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Presented by

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**ASSESSING FUTURE CLIMATE CHANGE IMPACTS ON HYDROPOWER  
GENERATION IN THE SHIRE RIVER BASIN-MALAWI**

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**Assessing Future Climate Change Impacts on Hydropower Generation in the Shire  
River Basin, Malawi**

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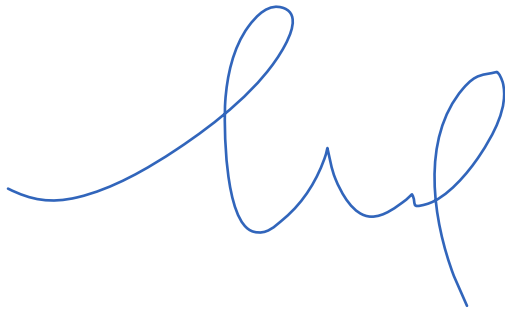
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Tlemcen, Algeria**

**March, 2024**

## **APPROVAL SHEET**

The undersigned approves that they have read and hereby recommend for submission to Pan African University of Water and Energy Sciences including Climate Change (PAUWES) a research thesis entitled: ASSESSING FUTURE CLIMATE CHANGE IMPACTS ON HYDROPOWER GENERATION IN THE SHIRE RIVER BASIN, MALAWI, in partial fulfilment of the requirements for the award of MASTER OF SCIENCE IN CLIMATE CHANGE (TECHNICAL FOCUS).

Prof Amos T. Kabo-Bah (Supervisor):

A handwritten signature in blue ink, appearing to be 'AKB', written in a cursive style.

## **STATEMENT OF THE AUTHOR**

I, Mervis Henry Namakhwa, hereby declare that this thesis/dissertation is my work. I have followed all ethical principles of scholarship in the preparation, data collection, data analysis, and completion of this thesis. I have given all scholarly matter recognition through accurate citations and references. I affirm that I have cited and referenced all sources used in this document. I have made every effort to avoid plagiarism.

I submit this document in partial fulfilment of the requirements for a degree from Pan African University. I declare that I have not submitted this document to any other institution for the award of an academic degree, diploma, or certificate.

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Date 22<sup>nd</sup> March, 2024

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## **DEDICATION**

I dedicate this dissertation to my parents, Henry and Daisy Namakhwa, for their constant support and encouragement.

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## ABSTRACT

The global hydropower sector relies on surface water flows of substantial and predictable volume, which makes it vulnerable to climate change. This study focused on assessing the risks posed by climatic factors on river flow regimes and their impact on future hydropower production in the Shire River Basin. The study employed Mann-Kendall test and Sen's slope estimator to detect climatic trends in the time series data and estimate the magnitude of the trend. Future river flow regimes were analysed using HEC-HMS by integrating future climatic projections data from CIMP6 models under ssp2-4.5 and ssp5-8.5 scenarios. The performance of the climate models was evaluated using the Coefficient of Determination ( $R^2$ ), Nash Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE) and Percent Bias (PBIAS), including a Pearson Matrix Scatter Plot for the historical data to check how well the models represented the study area. Similarly, the hydrological model's performance was assessed using the NSE and  $R^2$  of the simulated flows against the observed. Flow Duration Curves were used to assess the future impacts of the river flow regimes on hydropower generation at low flow regimes. Mann-Kendall results showed a significant increasing rainfall trend for 68% of the stations in the basin. Minimum temperatures did not show any significant trends, whereas all stations showed a significant increasing trend for maximum temperatures. Both climate and hydrological models showed good performance in representing observed data. Future rainfall patterns indicated a general increase of 13-28% in wetter months, and a decrease in drier months of 3-8% under all scenarios, with a more notable increase in the 2030-2064 period under ssp5-8.5. Future river flow regimes took a similar pattern as rainfall, with a marked increase in all scenarios, but particularly very high under ssp5-8.5 but showing lowest flows in the drier months in the 2030-2064 period. High flows highlight the potential of flooding events in the basin which could affect the hydropower equipment, but could also increase the potential of the sector. Frequency analysis on the low flows, shows susceptibility of the hydropower sector to climate change as it is projected to cause low power generation. The findings from this study underscore the importance of diversifying the energy mix, while protecting the hydropower infrastructure from potential flooding events.

Keywords: Hydropower, Flow Duration Curves, Climate Scenarios, Low flows.

## ABSTRAIT

Le secteur mondial de l'hydroélectricité dépend de flux d'eau de surface d'un volume important et prévisible, ce qui le rend vulnérable au changement climatique. Cette étude s'est concentrée sur l'évaluation des risques posés par les facteurs climatiques sur les régimes d'écoulement des rivières et leur impact sur la production hydroélectrique future dans le bassin de la rivière Shire. L'étude a utilisé le test de Mann-Kendall et l'estimateur de pente de Sen pour détecter les tendances climatiques dans les données de séries chronologiques et estimer l'ampleur de la tendance. Les futurs régimes d'écoulement des rivières ont été analysés à l'aide de HEC-HMS en intégrant les données de projections climatiques futures des modèles CIMP6 selon les scénarios ssp2-4.5 et ssp5-8.5. Les performances des modèles climatiques ont été évaluées à l'aide du coefficient de détermination ( $R^2$ ), de l'efficacité de Nash Sutcliffe (NSE), de l'erreur quadratique moyenne (RMSE) et du pourcentage de biais (PBIAS), y compris un diagramme de dispersion de matrice de Pearson pour vérifier les données historiques. Dans quelle mesure les modèles représentaient la zone d'étude. De même, les performances du modèle hydrologique ont été évaluées en utilisant le NSE et le  $R^2$  des débits simulés par rapport aux débits observés. Les courbes de durée d'écoulement ont été utilisées pour évaluer les impacts futurs des régimes d'écoulement des rivières sur la production hydroélectrique aux régimes d'étiage. Les résultats de Mann-Kendall ont montré une tendance significative à la hausse des précipitations pour 68 % des stations du bassin. Les températures minimales n'ont montré aucune tendance significative, alors que toutes les stations ont montré une tendance à la hausse significative pour les températures maximales. Les modèles climatiques et hydrologiques ont montré de bonnes performances dans la représentation des données observées. Les futurs régimes de précipitations indiquaient une augmentation générale de 13 à 28 % pendant les mois les plus humides et une diminution de 3 à 8 % pendant les mois les plus secs dans tous les scénarios, avec une augmentation plus notable au cours de la période 2030-2064 sous ssp5-8.5. Les futurs régimes d'écoulement des rivières ont suivi un schéma similaire à celui des précipitations, avec une augmentation marquée dans tous les scénarios, mais particulièrement très élevée sous ssp5-8.5, mais montrant les débits les plus faibles au cours des mois les plus secs de la période 2030-2064. Les résultats de cette étude soulignent l'importance de l'atténuation pour réduire l'impact du changement climatique sur les régimes d'écoulement des rivières et, de manière inhérente, sur la production hydroélectrique.

Mots clés : Hydroélectricité, Courbes de durée des écoulements, Scénarios climatiques, Étages.

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## LIST OF ABBREVIATIONS

ACCESS-CM2-	- Australian Community Climate and Earth System Simulator Coupled Model
AR4	- Assessment Report 4
AR5	- Assessment Report 5
AR6	- Assessment Report 6
CMIP	- Coupled Model Intercomparison Project
CN	- Curve Number
CORDEX	- Coordinated Regional Downscaling Experiment
DEM	- Digital Elevation Model
EGENCO	- Energy Generating Company
ESCOM	- Electricity Supply Cooperation of Malawi
FCFA	- Future Climate for Africa
FDC	- Flow Duration Curves
GCMs	- Global Climate/Circulation Models
GDP	- Gross Domestic Product
GHG	- Greenhouse Gases
GIS	- Geographic Information System
GoM	- Government of Malawi
HEC-HMS	-Hydrologic Engineering Center Hydrologic Modeling System
IHA	- International Hydropower Association
IPCC	- Intergovernmental Panel on Climate Change
IQR	- Interquartile Range
IWA	- International Water Association
JICA	- Japanese International Cooperation Agency
KDE	- Kernel Density Estimation
LEAP	- Long-range Energy Alternatives Planning system
MIROC6	- Model for Interdisciplinary Research on Climate Version 6
MK	- Mann-Kendall
MRI-ESM2-0	- Meteorological Research Institute Earth System Model Version 2
MW	- Megawatts
NAPA	- National Adaptation Programme of Action
NASA	- National Space Agency
NSE	- Nash Sutcliff Coefficient of Efficiency
PV	- Photovoltaic

RCMs	- Regional Climate Models
RCPs	- Representative Concentration Pathway
RMSE	- Root Mean Square Error
RoR HP	- Run of River Hydropower Project
SCS	- Soil Conservation Service
SDGs	- Sustainable Development Goals
SRB	- Shire River Basin
SSPs	- Shared Socioeconomic Pathways
SWAT	- Soil and Water Assessment Tool
UNFCCC	- United Nations Framework Convention on Climate Change
WEAP	- Water Evaluation and Planning
WMO	- World Meteorological Organisation

# 1. INTRODUCTION

## 1.1 Background Information

Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period, typically decades or longer, and it may be due to natural internal processes or external factors such as persistent changes to the atmosphere or changes in land use (IPCC, 2012). Article 1 of the United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." (S. K. Kaunda & F., 2013; UNFCCC, 1992).

Climate change is one of the world's greatest challenges of the 21st century as numerous studies, using diverse methodologies and measures of climate expertise, have quantified the scientific consensus, finding between 90% and 100% agreement on human-caused global warming with multiple studies converging on 97% agreement (Myers et al., 2021). Climate change is a critical factor in altering the hydrological cycle resulting in large-scale impacts on water availability, both globally and locally (Faquseh & Grossi, 2023). The global hydropower sector as it stands relies on surface water flows of substantial and predictable volume, which makes it vulnerable to climate change (Wasti et al., 2022). However, climate change impacts on hydropower generation will not be distributed uniformly across the globe (Obahoundje et al., 2022).

African economies that rely primarily on hydropower for electricity generation are particularly sensitive to climate variability (Kabo-bah et al., 2018). In sub-Saharan Africa, more than 580 million people do not have access to electricity (Lumbroso et al., 2015a). One of the causes is the region's underutilized hydropower potential, with only 11% of it being used (IWRD, 2021). As such, massive hydropower plant commissioning and planning are moving forward quickly (Borowski, 2022). It is undisputable that hydropower is playing an indispensable role in meeting the growing energy needs in the region, but at the same time, it is continually being impacted by climate change (Cáceres et al., 2022). Nevertheless, climate change impacts are rarely explicitly considered when planning new hydropower projects in the region as most countries do not have regulations that include climate change in their planning (Lumbroso et al., 2015a). As such, studies on the future of hydropower in

relation to climate change are of essential interest. According to Bhave et al. (2022), mainstreaming climate resilient development into on-going planning and policy making by governments is of vital importance. This can help identify risks emerging from the complex interactions of coupled human-environment systems, myriad non-climate stressors (e.g., population growth, urbanization, land degradation etc.) and climate stressors (variability and change).

## **1.2 Statement of the Problem**

Over 95% of the electricity produced in Malawi is from hydropower in the Shire River, making it the most significant energy source (Zuzani et al., 2019). However, for more than 50 years, the Shire River Basin has experienced an increase in the amplitude and frequency of rainfall fluctuation and extreme weather events, in part, attributed to climate change (FCFA, 2021).

Due to decreased basin runoff from irregular rainfall and more frequent and extended drought conditions, the basin's capability for energy production is lowered. The below normal rainfall seasons of 2015/2016 resulted in reduced river flow, which decreased hydropower generation by over 50% (ESCOM, 2017). The second scenario sees decreasing reservoir capacity (lifespan) and water quality due to erosion caused by increased sediment load to reservoirs as a result of increased rainfall intensity (Chaima et al., 2021). The 2022 flash floods during tropical storm Ana caused extensive damage to the Kapichira dam and fuse plug, resulting in the drawdown of the reservoir and putting the plant on the Shire River out of operation (Hydropower and Dams, 2022). Officials at the Electricity Generation Company (EGENCO), documented that Malawi lost about 130 megawatts representing 30% of the total hydropower generation following the shutdown of its Kapichira Power Station due to the storm (Masina, 2022). This resulted in over four months of power rationing which had a huge socio-economic impact (Gibson et al., 2017). These disruptions underscore the challenges of chronic electricity scarcity and impede the achievement of development targets, particularly the Sustainable Development Goal (SDG) number 7 that targets provision of sustainable, reliable, accessible and affordable electricity (Gannon et al., 2018). Even more so, World Bank (2020) highlights that Malawi loses up to 7% of its Global Domestic Product (GDP) a year due to power cuts. Nevertheless, the Malawi government has planned for new hydroelectric plants to be built along the Shire River in the near future (Bhave et al., 2022). As such, unpredictable changes in water availability clearly pose

significant risks to the future viability of hydropower and electricity security (Gannon et al., 2018).

### **1.3 Relevance of the Study**

In order to recognize and mitigate risks arising from climatic stressors and human systems, Bhave et al. (2020) emphasize the critical significance of mainstreaming climate resilient development into ongoing planning and policy. Although the Shire River Basin has been extensively studied, few studies have focused on the relationship between hydropower and climate change, hence creating a knowledge gap. It is important to note that availability of up-to-date hydrological data and monitoring systems is crucial for predicting and mitigating climate-related risks as they could inform decision making, policy planning and regulations for the vulnerable hydropower sector (C. S. Kaunda et al., 2012). The absence of such data can thus impede the development of climate-resilient projects.

This study thus aims to pinpoint risks that result from climatic factors on river flow regimes and their influence on future hydropower production for plausible adaptation alternatives for this sector. The development of appropriate policies for the management of the Shire River Basin to ensure the dependability and sustainability of hydropower generation would benefit greatly from these findings, which satisfy goals 7 and 13 of the Sustainable Development Goals (SDGs). The findings of the study also support efforts in achieving the African Union 2063 Agenda, particularly on Environmental Sustainability and Climate Resilience for a prosperous Africa.

### **1.4 Research Objectives**

#### **1.4.1 Main Objective**

The main objective of this study is to assess the future impacts of climate change on hydropower generation in the Shire River Basin.

#### **1.4.2 Specific Objectives**

The specific objectives are to:

- a) Analyse observed rainfall and temperature trends in the shire river basin from 1991 – 2020.
- b) Simulate future river flow regimes in climate scenarios in the Shire River Basin
- c) Assess impacts of simulated future river flow regimes on hydropower generation.

## **1.5 Research Questions**

The study is designed to address the following research questions which will be explored throughout the thesis.

- a) What are the observed rainfall and temperature trends in the Shire River Basin between 1991 to 2020?
- b) How are the future river flow regimes like in climate scenarios in the Shire River Basin?
- c) What are the future impacts of future river flow regimes on hydropower generation in the Shire River Basin?

## **1.6 Limitations of the Study**

The limitation of this study is that discharge gauging stations are not uniformly distributed throughout the catchment area and therefore assumptions have been made. This study also focuses mainly on the impacts of climate change without analyzing in depth the impacts of land use, population change and sedimentation which could also affect the river flow regimes in the study area.

## **1.7 Thesis Outline**

This Thesis is divided into six chapters:

Chapter One gives the background, problem statement, research objectives, research question, relevance of the study, Scope of the study and limitations. Chapter Two is a critical literature review on the study topic. Chapter Three describes the material, methods and approach used in the execution of the study. Chapter Four presents the data collected, analysed and results obtained from the research. This chapter also captures the discussion of the results by comparing and contrasting the current study findings with those from related studies. Chapter Five contains conclusions, and Chapter Six practical recommendations on sustainable hydropower generation in the face of climate change.

## **2. LITERATURE REVIEW**

### **2.1 Climate Change Concepts**

#### **2.1.1 Weather**

According to WMO (2023), weather describes short term changes in the atmospheric events - such as fog, rain, snow, blizzards, wind and thunder storms, tropical cyclones, etc. - in a specific place and time. Weather forecasts provide essential information for decision-making in many other areas for agriculture, water resources management, safe transportation etc. Even though there's only one atmosphere on Earth, weather is not the same all around the world. Weather is different in different parts of the world and changes over minutes, hours, days, and weeks.

#### **2.1.2 Climate Change**

Climate characterizes the average weather conditions for a particular location over a long period of time atmospheric, usually defined as 30 years or more. Climate change is defined in many ways. On one hand, Article 1 of the United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." (S. K. Kaunda & F., 2013; UNFCCC, 1992). On the other hand, (IPCC, 2012) defines climate change as a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period, typically decades or longer, and it may be due to natural internal processes or external factors such as persistent changes to the atmosphere or changes in land use.

### **2.2 Climate Modelling**

It is worth noting that the impacts of climate change depend critically on the relationship between temporal change and spatial heterogeneity because climate is multi-dimensional varying from place to place and reliant on factors such as latitude, vegetation, distance from the sea etc. (Ackerly et al., 2010). Nonetheless, many studies have used Global Climate Models (GCMs) to evaluate the impact of future climate change on hydropower in different regions, including at the global scale (Zhong et al., 2021). This is because, much research has evaluated the ability of GCMs to reproduce present and future climatology (Dosio et al., 2019; Sylla et al., 2018; Tellman et al., 2021). Despite the abundance of these GCMs running numerous scenarios, GCMs are however too coarse to assess the impact of climate change

at a country scale let alone for examining specific hydrological basins within a country (Fant et al., 2013). Therefore, downscaling is required to increase spatial resolution and reduce biases before climate projections can be used for impact assessment and adaptation planning (Bahati et al., 2021).

### **2.2.1 Climate Projection**

A projection of the response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/radiative-forcing scenario used, which are based on assumptions concerning, e.g., future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty (IPCC, 2012).

### **2.2.2 Climate Scenario**

A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios (IPCC, 2012).

### **2.2.3 Climate Models**

These are numerical representations of the climate system that is based on the physical, chemical, and biological properties of its components, their interactions, and feedback processes, and that accounts for all or some of its known properties (IPCC, 2012). Climate models are the primary means for scientists to understand how the climate has changed in the past and may change in the future. In many ways, climate modelling is just an extension of weather forecasting, but focusing on changes over decades rather than hours (Gusain et al., 2020). At their most basic level, climate models use equations to represent the processes and interactions that drive the Earth's climate. These advances have underpinned climate policy decisions on national and international scales for the past five decades (Salimi et al., 2023).

The main inputs into models are the external factors that change the amount of the sun's energy that is absorbed by the Earth, or how much is trapped by the atmosphere (van Vliet et al., 2016). These inputs are based on assumptions concerning future socioeconomic and technological developments that may or may not be realized and are therefore subject to

substantial uncertainty (Warnatzsch & Reay, 2019). Nevertheless, climate projections are widely used as the foundation for building climate scenarios, but they also typically require other data, such as observations of the actual climate (Falchetta et al., 2019). Climate scenarios are termed potential pathways for the concentration of greenhouse gases in the atmosphere, based on how technology, energy and land use change over the centuries ahead will vary (McSweeney and Hausfather, 2018).

Climate models are constantly being updated, as different modelling groups around the world incorporate higher spatial resolution new physical processes and biogeochemical cycles (Stouffer et al., 2017). The Coupled Model Intercomparison Project (CMIP) was started by the World Climate Research Program (WCRP) in 1995 (Meehl et al., 2000). The CMIP has undergone several phases, from CMIP Phase 1 (CMIP1); Phase 2 (CMIP2); Phase 3 (CMIP3); Phase 5 (CMIP5), to the most recent Phase 6 model (CMIP6), as a result of scientific advancement and a progressively better knowledge of the mechanisms causing climate change (Li et al., 2021). Model creation and refinement are encouraged for sharing simulated climate data, which is established by CMIP. As a result, it has gradually grown and evolved into a crucial component of climate research (Hausfather, 2020).

