ASSESSING THE IMPACT OF CLIMATE VARIABILITY ON KAMUZU DAM II

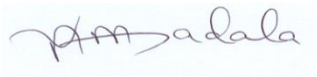
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ABSTRACT

Climate variability poses significant challenges to water resources, particularly in developing regions like Malawi, where dams such as Kamuzu Dam II are critical for running water supply. This study assesses the impact of climate variability on Kamuzu Dam II by analyzing historical trends in rainfall, temperature and dam volumes from 1990 to 2023.Using quantitative methods, including Mann-Kendall trend tests and Pearson correlation analysis, the research evaluates the relationships between climatic variables and dam volumes.

The results indicate no statistically significant trends in rainfall ($p = 0.350$), maximum temperature ($p = 0.216$), or dam volumes ($p = 0.128$). However, polynomial regression reveals nonlinear patterns, such as increasing maximum temperatures (26°C to 28.5°C) and volatile dam volumes, particularly during extreme events like the 2015–2016 El Niño drought (Government of Malawi, 2016). Weak correlations between rainfall and dam volumes ($r = -0.124$) and temperature and volumes ($r = 0.012$) suggest the influence of non-climatic factors, such as sedimentation and land-use changes (Mulwafu & Mwendera, 2019; IPCC, 2021).

The study underscores the vulnerability of Kamuzu Dam II to climate extremes and recommends adaptive strategies, including enhanced water conservation, sediment control, and diversified water sources, to ensure sustainable water management and most importantly, further research on this topic. These findings contribute to localized climate adaptation planning and highlight the need for further research on nonlinear climate-water dynamics in Malawi.

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LIST OF ACRONYMNS

CO_2	Carbon Dioxide
DCCMS	Department of Climate Change and Meteorological
ENSO	El Nino-Southern Oscillations
GHGs	Green-House Gases
LWB	Lilongwe Water Board
UHI	Urban Heat Island

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1. INTRODUCTION

Kamuzu II dam is one of the two Kamuzu dams constructed along the Lilongwe river from which Lilongwe Water Board abstracts its water. This dam was constructed between 1989 and 1992. The dam initially had a raw water storage capacity of 9.2 Mm^3 but was later raised by 5m in 1999 to increase water storage capacity of the dam to 19.8Mm^3 (Lilongwe Water Board, 2024). The Kamuzu Dam II has been one of the main sources of running water supply in the city. However, in recent years there has been increasing water problems in the city which can be attributed to changes occurring in the dam such as dropping water levels. It is most likely that climate variability and change is the main culprit behind these changes.

1.1. BACKGROUND

Climate variability refers to the variations in the mean state and other statistical properties of climate on temporal and spatial scales beyond individual weather events (IPCC, 2018). These variations manifest as changes in temperature, precipitation patterns and extreme weather events which have implications on water resources, agriculture and ecosystem health. In Malawi, climate variability has become a critical concern due to its direct impact on water resources and availability, food security and communities that are dependent on the natural resources. One of the water resources affected by this variability is the Kamuzu Dam II, which is located along the Lilongwe River in the capital city of Malawi, Lilongwe. This dam is very crucial for the city's water supply by acting as a water balancing reservoir for the Lilongwe River, together with the Kamuzu Dam I (Surbana Jurong , 2024). In addition to that, the dam also provides raw water to the three treatment plants owned by the Lilongwe Water Board(LWB) (Lilongwe Water Board, 2019) which ensures that there is a portable water source available to the people of Lilongwe city and the surrounding areas. As such, understanding the impact of climate variability on the dam is essential for sustainable water management and adaptation planning for the future.

The climate of Malawi is influenced by a lot of factors with the InterTropical Convergence Zone being one of the predominant influences which bring forth the seasonal rainfall

patterns. However, in recent decades, the country has experienced increasing variability in climate characterized by erratic rainfall patterns, prolonged droughts and intense flooding events. These changes have been attributed to global climate change as well as regional factors such as deforestation and land-use changes (Adhikari, 2016). For example, the 2015-2016 El-Nino event caused severe droughts in the country of Malawi, which led to reduced water levels in major water reservoirs including the Kamuzu Dam II (Government of Malawi, 2016). Such events highlight the vulnerability of the country's water resources to climate variability.

The primary function of the Kamuzu Dam II is to ensure a reliable water supply for the growing population and agricultural activities in the city of Lilongwe. However, the dam's operations are highly dependent on consistent water inflows, which are increasingly threatened by climate variability. Reduced rainfall and increased evaporation rates due to rising temperatures have led to declining water levels in the dam, raising concerns about water security for the Lilongwe District. For example, during the 2018 dry season, water levels in Kamuzu Dam II dropped to critically low levels, necessitating water rationing measures (Lilongwe Water Board, 2018). This not only disrupted daily life but also highlighted the urgent need to address the impacts of climate variability on water resources.

Several studies have examined the impacts of climate variability on water resources in Malawi, but few have focused specifically on Kamuzu Dam II. For example, Ngongondo et al. (2011) analyzed long-term rainfall and river flow trends in Malawi, identifying significant declines in water availability in some regions. Similarly, Kambombe et al. (2020) investigated the impacts of climate change on water resources in Malawi, highlighting the vulnerability of dams to changing hydrological conditions. However, there is a need for more localized studies that assess the specific impacts of climate variability on Kamuzu Dam II, considering its unique geographical and operational context.

