively. Moreover, the greatest rise of 36 °C in 2099 under SSP2 and 39 °C in 2097 under SSP5 is projected by ACCESS. Likewise, the baseline minimum temperature is observed to range between 19 and 22 °C, whereas it is projected to range between 20 and 24.5 °C and between 19.8 and 28 °C under the SSP2 and SSP5 scenarios, respectively. Correspondingly, the maximum increase of 24.5 °C in 2079 and 2099 under SSP2 and 27.8 °C in 2099 under SSP5 are also projected by ACCESS. From 2022-2040 to 2041-2070, the Tmax projections show an increase of 1°C for the ACCESS, CNRM, and MPI models under both the SSP2 and SSP5 scenarios, with the increase being more pronounced under SSP5, particularly for ACCESS. For Tmin, the increase is 1°C under SSP2 and more significant under SSP5, with ACCESS predicting a rise of 2°C.

From 2041-2070 to 2071-2099, maximum temperatures stabilise under SSP2 (no increase for ACCESS) and under SSP5 (stabilisation for ACCESS), with a 1°C increase projected by CNRM and MPI. For Tmin, the increase is 1°C under ACCESS, with more moderate increases in the other models, particularly under SSP5. The warming projections are more pronounced under SSP5, especially for ACCESS, highlighting the importance of implementing emission reduction measures to limit the extent of future warming.

These projections highlight the significant warming trends expected over the coming decades, with implications for regional climate adaptation and resource management strategies. The use

of the ensemble mean model helps to mitigate uncertainties associated with individual models, providing a more reliable estimate of future temperature changes.

The results emphasize the varying impacts of different climate scenarios on temperature trends, highlighting the necessity for tailored adaptation strategies in response to these anticipated changes. The more aggressive warming under SSP5 suggests that without substantial mitigation efforts, the region could face severe challenges related to heat stress, water availability, and ecosystem stability. This analysis underscores the importance of considering both moderate and high-emission scenarios in climate adaptation planning, particularly for sectors such as hydroelectric production, which are highly sensitive to temperature and hydrological changes.

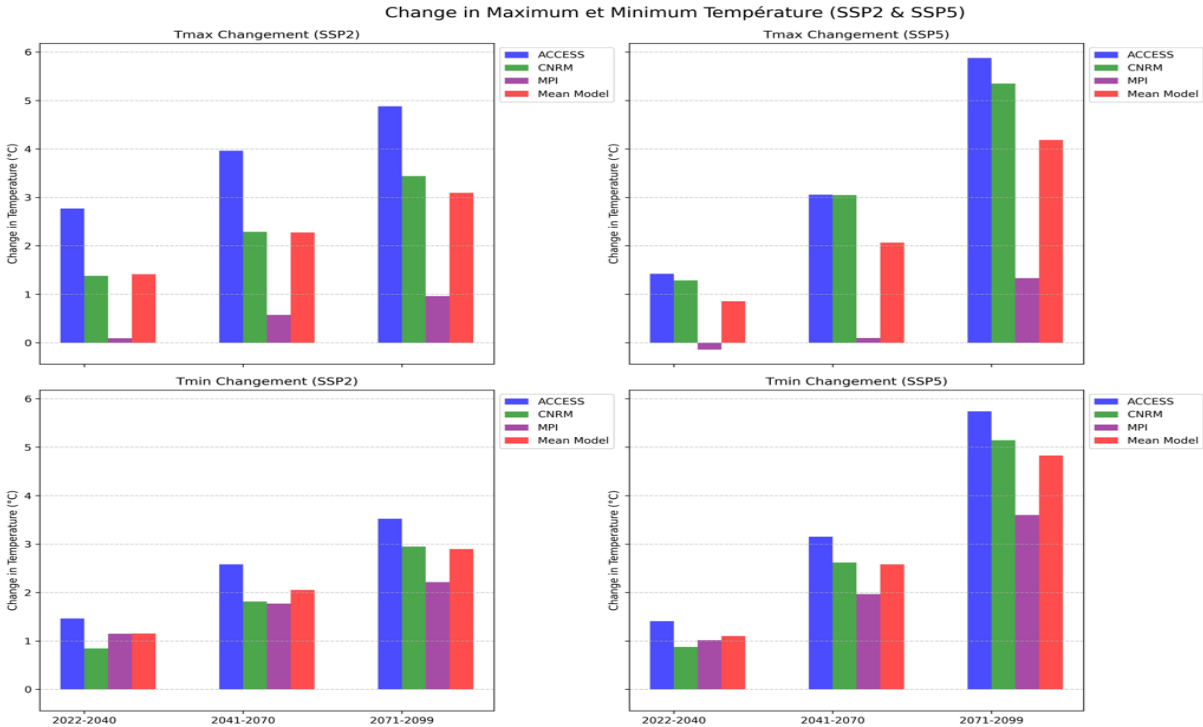


Figure 33: Change in maximum and minimum temperature for three different periods and RCMs under SSP2-4.5 and SSP4-8.5 scenario compared to baseline period of 1991 to 2014 for Bossembélé station.

Figure 4.14 further illustrates the change in maximum and minimum temperature. In the case of SSP2, it depicts similar trends of increase for both minimum and maximum temperatures across all RCMs, with an increase within 0.2 to 4.8 °C in all periods considered. Though, this is not the case for SSP5, the maximum temperature has been projected to increase by nearly 6 °C and the minimum temperature to overtop 5.6 °C in the last quarter of the century for ACCESS model showing slightly stronger warming compared to the others.

In contrast, the SSP5-8.5 scenario illustrates a more pronounced warming trend, particularly by the 2071–2099 period. The maximum temperature is expected to rise reach between 4.5 °C and

6 °C, with all models showing a marked increase, most notably ACCESS and CNRM. Minimum temperature also exhibits strong warming under this high-emissions scenario, increasing by 4 °C to 5.5 °C towards the end of the century. These projections reflect the enhanced radiative forcing and sustained emissions trajectory associated with SSP5. by nearly 6 °C, while the minimum temperature is projected to exceed 5.6 °C by the end of the century, particularly according to the ACCESS and CNRM models. The ensemble mean model also reflects this significant increase, underscoring the heightened impact of the SSP5 scenario compared to SSP2. The ensemble mean model further supports these trends, indicating a moderate but steady rise in temperatures under this scenario.

These results emphasise the varying impacts of different climate scenarios on temperature trends, highlighting the necessity for tailored adaptation strategies in response to these anticipated changes. The more aggressive warming under SSP5 suggests that without substantial mitigation efforts, the region could face severe challenges related to heat stress, water availability, and ecosystem stability. This analysis underscores the importance of considering both moderate and high-emission scenarios in climate adaptation planning, particularly for sectors such as hydroelectric production, which are highly sensitive to temperature and hydrological changes.