Over the years, most model projections have used one or more of the “Representative Concentration Pathways” (RCPs) from the CIMP5 which provide plausible descriptions of the future, based on socio-economic scenarios of how global society grows and develops (van Vliet et al., 2016). RCPs are a set of four pathways developed for the climate modelling community as a basis for long-term and near-term modelling experiments (Bahati et al., 2021). The four RCPs together span the range of year 2100 radiative forcing values from 2.6, 4.5, 6.0 and 8.5 W/m<sup>2</sup> hence termed RCP2.6, RCP4.5, RCP 6.0 and RCP8.5 respectively (Fan et al., 2019). CMIP6 represents a substantial expansion over CMIP5, in terms of the number of modelling groups participating, the number of future scenarios examined and the number of different experiments conducted (Li et al., 2021).

Instead of starting with 2005 for future scenarios in CMIP5, the recently released CMIP6 has a different start year (2015), with updated emission, concentration, and land-use scenarios, known as shared socioeconomic pathways (SSPs) (Kamruzzaman et al., 2021).

The goal of CMIP6 is to get a deeper understanding of climate variability by conducting a series of well-coordinated experiments (Zhao et al., 2022).

#### **2.2.4 The Shared Socioeconomic Pathways (SSPs)**

The SSPs span the range of year 2100 radiative forcing values from SSP1.9, SSP2.6, SSP4.5, SSP7.0 and SSP8.5 as defined in the IPCC Sixth Assessment Report on climate change in 2021 (Dosio et al., 2021). The CMIP6 models more accurately represent Earth's physics which allows for a better assessment of climate change impacts (Gusain et al., 2020). Even more so, CMIP6 models have greater resolution and enhanced dynamical processes (Sambou et al., 2023). Some studies have reported the robustness of the new CMIP6 over the CMIP5 across the globe in various river basins (Da Silva et al., 2022; Duratorre et al., 2020; Sha et al., 2021; Zhao et al., 2022).

The following are climate change scenarios of projected socioeconomic global changes up to the year 2100:

- SSP1-1.9 represents very low GHG emissions: CO<sub>2</sub> emissions cut to net zero around 2050
- SSP1-2.6 represents low GHG emissions: CO<sub>2</sub> emissions cut to net zero around 2075
- SSP2-4.5 represents intermediate GHG emissions: CO<sub>2</sub> emissions around current levels until 2050, then falling but not reaching net zero by 2100
- SSP3-7.0 represents high GHG emissions: CO<sub>2</sub> emissions double by 2100
- SSP5-8.5 represent very high GHG emissions: CO<sub>2</sub> emissions triple by 2075 (IPCC, 2021).

In summary, SSPs from CIMP 6 offer a more thorough framework for analysing how climate will change in the future. In addition to greenhouse gas emission scenarios, they take into account the socioeconomic and technological advancements that have an impact on the use of mitigation and adaptation measures for climate change. Incorporating SSPs allows for a more realistic picture of the future.

### **2.3 Climate Change and Hydropower Overview**

The energy supply sector is by far one of the greatest contributors to global warming due to its enormous emission of greenhouse gases (GHG). Hydropower is one of the most important renewable energy sources in the world (Berga, 2016; Dorber et al., 2020; Ubierna & Karki, 2022). It has a significant role to play in the era of Climate Change where Green Energy is the key to reducing global warming (Lu et al., 2020; Siri et al., 2021; Zhang et al., 2018). In

this regard, it becomes important to evaluate the contributions, strategies, risks, uncertainties, and opportunities related to hydropower generation and climate change (Antwi & Sedegah, 2018). This energy is directly dependent on water resources and the hydrological cycle which are significantly affected by climate change (Hamududu & Killingtveit, 2016; Jakimavič et al., 2020; Uamusse et al., 2020). However, the future global climate is uncertain and thus poses some risks for the hydropower generation sector (Bahati et al., 2021; Turner, Ng, et al., 2017). Ongoing climate changes are likely to influence the availability/amount of this energy resource (Gannon et al., 2018; Kouame et al., 2019; Stanzel & Kling, 2014). Also, hydro-climatic extremes can affect the reliability of electricity supply, particularly in countries that depend greatly on hydropower and have a limited adaptive capacity (Savelsberg et al., 2018).

Africa does not significantly contribute to greenhouse gas emissions, which exacerbate the effects of climate change, but the continent is at a greater disadvantage in dealing with the effects (Antwi & Sedegah, 2018). According to Kabo-bah et al.(2018), African economies that rely primarily on hydropower for electricity generation are particularly sensitive to climate variability. In sub-Saharan Africa, 160 million grid-connected electricity consumers live in countries where hydropower accounts for over 50% of the total power supply (Falchetta et al., 2019). However, most countries in the region do not explicitly consider climate change impacts in the planning of hydropower projects (Lumbroso et al., 2015). Moreover, water availability issues present a growing risk in light of competing water users for irrigation, municipal water supply and hydropower, especially for countries that experience unimodal rainfall patterns such as Malawi (Falchetta et al., 2019). According to Antwi & Sedegah (2018), the well-endowed river basins in Sub-Saharan Africa, if properly managed in the face of climate change, could provide the needed hydropower energy in the continent.

Existing literature focusing on the impacts of climate change on hydropower production, incorporates the GCMs, hydrological models, hydrological budget, and hydropower production to establish interlinkages. Other studies include historical climatic trends, land-use changes, and water management models e.g., WEAP (Water Evaluation and Planning system) and LEAP (Long-range Energy Alternatives Planning system) to assess their interactions on hydropower production (Fant et al., 2013; Obahoundje et al., 2022; Spalding-Fecher, 2018). The selection of hydrological models used for the assessment of hydropower generation depends on the type of facility. This is because there are three types of

hydropower facilities: diversion (run-of-river), impoundment/storage, and pumped storage. Some hydropower plants use dams and some do not (Energy.gov, 2021). For hydropower plants with an impoundment, reservoir-based models e.g. HEC-ResSim, SWAT, HEC-ResPRM among others are used in most studies (Stanzel & Kling, 2014; Sylla et al., 2018; Zhao et al., 2022). Whereas, the HEC-HMS and the Poli-Hydro model are used by most researchers for run-of-river schemes (Bombelli et al., 2021).

### **2.3.1 Types of Hydropower Plants**

- Run-of-River Type.

A run-of-river hydropower project (RoR HP), as shown schematically in Figure 2.1a, generates electricity from the river flow without significant impoundment. Water flow in the river depends on precipitation, groundwater flow and runoff: these parameters may have substantial daily, monthly, or seasonal variations. Therefore, ideally for a variable flow river, a RoR hydropower system will have a variable power generation that mimics the river flow profile. To ensure some limited degree of adaptation to the electricity demand profile, the RoR HP includes some short-term storage (known as pondage), to provide extra electricity demand (limited peak demand) when required. Without significant storage system, RoR HP schemes are vulnerable to changes in the river system that affect amount of flow and its water quality, for example, droughts, floods, and water abstractions (C. S. Kaunda et al., 2012).

RoR HP scheme is stated to be suitable for a river that has minimum flow variation or a river that is regulated by a large natural reservoir (e.g., a lake). The RoR HP projects are not associated with a lot of construction activities, and because of this, RoR HP projects possess economic as well as environmental advantages over other hydroelectricity generating systems of the same installed capacity. RoR hydropower generation technology is used in many countries of the world. For example, in Malawi, almost all of the hydropower electricity generation projects are RoR HP plants cascaded along the Shire River (C. S. Kaunda et al., 2012).

- Storage/Impoundment Hydropower.

A storage hydropower project has a reservoir behind a dam to store water for later power generation (and other purposes), as shown schematically in Figure 2.1b. The reservoir regulates the flow and, thus, storage hydropower plants have more power reliability than RoR HP plants. The generating stations may be located just at the dam toe or further downstream connected to the reservoir through tunnels or pipelines.

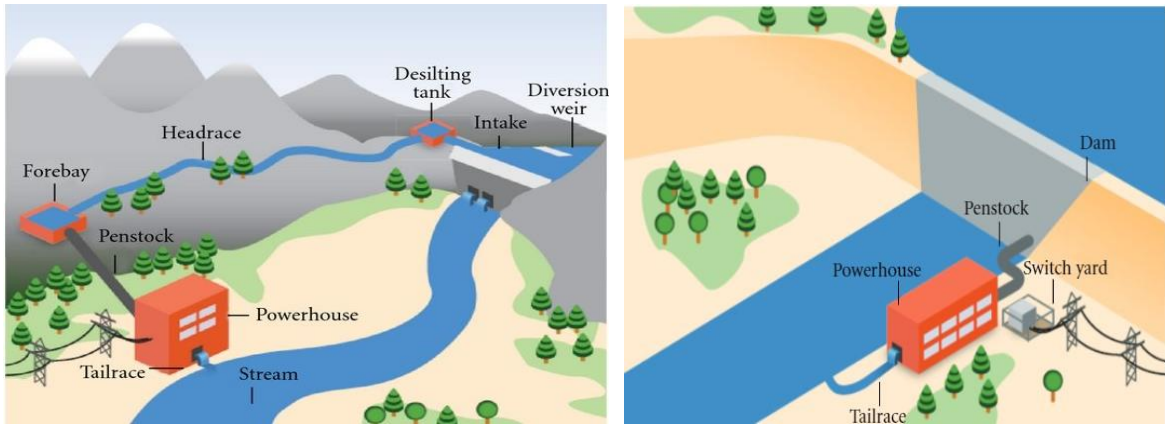


Figure 2.1.a&b. RoR and Storage Hydropower Technology (C. S. Kaunda et al., 2012)

Storage HP projects are typically used for highly variable flows in the middle reaches of a river system. The opportunities offered by the topography influence the design and type of reservoir that can be constructed on the river. Storage HP schemes constructed on gorges and canyons are associated with high output and efficiency (C. S. Kaunda et al., 2012).

- Pumped Storage

Pumped storage plants, are not energy sources, but are simply hydraulic energy storage devices. Practically, in terms of both design and economics, pumped storage technology is stated to be the only large form of grid-based electric energy storage currently available to the power utility. In pumped storage system, water is given hydraulic energy by a pump. Water is pumped from a lower reservoir into an upper reservoir, using excess electricity generated by the hydropower plant during off-peak hours or at any other times when demand is reduced (C. S. Kaunda et al., 2012).

## 2.4 Impacts of Climate Change on Hydropower Generation

Though an increase in amount of annual river discharge can sometimes simply translate to an increase in hydropower production, fluctuations in discharge affect different types of facilities differently (Duratorre et al., 2020). Run-of-river schemes, for example, may be more vulnerable to decreased amounts of discharge because they are directly dependent on the river's flow, whereas reservoir dams may be able to compensate better for decreased amounts of water by adapting the management plan for the reservoir volume (Likoya, 2019). Figure 2.2 below shows climate change effects on different characteristics of hydropower schemes. By delivering water supply at varied and unpredictable times, temporal variability negatively impacts hydroelectric production. However, it impacts reservoir dams less than

run-of-river facilities because reservoir dams have the capacity to store water, thereby accounting for these variations in reservoir volume. In the diagram, discharge refers to the annual discharge, which can be directly correlated to changes in precipitation (Blackshear et al., 2011).

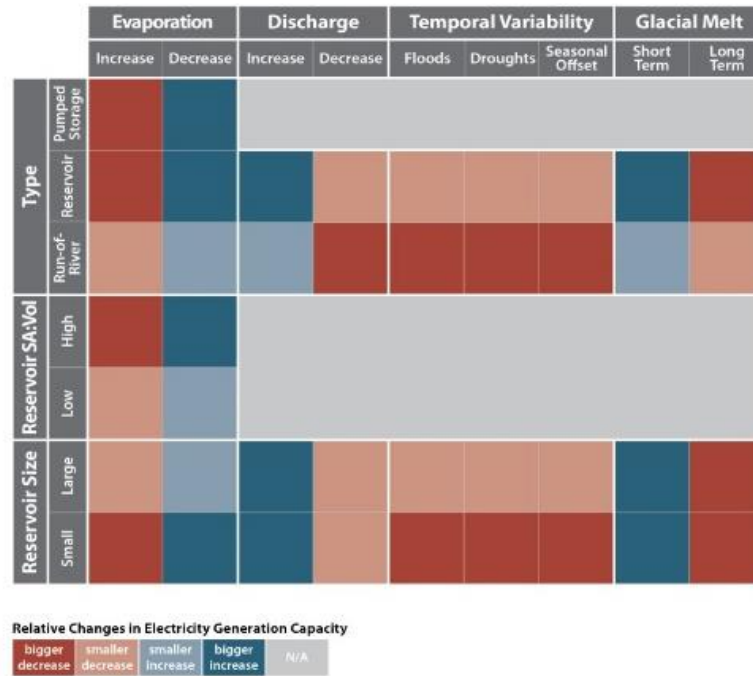


Figure 2.2: Framework of climate change effects on different characteristics of hydropower schemes (Blackshear et al., 2011).

- Flooding

Dams can control the flood pulse of a river and help buffer downstream areas from dangerous impacts. Flooding has the potential to increase river flows and hydropower generation as long as the excess river flow level remains within the dam’s reservoir capacity. However, in extreme cases, floods can also prove destructive to dams. The large sediment and debris loads carried by floodwaters can block dam spillways and powerful masses of water can damage important structural components (Uamusse et al., 2020).

- Droughts

The extent to which flooding is beneficial or detrimental depends heavily of the size of the dam’s reservoir. Droughts may present the most obvious threat to hydroelectric generation, as they reduce the amount of water available to produce electricity. Many regions have experienced droughts in the last several decades that greatly reduced energy production, reducing up to half of their electrical production capacity in some cases (Borowski, 2022).

In a nutshell, hydropower is playing an important role as the global energy system moves towards a less carbon-intensive and sustainable future. However, climate change uncertainties pose risks to the sustainability of hydropower. As such, assessing the impacts of climate change on hydropower generation is of vital importance. Such research would inform decision-making processes, facilitate the development of appropriate adaptation strategies, enhance the understanding of climate change dynamics, and contribute to broader climate change mitigation efforts.

## **2.5 Overview of Climate Change in Malawi**

Malawi is a land locked country located in Southern Africa, between latitudes 9°22'S and 17°3'S and longitudes 33°40'E and 35°55'E. The country is about 900 km long and 80 - 161 km wide, with a total area of 118,484 km<sup>2</sup> (11.8 million ha), of which 80% is land. The remaining 20% is covered by water, mainly comprising Lake Malawi, which is about 586 km long and 16 - 80 km wide. The rest of the water area is made up of the following lakes: Lake Chilwa, Lake Malombe and Lake Chiuta and there are also rivers, a majority of them flowing into Lake Malawi (Gamula et al., 2013).

Generally, Malawi experiences annual rainfall ranges from 600-2000 mm and its spatial and temporal distribution is greatly influenced by the heterogeneous topography and Lake Malawi (Gibson et al., 2017). Residual tropical cyclones that occasionally reach Malawi from the Indian Ocean cause heavy rainfall and damaging floods especially in the southern parts of the country (Banda&Ng'ambi, 2007). The temperature regime is tropical continental and is greatly modified also in its spatial and temporal distribution by the highlands and Lake Malawi. The country's latitudinal position exposes it to the influence of extra-tropical systems that move eastwards around the Southern African coast (Banda&Ng'ambi, 2007).

While, Africa is one of the lowest contributors to greenhouse gas emissions causing climate change, its key development sectors have already experienced widespread losses and damages attributable to human-induced climate change, including: biodiversity loss, water shortages, reduced food production, loss of lives and reduced economic growth (Simpson et al., 2022). Malawi has not been spared from the adverse impacts of weather and climate as evidenced by recent floods and drought causing loss of life, damage property and infrastructure, affect food security and hinder efforts in poverty eradication. The 2015–2016

drought across Malawi highlighted the cascading nature of impacts involving food insecurity, power cuts, and drinking water shortages (Siderius et al., 2021). The country has experienced more floods than any other natural disasters. Over the past five decades, it has experienced more than 19 major floods and seven droughts, with these events increasing in frequency, magnitude and scope over the years. Moreover, 15 out of 28 districts (which represent 54% of the districts) in Malawi are considered flood prone (JICA, 2022).

The sixth assessment report of the IPCC highlights that the probability of compound flooding (storm surge, extreme rainfall and/or river flow) has increased in some locations including south eastern Africa and will continue to increase due to both sea level rise and increases in heavy precipitation, including changes in precipitation intensity associated with tropical cyclones (high confidence)(IPCC, 2021). A projected reduction of 20% in annual rainfall by 2080 in southern Africa will only increase the regional socio-economic challenges (Mpandeli et al., 2018).

The threats posed by extreme climatic events led to the preparation of the Malawi's National Adaptation Programme of Action (NAPA). Concern about overdependence on hydropower is highlighted in the country's NAPA, yet, even though declining hydropower supply is attributed to climate change, the Malawi Growth and Development Strategy still aims to develop more hydropower plants along the Shire River (GoM, 2020).

## **2.6 Energy Mix in Malawi**

Energy is quoted as one of the key ingredients in the social and economic development process of any nation and especially so for the developing countries and grid electricity is the main source of modern energy in Malawi (C. S. Kaunda et al., 2012). In many African countries, electricity generation mix is weakly diversified, with hydropower accounting for a large part of generated electricity with few back-up options (Falchetta et al., 2019). This is also the case in Malawi where the major source of electricity is hydropower (John L. Tauro, 2015). Malawi's total installed capacity dropped to about 546 MW in 2022 after 78 MW diesel generators were removed in 2022 (Chaima et al., 2023). A state-owned company, Electricity Generation Company Ltd. (EGENCO), generates electricity from hydro and another state-owned company, the Electricity Supply Corporation of Malawi (ESCOM), then distributes the generated electricity.

The total installed generation capacity for grid electricity in Malawi is however not adequate enough to meet the current demand for both industrial and domestic use (over 1000 MW), making it one of the energy –stressed countries in the Southern African region (Khundi-Mkomba et al., 2021). According to Chaima et al.(2023), hydropower dominates power generation at 71%, followed by new solar PV plants with capacities of 60 MW and 20 MW in Salima and Dedza at 15% and Diesel at 12% respectively. Figure 2.3 below summarises the energy mix in Malawi.

Lack of infrastructure for modern energy supply services and a heavy reliance on biomass as a source of energy (mainly in the form of charcoal and firewood) are characteristic of many countries in sub-Saharan Africa, including Malawi. The provision of affordable and reliable electricity is challenging due to limited power infrastructure development that relies heavily on existing erratic hydropower generation (Chaima et al., 2023). As such, 95 percent of the population in Malawi use firewood and charcoal for cooking and heating which is also blamed for contributing to high rates of deforestation (World Bank, 2020).