This research project aims to fill this gap by examining the impact of climate variability on Kamuzu Dam II, with a focus on changes in dam water levels, sedimentation levels, land cover and land use changes, and temperature and rainfall trends. By analyzing these

historical climate data, hydrological records, and operational data from the dam, the study will provide insights into the extent to which climate variability has affected the dam's performance. The findings of this study will contribute to the growing body of knowledge on climate change impacts in Malawi and inform policy decisions aimed at ensuring sustainable water management.

1.2. PROBLEM STATEMENT

In previous years, the Kamuzu dam II has always had a constant water level with most of the water overflowing from the dam top. However, in recent years the levels of water in this dam have noticeably decreased, a phenomenon which can be attributed to climate variability, change and anthropogenic factors (Melchioly, 2021). This decline has affected the livelihoods of the majority of the people in Lilongwe who rely on the running water distributed by the LWB from the dam. This is so because the decreasing water levels have resulted in reduced volume of water available for distribution resulting in frequent water shortages and disruptions to the residents of the city. Furthermore, the consequences of water scarcity extend far beyond immediate water supply issue. Reduced water availability also affects agriculture which is a crucial sector in the economy of Malawi which in turn poses a threat to food security.

1.3. MAIN AND SPECIFIC OBJECTIVES

1.3.1. Main Objective

The main objective of this research project was to assess the possible impact of climate variability on the Kamuzu Dam II over the past decades from 1992.

1.3.2. Specific Objectives

- To analyze annual rainfall trends in the catchment area.
- To assess the temperature trends in the catchment area.
- To evaluate the water levels and their corresponding volumes in the dam in relation to rainfall and temperature trends.

1.4. RESEARCH QUESTIONS

i. How does historical data of rainfall and temperature trends justify changes on the dam caused by climate change?

ii. How is climate variability affecting the Kamuzu II dam in terms of water level, volume and sedimentation?

iii. What are the possible strategies that may be used to mitigate the effects of climate change on the dam?

1.5. SCIENTIFIC SIGNIFICANCE

This research project is extremely important in addressing the serious difficulties posed by climate variability and its consequences for water resource management in Malawi. Kamuzu Dam II is a critical water source for Lilongwe, providing water for domestic, industrial, and agricultural use. However, diminishing water levels in the dam, owing to changes in rainfall patterns and prolonged dry spells, have caused harm to livelihoods, water supplies, and ecological systems, needing immediate investigation and action.

Water scarcity is one of the most pressing issues for the residents of Lilongwe city whose reliance on LWB for water supply has been hindered by the decreasing water levels. The lower water levels at Kamuzu Dam II have caused frequent water shortages, significantly impacting families, businesses, and agricultural activities. As noted by Sibande.et.al (2020), variations in water availability linked to land use changes and rainfall variations affect a lot of socio-economic activities of communities that depend on a stable water supply. This project is of particular significance because it aims at finding out the underlying causes for these water shortages such as climate variability, human-induced drivers like land use and land cover changes and increased water demands from the ever growing population of the city. The possible findings from this project will not only help in mitigating water shortages, but also ensure the continuation of essential services from the LWB whilst also safeguarding the livelihoods of the people of the city who are dependent on this water supply.

Additionally, this research project significantly contributes to understanding climate change and its impact on local water resources. In as much as there is a is a lot of studies which were conducted on climate change, there is lack of context-specific data on regions such as Malawi which are particularly vulnerable to climate driven disruptions. By focusing on Kamuzu Dam II, this research aims at filling a critical knowledge gap and provides an insight into the hydrological and ecological changes caused by climate variability.

2. LITERATURE REVEW

"Climate variability refers to fluctuations in the mean state and other statistics (such as the standard deviation, extremes, or shape of frequency distribution) of climate elements on all spatial and temporal scales beyond those of individual weather events" (Roger G. Barry, 2010). Climate variability can be induced by both natural and anthropogenic factors. The natural factors include volcanic activity, solar radiation fluctuations and ocean-atmosphere interactions. Green-house gas emissions and land use change are the most common anthropogenic factors influencing variability (Trenberth, 2011).

2.1. Causes of Climate Variability

Climate variability is driven by a complex interplay of both natural processes and human induced changes with growing evidence highlighting the dominance of anthropogenic factors in recent decades (IPCC, 2023). Natural drivers include solar irradiance fluctuations, which follow an 11-year cycle and contribute to minor variations in the Earth's energy budget (Kopp, 2021). Additionally, volcanic eruptions release reflective aerosols such as Sulphur dioxide, into the atmosphere, thereby causing short-term global cooling (Aubry et al., 2022). Large scale ocean-atmosphere interactions, particularly the ENSO, play a critical role in redistributing heat and altering precipitation pattern worldwide (WMO, 2023), thereby influencing climate variability.

However, since the pre-industrial era, human activities have become the primary driver of climate variability. The combustion of fossil fuels has elevated atmospheric CO_2 concentrations to unprecedented levels, thereby intensifying the GHG effect (Global Carbon Project, 2023). Deforestation further worsens warming by reducing carbon sequestration, while agricultural expansion increases methane emissions from livestock and rice paddies (FAO, 2022). Urbanisation amplifies regional climate variability through the Urban Heat Island (UHI) effect, where concrete and asphalt absorb and retain heat (Santamouris, 2020).

2.2. Hydrological Impacts of Climate Variability

The potential impact of climate variability will cause significant problems in a lot of regions across the globe especially in underdeveloped countries where the effects of climate change and variability are heavily felt (Rasha Abed., et al, 2023) including in water resources. One such country that can be affected by climate variability is Malawi which is also a developing country. Climate variability affects different socio-economic aspects of society including agriculture, water supply and hydropower generation. All of these have linkage to dams. Therefore, dams and other water resources are also affected climate variability. Climate variability significantly alters the hydrological cycle by impacting water availability, increasing sedimentation and inducing water quality degradation.