**IV.7.2 Mann Kendall Tests**

*Table 5: Mann Kendall Trend test for Max and Min T in all models under SSPs Scenarios*

| Model            | Tau                 | P-value                 | Z                  |
|------------------|---------------------|-------------------------|--------------------|
| Tmax_ACCESS_SSP2 | 0.30143792165363514 | 2.2999569177542665e-43  | 13.807521786048238 |
| Tmax_CNRM_SSP2   | 0.21367570198808475 | 1.2740060915156563e-22  | 9.787527376000444  |
| Tmax_MPI_SSP2    | 0.11664289991937374 | 9.368565292164459e-08   | 5.342889086381063  |
| Tmin_ACCESS_SSP2 | 0.34898086509023296 | 1.6219658515373605e-57  | 15.98525119604587  |
| Tmin_CNRM_SSP2   | 0.353932731921837   | 4.149680128224735e-59   | 16.212074048273287 |
| Tmin_MPI_SSP2    | 0.18300820886736444 | 5.172256312535597e-17   | 8.382786801009408  |
| Tmax_ACCESS_SSP5 | 0.5444535692240764  | 3.8314238773839055e-137 | 24.93898072715331  |
| Tmax_CNRM_SSP5   | 0.3790696110482003  | 1.7748452108468176e-67  | 17.363481954307517 |
| Tmax_MPI_SSP5    | 0.17819811402390526 | 3.4240201964202057e-16  | 8.162457888908113  |
| Tmin_ACCESS_SSP5 | 0.5843147785344834  | 8.32952938156132e-158   | 26.764844284572902 |
| Tmin_CNRM_SSP5   | 0.5877104777472824  | 1.2763296647378594e-159 | 26.920386064460377 |
| Tmin_MPI_SSP5    | 0.3602428829753499  | 3.608592831908434e-61   | 16.501113820265704 |

The analysis under the SSP2 scenario reveals a consistent and statistically significant upward trend in both maximum (Tmax) and minimum (Tmin) temperatures. Among the three models

assessed, ACCESS and CNRM demonstrate stronger and more coherent correlations over time compared to MPI, suggesting greater sensitivity to climatic shifts. The extremely low p-values associated with all model outputs reinforce the robustness of these trends. These findings underscore the importance of incorporating multiple climate models to capture a range of possible future outcomes, particularly in relation to temperature extremes, which are critical variables in assessing the long-term impacts of climate change on hydropower generation and water resource management. Under SSP5, both Tmax and Tmin show significant upward trends under the SSP5 scenario, with ACCESS and CNRM models showing the strongest correlations, particularly for Tmin. MPI, while still showing positive trends, presents weaker correlations compared to the other two models. These findings underscore the importance of considering multiple models in assessing the potential future impacts of climate change, especially under a high-emission scenario like SSP5, which leads to more pronounced temperature increases.

**✚ Precipitation**

However, while a specific trend in temperature change has been identified, precipitation trends appear to be more variable and less consistent. Given that the hydrological regime of the M'bali watershed is heavily dependent on rainfall, it is essential to analyse seasonal precipitation patterns.

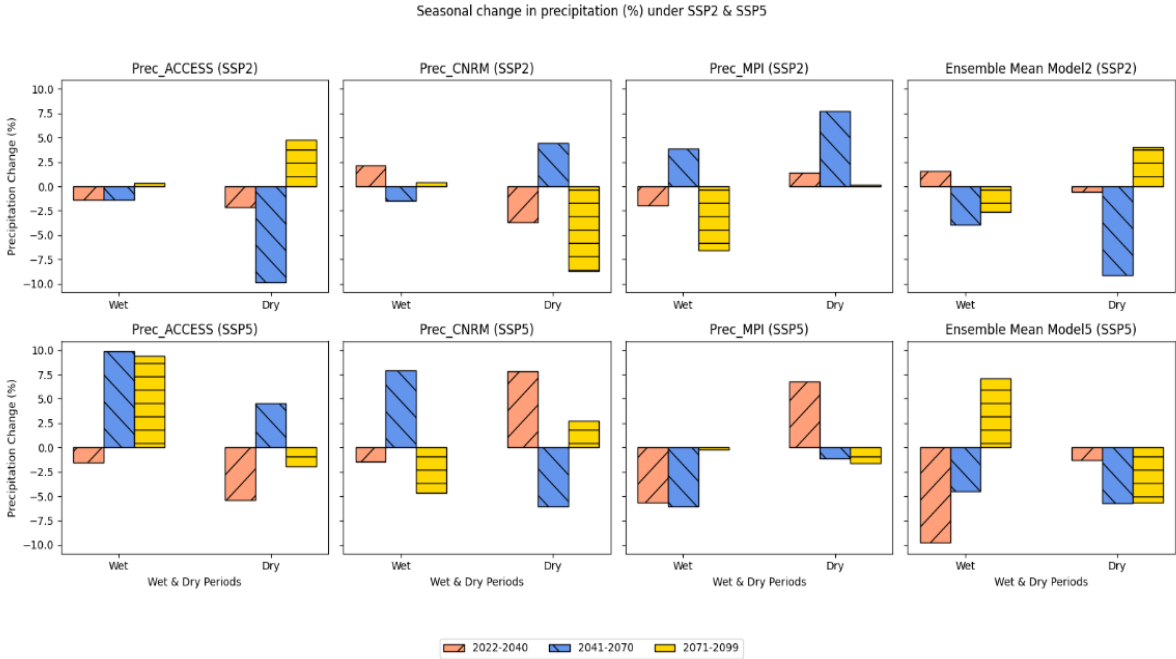


Table 6: . Seasonal change in precipitation in different periods for three RCMs ACCESS, CNRM and MPI under RCP 4.5 and RCP 8.5 in M’Bali Catchment.

The seasonal evolution of precipitation under SSP2-4.5 and SSP5-8.5 scenarios reveals substantial variability across different regional climate models (RCMs), contrasting sharply

with the more uniform warming patterns typically observed in temperature projections. Given that Bossembélé station lies upstream of a reservoir-fed hydroelectric facility, seasonal precipitation analysis is of critical importance for long-term water resource planning. As illustrated in Figure 4.15, the wet season is generally projected to experience a decline in precipitation across most models and timeframes, with reductions ranging from approximately 0.3% to nearly 10% under SSP2. Notably, the ACCESS model indicates a progressive intensification of this decline, rising from around 0.3% in the 2022–2040 period to over 9% by mid-century. Under SSP5, this decline becomes more pronounced, reaching almost 10% by the end of the century with the same model.

Despite the dominant pattern of decline, exceptions are observed in certain periods and models. For instance, both the ACCESS and CNRM models project modest increases in wet season precipitation under SSP5, although these remain under 10%, limiting their potential hydrological benefit. In contrast, projections for the dry season exhibit more pronounced variation. Under SSP5, the CNRM model forecasts an increase in precipitation of up to 7.5% during the 2041–2070 period, although this concerns a season with characteristically low rainfall, thus contributing minimally to annual water availability. Similarly, under SSP2, the MPI model anticipates a peak dry season increase of approximately 6% between 2041 and 2070. Under SSP5, dry season increases ranging from 3% to 7% are projected across all future horizons.