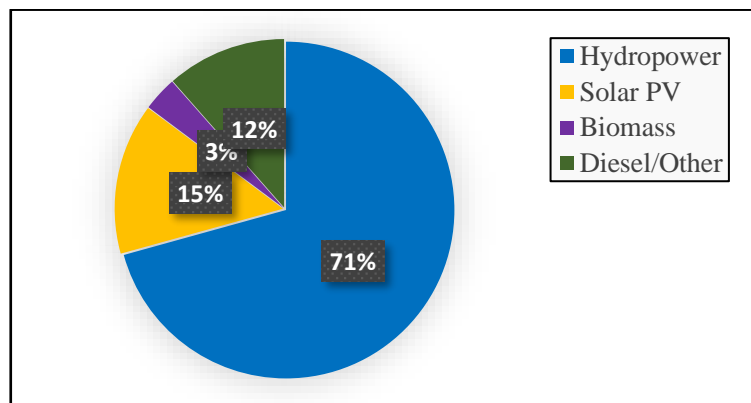


Figure 2.3. Energy Mix in Malawi

### 2.7 Hydropower and Climate Change in the Shire River Basin

Over 95% of Malawi's electricity is generated by hydropower, largely from three "run-of-river power plants - Tedzani, Nkula, and Kapichira – with expansion anticipated at the latter two, and plans for additional hydropower stations (Kholombidzo and Mpatamanga) located along the Shire River (Aj et al., 2022; Zuzani et al., 2019). Other hydropower plants in Malawi in other river basins are Wovwe and Songwe with 4.35MW and 180MW capacity respectively. Table 2.1 below shows the characteristics of the hydropower plants cascaded along the Shire River. The three run-of-the-river hydropower stations in Shire River require

approximately the same river discharge of ~265 m<sup>3</sup> /s for peak hydropower production, which falls linearly with reducing discharge (Siderius et al., 2021).

The country's electricity supply is considered vulnerable to the impacts of climate variability and climate change (Taulo, 2015). With an electricity access rate of 11%, access to reliable energy is currently the most pressing need in Malawi (World Bank, 2020). Wood fuels dominate Malawi's energy sector and are used by 98 % of the population. As a result, most forests including the Shire River Basin remain prominent hotspots of land degradation in the face of climate change (World Bank, 2019). Consequently, high loads of sediment are deposited in river beds, reservoirs and floodplain wetlands, affecting irrigation canals and hydropower generation (IWA, 2022). Existing hydropower plants on the Shire River are thus often unable to meet peak demand, partly due to low flows and sediments in the river caused by degradation of catchments upstream of the plants (IHA, 2022).

In addition to its importance for hydropower production, the Shire River supplies drinking water to adjoining cities and towns including water for irrigation purposes to crop plantations and fisheries (Gama et al., 2014). It is important to note that well-planned hydropower projects can contribute to the supply of sustainable energy (Amos & Mensah, 2018).

The Malawi National Adaptation Programme of Action (NAPA) highlights that the Shire basin is vulnerable to climate variability and change (GoM, 2020). The major hydroelectricity power stations along the Shire River, are thus not able to generate enough electricity to meet the ever-increasing demand (Gibson et al., 2017). This is because for more than half a century, a combination of factors such as land degradation, increased rainfall, and extreme weather events have increased in magnitude and frequency as a result of climate change threatening hydropower operations in the Shire River Basin (Future Climate for Africa, 2019).

Table 2.1: Hydro stations characteristics in the Shire River Basin (Mtilatila et al., 2020)

<b>Station</b>	<b>River</b>	<b>Country</b>	<b>Type of Plant</b>	<b>Capacity (MW)</b>
Nkula Falls A&B	Shire	Malawi	Run-of-river	124
Tedzani I, II& III	Shire	Malawi	Run-of-river	110
Kapichira I&II	Shire	Malawi	Run-of-river	128

According to IHA (2022), the Basin has experienced significant changes in weather patterns flooding events, such as the severe flash flooding of 2001/2 and 2015. The floods of January 2015 were the worst in recorded history and continued to further contribute to the degradation of the lower basin. Furthermore, the 2022 flash floods during tropical storm Ana caused extensive damage to the Kapichira dam and fuse plug, resulting in the drawdown of the reservoir and putting the plant on the Shire River out of operation (Hydropower and Dams, 2022). Officials at the Electricity Generation Company (EGENCO), documented that Malawi lost about 130 megawatts representing 30% of the total hydropower generation following the shutdown of its Kapichira Power Station due to the storm (Masina, 2022). According to Reuters (2015), the 2015 drought in Malawi affected significantly water levels in the Shire River Basin, reducing generated power by 66% due to erratic rains. In addition, it was established that water flow on the river, was 20% below what is needed to operate the plants and this resulted in over four months of power rationing which had a huge socio-economic impact (John L. Taulo, 2015).

These disruptions underscore the challenges of chronic electricity scarcity and impede the achievement of development targets, particularly the Sustainable Development Goal (SDG) number 7 that targets provision of sustainable, reliable, accessible and affordable electricity (Gannon et al., 2018).

## **2.8 Climate Change and Hydropower Studies**

A vivid debate is taking place in the academic literature and in decision making spheres on whether and how in the coming years anthropogenic climate change – and thus changing precipitation and temperature patterns will affect hydropower potential and reliability, along with demographic and socio-economic stressors (Falchetta et al., 2019).

Several studies have employed Global and Regional Climate Models to investigate potential climate change impacts at global, regional and local levels on water resources and hydropower (Ndhlovu & Woyessa, 2020; Stanzel & Kling, 2014; Warnatzsch & Reay, 2019). Moreover, much research has also evaluated the ability of Global and Regional Climate Models to reproduce present and future climatology (Dosio et al., 2019; Sylla et al., 2018; Tellman et al., 2021). This has enabled scholars (Abera et al., 2018; Cole et al., 2014; Huangpeng et al., 2021; Yeboah et al., 2022) to determine present and future climate scenarios and their impacts on hydroelectricity generation which has doubled during the last thirty years and is projected to double the current production level by 2050 globally (Zhang et al., 2018).

For instance, Turner (2017) projected 21st century global hydropower production by forcing a coupled, global hydrological and dam model with three GCMs projections run under RCP 4.5 and 8.5. The results showed that hydropower production is projected to be reduced by approximately 40% on average by the end of the century under a high emissions scenario in southern Europe, northern Africa and the Middle East. However, in central Asia and Scandinavia countries, they are projected to reap a significant increase in total electrical production between 5–15% without investing in new power generation facilities.

According to a study by Blackshear et al. (2011), South Asia's climate and hydrological cycles are significantly impacted by the monsoon, which has already been altered by climate change. Scenarios predicted that there will be an increase in the severity of rainfall events as well as storms, causing overall increased temporal variability in water supply. The difference in distribution of precipitation timing in this area would cause significant variations in the Mekong River's discharge. All of these various climate change impacts are interconnected and have significant repercussions for hydropower. As climate change impacts intensify, this variation will be exacerbated, making it more difficult for hydropower facilities along the Mekong River to predict river discharge and to generate an even supply of electricity.

Another study by Gøtske & Victoria (2021) in Europe, investigated future hydropower reservoir inflow for 22 European countries at the beginning of the century from 1901 to 2020 and the end of the century from 2071 to 2100 under three emission scenarios (RCP 2.6, 4.5 and 8.5) for 10 GCM-RCM climate model combinations as well as the average ensemble. The results showed annual inflow decreases by 31% (20%) in Southern countries and increases by 21% (14%) in Northern countries for high (mid)-emission scenarios.

A study by Duratorre et al. (2020) examined the effects of potential climate change scenarios at 2100 on hydropower production from the Chavonne plant, Italy for a run-of-the-river plant. The Poli-Hydro, a state-of-the-art hydrological model, was employed to simulate the hydrological budget of the area. Projections of the hydrological budget were built until 2100 employing selected climate change scenarios, under proper downscaling. Three GCMs, under RCP 2.6, RCP 4.5, and RCP 8.5 were run from AR5 of IPCC, and their updated version under four Shared Socio-Economic Pathways SSP1-2.6, SSP- 4.5, SSP3-7.0, and SSP5-8.5 from AR6. This study was interesting as it made a comparison for both CIMP5 and CIMP6 pathways on a run-of-river scheme. The Results showed that hydropower production displays a large dependence upon monthly discharge patterns, with mostly positive variations (+2.90% on average at half century, +6.95% on average at end of century), with its change driven by exceedance of plant's capacity.

In west Africa, according to a study by Obahoundje et al. (2021), the ensemble mean of three-climate dataset analysis revealed that temperature is projected to increase significantly while precipitation change is uncertain under RCP 4.5 and 8.5 in the near (2020–2050) and the far (2070–2090) futures. Nonetheless, this was found to exacerbate the burden that constitutes water availability for hydropower generation using (RCMs) from Coordinated Regional Downscaling Experiment (CORDEX). Interestingly, a study within the same region conducted by Sylla et al. (2018) using a 23-member high resolution ensemble of RCM simulations performed as part of CORDEX, found that West African basins will likely face severe water shortages in the near and far futures under 1.5 °C and 2 °C global warming scenarios.

In Southern Africa, R. Spalding-Fecher et al.(2017) used 22 GCMs from AR4 and 23 GCMs from AR5 applied to RCP 2.6, 4.5 and 8.5 to examine climate change impacts on water resources. The results showed that the output from major Zambezi hydropower plants could decline by 10–20% under a drying climate in the near term. Whereas Ndhlovu & Woyessa (2020) found that future catchment water balance under RCP4.5 will have insignificant variation from the current catchment water balance in Zambezi basin. Meanwhile under RCP8.5, annual statistics showed that rainfall will increase by 19 % while water yield and runoff will increase by 40 % and 65% respectively and resulting in a significant increase in catchment water balance. Interestingly, in the same Zambezi basin, Stanzel & Kling (2014) found a marked increase of hydropower production of 11% for a near-future period (2021–

2050) and 9% for a far-future period (2071–2100) using HEC-ResSim model in a wetting climate scenario. In a drying climate scenario, they determined that hydropower generation decreases by 6% in the near future and 13% in the far future.

While in central Africa, a study in the Inga falls of the Congo River Basin indicated that the water resources potential for hydropower in the river basin is likely to increase by between 1 and 4 % towards the end of the century. Seasonal analysis indicated that there will be a slight increase in all seasons apart from the period of March to May during which time decreases in runoff are expected (Hamududu & Killingtveit, 2016).

Mtilatila et al. (2020) investigated potential climate change impacts specifically on hydropower generation in the Shire River Basin with run-of-river plants in Malawi. The study used the climate change projections from 20 CORDEX models for Africa based on two scenarios RCP 4.5 and 8.5 and the mesoscale Hydrological Model (mHM) to assess the water budget and hydropower production in SRB for the periods 2021–2050 and 2071–2100. The study projected a reduction in annual hydropower production between 1% (RCP8.5) and 2.5% (RCP4.5) during 2021–2050 and between 5% (RCP4.5) and 24% (RCP8.5) during 2071–2100. The researchers used a significant number of models for the analysis, which is invaluable in reducing uncertainties in projections. However, the study did not assess and analyze historical climatic conditions in the basin for the period 1991-2020 which is an important element because long-term historical data helps in understanding whether past changes have exceeded the variability expected from natural causes which provide insights for science and societies (Knutson et al., 2010). In addition, this study used CIMP5 as compared to the latest CIMP6 models of the Intergovernmental Panel on Climate Change (IPCC).

## **2.9 Gaps in Literature**

Literature review shows that the Shire River Basin's hydrological system represents Malawi's most important water resource, providing essential water to sectors critical to Malawi's development and economy, such as power, agriculture, public water supply, fisheries, and navigation. Despite its vulnerability to flooding and droughts, only a few studies have assessed the future of hydropower generation in the face of climate change in the basin. Even more so, none of the studies has employed the latest CMIP6 models which offer a more thorough framework for analysing how climate will change in the future.

Literature also shows that climatic trends in the basin have not been analysed for the period between 1991-2020 which is important in understanding whether past changes have exceeded the variability expected from natural causes. Consequently, this study will complement and improve scientific literature by addressing a knowledge gap which has been less explored in previous studies to contribute to the development of appropriate policies and adaptation strategies for sustainable and dependable hydropower, and overall water resources management.

### 3. METHODOLOGY

#### 3.1 Location of the Study Area

The Shire River is the longest and largest river in Malawi and is the only outlet from Lake Malawi. It is 401 km long, has a catchment area of 23,500 km<sup>2</sup>, and joins the Zambezi River in Mozambique as its most downstream tributary (Coulibaly et al., 2015). The basin covers 16% of Malawi's area (Kelly et al., 2019). Figure 3.1, shows the location of Shire River Basin and positions of current hydro power plants.

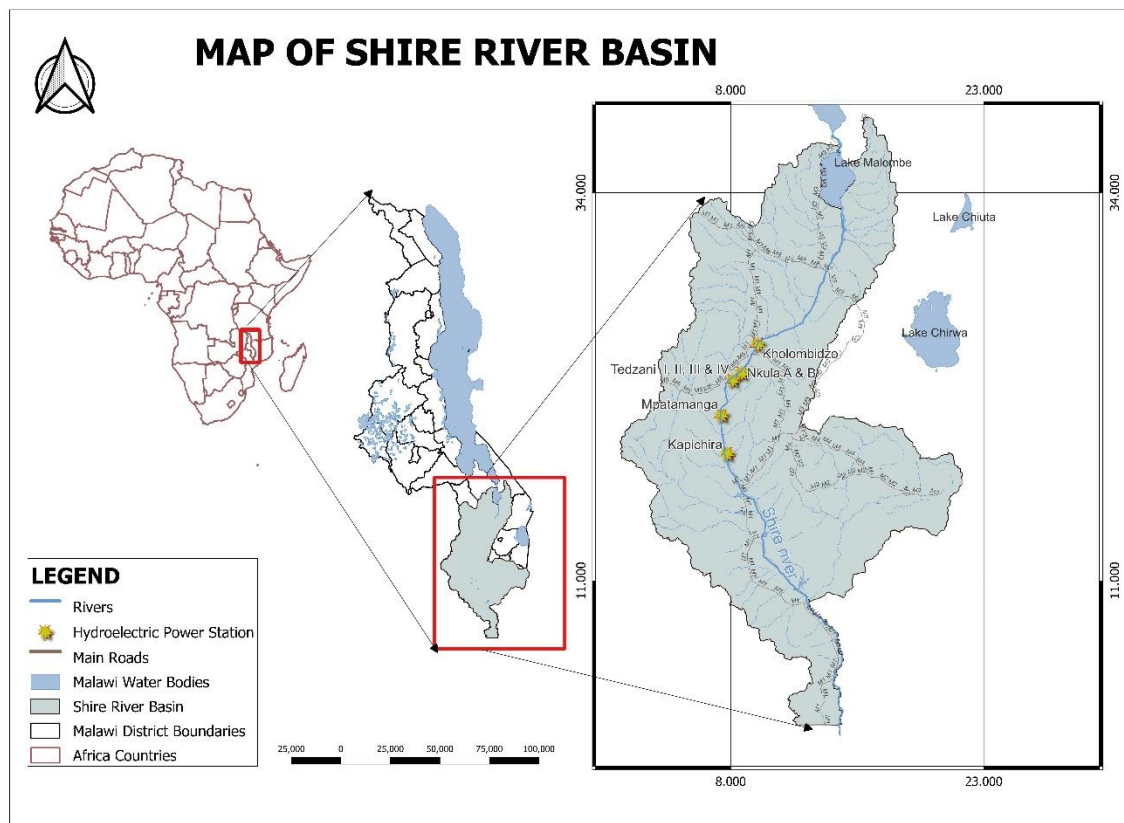


Figure 3.1. Location Map of the Shire River Basin

#### 3.2 Climate and Hydrology

The basin is dominated by a tropical climate throughout the year and is occasionally traversed by residual tropical cyclones, with a pronounced rainy season between October and April (Bhave et al., 2020). The largest rainfall amounts fall between December and April, ranging from 800 to more than 1800mm. It is generally dry from June to September, with monthly rainfall below 10 mm on average in this period (Gibson et al., 2017). During peak flooding, mean monthly runoff is approximately 800 m<sup>3</sup>/s and maximum annual flows range between 1000 m<sup>3</sup>/s and 1800 m<sup>3</sup>/s. In the dry season, minimum discharge can fall to

between 64 - 765 m<sup>3</sup>/s (IHA, 2022). Shire River has many tributaries but the five major ones are Rivirivi, Lisungwi, Wamkulumadzi, Mwanza and Ruo Rivers. The supply of the water from minor tributaries is usually perennial and 80% of their contribution is during the rainy season between November and April. The biggest Shire River tributary is Ruo that originates from Mulanje Mountain and flows along Mozambique-Malawi boarder before joining the Shire River at Chiromo (Mtilatila et al., 2020).

### 3.3. Topography

The Middle Shire is distinguished by the steep topography either-side of the gorges around the river providing hydropower potential, and currently seven hydropower plants are installed that contribute 98% of installed hydro electrical power in Malawi. The middle Shire, where hydro-power generation takes place is 80 km long with a 370m hydraulic gradient and is characterized by deep gorges with steep slopes. The lowest altitudes are located in Lower Shire Valley where the altitude is below 60 m.a.s.l. making it susceptible to floods. The highest point in SRB as well as Malawi is the Mulanje Mountain located within the Southern highlands which its highest peak, Sapitwa, is at about 3,002 m.a.s.l. Mulanje Mountain is the origin of several rivers including Ruo which is one of the main tributaries of Shire River (Mtilatila et al., 2020). Figure 3.2 shows the variation of elevation and slope of the basin.

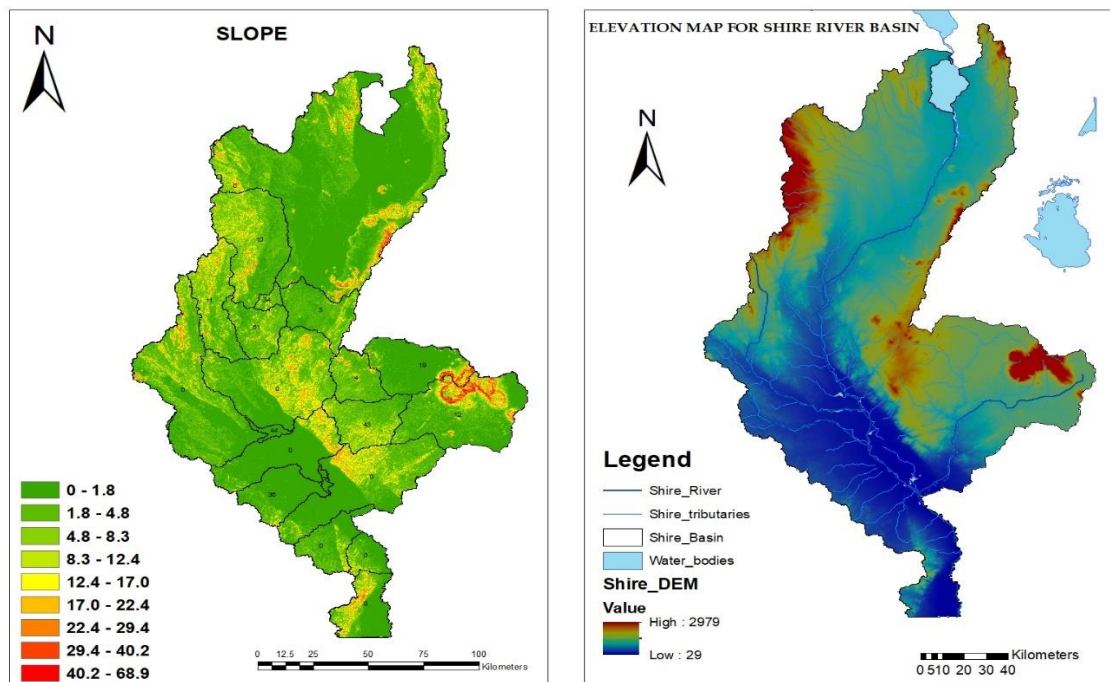


Figure 2.2 Elevation and Slope Map for the Study Area

### 3.4. Population and Economic Activities

The basin represents Malawi's most important water resource, providing essential water to sectors critical to Malawi's development and economy, such as power, agriculture, public water supply, fisheries, and navigation, despite its vulnerability to flooding and droughts. (Hussein et al., 2019; Zuzani et al., 2019). The main Southern Region cities and towns draw water from the Shire River for domestic and industrial use and there is a steady increase in new water connections every year as the population in the cities and towns is growing (Tiwale et al., 2018). The riparian communities also depend on the same river for portable water as 37.9% of country's population is found in this area (National Statistical Office, 2018).