2.2.1. Erratic Rainfall patterns and Prolonged Droughts affecting Water Availability

Globally, changes in precipitation patterns and increased temperatures have disrupted the balance of most water resource systems. Regions are experiencing more frequent and intense weather events such as prolonged dry spells and droughts, heavy rains and heat waves (IPCC, 2021). Climate variability, particularly in regions experiencing increased aridity, is leading to prolonged droughts and reduced river inflows into reservoirs. For instance, the Colorado River Basin has seen a 20% decline in annual flow since 2000 due to prolonged droughts conditions (Udall & Overpeck, 2017). In addition to that, increases in temperatures due to climate variability is further aggravating the problem by leading to higher evaporation rates from water bodies which leads to reduced amount of water available for human use and ecosystems.

While some regions face droughts, others experience more intense rainfall due to shifting climate patterns. Heavy precipitation events can lead to rapid reservoir filling which increases flood risks. For example, the India's Kerala floods in 2018 were made worse by excessive rainfall and dam releases (Hunt & Menon, 2020). This heavy precipitation can also lead to siltation and thereby sudden sediment influxes into water resources resulting in reduced water capacity of these reservoirs.

2.2.2. Increased Sedimentation

Climate variability is linked to more frequent and high intensity rainfall event which facilitate soil erosion in dam catchment areas. Heavy rains increase surface runoff which strips the top soil and transports the sediments into reservoirs (IPCC, 2021). For example, the Yangtze River Basin in China a 40% increase in sediment yield after extreme monsoon rains (Yang et al..,2021).

To add up to that, prolonged droughts diminish river flows, reducing their ability to transport sediment downstream. As a result, silt accumulates in reservoirs thereby shrinking their storage capacity. Global studies have indicated that reservoirs are losing about 0.5-1% of their capacity annually to sedimentation during dry periods (Perera, Williams, & Smakhtin, 2022). This effect of climate variability is leading to significant reduction in surface water resources thereby making the situation dire.

2.2.3. Water Quality Degradation

Climate variability significantly deteriorates water quality in dams and reservoirs which threatens ecosystems, human health and water usability.

Warmer waters due to rising temperatures and nutrient runoff can encourage harmful algal blooms in water bodies which produce toxins such as Microcystis, posing risks to drinking water (IPCC, 2021). These warming waters also enhance stratification in water bodies which reduces mixing thereby causing oxygen depletion in deeper layers and this harms aquatic life.

2.3. Kamuzu Dam II: Overview

Dams and reservoirs have a crucial role in social and economic development. They contribute about 12% of the water for global food production and 20% of the world's energy through hydropower generation (Arnout, 2013). Kamuzu Dam II is an example of one of these dams found in Malawi which is crucial in terms of water supply to the general population.

Kamuzu Dam II is one of the two dams constructed along the Lilongwe river. It is located about 25km southwest of the Lilongwe city. Kamuzu Dam II belonging to Lilongwe Water

Board is one of the dams from which the Board acquires its water supply for distribution to the population of the Lilongwe City. The construction of this dam started in 1989 and it was finished in 1992. When the dam had been finished, it had an initial raw storage capacity of 9.2 million^3 litres. However, the dam was later raised by 5 metres in 1998 which increased its water storage capacity to 19.8 million^3 litres (Lilongwe Water Board, 2024). The raising of the dam helped to cater enough piped water to the large population of the city when it was finished 26 years ago.

Over the years, the population of the city has significantly increased leading to an increasing demand in piped water. However, in recent years there has been a deficit in the water coming from the dam which. This has led to increasing water problems in the city such as water cut-offs to very long periods and distribution of unsuitable and dirty water. This can be attributed to several factors one of them being climate variability.

Despite its importance, Kamuzu Dam II faces several challenges that threaten its long-term sustainability. Sedimentation caused by soil erosion in the catchment area has increasingly reduced the dam's effective storage capacity. The issue is compounded by deforestation which is rampant especially in Dzalanyama Forest Reserve and poor land management practices which increases sediment loads during rainfall events (Mulwafu and Mwendera, 2019). Climate variability further complicates these challenges as erratic rainfall patterns lead to unpredictable inflows and heightened pressure on the reservoir.

2.4. Climate Variability on Kamuzu Dam II

Kamuzu Dam II has become increasingly vulnerable to the observed and projected impacts of climate variability, which affects its hydrology, storage capacity and overall operational reliability. These impacts are evident in disruptions to inflow patterns, water levels and sedimentation processes. Each of these pose challenges to the dam's sustainability and its ability to meet the growing water demands of Lilongwe and surrounding areas.

Over recent years, Malawi has experienced more frequent and intense climate extremes including droughts and heavy rainfall events influenced by frequenting tropical cyclones.

These extremes have had direct consequences for many water resources including Kamuzu Dam II.

2.4.1. Impact of Drought

During prolonged dry spells and drought periods, such as those associated with the El Nino events which have hit the country over the years, inflows into the dam were significantly reduced and this led to critical declines in water storage levels (World Bank, 2018). The most recent El Nino event which struck Malawi during the 2023/24 rainfall season was characterized by late onset of rainfall and prolonged dry spells particularly in the southern and central regions. The situation during this period became so critical that a state of disaster was declared in 23 out the 28 districts of Malawi (Scotland Malawi Situation, 2024). The El Nino induced drought and accompanying high temperatures resulted in the scarcity of water in many districts in the country including Lilongwe where the Kamuzu Dams are located. These districts and their communities experienced dry boreholes, wells and streams. In the Kamuzu Dam II, was also directly affected by this phenomenon which made its water levels to drop dangerously. The reduction in water storage compromised the dam's ability to supply water to households, agriculture and industries in Lilongwe. Moreover, low water levels during the drought seasons have affected the water quality, as reduced flows increase the concentration of pollutants in the reservoir. This led to distribution of poor-quality water that left the citizens of the city at a risk of contamination and diseases.