Among the RCMs, MPI emerges as the model predicting the greatest decrease in wet season precipitation, with a reduction of up to 6% under SSP2 in the 2080s. Conversely, CNRM presents the most pronounced increase in dry season rainfall, projecting a 6% rise under SSP5 between 2022 and 2040. These contrasting tendencies underscore the complex nature of future precipitation dynamics under climate change and highlight the value of multi-model ensemble means in addressing inherent uncertainties. It is also essential to recognise that any reduction in precipitation is likely to coincide with diminished streamflow, thereby posing a risk to hydropower generation capacity and regional water security.

The reductions in precipitation will directly lead to decreased discharge levels in rivers and reservoirs, as less water is available to flow into these systems. This reduction in discharge can impact hydropower production in several ways:

- ✚ **Reduced Water Availability:** Lower discharge translates to less water available for hydropower generation, which can limit the amount of electricity produced.

- ✦ **Operational Efficiency:** When water levels drop, turbines may not operate at optimal efficiency, leading to decreased energy output.
- ✦ **Increased Operational Costs:** Hydropower facilities may need to rely on supplementary energy sources to meet demand, which could increase operational costs.
- ✦ **Altered Generation Schedules:** Seasonal shifts in precipitation can disrupt planned generation schedules, making it challenging to meet peak demand periods.
- ✦ **Environmental Impacts:** Reduced discharge can also affect river ecosystems, leading to long-term consequences that may further complicate hydropower operations.

In addition, a reduction in precipitation due to climate change concurrently diminishes discharge. The performance evaluation results of the static bias correction method for maximum temperature, minimum temperature, and precipitation are illustrated in Table S2 of the supplementary table. These findings underscore the need for adaptive management strategies to mitigate the potential impacts of changing precipitation patterns on hydropower production and water resource management, particularly given the strong dependence of the M'bali watershed on rainfall.

#### IV.7.3 Mann Kendall Tests

The analysis of precipitation trends under the SSP2 and SSP5 scenarios reveals contrasting patterns in statistical significance and correlation strength. Under the SSP2 scenario, all three models (ACCESS, CNRM, and MPI) exhibit extremely weak correlations with time (Kendall's tau ranging from 0.0046 to 0.0210), and their corresponding p-values are not statistically significant, suggesting no discernible trend in precipitation. Conversely, under SSP5, the ACCESS model shows a weak but statistically significant positive trend (tau = 0.0636, p = 0.0037), indicating a slight increase in precipitation over time. The other SSP5 projections (labelled 'Prec\_fut\_SSP5') display very low tau values and non-significant p-values, highlighting negligible trends.

*Table 7: Mann Kendall Trend test for Precipitation in all models under SSPs Scenarios*

| Model            | Tau                   | P-value               | Z                   |
|------------------|-----------------------|-----------------------|---------------------|
| Prec_ACCESS_SSP2 | 0.021010826046754374  | 0.33851751224604854   | 0.9624118849810026  |
| Prec_CNRM_SSP2   | 0.0063501416410170165 | 0.7729634418183092    | 0.29087156178572066 |
| Prec_MPI_SSP2    | 0.004598250218853532  | 0.8361924360750119    | 0.21062525818325675 |
| Prec_ACCESS_SSP5 | 0.06364635625115729   | 0.0037382867372598673 | 2.9153546631409504  |
| Prec_fut_SSP5    | 0.03386315232803389   | 0.12415406485408187   | 1.5511194177182899  |
| Prec_fut_SSP5    | 0.00841833400999307   | 0.7056188309321099    | 0.38560619582154154 |

These findings suggest that, in contrast to temperature variables, future changes in precipitation are less consistent across models and scenarios. The lack of significant trends under SSP2 and the marginal signal under SSP5 imply greater uncertainty in future precipitation patterns. This reinforces the need for cautious interpretation when assessing hydrological impacts on

hydropower generation, as water availability driven by precipitation remains less predictable under projected climate conditions.

**IV.7.4 Changement saisonnier de l'évapotranspiration potentielle (ETp)**

Potential evapotranspiration (ETp) is a key variable influencing both agricultural water demand and hydrological balance. Its evolution under climate change scenarios provides essential insight into future water stress, particularly in regions reliant on hydropower such as M'Bali. The seasonal changes in ETp under SSP2 and SSP5 scenarios are presented in Figure 4.16.