### 3.5 Methodology for Assessing Rainfall and Temperature Trends

#### 3.5.1 Data collection

The basic datasets that are required by the trend analysis test and indicators of climate variability and change are precipitation and temperature. Examination of climate trends and variability needs long and high-quality records of climatic variables. There are 22 precipitation and temperature recording stations located in the Shire River Basin. The stations have continuous records for the past 3 decades which are essential for hydro-climatic studies. In this study, monthly and annual recorded data for rainfall and temperature corresponding to the 22 available stations sites in the SRB were collected from the Malawi Department of Meteorological and Climate Change Services for the period 1991-2020. The spatial distribution of the 22 meteorological and 7 hydropower stations is shown in Figure 4.1

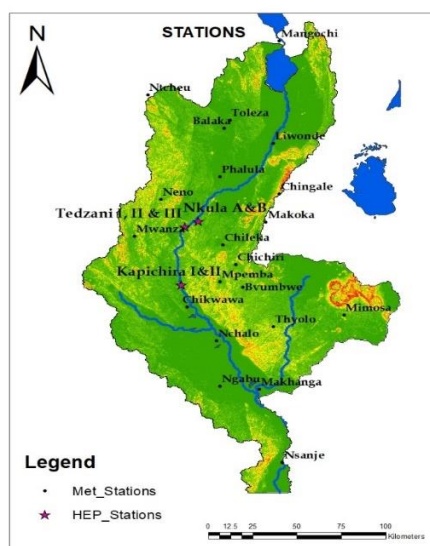


Figure 3.3 Spatial Distribution of Meteorological Stations in the Study Area

### 3.5.2 Data Quality Control

It is essential to devote careful screening and quality check for all data before use in any climatological analyses. The climatic data was sorted and arranged in Microsoft Excel and checked through visual inspection to detect outliers and any gaps missing data. Missing values were detected in the mean monthly rainfall dataset, particularly in the month of April, in the year 2020. The gaps were filled using NASA Power Climate Data which showed regression coefficient ( $R^2$ ) values ranging 0.89-0.92. The NASA Power Climate dataset was obtained from <https://power.larc.nasa.gov/data-access-viewer/>. Other researchers have used NASA power data for their research, and have justified its usefulness for data scarce regions like Zambia, Mozambique and Zimbabwe (Hamududu & Killingtveit, 2016; Uamusse et al., 2020). Table 3.1 summarises information of the meteorological stations used in this study.

Table 3.1: Information summary of meteorological stations in the study area

<b>Station Name</b>	<b>Longitude</b>	<b>Latitude</b>	<b>Data Period</b>	<b>Average</b>	<b>% Missing</b>
Balaka	34.9700	-14.9800	1991-2020	779.3	1.2
Bvumbwe	35.0667	-15.9167	1991-2020	1074.9	0
Chichiri	35.0300	-15.7833	1991-2020	1123.2	0.3
Chikwawa	34.7833	-16.0333	1991-2020	782.2	0.6
Chileka	34.9667	-15.6667	1991-2020	1101.1	0
Chingale	35.2500	-15.3667	1991-2020	1128.1	0
Liwonde	35.2200	-15.0700	1991-2020	1101.7	0
Makhanga	35.1500	-16.5167	1991-2020	906.4	0
Makoka	35.1833	-15.5333	1991-2020	938.6	0.3
Mangochi	35.2500	-16.95	1991-2020	813.0	0.3
Mimosa	35.5800	-14.4667	1991-2020	1251.9	0
Monkey-Bay	34.9167	-16.0800	1991-2020	819.2	0.3
Mpemba	34.9500	-14.0833	1991-2020	1008.3	0.3
Mwanza	34.5167	-15.8833	1991-2020	975.1	0
Nchalo	34.93333	-15.6167	1991-2020	1074.9	0
Neno	34.65	-16.2333	1991-2020	1152.3	0.3
Ngabu	34.95	-15.4	1991-2020	906.4	0
Nsanje	35.26667	-16.5	1991-2020	1147.9	0
Ntcheu	34.58333	-14.7833	1991-2020	812.9	0

Phalula	34.95	-15.2667	1991-2020	1101.2	0
Toleza	35	-14.9333	1991-2020	779.3	0
Thyolo	35.22	-16.15	1991-2020	1074.9	0

### 3.5.3 The Mann-Kendall Test

The trend analysis is one of the methods that is used to assess the change signal in timeseries. The purpose of performing trend analysis is to determine whether there is either an increasing or decreasing trend in a series (Li et al., 2021). There are commonly two ways when a trend can occur, and these are: monotonic trend; thus, when the change is gradual over time and step trend; where the shift is abrupt (Asgher et al., 2021). The trend analysis can be applied on a site data and does not require calibration (Li et al., 2021). Trend analysis is usually applied to observed climate data to assess historical climate change signals. An example of commonly used method is the non-parametric Mann-Kendall (MK) test (Kendall, 1975; Mann, 1945).

The MK test which is based on the ranked-transformed time series identifies the presence of the monotonic trend in the timeseries without any assumptions on the underlying statistical distribution. Unlike the parametric methods, the MK method is more robust against outliers, skewed distribution and missing data as such it is also commonly applied in climatological and hydrological studies (Zuzani et al., 2019). However, though the trend analysis indicates the direction of change, it does not provide the cause of change (Mtilatila et al., 2020).

It uses the null hypothesis,  $H_0$ , and alternative hypothesis,  $H_A$ . The null hypothesis is that the data come from a population with independent realizations and are identically distributed. The alternative hypothesis is that the data follow a monotonic trend (Mzuza et al., 2019). The Mann-Kendall trend test uses a test statistic, which is calculated according as:

$$S = \sum_{j=k+1}^{n-1} sgn(X_j - X_k) \text{ with } sgn(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x = 0 \\ -1 & \text{if } x < 0 \end{cases} \dots\dots\dots \text{equation 1}$$

Where  $X_j$  and  $X_k$  are the annual values in years'  $j$  and  $k$  moreover,  $j > k$ .

If  $n$  is 9 or less, the absolute value of  $S$  is compared directly to the theoretical distribution of  $S$  derived by Mann and Kendall. The two-tailed test is used for four different significance levels  $\alpha$ : 0.1, 0.05, 0.01, and 0.001. At a certain probability level  $H_0$  is rejected in favor of  $H_A$  if the absolute value of  $S$  equals or exceeds a specified value  $S_{\alpha/2}$ , where  $S_{\alpha/2}$  is the smallest

S which has the probability less than  $\alpha/2$  to appear in case of no trend. A positive value of S indicates an upward trend whereas a negative value indicates a downward trend. The significance level 0.001 means that there is a 0.1% probability that the values  $X_i$  are from a random distribution and with that probability we make a mistake when rejecting the  $H_0$  of there not being a trend. However, if there are several tied values (i.e., equal values) in the time series, it may reduce the validity of the normal approximation when the number of data values is close to 10. First, the variance (S) is computed by the following equation which takes into account that ties may be present.

$$VAR(s) = \frac{1}{18} [n(n - 1)(2n + 5) - \sum_{p=1}^q (T_p - 1)(2T_p + 5)] \dots \dots \dots \text{equation 2}$$

Here q is the number of tied groups and  $T_p$  is the number of data values in the  $p^{\text{th}}$  group. The values of S and VAR(S) are used to compute the test statistics Z as follows:

$$Z = \left\{ s - 1/\sqrt{Var(s)} \right\}$$

$$Z = \left\{ s + 1/\sqrt{Var(s)} \right\}$$

\dots \dots \dots \text{equation 3}

$$\left\{ \begin{array}{l} \text{if } s > 0 \\ \text{if } s = 0 \\ \text{if } s < 0 \end{array} \right\}$$

The presence of a statistically significant trend is evaluated using the Z value and here the statistic Z has a normal distribution. Significance level  $\alpha$  is used for testing either an upward or downward monotone trend (a two-tailed test). If Z appears greater than  $Z_{\alpha/2}$  where  $\alpha$  depicts the significance level, then the trend is considered to be significant. The value for  $Z_{\alpha/2}$  is obtained from the standard normal cumulative distribution tables for the significance levels ( $\alpha$ ) 0.001, 0.01, 0.05, and 0.1 (A. T. Kabo-Bah et al., 2016).

The Addinsoft's XLSTAT 2018 was used to determine whether there is evidence of specific trends in the characteristics of annual rainfall and temperature (minimum and maximum) events in the whole basin. The trends in precipitation and temperature were used as indicators of climate change in the basin and plotted using Origin Pro Software against the 0.05 level of significance. Average Annual rainfall and mean monthly rainfall distribution were plotted as box and whisker charts using OriginPro Software, while spatial average annual rainfall distribution was done using ArcGIS 10.8. For minimum and Maximum temperature data, there were no gaps detected, and the data was also plotted on box and whisker chart to obtain the distribution on a monthly scale in the basin using OriginPro.

### 3.5.4 Sen's slope estimator

Theil-Sen's slope estimator ( $Q_{med}$ ) results from consideration of all possible combinations of data pairs within the whole data set. A positive value of  $Q_{med}$  indicates an "upward trend" (increasing values with time), while a negative value of  $Q$  indicates a "downward trend". If a linear trend is present in a time series, then the true slope (change per unit time) can be estimated by using a simple non-parametric procedure developed by. This means that linear model  $f(t)$  can be described as:

$$f(t) = Qt + B \dots \dots \dots \text{equation 4}$$

where  $Q$  is the slope and  $B$  is a constant. To derive an estimate of the slope  $Q$ , the slopes of all data pairs are calculated as:

$$Q_i = \frac{x_j - x_k}{j - k} \quad i = 1, 2, \dots, n, j > k \dots \dots \dots \text{equation 5}$$

If there are  $n$  values  $X_j$  in the time series, we get as many as  $N = n(n-1)/2$  slope estimates  $Q_i$ . The Sen's estimator of slope is the median of these  $N$  values of  $Q_i$ . The  $N$  values of  $Q_i$  are ranked from the smallest to the largest and the Sen's estimator is

$$Q = \begin{cases} \frac{Q_{N+1}}{2} & \text{if } N \text{ is odd} \\ \frac{Q_N}{2} + \frac{Q_{N+2}}{2} & \text{if } N \text{ is even} \end{cases} \dots \dots \dots \text{equation 6}$$

A  $100(1-\alpha)$  % two-sided confidence interval about the slope estimate is obtained by the non-parametric technique based on the normal distribution. The method is valid for  $n$  as small as 10 unless there are many ties. At first, we compute:

$$Ca = Z_{1 - \frac{\alpha}{2}} \sqrt{VAR(S)} \dots \dots \dots \text{equation 7}$$

where  $Z_{1 - \frac{\alpha}{2}}$  is obtained from the standard normal distribution and  $VAR(S)$  has been defined in equation 2. Next  $M_1 = (N - Ca)$  and  $M_2 = (N + Ca)$  are computed. The lower and upper limits of the confidence interval,  $Q_{min}$  and  $Q_{max}$ , are the  $M_1$ th largest and the  $(M_2 + 1)$ th largest of the  $N$  ordered slope estimates  $Q_i$ . If  $M_1$  and/or  $M_2$  are not whole numbers, the respective limits are interpolated. To obtain an estimate of  $B$  the  $n$  values of differences  $x_i - Q_i t_i$  are calculated. The median of these values gives an estimate of  $B$ . The estimates for the constant  $B$  of lines of the 99% and 95% confidence intervals are calculated by a similar procedure (A. T. Kabo-Bah et al., 2016).

### **3.6 Methodology for Simulating Future River Flow Regimes**

#### **3.6.1 Rainfall-Runoff Modelling**

There are numerous hydrologic models that can be and have been applied for climate change impact analysis and hydrology. Understanding of future climate change on the hydrological cycle within a watershed scale is crucial for water resources planning (Nam et al., 2015). This makes the selection of hydrologic modeling technique crucial to the validity and accuracy of results. Impacts of climate change on the hydrological behavior of a particular watershed are only meaningful if the physical, spatial, and hydrological cycles are accurately represented (Jury, 2014).

The HEC-HMS model, designed in 1992 by the US Hydrologic Engineering Centre, simulates precipitation runoff processes in dendritic watershed systems using input data like digital elevation models, land-use data, and soil. It is used for large river basins, flood hydrology, and small urban and natural watershed systems. The model can represent various watershed systems at a given time, aiding in water availability, flow forecasting, and flood damage control (Yamani et al., 2016).

The model uses underlying DEM information to partition the basin into sub-watersheds. The size of the sub-watershed is determined a priori by the modeler, and few or no guidelines are available for sub-watershed selection. In most cases, the balance between the resolution of the distributed information and the computation time required for simulation is the main factor considered for this selection. The model can simulate individual storm events as well as continuous precipitation input at minute, hourly, or daily time steps (Skhakhfa & Ouerdachi, 2016). The main advantage of the HEC-HMS model is that it contains an automatic calibration package which can estimate certain model parameters and initial conditions when observed data of the hydro meteorological conditions are provided (Abera et al., 2018).

#### **3.6.2 Data Overview**

The HEC-HMS model uses readily available input data such as digital elevation model (DEM), SCS Curve number, precipitation and discharge data. Table 3.2 summarises the characteristics and functions of each dataset.

Table 3.2: Summary of characteristics of Rainfall-Runoff Modelling Inputs

<b>Data Type</b>	<b>Description</b>	<b>Scale</b>	<b>Data Source</b>
Digital Elevation Model-Raster	For delineation of the watershed and define hydrological response unit	90m	<a href="http://gdex.cr.usgs.gov/gdex/">http://gdex.cr.usgs.gov/gdex/</a>
SCS Curve Number-Raster	Generates a curve number map for subbasins	10m	<a href="https://earthmap.org/">https://earthmap.org/</a>
Precipitation Data	Necessary for model simulation	Daily	<a href="https://power.larc.nasa.gov/">https://power.larc.nasa.gov/</a>
Discharge Data	Necessary for model calibration	Daily	Department of Water Resources of Malawi

### 3.6.3 Hydrologic Model Development

The downloaded DEM for the study area was used to delineate the watershed and generate its streams. The boundary limit of the watershed was also developed and the resulting shape file used for clipping other GIS based raster data for the study area. This process was preceded by DEM reconditioning, filling of the sinks, flow direction and flow accumulation processes. This was done to ensure the elevation data was consistent with the vector stream network.

The downloaded SCS Curve Number raster file assisted in estimating the main parameters such as SCS curve number, the channel routing coefficients and the time of concentration among other parameters. For the channel routing, the Muskingum routing method was adopted in this study since it relates the amount of water stored in the river to both the inflow and outflow of the system. This Muskingum routing method was represented using the following equations:

$$\frac{dW}{dt} = I - Q; W = [xI + (1 - x)Q] \dots \dots \dots \text{equation 8}$$

where W = channel storage; I and Q = inflow and outflow rates, respectively. An assumed Muskingum X value of 0.4 was used which in general is usually used to indicate a big, natural stream. The Muskingum K value was assumed to be equivalent to the basin CN lag number for each sub basin in hours as defined by the HEC-HMS 4.2 user’s manual. The reach value of 2 was assumed as the initial value for conveying the streamflow within the small sub basin.

Once all the parameters were put in place as shown in Figure 3.4, various simulations were run to show the hydrologic response of the watershed using the provided meteorological data. The simulation runs applied meteorology conditions to the watershed's land surface to estimate the runoff. Each simulation run was composed of one basin model, one meteorology model and one control specification. Due to lack of sufficient discharge data within the watershed, the daily rainfall data for one station at Liwonde within Shire River basin was used. The computed results of the simulation runs were displayed in form of bar charts.

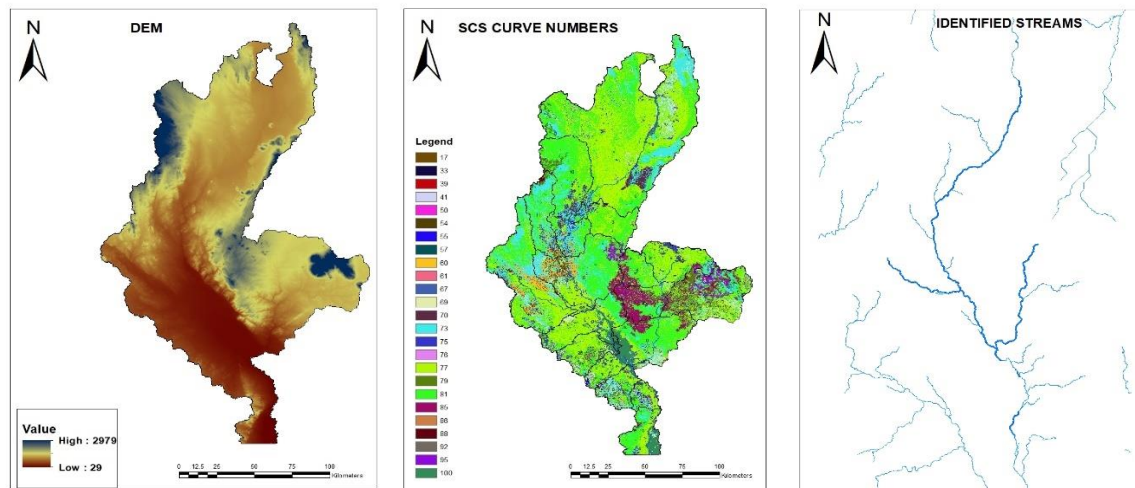


Figure 3.4 shows some of the rainfall-runoff modelling inputs

### 3.6.4 Model Calibration

This was automatically done using the Optimization Trial Manager which makes subjective adjustment of parameters that give an appropriate fit between observed and simulated hydrographs. The parameters that were calibrated included the loss functions such as the initial abstractions and curve number (CN), transform functions such as the SCS lag, and routing functions such as the Muskingum routing parameters. The output discharge values were plotted to get coefficient of determination ( $R^2$ ). Moreover, the calibrated model performance was also evaluated using the Nash–Sutcliffe model efficiency (NSE) (Nash, Sutcliffe 1970; Miao et al. 2013). The NSE is used to assess the agreement between observations and simulations. Mathematically, it is expressed as where:  $Q_o$  = observed discharge,  $Q_s$  = simulated discharge; all  $Q$  variables have the unit runoff volume per time step (e.g.,  $m^3 \cdot s^{-1}$ ). Nash–Sutcliffe efficiencies can range from  $-\infty$  to 1. An efficiency of 1 ( $NS = 1$ ) corresponds to a perfect match between the modelled and observed time series, whereas an efficiency of 0 ( $NS = 0$ ) indicates that the model predictions are as accurate as

the mean of the observed data. If the efficiency is less than 0 ( $NS < 0$ ), the observed mean is a better predictor than the model (Yeboah et al., 2022).