2.4.2. Impact of Extreme Precipitation

Conversely, heavy rainfall events, often linked to La Nina conditions and cyclonic systems which have plagued the country in recent years, cause sudden surges in inflow. For example, Cyclone Freddy which hit Malawi in 2023 and lasted for a week brought heavy and intensity rainfall and the country received six months' worth of rainfall in a week (Care Climate Change, 2024). This event caused devastating flooding and mudslides. As already mentioned, such extreme rainfall events lead to sudden surges in inflows into reservoirs such as dams. While these inflows of water temporarily replenish reservoirs, they also lead

to challenges such as excessive runoff and sedimentation. Sedimentation driven by soil erosion in the dam's catchment area, gradually reduces its water storage capacity.

Fluctuating inflow patterns in the Kamuzu Dam II caused by dry spells and extreme rainfall make it difficult to predict and manage water resource availability thereby complicating operational planning for the dam.

2.4.3. Potential Impacts

Projections indicate that climate variability in Malawi is likely to intensify in the coming decades, with rainfall becoming more erratic and temperatures rising (Niang et al., 2014). For Kamuzu Dam II, these changes are expected to worsen existing challenges and introduce new risks. Extended dry spells could further reduce inflows, placing greater stress on the dam's capacity to meet water demands. Rising temperatures could lead to increased evapotranspiration which could lead to compounding water losses from the reservoir.

On the other hand, intense rainfall events are predicted to become more frequent thereby increasing the risk of flooding and sedimentation. These events have the potential to overwhelm the dam's catchment area, leading to higher rates of soil erosion and sediment deposition into the dam. Over time, this would accelerate the loss of storage capacity and requirement for more frequent maintenance. Additionally, increased sedimentation will impact the quality of water stored in the reservoir, thereby posing risk to the general public and necessitating additional treatment measures to ensure safety and usability and this could prove to be costly.

3. METHODOLOGY

3.1. RESEARCH DESIGN

This research project aimed to study the impact of climate variability on a dam and as such, it used a quantitative research method due to the nature of the data involved in such a research. The data involved included data on dam volumes from 1998 to 2024, averahe monthly rainfall data from 1990 to 2023, and maximum and minimum temperatures ranging from 1990-2023.

The data collected and used to conduct the research was mostly secondary data of rainfall, temperature and water volume data which is mostly in numbers and was presented in tables and graphs hence making the quantitative method more suitable for the research project. By using this approach, it made it possible to determine a relationship between climate variability elements such as rainfall and temperature and the dam volumes to determine if climate variability is indeed affecting the Kamuzu Dam II.

The independent variables in this research were annual rainfall trends, annual temperature trends. The major dependent variable was dam volumes.

3.2. STUDY AREA

This study was conducted at Kamuzu Dam II in Lilongwe. This dam is one of the two dams located along the Lilongwe River owned by the LWB. The dam is located at Traditional Authority Masumbankhunda, in Lilongwe. The dam is approximately 25 km southwest of Lilongwe city in MalawiInvalid source specified.. The dam on Lilongwe River is fed by the network of rivers in the Dzalanyama catchment area. Below is a map of the study area:

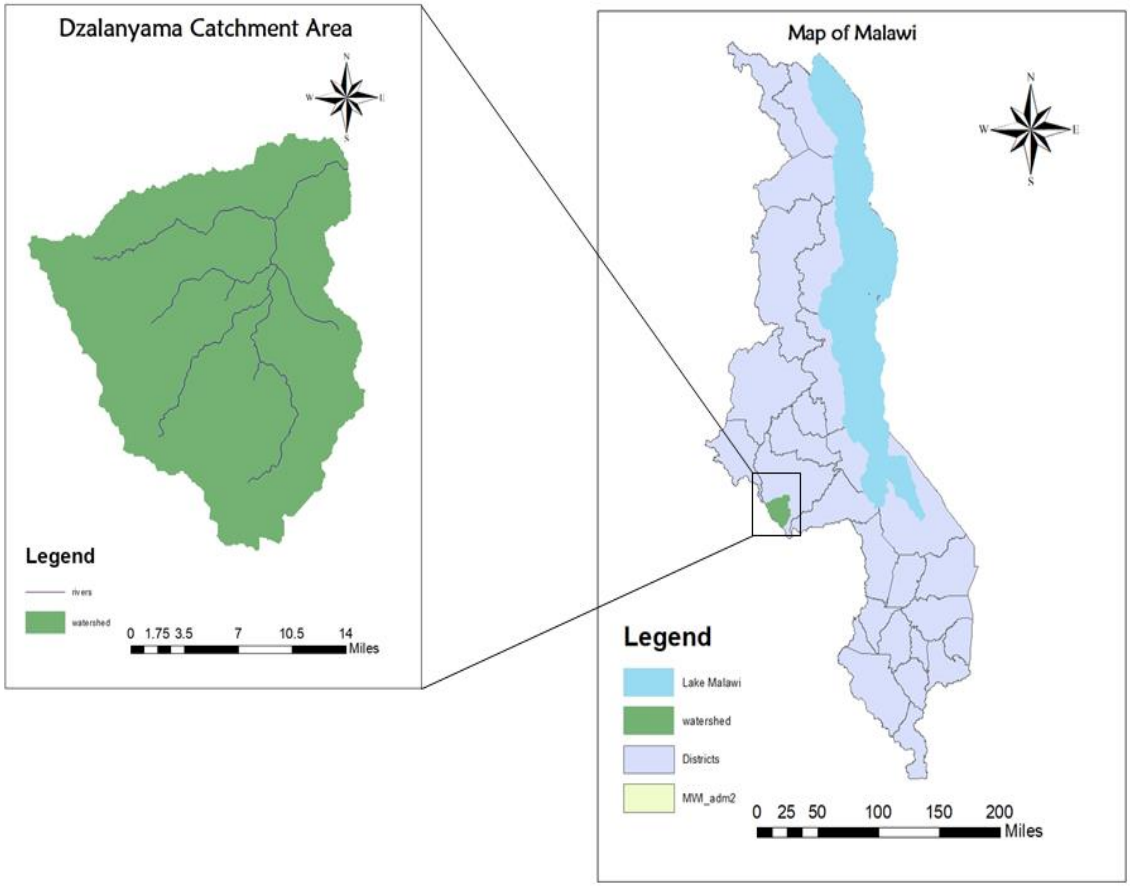


Figure 1: Map of Study Area

3.3. DATA SOURCES AND TYPES

3.3.1. Climatological Data

The data on rainfall and temperature trend was collected from both the Department of Climate Change and Meteorological Services (DCCMS) in Blantyre and the LWB in Lilongwe. The LWB provided data on rainfall and temperature and it comprised of daily Maximum, Minimum and Precipitation data from 1974 up to 2014 observed at the Chitedze research station.

The data from the DCCMS comprised of averaged monthly Maximum and Minimum temperatures and averaged monthly rainfall. This was data observed from the Chitedze Research Station and it ranged from 2014-2023.

3.3.2. Dam Volumes Data

Information on the dam water levels was collected from the Lilongwe Water Board (LWB) offices in Lilongwe. The quantitative data ranging from 1998 to 2024 comprised of daily dam volumes of the dam. It was in Excel format.

3.4. MATERIALS AND METHODS

3.4.1. Jupyterlab and Python

The materials used during this research were Jupyterlab, Microsoft Excel Spreadsheet, datasets on dam volumes, temperature and rainfall and ArcGIS. The research also used statistical tools for analysis of trends. This tools were the Mann Kendall trend test, Pearson Correlation Analysis and the Moving Averages test.

Data processing and analysis on dam volumes, temperature and rainfall during this research was performed using Jupyterlab interactive environment to produce tables, graphs, means, histograms in testing the hypothesis to observe trends. Jupyterlab is an open-source, web-based interactive development environment (IDE) widely used for scientific computing and data analysis. Jupyterlab provides an integrated platform where code, visualisations, equations and narrative text can be combined in a single document (Project Jupyter Contributors, 2018). This helped in easy exploration, visualization and interpretation of the climatic and hydrological data used in this research project.

This data processing, statistical analyses and visualisations were conducted using the Python programming language (version 3.13), which offers an ecosystem of libraries (McKinney, 2010) which were best suited for this project.

The key python libraries which were used included:

- **Pandas** used for data manipulation and time series analysis.
- **NumPy** used for numerical computations.
- **Matplotlib** and **Seaborn** which are used for data visualization.
- **SciPy** and **Statsmodels** for statistical analysis.
- **Xarray** for handling multi-dimensional climate data.

- **Scikit-learn** for exploratory data analysis and basic machine learning tasks (if applicable).
- **PyMannKendall**: for non-parametric trend detection in time series using the Mann–Kendall test.

These two tools enabled efficient analysis of temperature, rainfall and dam volume datasets to assess the impact of climate variability on Kamuzu Dam II. The modular and reproducible nature of Python scripts within Jupyterlab also ensured transparency and repeatability of the analytical workflow.

The Excel statistical tool was mostly used to store datasets by using tables, graphs, means, histograms. Microsoft Excel application was also used in conducting the Pearson Correlation Analysis in a quick, accurate and efficient way. ArcGIS is a mapping tool which was used during this research to produce a map of the study area.

3.4.2. Mann Kendall Trend Test

To achieve objectives one, the Mann Kendall trend test was used. This method gave the trends of annual rainfall amounts, average maximum and minimum temperature. The Mann-Kendall test was used to determine whether or not there is a linear monotonic trend in a given time series data. The null hypothesis, H0, states that there is no monotonic trend, while Ha (alternative hypothesis) means that there is either an upward monotonic trend or a downward monotonic trend series (Kendall et al., 2022). It is a good method for trend test in climatological time series analysis because it does not assume that the data is distributed according to any particular rule, it is not effected by unavailable data and it is not affected by the length of the time series (Kendall et al., 2022). The test was also conducted in Jupyter Notebook using Python code;

```
pip install pymannkendall

file_path='C:\\Users\\AnnaMakwale\\Desktop\\DATA\\data\\output\\annual_sum_rainfall.xlsx'

data = pd.read_excel(file_path, sheet_name='annual_sum_rainfall')
```

```
data.columns = data.columns.str.strip().str.lower().str.replace(' ', '_')

print(data)


rainfall = data['rainfall']

result = mk.original_test(rainfall)

print(result)

mk_result = mk.original_test(data['rainfall'])

print(f"Test Statistic (S): {mk_result.s}")

print(f"Variance (Var(S)): {mk_result.var_s}")

print(f"Z Statistic: {mk_result.z}")

print(f"P-value: {mk_result.p}")

print(f"Trend: {mk_result.trend}")
```

This test was conducted at an alpha value of 0.05. The P value is used to see whether the trend is significant or not. A P value of less than 0.05 shows that there is a significant trend either a significant increasing trend or a significant decreasing trend.