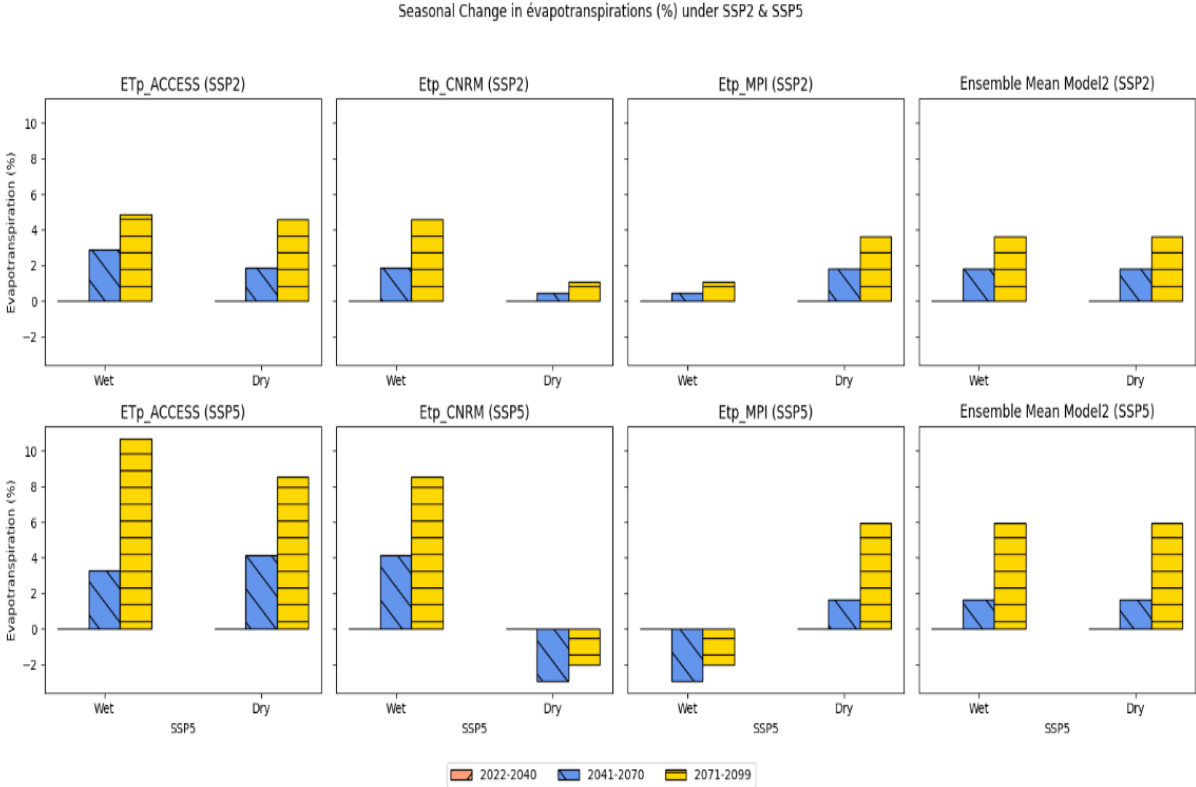


Figure 34: Seasonal change in reference evapotranspiration (ETp) under SSP2-4.5 and SSP5-8.5 scenarios from 2022 to 2099 for Bossembélé station

Under both scenarios, ETp exhibits a general increasing trend across the majority of models and future periods, particularly under SSP5. This trend is most notable for the ACCESS model, which projects a substantial increase of more than 10% in wet season ETp and approximately 8% to 9% in the dry season by the end of the century under SSP5. These increases are consistent with the anticipated rise in temperature and atmospheric demand, reflecting the intensification of evaporative losses.

Under SSP2, ETp projections are more moderate. The Ensemble Mean model estimates increases between 2% and 5% in both seasons, while models like MPI and CNRM present more subdued changes, particularly in the wet season. Notably, some models such as MPI and CNRM

project negative or near-zero changes in dry season ETp under SSP5 during earlier periods (2022–2070), suggesting inter-model differences in sensitivity to climatic forcing. By contrast, all models under SSP5 show an upward trend in ETp by the 2080s, reinforcing the expected impact of high-emission scenarios on atmospheric moisture demand.

These projections highlight the potential for increased water stress, as higher evapotranspiration rates may exacerbate the drying of soils and increase irrigation requirements, particularly during the dry season. This could lead to water stress and negatively affect hydropower generation in reservoir-dependent systems such as that of M’Bali. The findings emphasise the importance of integrating seasonal ETp dynamics into climate adaptation strategies and long-term water resource planning (Jacob et al., 2014; Taylor et al., 2012).

**IV.7.1 Mann Kendall Tests**

*Figure 35: Mann Kendall Trend test for ETp in all models under SSPs Scenarios*

| Model           | Tau                   | P-value               | Z                   |
|-----------------|-----------------------|-----------------------|---------------------|
| ETp_ACCESS_SSP2 | 0.1368024132730015    | 3.697131289386874e-10 | 6.266306147842178   |
| ETp_CNRM_SSP2   | 0.1096805155628685    | 5.061324328353168e-07 | 5.0239734265400005  |
| ETp_MPI_SSP2    | 0.014342520224873163  | 0.5112023629804981    | 0.6569666463508987  |
| ETp_ACCESS_SSP5 | 0.2620869326751679    | 3.343461219088217e-33 | 12.005029138002945  |
| ETp_CNRM_SSP5   | 0.18991727227021343   | 3.340551577269477e-18 | 8.699260066657919   |
| ETp_MPI_SSP5    | -0.052593811417340826 | 0.015992482446187017  | -2.4090870616825346 |

The Kendall’s Tau test reveals distinct trends in potential evapotranspiration (ETp) projections across climate models under SSP2 and SSP5 scenarios. Under SSP2, ACCESS and CNRM exhibit statistically significant increasing trends ( $\tau = 0.137$  and  $0.110$ , respectively;  $p < 0.001$ ), indicating a progressive rise in ETp, while MPI shows no significant trend ( $\tau = 0.014$ ,  $p = 0.511$ ). The stronger response from ACCESS suggests greater sensitivity to intermediate warming. In contrast, under the high-emission SSP5 scenario, both ACCESS and CNRM display markedly steeper increases ( $\tau = 0.262$  and  $0.190$ ,  $p < 0.001$ ), highlighting how elevated emissions amplify ETp. Notably, MPI diverges with a slight decreasing trend ( $\tau = -0.053$ ,  $p = 0.016$ ), possibly reflecting model-specific hydrological feedbacks. These results underscore substantial inter-model variability, with ACCESS projecting the most aggressive drying conditions, particularly under SSP5. The findings emphasize the need for multi-model assessments in climate adaptation planning, as rising ETp could intensify water stress in agricultural and natural systems. Policymakers must consider these projections, especially the

stark differences between SSP2 and SSP5 outcomes, to inform mitigation and water-resource strategies. Further research should explore regional-scale impacts and the drivers behind MPI’s anomalous trend to refine hydrological forecasts.