### **3.6.4 Model validation**

The validation of the model performance was done by comparing the observed and simulated stream flows at Liwonde gauging station in subbasin 10. The simulated stream flows were expected to produce a similar trend as the observed stream flows. In order to evaluate the hydrologic goodness of fit, a statistical criterion was applied on the observed and the simulated stream flows. These results were compared using the Nash-Sutcliffe Efficiency (NSE) and coefficient of correlation ( $R^2$ ).

### **3.6.5 Future Rainfall Scenarios**

General Circulation Models (GCMs) are currently the most advanced tools available for simulating the response of the global climate system to changing atmospheric composition. In general, the GCM is a numerical representation of the atmosphere and its phenomena over the entire Earth and it incorporates a variety of fluid-dynamical, chemical or even biological equations (IPCC, 2012). Climate models and scenarios were selected to obtain projections of future climate change in the study area. Appropriate climate models and scenarios were identified through literature review of studies that evaluated CMIP6 models skills on simulating the climate of the study area (Mmame & Ngongondo, 2023).

The output from GCMs are however too coarse ( $>100$  km) to be used in impact assessment studies, adaptation planning, and decision-making processes at a local or regional scale (Kwakye & Bárdossy, 2022). In addition to the coarse resolution, biases and uncertainties associated with GCMs increase from global to regional and local scales, which limit the suitability and applicability of GCMs in local-scale impact assessment studies (Zhao et al., 2022). Therefore, downscaling is required to increase the spatial resolution and reduce biases before climate projections can be used for impact assessment and adaptation planning (Dosio et al., 2019).

Future climate projection data for precipitation, were considered. The dataset is based on 3 forcing GCMs, including the Meteorological Research Institute 6 (MRI-ESM2-0) (Yukimoto et al., 2019), Atmospheric and Ocean Research Institute (MIROC6) (Shiogama et al., 2019) and the Commonwealth Scientific and Industrial Research Organisation and

(Australian Research Council Centre of Excellence for Climate System Science) (ACCESS-CM2)(Dix et al., 2019). Table 3.4 below provided a summary of the GCMs' characteristics.

Table 3.3: Summary of characteristics of selected GCMs

<b>GCM</b>	<b>Modelling Group</b>	<b>Resolution</b>	<b>Reference</b>
ACCESS-CM2	CSIRO-ARCS	1.8*1.2	(Dix et al., 2019)
MIROC6	Atmospheric and Ocean Research Institute	1.4*1.4	(Shiogama et al., 2019)
MRI-ESM2-0	Meteorological Research Institute	1*1	(Yukimoto et al., 2019)

Two emission scenarios of the Shared Socioeconomic Pathways, namely SSPs (2-4.5 and 5-8.5) of the Sixth Phase of the Climate Model Intercomparison Project (CMIP) of the IPCC Sixth Assessment Report (AR6) were considered (IPCC, 2021). They represent greenhouse gas and aerosol concentrations as well as land use pathways, characterized by radiative forcing values of 4.5 and 8.5 W/m<sup>2</sup> produced by CO<sub>2</sub> emissions by the end of the 21st century (Gusain et al., 2020). The IPCC's AR6 report described SSP2- 4.5 as an intermediate scenario where the emissions peak around 2050, then falling but not reaching net zero by 2100. On the other hand, SSP5-8.5 pathway represents a worst-case scenario where emissions would have tripped by 2075 (IPCC, 2021). The future scenarios were divided into 2 different time windows with 35 years intervals including 2030 to 2064 (the near future), and 2065 to 2100 (the far future).

In this study, GCMs simulation was downscaled to station scale through distribution mapping (quantile mapping) techniques of precipitation using the CMhyd (Climate Model data for hydrologic modelling) tool, designed to provide bias-correction of simulated climate data obtained from GCMs and RCMs. Zhang et al. (2018) noted distribution mapping as performing best after employing five bias-correction methods.

### **3.6.5.1 Bias Correction Performance Evaluation**

The evaluation metrics used in this study include the coefficient of determination ( $R^2$ ), Nash-Sutcliffe coefficient (NSE), Root Mean Square Error (RMSE), and Percent bias (Pbias) to assess the accuracy of the bias-corrected model. RMSE was utilized as the goodness of fit

technique to indicate the standard deviation of the model in simulating the observed data. The model performs better when RMSE is smaller. The  $R^2$  which ranges from 0 to 1 was used to evaluate the goodness of fit of the models and observed data. Where one means a perfect fit of the model. The NSE ranges from  $-\infty$  to 1, where  $\geq 0.5$  are satisfactory, and values  $\geq 0.7$  are a very good fit. The Pbias was used to evaluate whether the model under or overestimated the observed data. The model becomes more accurate when Pbias approaches 0 (Yeboah et al., 2022). Moreover, a scatter matrix comprising Pearson correlations ( $r$ ) was used to compare simulated data from a different climate models and ensemble of models with the observed data. These metrics, were evaluated on monthly precipitation outputs. Table 3.4 summarises the characteristics of the evaluation metrics.

Table 3.4. Summary of the characteristics of the evaluation metrics.

Metric	Formula	Evaluation Limits
$R^2$	$R^2 = 1 - \frac{\sum_{i=1}^N (Y_{obs} - Y_{sim})^2}{\sum_{i=1}^N (Y_{obs} - \bar{Y}_{obs})^2}$	0 to 1
NSE	$NSE = 1 - \left[ \frac{\sum_{i=1}^N (Y_{obs} - Y_{sim})^2}{\sum_{i=1}^N (Y_{obs} - \bar{y}_{obs})^2} \right]$	$-\infty$ to 1
RMSE	$RMSE = \sqrt{\frac{\sum_{i=1}^N (Y_{obs} - Y_{sim})^2}{N}}$	( $\pm$ )15%
PBIAS	$PBIAS = \frac{\sum_{i=1}^N (Y_{obs} - Y_{sim})}{\sum_{i=1}^N (Y_{obs})}$	Approach 0

### 3.7 The Climate Change Impact Assessment on the River Flow Regimes

Usually, hydrological models use climate variables from GCMs or downscaled outputs (GCMRCMs) as inputs to obtain the impacts of climate or climate change on water resources, and this is referred to as top-down approach. Thereafter, the possible range of climate impacts are generated to provide the estimate on how the water resources respond to climate change (Bronstert et al., 2023). Furthermore, in this project, the impacts of climate change on hydropower are derived from the possible future changes of Shire River discharge. In this study, the ensemble mean scenarios of the downscaled GCMs were used

to plot flow duration curves (FDC). The current/reference flow (water availability) of the study area was determined from the dependable discharges that correspond to 95% exceedance probability, Equation 9, herein considered as firm flow. The firm discharge is the discharge that can be exclusively used for hydropower generation almost every day of the year. It ranges from flow corresponding to 90–95% exceedance probability. FDC is estimated by sorting the daily mean flows for the period of record from the largest value to the smallest value and assigning flow value a rank from 1 to the largest value. The frequencies of exceedance are then computed using the Weibull formula for computing plotting position.

$$p = \frac{m}{n+1} \quad \dots\dots\dots \text{equation 9}$$

where p is the probability that a given flow will be equaled or exceeded (percentage of the time) m is the ranked position (dimensionless), and n is the number of events for the period of record (dimensionless). Flow duration analysis for this report was estimated using the above equation and plotted graphically. To be consistent with low-flow statistics, flow durations were computed based on daily mean flows available through 1983–2020. The flow duration curve constructed for daily time series enables a detailed examination of the flow duration characteristics of the Shire River.

### **3.8 Climate Change Impact Assessment on Hydropower Reliability**

Data of generated power was obtained from the Energy Generating Company (EGENCO) for the period 2001-2022. This data was used to establish interlinkages with future flow rates. Flow rates between Q<sub>0</sub> and Q<sub>10</sub> are considered high flow rates, and Q<sub>0</sub> to Q<sub>1</sub> would be extreme flood events. It is important that hydropower systems are designed to cope with such extreme flows. Flows from Q<sub>10</sub> to Q<sub>70</sub> would be the ‘medium’ range of flows and the hydropower system would not operate efficiently right across these flow rates. Flow rates from Q<sub>70</sub> to Q<sub>100</sub> are the ‘low flows’ when hydropower systems will just be operating but at a low power output, and moving further to the right on the FDC hydro systems will begin to shut down due to low flow. As flow rates move from Q<sub>95</sub> towards Q<sub>100</sub> that signifies the low-flow drought flows (Kwakye & Bárdossy, 2022) . Impact analysis was evaluated at these low flows Q<sub>80</sub>, Q<sub>90</sub> and Q<sub>96</sub> using FDCs taking into cognisance that the required flow for hydropower plants in the Shire River is 265m<sup>3</sup>/s on average (Siderius et al., 2021).

## 4. RESULTS AND DISCUSSION

### 4.1 Probability density plots for rainfall and temperature data 1991-2020

The graph in Figure 4.1 depicts a Kernel Density Estimate (KDE), which is a way to estimate the probability density function of a continuous random variable. In this case, it represents the density of rainfall amounts. The curve has a peak and then trails off as rainfall amounts increase, which is typical for rainfall data as most regions experience moderate rainfall amounts more frequently than very high amounts. The graph is right-skewed, as the tail on the right side of the distribution is longer or bigger than the left side. This indicates that there are occurrences of very high rainfall, but they are less frequent. Rainfall values range from 0 to over 2500mm. The probability density function values, are interpreted as the relative likelihood of the rainfall amount occurring within the dataset. In this case, the highest density of rainfall occurrences is revealed to appear just under 500mm. While the spread reflects the variability within the rainfall data, the right skew suggests that most rainfall events are moderate, extreme events, though rarer, do occur and can be significant.

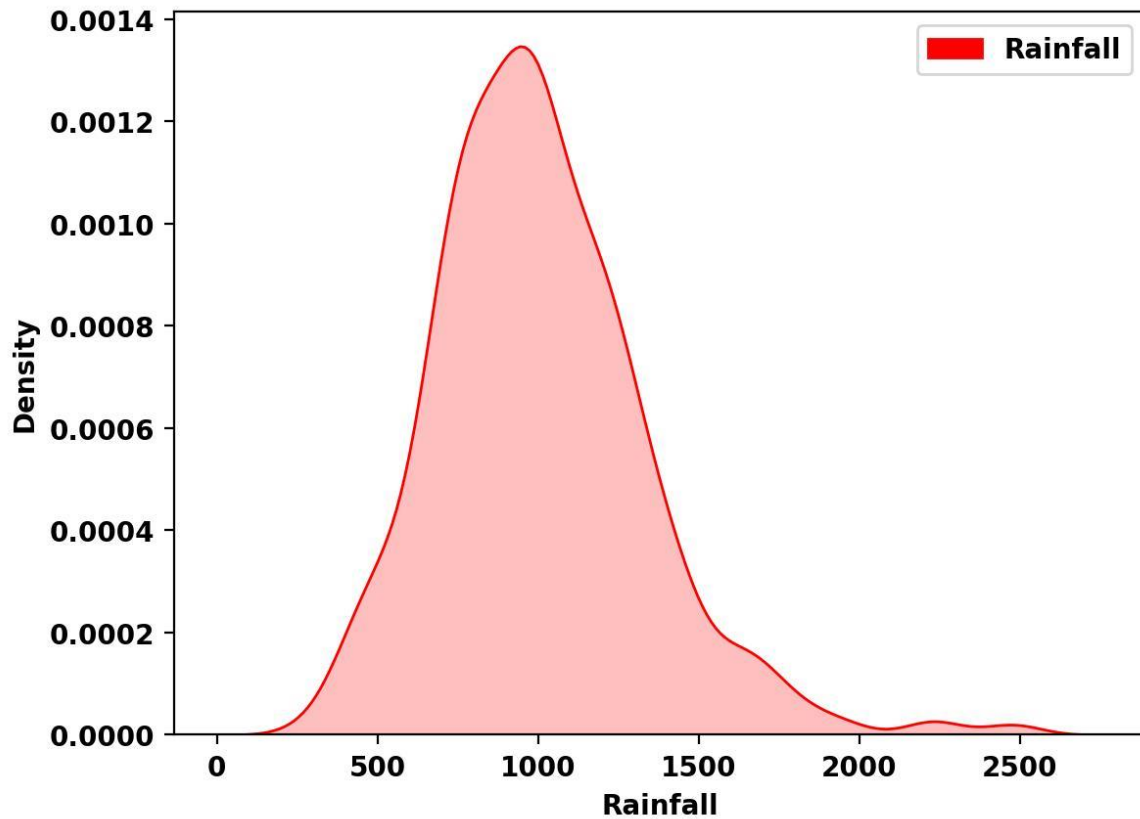


Figure 4.1. Rainfall Data Density in the Shire River Basin 1991-2020

For temperature, Figure 4.2 shows the distribution of maximum and minimum temperatures in degrees Celsius in the Shire River basin. The graph has two distinct peaks, one for the minimum temperature (green) and one for the maximum temperature (yellow), indicating the most common temperatures for each category. The peak for the minimum temperature is sharp and occurs at a lower temperature range (10°C -20°C), suggesting a narrower distribution and less variability in minimum temperatures.

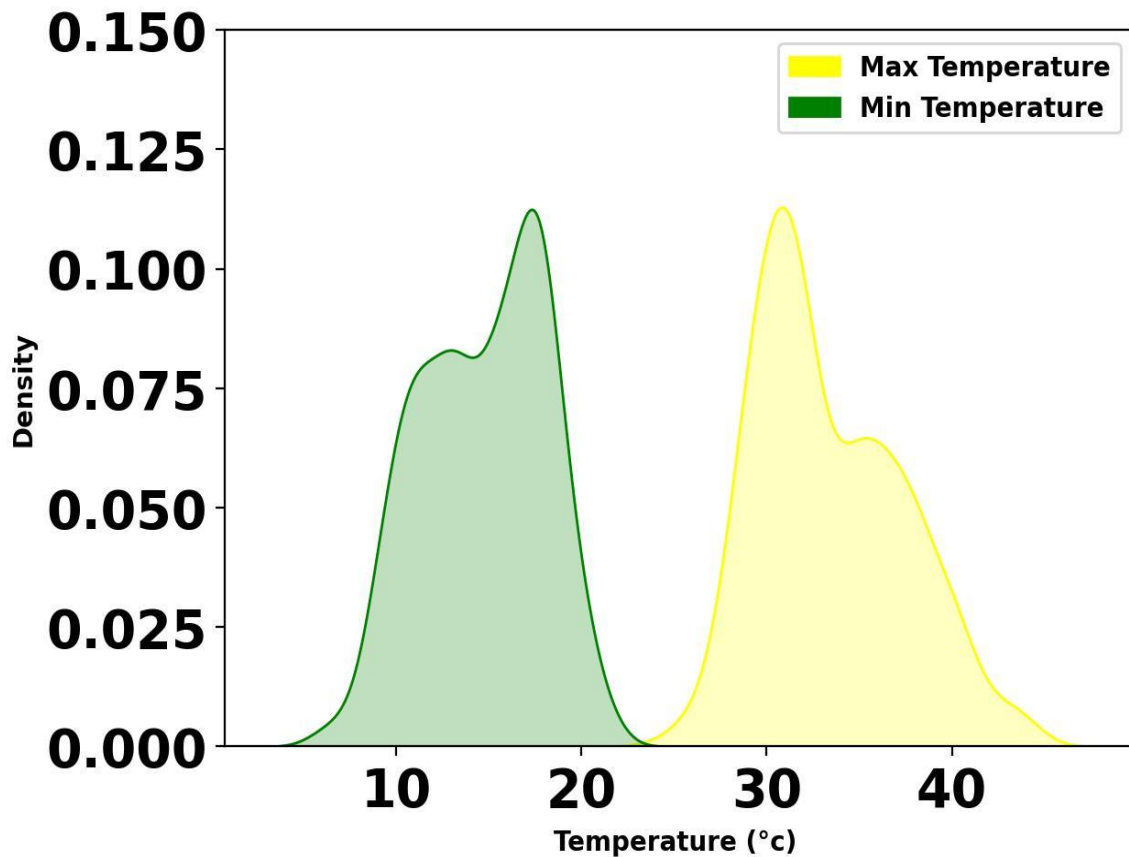


Figure 4.2 Temperature Data Density in the Shire River Basin 1991-2020

The maximum temperature curve has a broader peak, indicating a wider range of maximum temperatures (20°C-45°C) and greater variability. There are tail ends to the right of the peaks where less frequent high-temperature (40°C-45°C) occurrences are recorded. Moreover, there is a small overlap between the two distributions around the 20-25°C range, which could be transitional temperatures that are sometimes recorded as either maximum or minimum. The wider distribution for maximum temperatures could be due to a variety of factors, including daily weather variability, seasonal changes, and geographic location differences of the stations in the basin.

## 4.2 Rainfall and Temperature Distribution in the Shire River Basin 1991-2020

### 4.2.1 Spatial Distribution of Rainfall

Figure 4.3 shows the spatial distribution of annual rainfall from 1991 to 2020. The annual average precipitation in the Shire River Basin varies between 745 mm and 1382mm. The Inverse Distance Weighting interpolation suggests that the highest precipitation occurs around the upper region of the basin (985 mm–1383 mm) and the lowest precipitation (685 mm–745mm) occurs around the middle and lower sections of the basin. The 2011-2020 period shows high rainfall (1158mm-1186mm) being experienced in the upper, middle and eastern sections of the basin. Within the same period, the lower section of the basin, experienced the lowest amounts of rainfall (685mm-915mm) in comparison to 1991-2000 and 2001-2010 period.

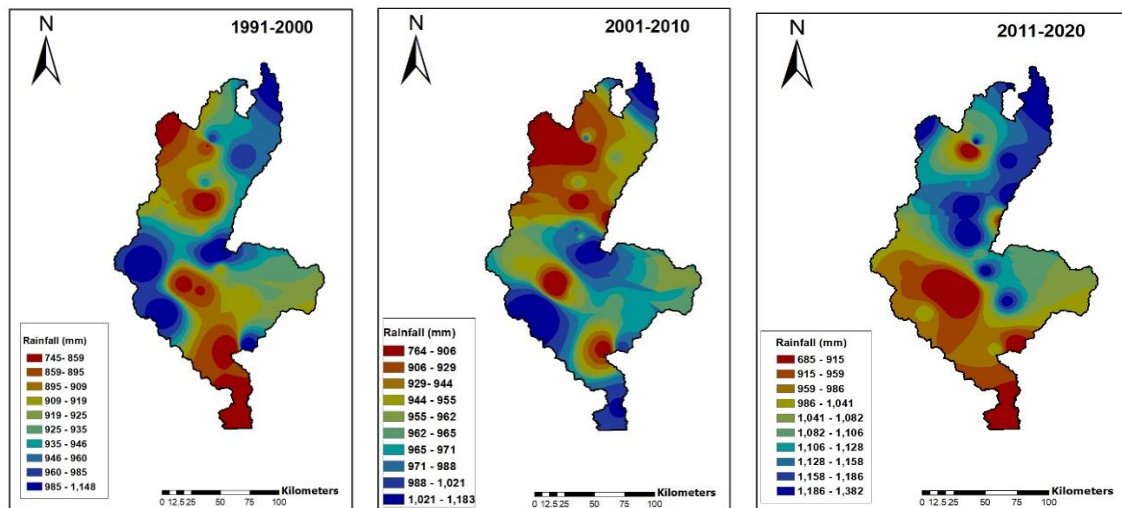


Figure 4.3 Spatial distribution of annual rainfall from 1991-2020

### 4.2.2 Temporal Distribution of Rainfall

The box plots represent the interquartile range (IQR), which is the middle 50% of the data, with the bottom of the box at the first quartile (25%) and the top at the third quartile (75%). The height of the box indicates the range of the middle half of the data, which shows the variability within that half. It is being used to compare the rainfall distributions across different months and locations in the basin.