3.4.3. The Pearson Correlation Analysis

Linear relationships between the independent variables such as rainfall, minimum temperature, maximum temperature and the dependent variable which was dam volumes were assessed using the Pearson Correlation Analysis. The Pearson correlation coefficient (r) measures the strength and direction of a linear association between two continuous variables ranging from -1 to +1 (Pearson, 1985). A value of +1 indicates a perfect positive linear relationship while a value of -1 indicates a perfect negative linear relationship, and

0 implies no correlation. Pearson Correlation Analysis is calculated manually through the formula;

$$r = \frac{n(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[\mathrm{n}\sum \mathrm{X}2 - (\sum \mathrm{X})2][n\sum Y2 - (\sum Y)2]}}$$

Where;

- X = Independent variable (e.g., Rainfall, temperature),
- Y = Dependent variable (e.g., dam volumes)
- n = number of observations
- $\sum XY$ = sum of the product of paired scores
- $\sum X$, $\sum$Y = Sum of X and Y scores,
- $\sum X^2$, $\sum Y^2$ = Sum of squared X and Y scores.

The statistical significance (p-value) was determined to assess whether the observed correlation was unlikely to have occurred by chance, with a threshold of $p<0.05$ was considered statistically significant.

For efficiency, the Pearson Correlation Analysis was performed using Microsoft Excel. This was achieved through the following steps:

Data Organization: Rainfall and volume data were input into two adjacent columns (e.g., Column A: Rainfall, Column B: Volumes).

Correlation Coefficient: The =PEARSON(array1, array2) function was used to compute the "r" value, where array1 and array2 were the ranges of the rainfall and volume data, respectively.

Significance Testing: The =T.TEST(array1, array2, tails, type) function was applied to calculate the two-tailed p-value, assuming a linear relationship (type = 2).

4. RESULTS AND DISCUSSIONS

This chapter covers data analysis and discussion, and this chapter corresponds to the objectives of the study. The main objective of the study was to assess the impact of climate variability on Kamuzu Dam II from 1990 to 2023.

4.1. TREND RESULTS FOR RAINFALL

This section gives analyses of variability in annual rainfall of Chitedze research weather station in Lilongwe from 1990 to 2023 obtained from the Department of Climate Change and Meteorological Services (DCCMS) and the LWB. Using python script, a trend of the annual rainfall with a regression from 1990-2023 was drawn. The graph below shows the trend:

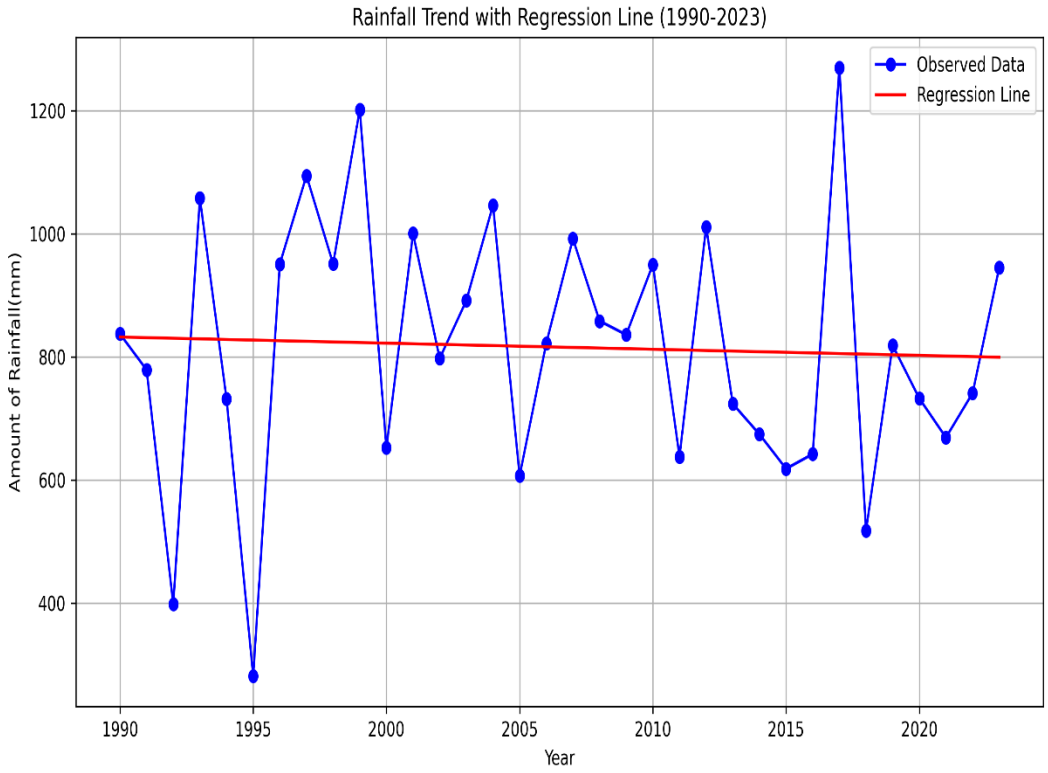


Figure 2: Rainfall trend(1990-2023)

The time-step analysis indicated that there is high variability of rainfall in short term periods but the longer timescales (1990-2023) regression indicate that there is a slight decreasing trend in the amount of rainfall being received.