**IV.7.2 Electricity generation forecast**

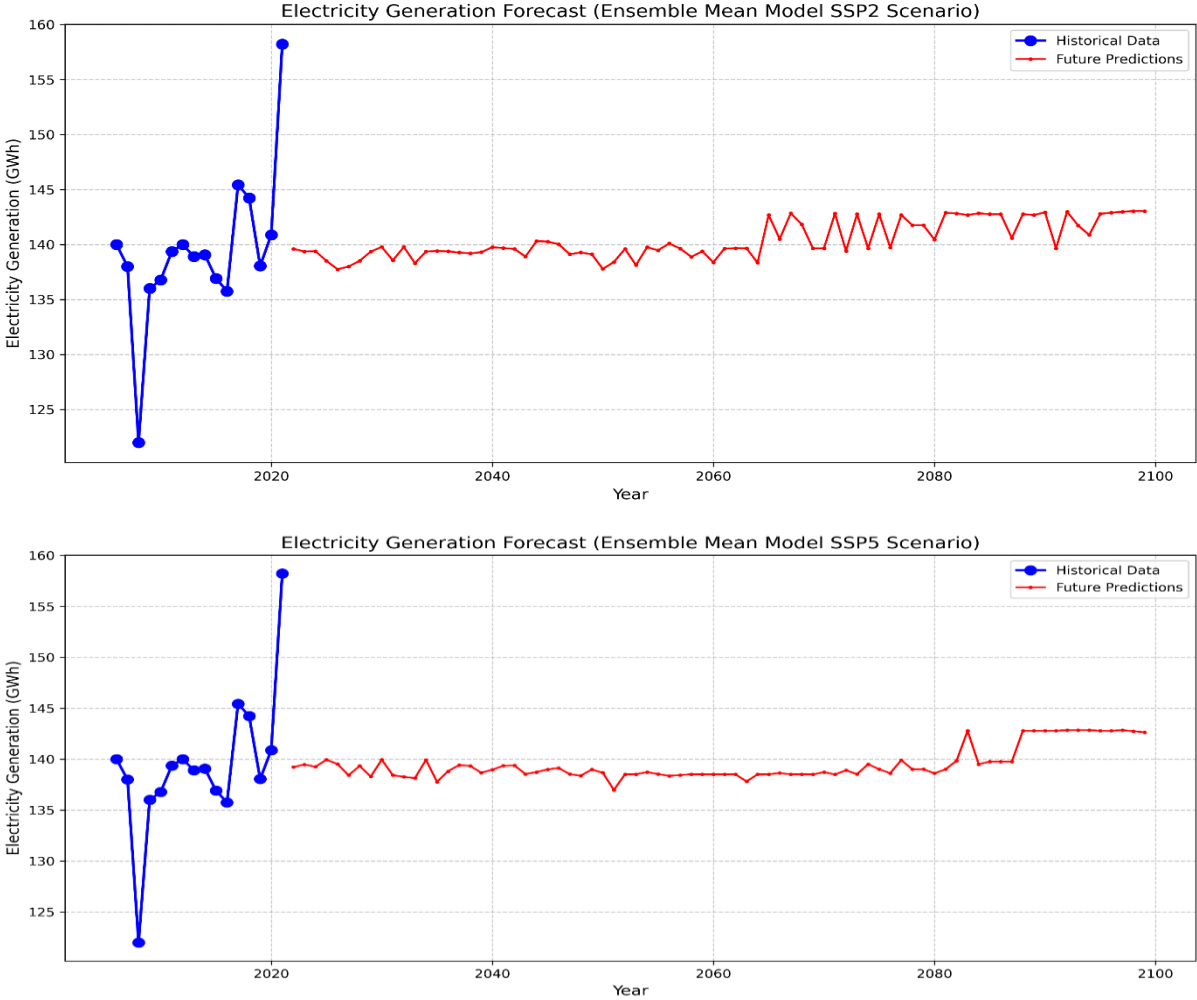


Figure 36: BHS Hydropower Generation Forecast from 2022 to 2099 using Random Forest model

The application of the Random Forest model to forecast electricity generation under various climate and socio-economic scenarios (ACCESS, CNRM, MPI under SSP2 and SSP5) provides valuable insights into potential climate change (CC) impacts on the Boali Hydroelectric Power Plant. The impact of climate change on hydroelectric power generation, as shown in the projections under the SSP2 and SSP5 scenarios, reveals distinct dynamics based on emission pathways. Under the SSP2 scenario, which assumes moderate development with moderate climate policies, future electricity production stabilises at an average of 140.4 GWh, with a range between 137.8 GWh (minimum forecast in 2026) and 143.0 GWh (maximum forecast in 2098). This suggests that the hydroelectric system could maintain relatively stable production despite climatic challenges, due to effective resource management strategies and adaptation

measures. In contrast, under the SSP5 scenario, characterised by high emissions and more pronounced climate change, electricity production also averages around 139.5 GWh, but with slightly greater variation, ranging from 137.0 GWh (minimum forecast in 2051) to 142.8 GWh (maximum forecast in 2092). The increased variability in the SSP5 scenario can be attributed to the impacts of extreme climatic events, such as prolonged droughts or floods, which may disrupt reservoirs and infrastructure.

This variability underscores the heightened vulnerability of the hydroelectric system in a high-emission world. Furthermore, reservoir management and the adoption of resilient technologies will become critical to maintaining stable production, especially in response to extreme weather events. In summary, while projections indicate an average generation of approximately 140 GWh in both scenarios, the impacts of climate change on hydroelectric power production would be significantly more pronounced under SSP5, requiring proactive risk management strategies for coping with seasonal climate variability, particularly in the coming decades.

## **IV.8 Discussion**

The analysis of climate and hydrological data from the M'Bali catchment over the period 1991 to 2021 highlights significant climatic trends that impact hydropower generation at the Boali Hydroelectric Power Station. The observed increase in annual mean maximum temperature by approximately  $0.1091^{\circ}\text{C}$  and annual mean minimum temperature by  $0.077^{\circ}\text{C}$  aligns closely with global warming trends reported elsewhere. These findings are consistent with studies indicating global temperature increases of approximately  $1^{\circ}\text{C}$  since pre-industrial times (IPCC, 2023; NOAA, 2022).

Precipitation trends indicate a gradual decline, with an annual negative trend of 1.07 mm, translating to a decadal decrease of about 10.7 mm. Similar findings were observed in other regions; for instance, Singh et al. (2023) documented comparable precipitation declines due to climatic changes impacting water availability and subsequently affecting hydropower potential.

River flow analyses demonstrated significant reductions in peak discharge at Bossembélé, decreasing from  $112.1\text{ m}^3/\text{s}$  in the first decade (1991-2000) to  $104.7\text{ m}^3/\text{s}$  in the most recent decade (2013-2021). Correspondingly, Boali dam inflows reduced from  $160.2\text{ m}^3/\text{s}$  to  $104\text{ m}^3/\text{s}$  over the same period. These hydrological changes mirror findings from studies conducted in other African catchments, such as those by Abdelkader et al. (2023) and Obahoundje et al. (2022), where reductions in river flows significantly affected hydropower output due to declining rainfall and increasing temperatures.

Analysis of inflow and reservoir water levels at Boali Dam indicated a decreasing inflow rate of approximately 0.0153 m<sup>3</sup>/s per year, corroborating with findings from Nzango (2019), who reported declining reservoir inflows due to climatic variability. This decline severely impacts reservoir operational capacity, threatening consistent hydropower generation, particularly during dry seasons.

The upward trend in potential evapotranspiration (ET<sub>p</sub>), with an increase of 0.1616 mm per year, is consistent with the IPCC's findings on elevated evaporation rates linked to global warming (IPCC, 2023). Similar regional trends were reported by Arnel and Reynard (1993), emphasizing the increasing atmospheric demand and its implications for water resources management, particularly under warming scenarios.

Future climate projections using Regional Climate Models (ACCESS, CNRM, MPI) under SSP2 and SSP5 scenarios indicated temperature increases ranging from 0.5 to 6°C by the end of the century, with SSP5 scenarios demonstrating higher temperature rises. Comparable projections were reported by Kriegler et al. (2017), who emphasized the significant warming under high-emission pathways (SSP5).

In contrast, precipitation projections displayed greater variability, with reductions in wet season rainfall up to nearly 10%, particularly under SSP5. This variability aligns with findings from Jacob et al. (2014), who highlighted uncertain future rainfall patterns under climate change scenarios. Consequently, such variability poses substantial challenges to water availability for hydropower generation.

The application of the Random Forest model for electricity generation forecasts indicated an average annual electricity production of 140.4 GWh under SSP2, with minimal fluctuations, implying effective adaptation strategies and resource management can mitigate moderate climatic impacts. However, SSP5 projections presented higher variability (average 139.5 GWh with fluctuations), reinforcing similar results from studies by Wasti et al. (2022) and Dallison (2021), who reported that extreme weather events and precipitation variability significantly disrupted hydropower systems.