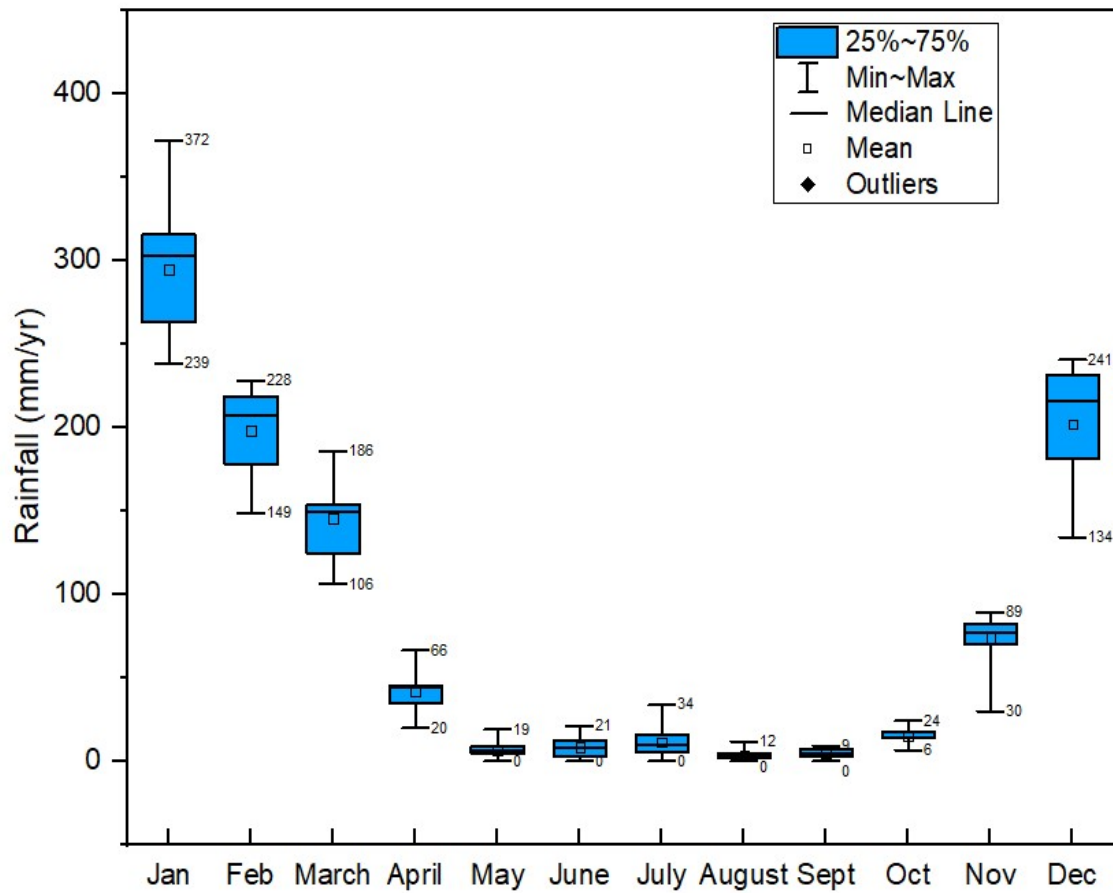


Figure 4.4 Showing the Interquartile Range of Rainfall

Generally, the SRB experiences a tropical climate throughout the year, with a pronounced unimodal rainy season between November and April. It is generally dry from May through October with rainfall we below as 12mm on average. For the 1991-2020 period, the maximum monthly values within these months ranged from 89mm-372mm in the basin as shown in Figure 4.4. The month with the highest recording was January (239mm-372mm), and the lowest (0mm-9mm) was September. In absolute terms, during the wetter months, the river flows in the Shire River are very high as compared to the drier months(Chaima et al., 2021). According to Senganimalunje & Tenthani ( 2015), the dry months have reduced cloud cover which pose a great potential source for solar energy production, except for the month of June when the sun is farthest from the country. They thus recommend optimization of hydropower with pumped hydro and solar energy during the dry months.

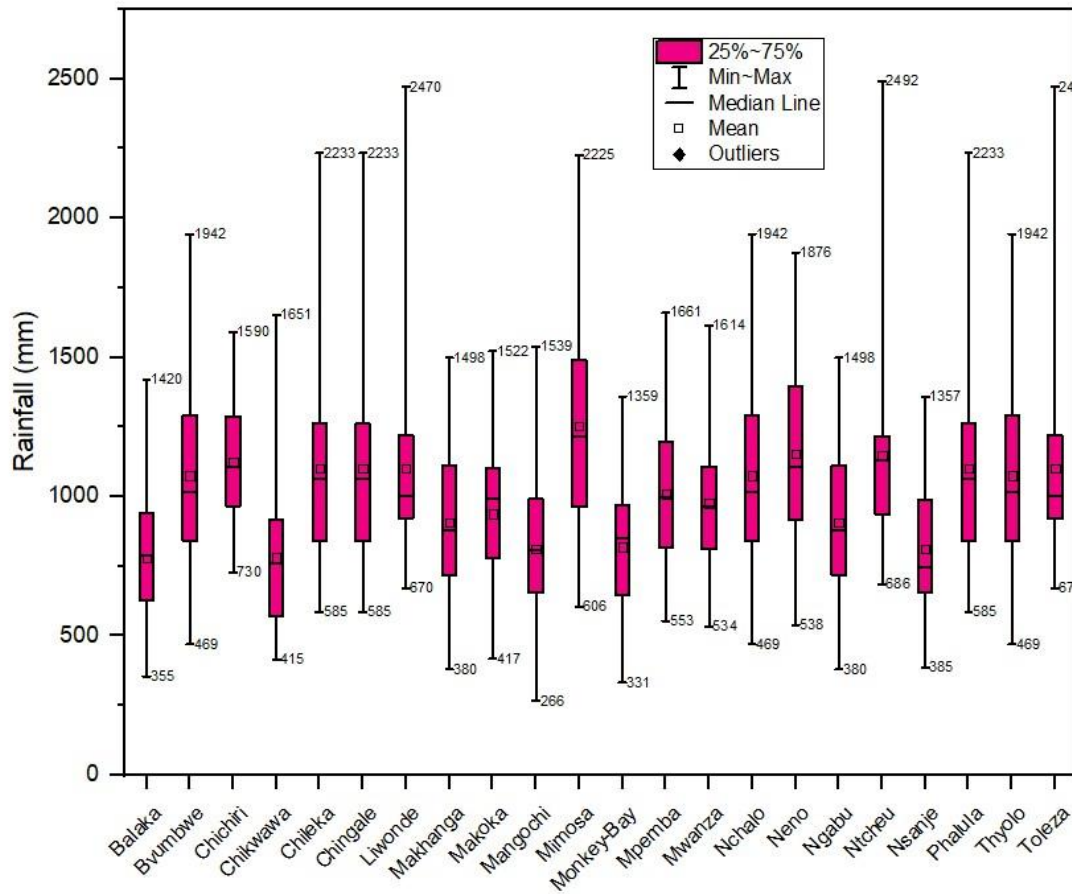


Figure 4.5 Total Annual Rainfall in the Shire River Basin

As revealed in Figure 4.5, maximum total annual rainfall ranged from 1359-2492mm in the basin, with the highest experienced in Ntcheu. Minimum total annual rainfall ranged from 266mm-730mm, with the lowest experienced in Mangochi. The median lines of Zomba, Phalombe, and Thyolo are relatively higher compared to those of Mwanza and Neno. This reveals a higher average rainfall in the former locations than the latter.

### 4.3 Temporal Distribution of Temperature

Figure 4.6 revealed that the highest recording of maximum air temperature (40°C-44 °C) was experienced in the months of September to December in the 1991-2020 period. The month of November showed the highest recording (35°C-44°C), whilst June showed the lowest (25°C -34°C). As for minimum temperature, Figure 4.6 reveals that the lowest recording (6°C -9°C) was in the months of May to September. Temperature is generally

higher in the middle of the year (around June to August), which is a generally drier period in the basin.

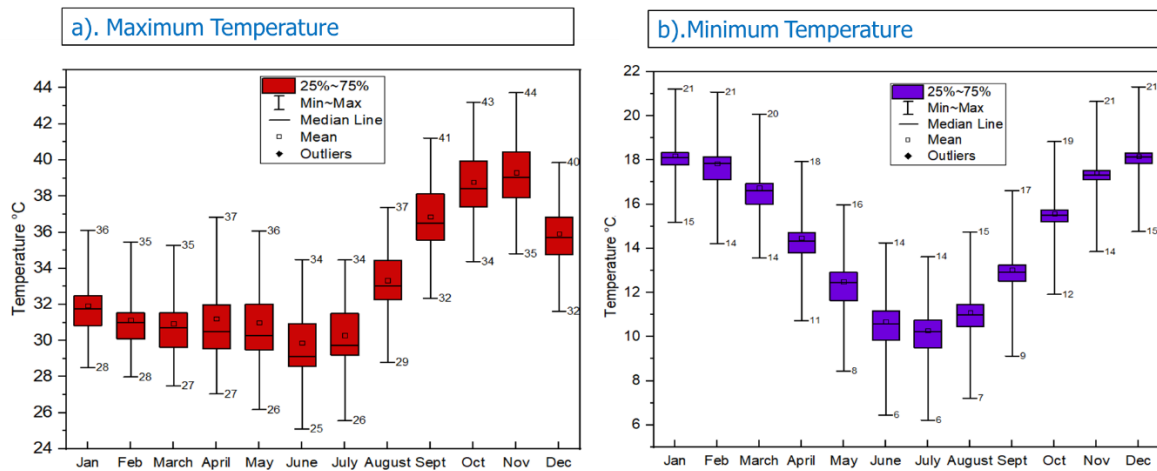


Figure 4.6 a & b, Showing Maximum and Minimum Temperature Distribution

#### 4.4 Mann-Kendall Results in the Shire River Basin 1991-2020

In this section, temporal trends in annual rainfall and mean monthly temperature are presented which were analysed for the period 1991-2020 statistically for each station in the basin. The results are represented by a bar chart in Figure 4.7 and 4.8 with each bar corresponding to a different station in the basin. The y-axis represents p-values, ranging from 0 to 0.50, and each bar corresponds to a p-value for its respective station. Bars that are below the dashed line at  $p\text{-value}=0.05$ , indicate stations where the test results are statistically significant. Bars that are above the dashed line indicate stations where the test results are not statistically significant. This means that for these stations, the observed data do not provide enough evidence to reject the null hypothesis.

For rainfall, the Mann-Kendall test results shown in Figure 4.7 reveal that the p-value was less than 0.05 for 15 out of 22 stations, representing 68% of the basin stations. 93% of these stations indicated an increasing trend in the basin. Only 1 station, Liwonde, indicated a negative significant trend. Furthermore, 7 out of the 22 stations, namely: Balaka, Chichiri, Makoka, Mangochi, Neno, Mwanza and Mpemba, showed a p-value of more than 0.05, indicating insignificant rainfall trends in the basin, thus accepting the null hypothesis.

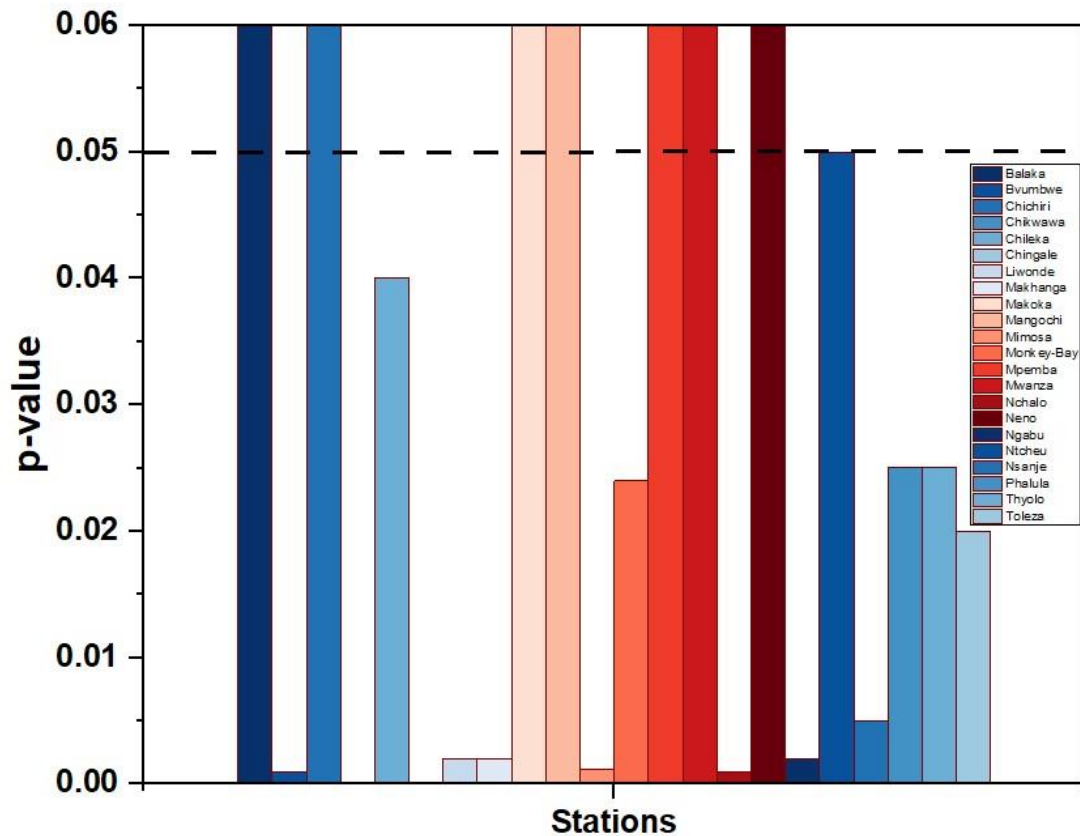


Figure 4.7 Mann-Kendall Rainfall Results

As for minimum temperature, the Mann-Kendall test results showed insignificant increasing trends for all stations in the basin as shown in Figure 4.8 below. All the stations had a p-value of more than 0.05, hence accepting the null hypothesis. On the other hand, the maximum temperature trends showed a significant increasing trend for all stations in the basin as depicted in Figure 4.9, as all stations had a p-value of less than 0.05. These results are consistent with Mtilatila et al. (2020) who examined hydrometeorological trends in the Shire River Basin from 1970-2013. Their study also revealed an increasing trend in temperature in the basin.

The rate of rise in the air temperature could lead to more evaporation in the basin which could affect stream flows significantly. With the anticipated temperature increase in the future the demand for cooling services is expected to be higher hence increasing the electricity consumption. Observations in Malawi are consistent with Sub-Saharan Africa and global trends in terms of temperature related extremes the frequency of hot days and hot nights has increased in all seasons (Trocaire Organisation, 2018).

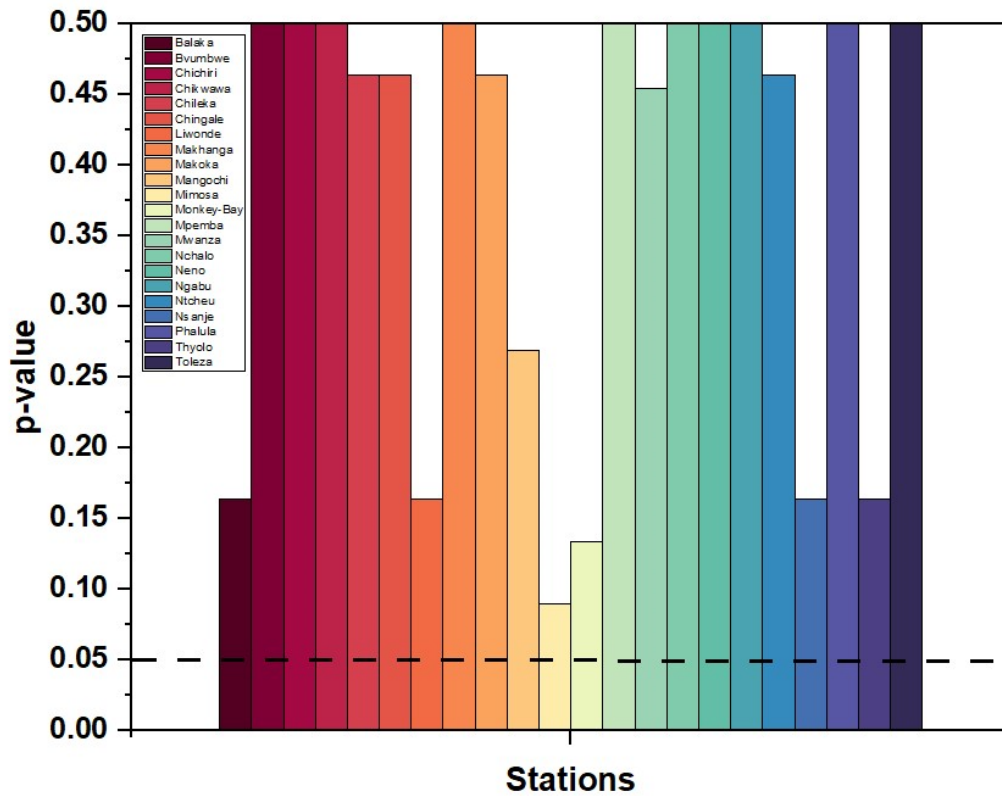


Figure 4.8 Mann-Kendall Minimum Temperature Results

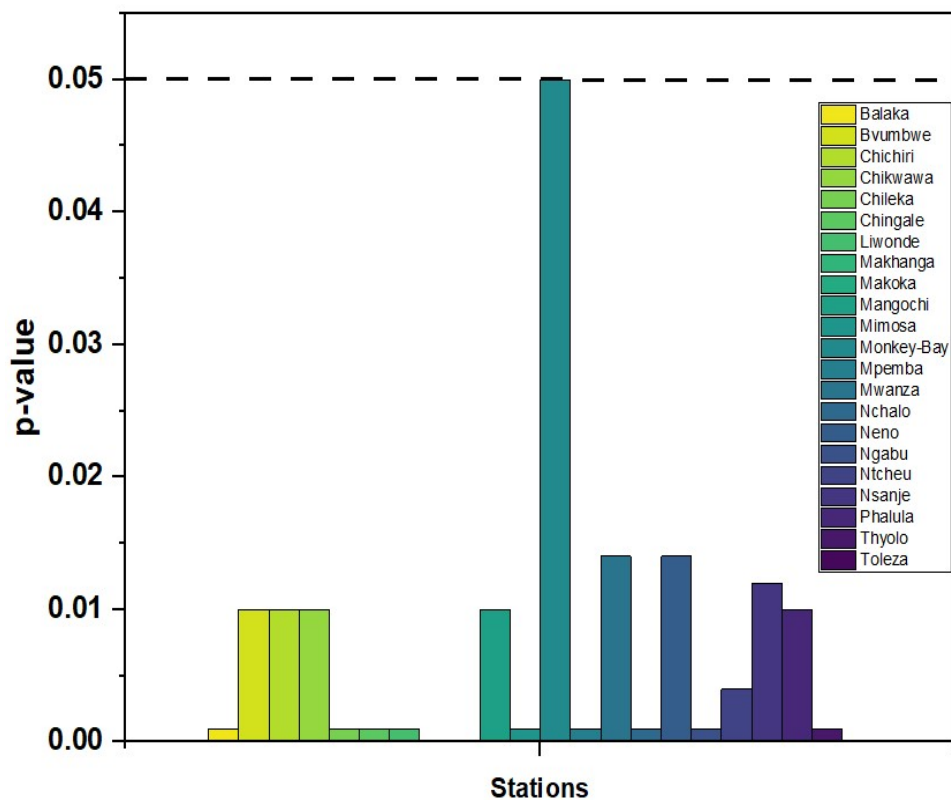


Figure 4.9 Mann-Kendall Maximum Temperature Results

## 4.5 Future Rainfall

### 4.5.1 Evaluation of Performance of GCMs

Figure 4.10 shows a scatter matrix comprising Pearson correlations ( $r$ ). Each scatter plot compares simulated data from a different climate model (MIROC6, MRI-ESM2, ACCESS-CM2), ensemble of models and observed data.

Each plot displays Pearson's correlation coefficient ( $r$ ), a measure of the linear correlation between the two datasets being compared. The values of  $r$  range from approximately 0.47 to 0.82, indicating varying degrees of positive linear correlation. The closer the Pearson's  $r$  value is to 1, the stronger the linear relationship between the model's output and the observed data. For instance, the ensemble mean revealed to perform the best with the highest correlation ( $r=0.74344$ ) with observed data, while MIROC6 had a correlation ( $r=0.6449$ ) with the observed data. ACCESS-CM2 demonstrated the lowest correlation ( $r=0.56396$ ) with the observed data. The varying correlations suggest that different models have different levels of agreement with the observed data, which can be due to different modelling approaches, resolutions, or physical representations within the models.

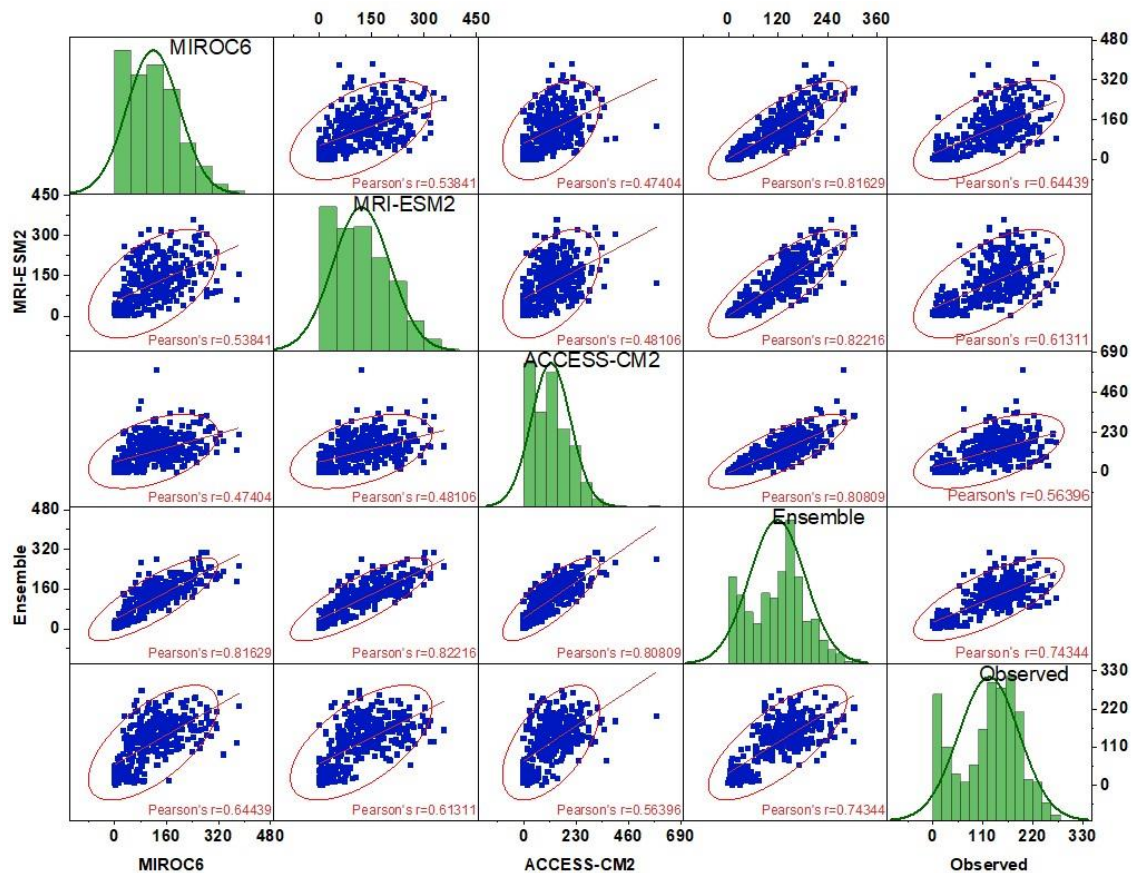


Figure 4.10. Scatter Matrix Plot for GCMs Performance Against Observed Data

For the MIROC6 model, the correlations with the ensemble, showed a high positive linear relationship ( $r=0.81629$ ). MRI-ESM2 showed a similar high positive correlation with the ensemble ( $r=0.82216$ ). ACCESS-CM2 also demonstrated a high positive correlation with the ensemble ( $r=0.80809$ ). The ensemble approach, which averages outputs from multiple models, seems to offer a simulation that is more closely aligned with the observed data, as evidenced by the highest correlation values and the scatter plot pattern.

The elliptical red lines indicate the concentration and spread of data points, suggesting the variance and covariance of the datasets. A tighter, more elongated ellipse indicates a stronger linear relationship with less scatter around the line of best fit for instance that of ACCESS-CM2 and the Ensemble scatter plot.

The histograms on the diagonal of the matrix show the frequency distribution of either the observed and the models' simulated data. For example, the "Observed" histogram indicates a relatively symmetric distribution of observed rainfall amounts, whereas the model distributions vary in shape and spread. Some histograms show a skew in the distribution, either to the left or right. For instance, the histogram for MIROC6 appears slightly skewed to the right, indicating a tail with higher rainfall events.

In general, the ensemble mean has strong to very strong correlations with the GCMs and observed data. Moreover,  $R^2=0.74$ ,  $PBIAS=3.13\%$ ,  $NSE=0.67$  indicating overall good performance of the GCMs and bias correction methods.

#### **4.5.2 Future Monthly Rainfall Results**

Figure 4.10 depicts monthly rainfall data across several scenarios, contrasting observed data with future projections under two SSPs, SSP2-4.5 and SSP5-8.5, for two separate time periods (2030-2064 and 2065-2100). The plot reveals that there is a clear seasonal pattern, with peak rainfall typically occurring from November to April, and this pattern is generally reflected in both SSP scenarios, although the projected amounts differ. In comparison to the observed data, the projected rainfall under both SSP scenarios shows an increase in rainfall for these peak months in the future. Notably, ssp5-8.5 shows the highest increase across all months at an average of 28% increase in rainfall in the 2030-2064 period, which indicates wetter conditions than the historical period. However, under the same scenario,

but in 2065-2100 period, rainfall is depicted to decrease in the drier months of May to October.

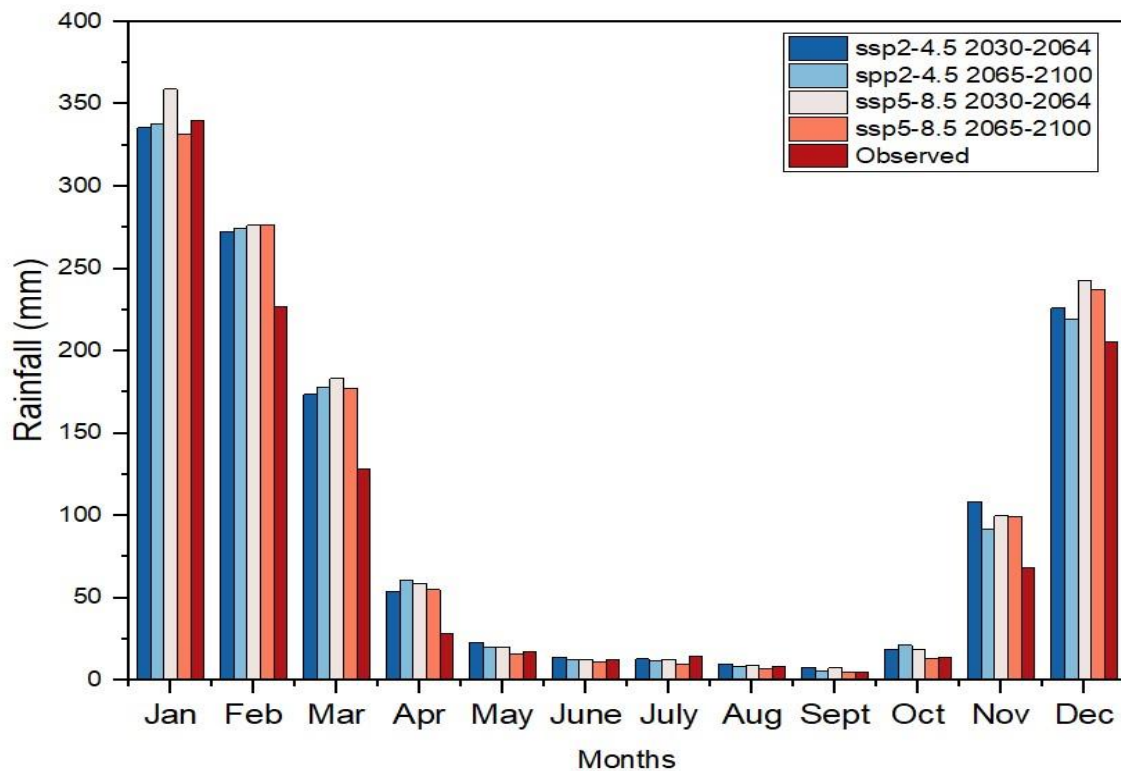


Figure 4.10 Future Rainfall in Climate Scenarios

This indicates drier conditions in the non-rainfall months in comparison to the observed data. Ssp2-4.5 shows a marked increase in rainfall in both time windows, in comparison to the observed rainfall, except for the drier month of July. According to Mittal et al. (2017), 19 models projected changes of less than +/-5% by the 2040s in rainfall, citing higher likelihood of intense rainfall events (often associated with flooding) and also dry spells in drier months. A study by Zuzani et al., (2019), rainfall trends generally tend to increase during high rainfall periods and decrease during low rainfall periods. These analyses indicate that climate change may pose intense rainfall in wetter months, in turn resulting in high river flows that carry sediments that can affect efficiency of equipment, but at the same time, high flows also increase the hydropower potential. While low rainfall in drier months pose stream flow concerns necessary for hydropower generation especially for the run-of-the river type of hydropower plants cascaded in the Shire River. In the dry period, plants would be operated in partial load due to insufficient flows resulting into short electric power supply that would affect socioeconomic activities.

## 4.6 Future River Flow Regimes

### 4.6.1 Model Calibration and Validation

Figure 4.11 shows a time series comparison between observed and simulated river flow data for the period 1970 to 2000. Calibration was done for the period 1970-1990 and validation for the period 1991-2000. The section labeled calibrated curve shows the time period during which the model parameters were adjusted to closely match the observed data ensure the model accurately represents the system being studied. While the model's predictive accuracy was tested/validated by comparing its output to observed data that was not used in the calibration process. This is done to confirm that the model can reliably simulate conditions different from those it was calibrated against. The graph shows a close match between observed and simulated data during the calibrated period, demonstrating that the model was able to replicate past conditions effectively. Moreover, the coefficient of correlation  $R^2 = 0.8$  showing a strong correlation and  $NSE = 0.64$  sighting overall good performance of the model in simulating the river flows of the basin.

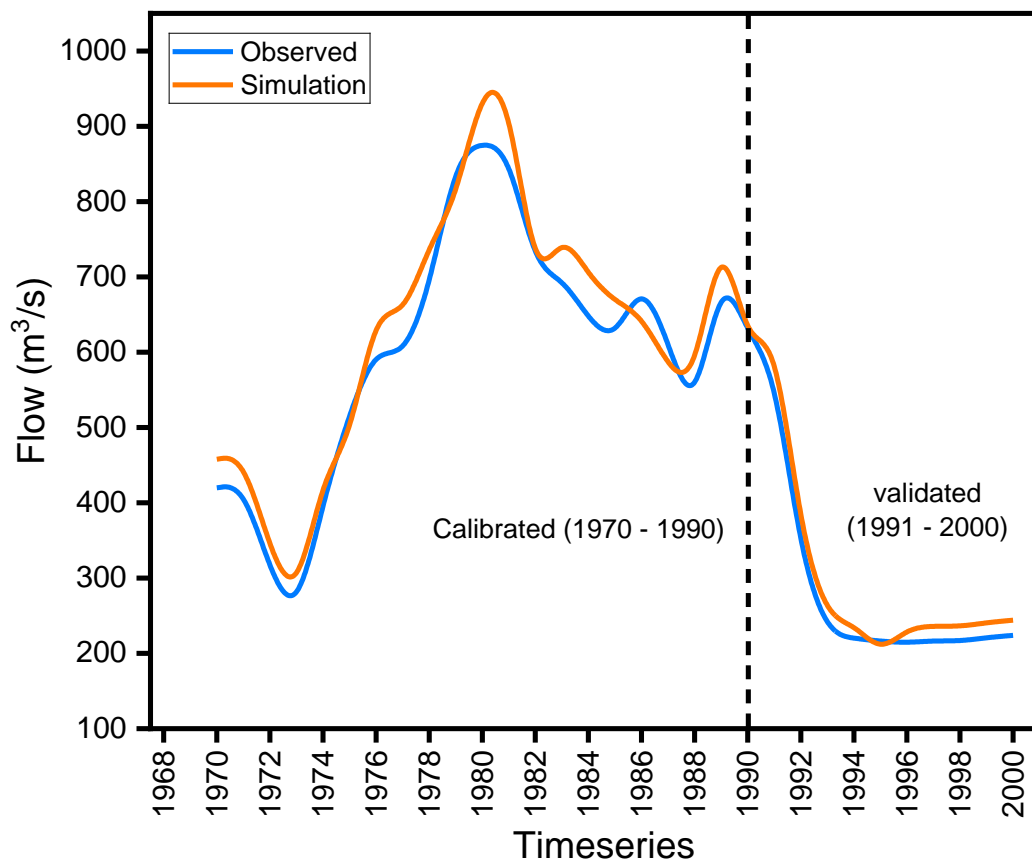


Figure 4.11 Results for Calibration and Validation

#### 4.6.2 Future River Flow Regimes Results

The provided graph in Figure 4.12 is a bar chart overlaid with a line graph that presents river flow data over a timeseries of months, from January to December. Observed data serves as a baseline to compare against the SSP projections. The SSP scenarios predict a similar pattern but with different magnitudes. Comparing the SSP scenarios, ssp5-8.5 predicts higher flows of over 20% more than the observed data, and also the ssp2-4.5 scenarios, particularly in the future period of 2065-2100. This could be related to anticipated higher rainfall and due to more intense climate change effects. For both SSP scenarios, there is an apparent increase in predicted flow from the first timeframe (2030-2064) to the second (2065-2100), which may suggest that the effects of climate change are projected to increase river flows over time.

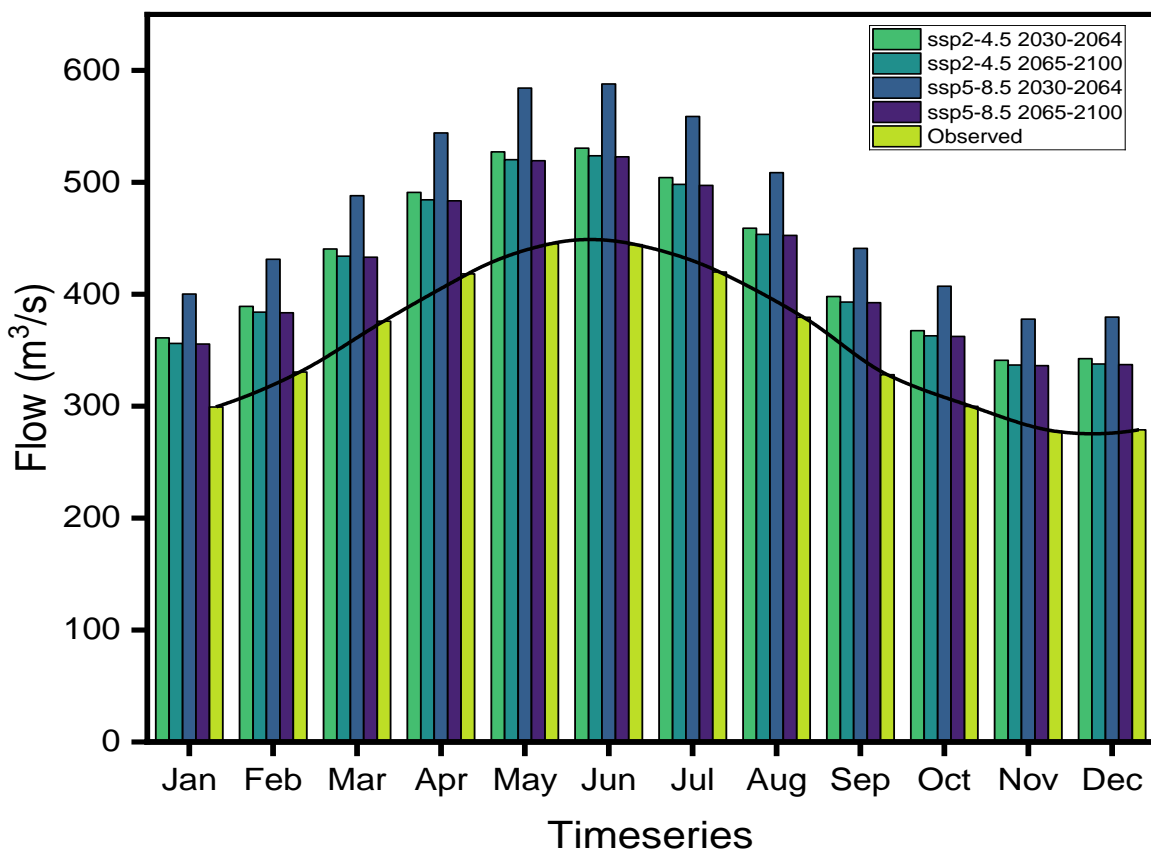


Figure 4.12 Future River Flow Regimes in the Shire River Basin

These results are consistent with a study by Hussein et al. (2019) that revealed that all three hydrometeorological extremes (mean annual temperature, average rainfall and baseflow index) increased, suggesting that both the intensity and frequency of flooding in the Shire River Basin would also increase in absolute terms. Another study by (Gama et al., 2014) projected higher discharges in the Shire River, highlighting explicit potential increase of

flood risks in the basin, thus increasing the probability, more damage to infrastructure. On the other hand, high discharges could also increase inflow into the turbines of the cascade hydropower plants.