Overall, these results underscore the critical need for adaptive management strategies to address climate-induced hydrological variability. Effective reservoir management, technological upgrades, and policy interventions are essential to ensuring hydropower resilience in the M'Bali catchment under future climate scenarios. The findings from this study contribute valuable localized insights that can inform sustainable energy planning and climate adaptation strategies,

addressing knowledge gaps highlighted by Shrestha et al. (2021) and Graham et al. (2020) in regional hydropower vulnerability assessments.

## **CHAPTER FIVE: ADAPTATION STRATEGIES AND CONCLUSIONS**

This final chapter presents **adaptation strategies** aimed at **maintaining and increasing electricity production** at the BHS Hydroelectric Power Plant (or full name if preferred). Building on the challenges identified in previous chapters; whether technical, environmental, or socio-economic; this section explores innovative and sustainable solutions to enhance the

dam's performance. We first examine **technical measures** (equipment modernisation, efficiency improvements), followed by **environmental approaches** (sediment management, climate change adaptation), and finally **institutional strategies** (policy frameworks, regional cooperation). These recommendations are grounded in prior analyses to ensure a resilient energy transition. In conclusion, the chapter synthesises key findings and outlines future prospects for the BHS, emphasising the need for **integrated management** to balance energy production with long-term sustainability.

## **V.1 Evaluation of Relevant Adaptation Strategies for the BHS Hydroelectric Plant**

The sustainability and long-term efficiency of the BHS hydroelectric plant depend on the successful implementation of well-designed adaptation strategies. These strategies must address technical limitations, environmental challenges, and socio-economic considerations to ensure that the plant remains productive in the face of evolving energy demands and climatic conditions. A thorough evaluation of these strategies is essential to assess their feasibility, effectiveness, and potential trade-offs.

### **V.1.1 Technical Adaptation Measures**

#### **V.1.1.1 Modernisation of Hydroelectric Equipment**

Modernising hydroelectric equipment is a crucial step in enhancing the operational efficiency of the plant. Ageing turbines and control systems often experience reduced performance due to wear and technological obsolescence. For instance, the modernisation of the Tehri hydroelectric plant in India resulted in a 15% increase in electricity production despite decreased water flow.

Additionally, modernising the high-voltage network connecting Boali and Bangui is vital to minimise transmission losses. An upgraded network would facilitate more efficient electricity transport, thereby reducing losses associated with resistance in transmission lines. However, these modernisation efforts entail significant financial costs and may require temporary shutdowns, potentially disrupting electricity supply. A phased implementation approach, prioritising the most critical units, could mitigate these disruptions while allowing for gradual budget allocation.

#### **V.1.1.2 Integration of Advanced Energy Storage Solutions**

Another promising technical strategy is the integration of advanced solutions, such as an offshore photovoltaic plant combined with a storage system. This system would cover much of the usable surface area of Lake M'Bali, acting as a floating cover to reduce evaporation, thereby

conserving up to 30% more water during drought periods. This contributes to maintaining hydroelectric production and optimising the energy mix. These technologies can help balance supply and demand, especially during periods of low water availability or peak electricity consumption. Although the initial investment is substantial, the long-term benefits—such as grid stability and reduced reliance on fossil fuel backups—make it a viable option. Pilot projects could serve as testing grounds to assess performance and cost-effectiveness before large-scale deployment.

## **V.1.2 Environmental Adaptation Strategies**

### **V.1.2.1 Sediment Management**

Sediment management programmes must be implemented to reduce sediment accumulation in reservoirs. In China, the Three Gorges Dam utilises upstream settling basins to trap sediments before they reach the main reservoir, ensuring optimal storage capacity. However, this approach may have environmental impacts, affecting upstream aquatic ecosystems. A balanced approach that combines this solution with natural sediment flow restoration practices could provide a more sustainable outcome.

### **V.1.2.2 Climate Change Adaptation**

Climate change presents additional challenges, particularly regarding changing precipitation patterns and water availability. Adaptive water management strategies, including revising reservoir operating rules, can help the plant address these uncertainties. For example, early warning systems have been developed in Kenya to minimise disruptions in electricity production caused by extreme weather events. However, the unpredictability of future climatic conditions complicates long-term planning. Hydrological modelling and scenario analysis should be employed to anticipate potential changes and develop flexible operational guidelines. Investment in early warning systems for droughts or floods could further enhance the plant's resilience.

## **V.1.3 Institutional and Policy Strategies**

### **V.1.3.1 Strengthening Institutional Frameworks**

Robust institutional frameworks and cooperative agreements are essential for the successful implementation of adaptation measures. Multi-stakeholder cooperation, particularly in transboundary water management, can ensure equitable resource sharing and prevent conflicts. Effective coordination among institutions responsible for water and energy management maximises hydroelectric production while protecting riverine ecosystems. However, political

and regulatory differences between regions may hinder progress. Establishing joint technical committees with representatives from all stakeholders could facilitate dialogue and foster collaborative decision-making.

#### **V.1.3.2 Policy Incentives for Adaptation**

Policy incentives, such as feed-in tariffs or subsidies for renewable energy, can also play a key role in supporting the adaptation efforts of the plant. In Germany, subsidies for renewable energy projects have encouraged investment in solar and wind energy. These measures can attract private investments and promote the adoption of complementary technologies, such as hybrid solar or wind systems. Nevertheless, poorly designed policies risk creating market distortions or unsustainable financial burdens. To avoid these pitfalls, policymakers should implement clear, time-limited incentives with integrated evaluation mechanisms to assess their effectiveness and make necessary adjustments.

#### **V.1.4 Optimising Water Resource Management**

##### **V.1.4.1 Dynamic Reservoir Management**

Adopting dynamic reservoir management is crucial for maximising the use of available water, particularly during drought periods. This involves adjusting storage levels based on short- and long-term weather forecasts. For instance, the dynamic reservoir management system of the Itaipu Dam in Brazil has maintained stable hydroelectric production despite seasonal precipitation variations, thereby reducing water losses due to evaporation.

The evaluation of these adaptation strategies highlights the need for a balanced and integrated approach. No single solution can address all the challenges faced by the BHS hydroelectric plant; a combination of technical, environmental, and institutional measures is required. Prioritising low-risk, high-impact interventions—such as equipment upgrades and sediment management—while gradually introducing innovative solutions, will ensure immediate benefits and long-term sustainability.

A robust monitoring and evaluation framework should accompany all adaptation efforts, enabling continuous assessment and iterative improvements. By adopting a proactive and flexible approach, the BHS plant can not only maintain but also increase its electricity production capacity, contributing to a resilient and sustainable energy future. The success of these strategies ultimately depends on the commitment of all stakeholders—governments, private actors, and local communities—to collaborate towards common goals.