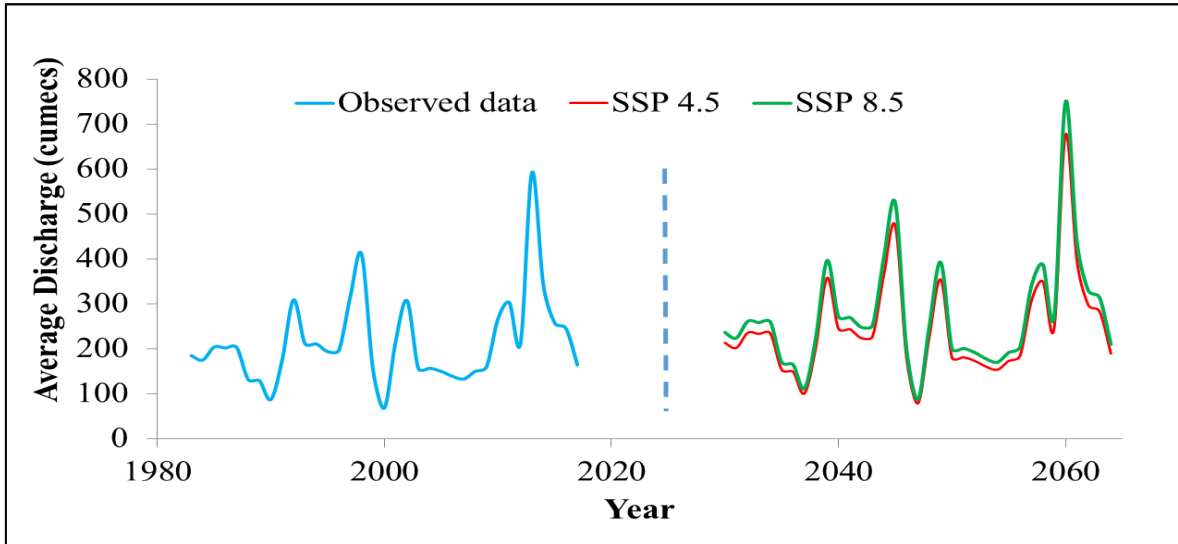


Figure 4.13 Future River Flow Regimes on Annual Scale

However, the power plants only generate electricity based on capacity limit of 350 MW. Hence, runoff discharge into the run-of-river plants would be partially utilized because there is no reservoir with large regulation capacity through which operators could redistribute runoff between the rainy season and the dry season for better energy supply (Chaima et al., 2021).

The annual trends in the basin indicate that future flows under all scenarios will keep on increasing as shown in Figure 4.13. This augments the earlier findings that flows in Zambezi River basin will keep on increasing due to climate change (Spalding-fecher & Chapman, 2014). The increase in rainfall intensities in the basin therefore directly relates with an increase in the runoff and other parameters of the water basin thereby providing significant amounts of parameters for hydropower generation. Despite that these increase in discharge will increase the potential for electricity generation, it is also important that further studies be done to explore and assess the watershed vulnerability to floods as these would equally cause challenges to the hydropower infrastructure.

### 4.6.3 Impacts of Climate Change on Hydropower Generation

#### 4.6.3.1 Current Impacts

The trends in electricity seem to be reducing in the current regimes as show in Figure 4.14. This could be due to climate change which is evident in the basin due to poor agricultural practices, deforestation, pressure on resources that lead to siltation which in turn reduce the capacity of reservoirs. Previous cyclones such as Cyclone Ana, Cyclone Idai, Cyclone Gombe and Cyclone Freddy greatly impacted electricity generation in Malawi (Government of Malawi, 2023). There also has a lot of competing water demands and usage which could further hinder the reduction of electricity generation (Mzuza et al., 2019). In furtherance, the regulatory frameworks lack coordination to sustainably develop and maintain hydropower generation in the basin (Chisale & Lee, 2023).

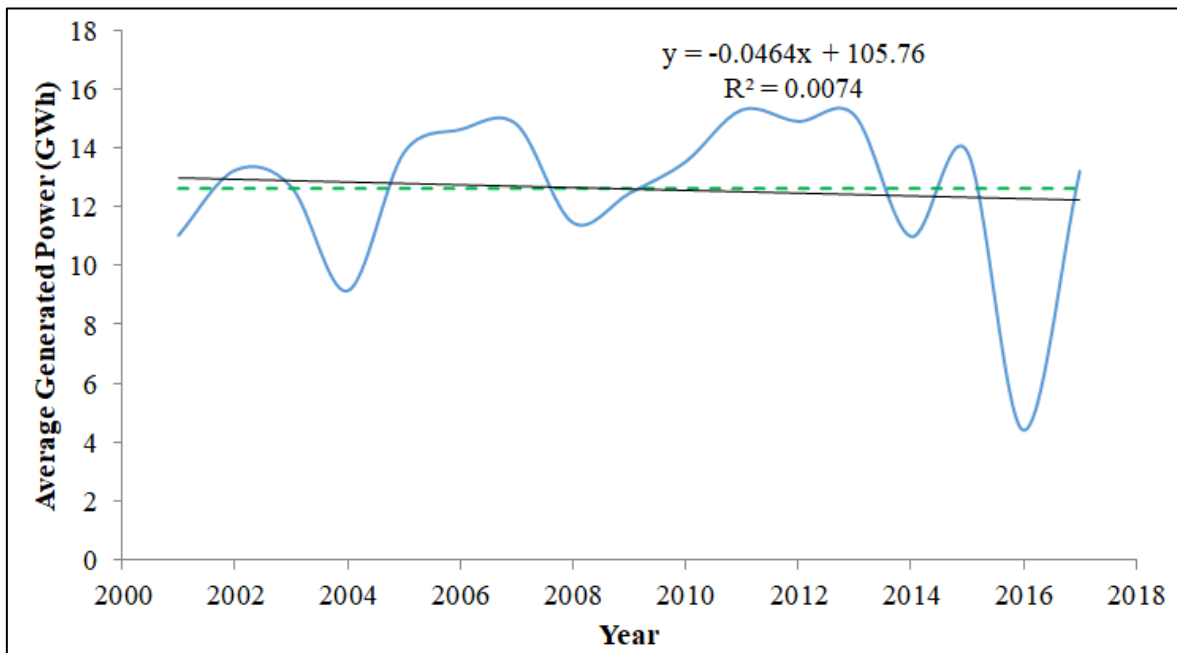


Figure 4.14 Generated Power in Time Series

This study also explored relationships between observed discharge and the amount of electricity generated in the basin. Even though the generated electricity shows varying trends, it also displays an interesting pattern where the peak curve shows almost a constant plot below 16 GWh as shown in Figure 4.15. With the projected increase in discharge, the potential could also increase thereby creating room for more industries in the country.

These results differ with those by (Hamududu & Killingtveit, 2016) that projected reduced rainfalls and increased precipitation in the Zambezi River basin where this study area belongs. This could be due to the significant uncertainty in the projections as a result of lack of long climatic data and the approach that was adopted in addition to different approaches that these two studies have employed. However, the results agree with that of (Zuzani et al., 2019) and (Bronstert et al., 2023) that showed that the impacts of climate change are becoming so prevalent in the basin.

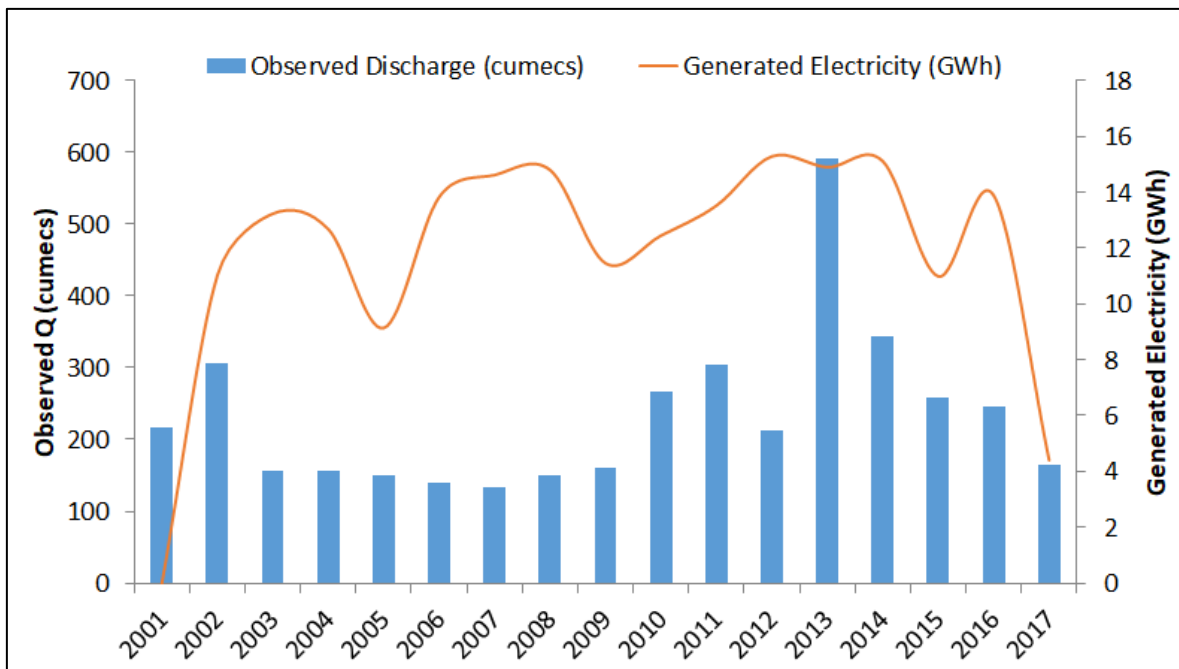


Figure 4.15 Comparison of Observed Flows and Generated Power

#### 4.6.3.2 Future Impacts

Figures 4.16 and 4.17 exhibit the flow duration curves for the Basin. The average flows at different probabilities were used specifically Q80, Q90 and Q96. Q80 was used to estimate the environmental flows whereas Q90 and Q96 were used to describe the adequacy and reliability of the water source for hydroelectric power generation respectively. The mean discharge in the river was determined as 263 m<sup>3</sup>/s. The adequacy of a water source for hydropower was defined by the ability to meet the average daily demand at a specific probability of exceedance.

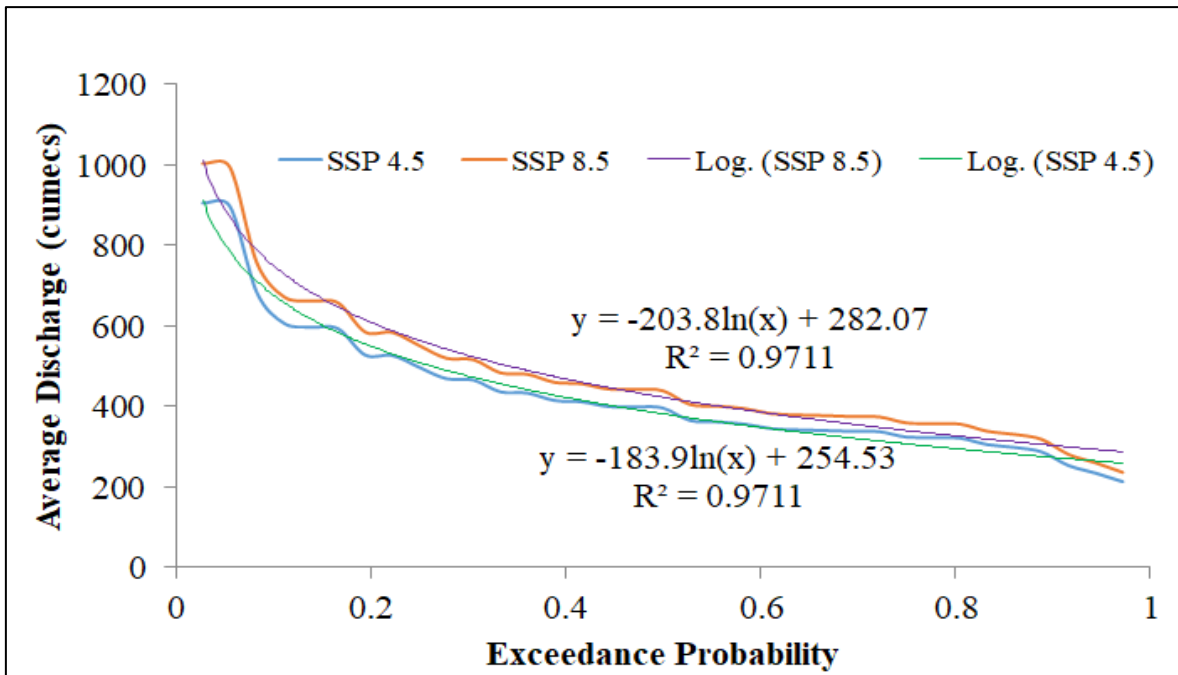


Figure 4.16 Average Discharge Frequency Analysis

Low frequency analysis was conducted in this study to understand the minimum flows always available in the river crucial for hydropower generation. With respect to SSP2- 4.5 and SSP5-8.5, these low flows would enhance the understanding of the river in response to the availability of water for hydropower generation

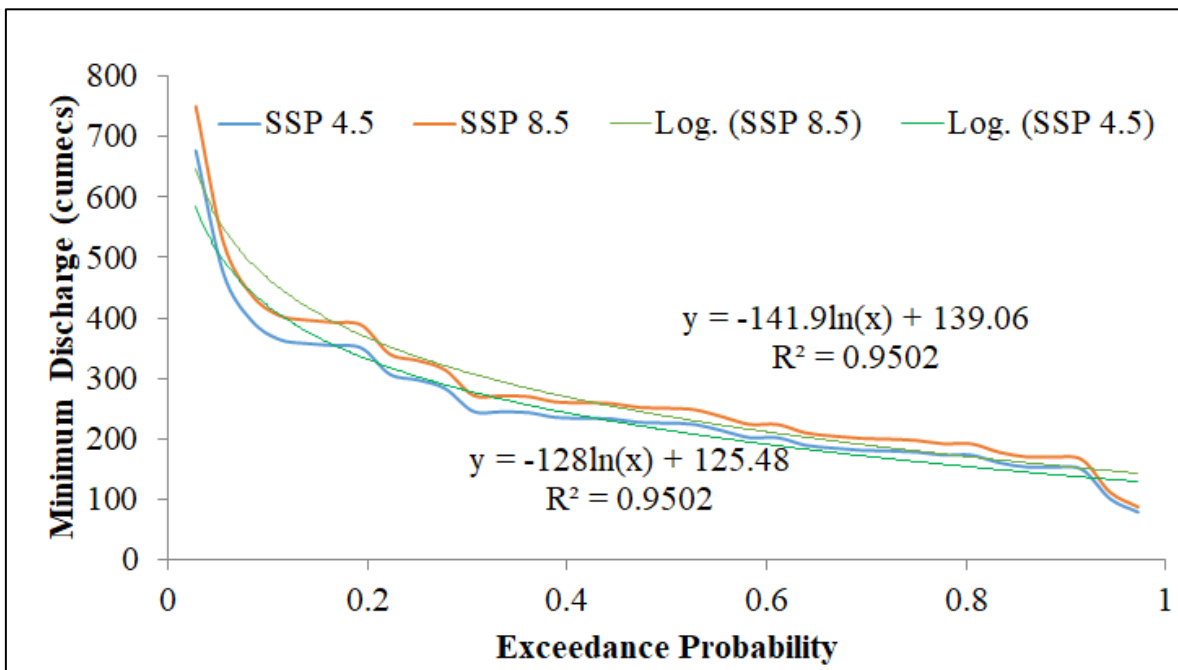


Figure 4.16 Minimum Discharge Frequency Analysis

Table 4.1 Summary of low flows in climate scenarios

	2030-2064		2065-2100	
	SSP 4.5	SSP 8.5	SSP 4.5	SSP 8.5
Q <sub>80</sub>	170.7	154.0	295.6	327.5
Q <sub>90</sub>	154.0	139.0	273.9	303.5
Q <sub>96</sub>	144.9	130.7	262.1	290.4

In the period of 2030-2064, Q<sub>80</sub> was determined as 170.7 m<sup>3</sup>/s which is less than the required, approximately, 263m<sup>3</sup>/s. This indicates that under SSP2- 4.5 in the period between 2030 and 2064, this amount of water in the river will be equaled or exceeded all the time indicating a relatively lower flow condition than the present average discharge. Further observation has been noted under SSP8.5 in the 2030-2064 period where all flows are less than the required. This indicates traces of changing climate as the low flows keep decreasing in the river as compared to the normal flows which would lead to low generated power in the basin. Table 4.1 summarises the values of the flows under climate scenarios. These values are important for hydropower studies as they may be used as reference points for environmental impact assessments, and designing hydropower related infrastructure within the basin.

## 5. CONCLUSION

This study has looked at the cascading effect of climate on water resources and then how the water affects energy production in return. Rainfall and temperature data analysed for the 1991-2020 period data revealed that Shire River Basin experiences a unimodal pattern of rainfall which poses river flow challenges in drier months for hydropower generation. A wider distribution for maximum temperatures was detected which could be due to a variety of factors, including daily weather variability, seasonal changes, and geographic location differences of the stations in the basin. A rising trend in maximum temperature for all stations indicates a concern on evaporation rates in the basin, but shows potential for solar energy. Rainfall also shows an increasing trend for all stations in the basin which could entail more hydropower potential in the basin, but could result in flood events in the basin.

Climate models, project a general increase in rainfall for the wetter months, and a decrease in some of the drier months. Similarly, future river flow regimes take the same pattern as the future rainfall, indicating high flows in wetter months as compared to low flows in the drier months. High flows in the wetter months underscore the significance of flood risk analysis in the basin to come up with flood risk management framework. Frequency analysis at low flows shows the potential challenges the hydropower sector will incur in the face of climate change. These issues highlight the vulnerability of the hydropower sector to climate change, and the need for proactive measures to mitigate the impacts.

The study however was limited as it could not include the effects of sediment yield, population change and land-use on hydropower generation. This accentuates the need for a comprehensive study incorporating these factors.

## **6. RECOMMENDATIONS**

Energy sources should be diversified, with those that are less vulnerable to climate change, such as Solar energy since the Shire River basin is vulnerable to climate change.

The Malawi government should put investment in climate resilient hydropower infrastructure to safeguard different infrastructure from effects of very high rainfall intensities /floods, and also leverage on the hydropower potential.

Even more so, the government should invest in data collection and monitoring to enhance proper modelling of river basin for impact assessments and development of adaptation measures.

The country should also make deliberate efforts to train more people on climate modelling and disaster risk management.

## **7. LIMITATIONS OF THE STUDY AND RECOMMENDATIONS FOR FUTURE STUDIES**

The limitation of this study is that discharge gauging stations are not uniformly distributed throughout the catchment area and therefore assumptions have been made. This study also focuses mainly on the impacts of climate change without analyzing in depth the impacts of land use, temperature change, population change and sedimentation which could also affect the river flow regimes in the study area. As such future studies can focus on:

- Combined effects of climate change and land-use on Hydropower Generation in the Shire River Basin;
- Impacts of climate change on sediment yield and Hydropower Generation in the Shire River Basin;
- A Comprehensive Study on Flood Risk Assessment in the Shire River Basin.

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