## **V.2 Monitoring and Evaluation of Adaptation Strategies**

The successful implementation of adaptation strategies at the BHS hydroelectric plant requires a structured framework for monitoring and evaluation (M&E). This ensures that adaptation actions remain effective, efficient, and responsive to evolving climatic and socio-economic conditions. The M&E framework should encompass performance indicators, feedback mechanisms, and a scenario-based approach aligned with the SSPs to capture long-term trends and uncertainties.

### **V.2.1 Performance Indicators and Targets**

Defining relevant Key Performance Indicators (KPIs) is essential for tracking the progress and success of each adaptation measure. These indicators must be specific, measurable, achievable, relevant, and time-bound (SMART). Examples include:

- ✚ **Energy Output Efficiency:** Monitoring kWh generated per cubic metre of water used, pre- and post-modernisation.
- ✚ **Reservoir Evaporation Losses:** Measuring annual water savings from floating photovoltaic systems.
- ✚ **Sediment Load Reduction:** Evaluating reductions in sediment accumulation through upstream sediment traps.
- ✚ **Response Time to Climatic Extremes:** Assessing early warning system activation and operational response times during floods or droughts.
- ✚ **Institutional Cooperation Index:** Quantifying engagement frequency, shared decisions, and conflict resolutions among water and energy agencies.

Baseline data should be established using historical records (1991–2021) to allow comparisons with future performance under SSP2 and SSP5 scenarios.

### **V.2.2 Scenario-Based Feedback and Learning**

Given the divergent outcomes projected under SSP2-4.5 and SSP5-8.5, adaptive management must be scenario-responsive. For instance, under SSP5's high emissions pathway, larger investments in storage and evaporation reduction (e.g., floating PV) are justified by increased ETp and reduced precipitation. Conversely, SSP2 may prioritise sediment control and equipment upgrades due to milder but still impactful climate changes.

Periodic scenario reviews (e.g., every five years) should reassess whether the observed climate indicators (rainfall, discharge, ETp) align more closely with SSP2 or SSP5 trajectories. Such reviews support adaptive learning and strategy refinement.

### V.2.3 Feedback Loops and Experience-Based Adjustment

M&E results should feed into decision-making through structured feedback loops:

- ✚ **Annual Technical Reviews:** Evaluate system performance against targets.
- ✚ **Stakeholder Roundtables:** Gather input from local communities, engineers, and policy-makers on adaptation outcomes.
- ✚ **Cross-Learning Mechanisms:** Compare results with similar regional hydroelectric projects to identify transferable lessons.

For example, if sediment control underperforms in reducing reservoir siltation, operational protocols or infrastructure designs must be revised. Similarly, if floating PV systems prove highly effective in reducing evaporation and boosting energy yield, expansion phases can be accelerated.

### V.2.4 Evaluation under SSP Scenarios

Using SSP2 and SSP5 as guiding frameworks enables dynamic evaluation of strategy resilience:

- ✚ **Under SSP2-4.5,** moderate adaptation is sufficient but must emphasise efficiency and ecosystem preservation.
- ✚ **Under SSP5-8.5,** aggressive investment in water-saving technologies and energy diversification becomes imperative.

Indicators such as a 5% drop in precipitation (wet season) or a 10% rise in ETp (dry season) should trigger pre-defined adaptation escalations.

### V.2.5 Conclusion: Towards a Resilient and Adaptive System

A strong M&E system rooted in quantitative metrics and qualitative stakeholder input ensures that adaptation strategies evolve with emerging challenges. Regular review cycles, tied to climate scenario evolution and empirical data, create an adaptive management ecosystem. This promotes accountability, encourages innovation, and safeguards the long-term viability of the BHS hydroelectric system amid uncertainty. Ultimately, integrating monitoring, evaluation, and learning into adaptation planning enhances resilience and enables informed decision-making in the face of climate change.

## **GENERAL CONCLUSION**

This study has provided a comprehensive and detailed evaluation of the potential impacts of climate change on the Boali Hydropower Station (BHS) in the Central African Republic, leveraging climate projections based on Shared Socioeconomic Pathways (SSPs) SSP2-4.5 and SSP5-8.5. The extensive analysis conducted on temperature and precipitation trends from 1991 to 2021 within the M'Bali River basin illustrates significant warming, with annual maximum temperatures rising by about 0.1091°C and minimum temperatures by roughly 0.077°C. This temperature rise directly escalates evapotranspiration rates, reducing water availability

necessary for efficient hydroelectric production, thus affirming Hypothesis H1 regarding climate impacts on water resource sustainability.

Simultaneously, the precipitation patterns exhibited a declining trajectory, registering an approximate decadal decrease of 10.7 mm, consequently complicating sustainable water management efforts. Addressing research question Q1, the observed pronounced seasonal variations in both temperature and rainfall markedly influence the basin's hydrological regime, directly affecting the operational dynamics and stability of the hydropower station.

Regarding research question Q2 on inflow fluctuations to the M'Bali reservoir, a notable downward trend has been identified, decreasing from 68.5 m<sup>3</sup>/s in 1991 to 62.9 m<sup>3</sup>/s in 2021. This decline corroborates Hypothesis H2, asserting that climate change significantly affects the basin's hydrology. This relationship is essential to understanding how climatic variations impact both local ecosystems and the operational reliability of the hydropower infrastructure.

In response to research question Q3 on the future viability of electricity generation at BHS, predictive analyses employing the Random Forest model suggest that, under the moderate SSP2 scenario, electricity output could remain relatively stable, averaging around 140 GWh per annum. Conversely, under the more extreme SSP5 scenario, projected peak temperature rises up to 39°C by 2099, combined with reduced inflows, considerably threaten the station's capacity, confirming Hypothesis H3. These insights underscore the urgent need for strategic planning and robust adaptive management of water resources.

Nevertheless, this study has confirmed Hypothesis H4, demonstrating that proactive and comprehensive adaptation strategies can be developed and effectively implemented to maintain or even enhance electricity production despite climate uncertainties. Recommended interventions encompass upgrading aging hydroelectric equipment, adopting innovative technologies such as floating solar photovoltaic installations to mitigate evaporation losses, implementing strategic sediment management, and dynamic water resource management. Furthermore, exploring additional hydropower sites, notably Labaye and Kotto, alongside the expansion of photovoltaic power stations, presents viable solutions to diversify and strengthen the national energy portfolio, thereby increasing resilience to climate-induced uncertainties.

This research underscores the critical urgency of adopting balanced, integrative, and adaptive water resource management practices to mitigate the anticipated impacts of climate change effectively. The documented annual inflow reduction rate of approximately 0.0153 m<sup>3</sup>/s accentuates the necessity for proactive, evidence-based policymaking and infrastructure

adaptations to future climatic conditions. Given the complexity and scale of the challenges, prioritizing immediate and impactful actions, alongside incremental adoption of innovative solutions, will be essential to ensuring both immediate and sustained long-term energy security.

Implementing a robust framework for monitoring and evaluation will enable continuous refinement and adaptability of these strategies, responding dynamically to evolving climatic and socio-economic contexts. The collaborative engagement of governmental bodies, private sector stakeholders, and local communities is paramount for the success of these strategies. This comprehensive assessment thus provides a solid foundation for future research aimed at deepening understanding of hydrological dynamics and further enhancing the resilience and sustainability of hydropower systems within the Central African Republic.

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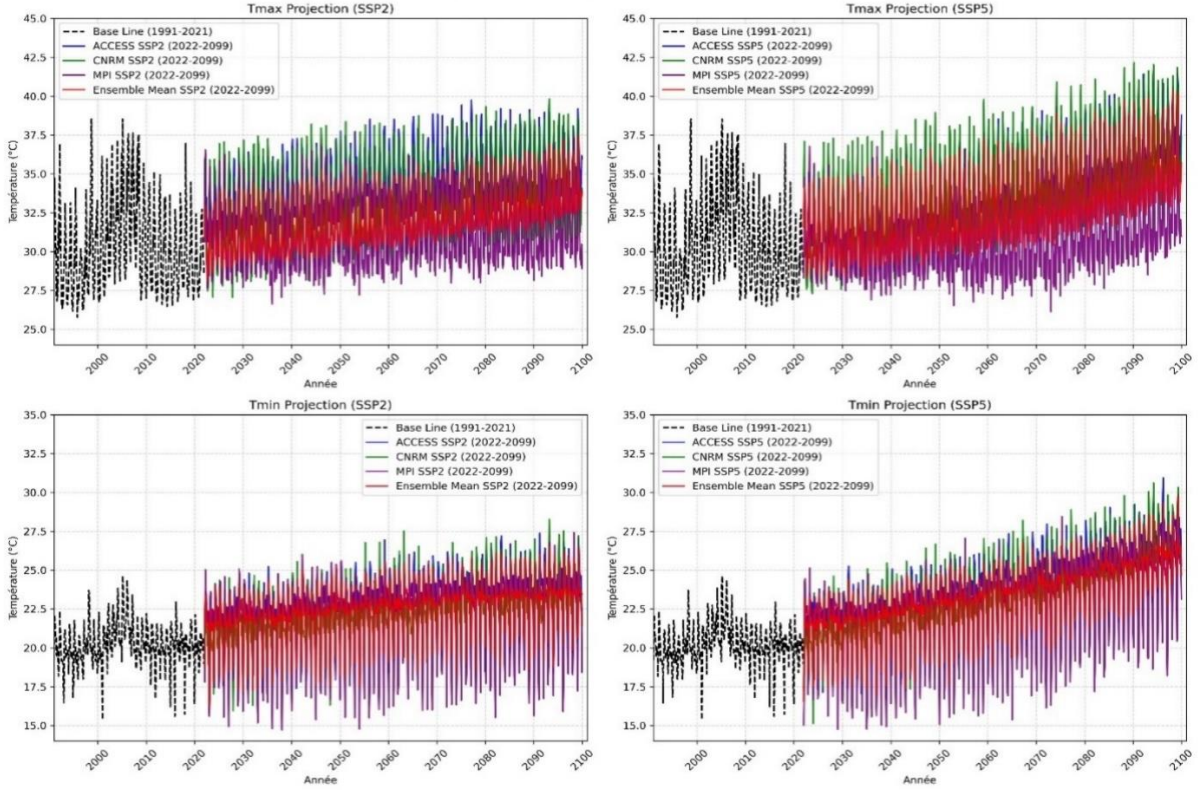
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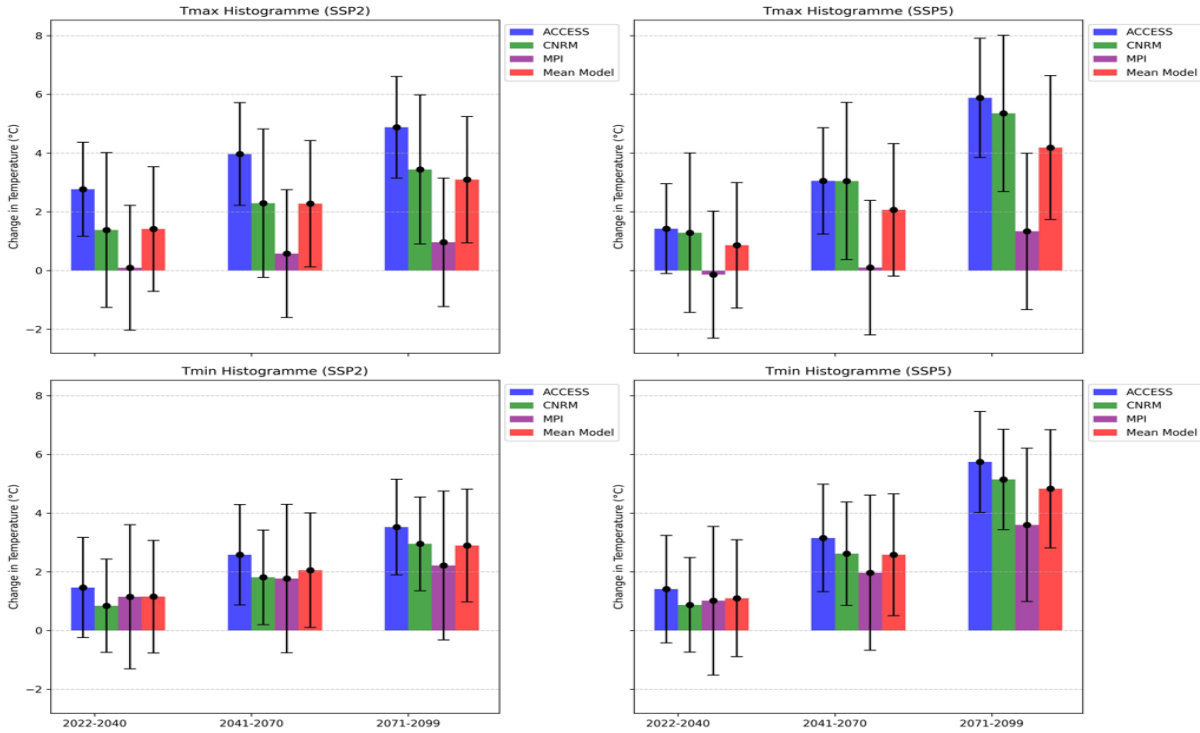
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# ANNEXE

Projections de Température (SSP2 & SSP5)



Change in maximum and minimum temperature (SSP2 & SSP5)



### Electricity Production Forecast per Climate Scenario