In order to conduct a trend test to determine whether there was really a trend in the rainfall, a Mann Kendall Trend test and Moving Average test. Both of these were conducted using python script. The Mann Kendall trend test produced the following results:

```
mk_result = mk.original_test(data['rainfall'])

print(f"Test Statistic (S): {mk_result.s}")
print(f"Variance (Var(S)): {mk_result.var_s}")
print(f"Z Statistic: {mk_result.z}")
print(f"P-value: {mk_result.p}")
print(f"Trend: {mk_result.trend}")
```

```
Test Statistic (S): -63.0
Variance (Var(S)): 4550.333333333333
Z Statistic: -0.919115486042438
P-value: 0.35803517004775176
Trend: no trend
```

Figure 3: Mann Kendall trend test for rainfall

The Mann-Kendall trend test gave a p-value of 0.350 which is above the 0.05 threshold which indicated that there was no significant trend in the rainfall. However, a moving average test was also conducted which produced the following graph:

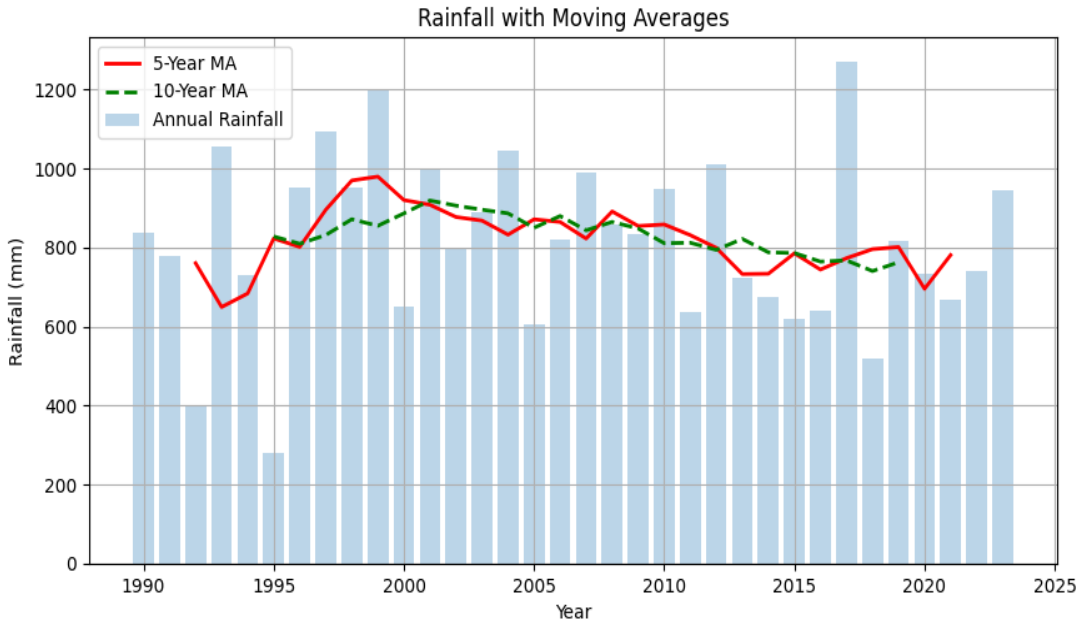


Figure 4: Moving averages graph

The moving average analysis reveals three key characteristics of the rainfall record. Firstly, the 10-year moving average remains relatively stable over the study period (1990-2023) which indicates no statistically significant long term trend in annual rainfall totals. However, the 5-year moving average shows some fluctuations which appear cyclical. This suggests recurring wet/dry phases at approximately 5-7 year intervals, likely linked to regional climate oscillations. The last thing is that substantial variability is evident with notable extremes including severe drought in 1992 (398.2) which was influenced by the 1991/92 El Nino event (Dilley, 2000) and the wet year of 1999(1201.4) influenced by the 1998-2000 extreme La Nina event (Reason & Keibel, 2004). These patterns demondtrate that while the region's mean precipitation has remained somewhat consistent over multi-decadal timescales, it still experiences pronounced short term variability that may reflect influences from modes if climate variability such as ENSO.

4.1.1.1. Rainfall and Dam Volumes Correlation

In order to draw and understand the correlation and determine if there is a relationship between the rainfall trend and dam volumes, a scatterplot was produced using the annual rainfall and average annual dam volumes using jupyterlab. The result of the plotting was as follows:

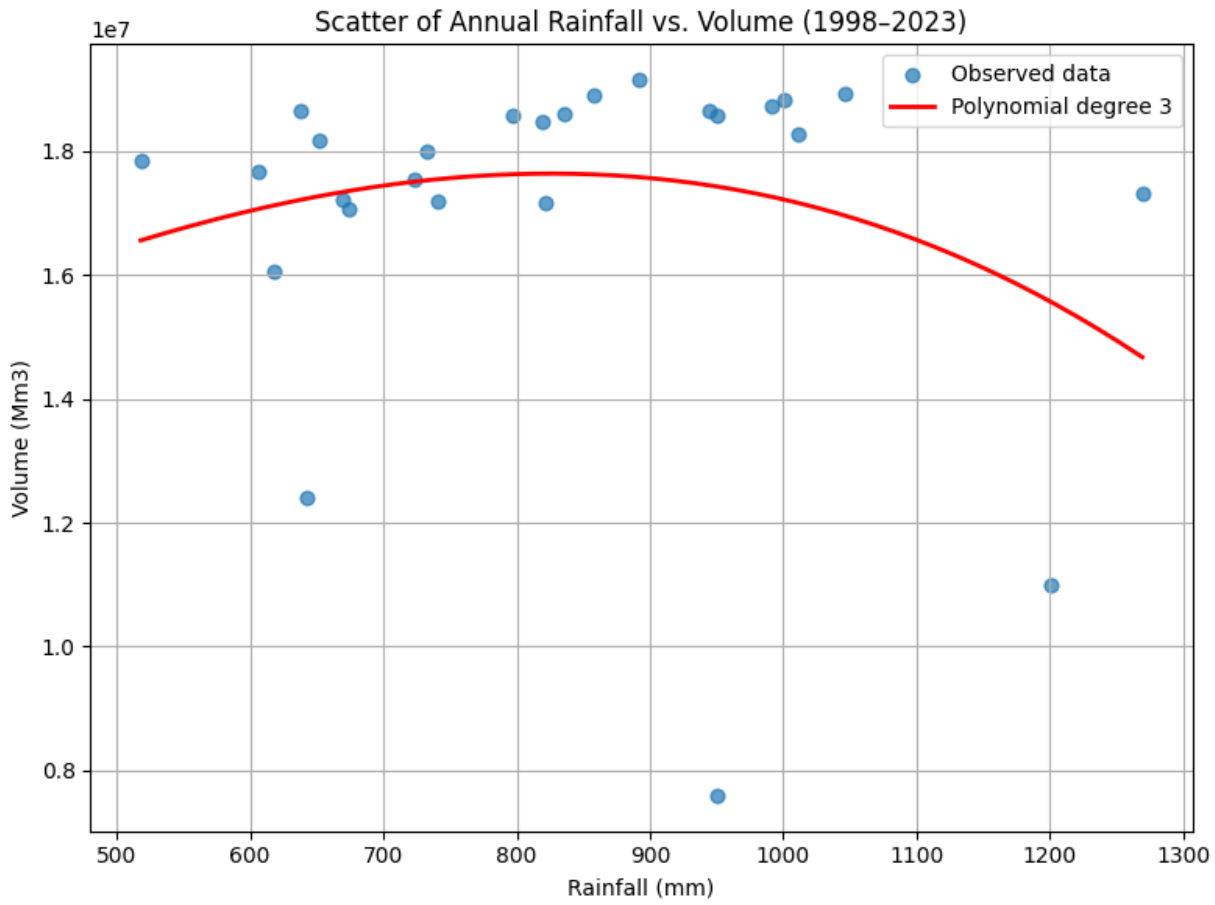


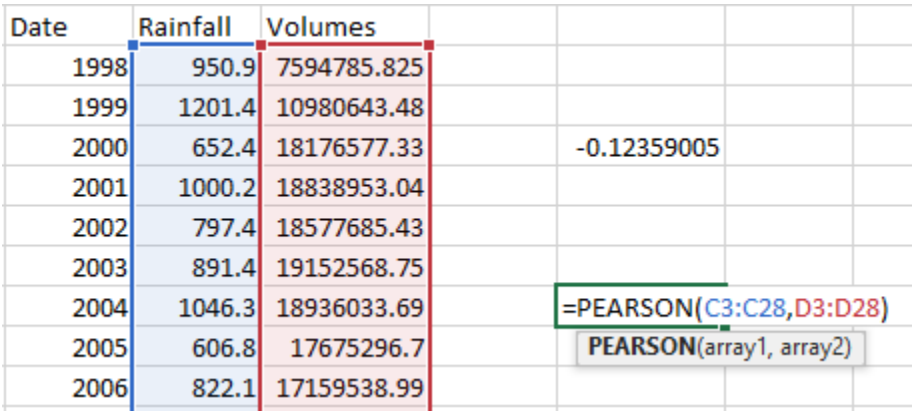
Figure 5: Annual rainfall vs dam volumes scatterplot

The scatter plot illustrates the relationship between annual rainfall (mm) and dam volumes (Mm^3) over a 25-year period (1998-2023), fitted with a 3rd degree polynomial regression to capture nonlinear trends. The plot shows two key observations:

Firstly, the polynomial fit suggests a complex relationship between rainfall and volume. This implies that the impact of rainfall on volume is not constant but varies depending on rainfall. In addition to that, the plot indicates that at higher rainfall levels, the watershed may reach a threshold where additional rain does not proportionally increase stored water (e.g., due to full soil moisture or increased discharge).

Secondly, the scatter of observed data points around the polynomial curve indicates moderate dispersion which means that while rainfall is a significant predictor, the dam volume is also influenced by other variables which may include evaporation, groundwater recharge or human water use.

Upon doing a Pearson Correlation analysis using Excel spreadsheet, the Pearson coefficient came up to -0.12359005.



Date	Rainfall	Volumes
1998	950.9	7594785.825
1999	1201.4	10980643.48
2000	652.4	18176577.33
2001	1000.2	18838953.04
2002	797.4	18577685.43
2003	891.4	19152568.75
2004	1046.3	18936033.69
2005	606.8	17675296.7
2006	822.1	17159538.99

Figure 6: Rainfall Pearson Correlation Analysis

The Pearson coefficient of -0.124 implies a weak negative relationship as it falls within the range of -0.3 to +0.3 which is considered negligible or very weak correlation. This indicates an inverse relationship where increase rainfall tends to associate with decreased dam volumes, although the relationship is minimal.

4.2. TREND RESULTS FOR TEMPERATURES

This section gives analyses of variability in average annual minimum and maximum temperatures from Chitedze research weather station in Lilongwe from 1990 to 2023 obtained from the Department of Climate Change and Meteorological Services (DCCMS) and the LWB. Using python script, a trend of the average annual minimum and maximum with a regression from 1990-2023 was drawn.

4.2.1. Maximum Temperature Trend

The computed annual maximum temperatures were plotted into a graph using jupyterlab to give the following results:

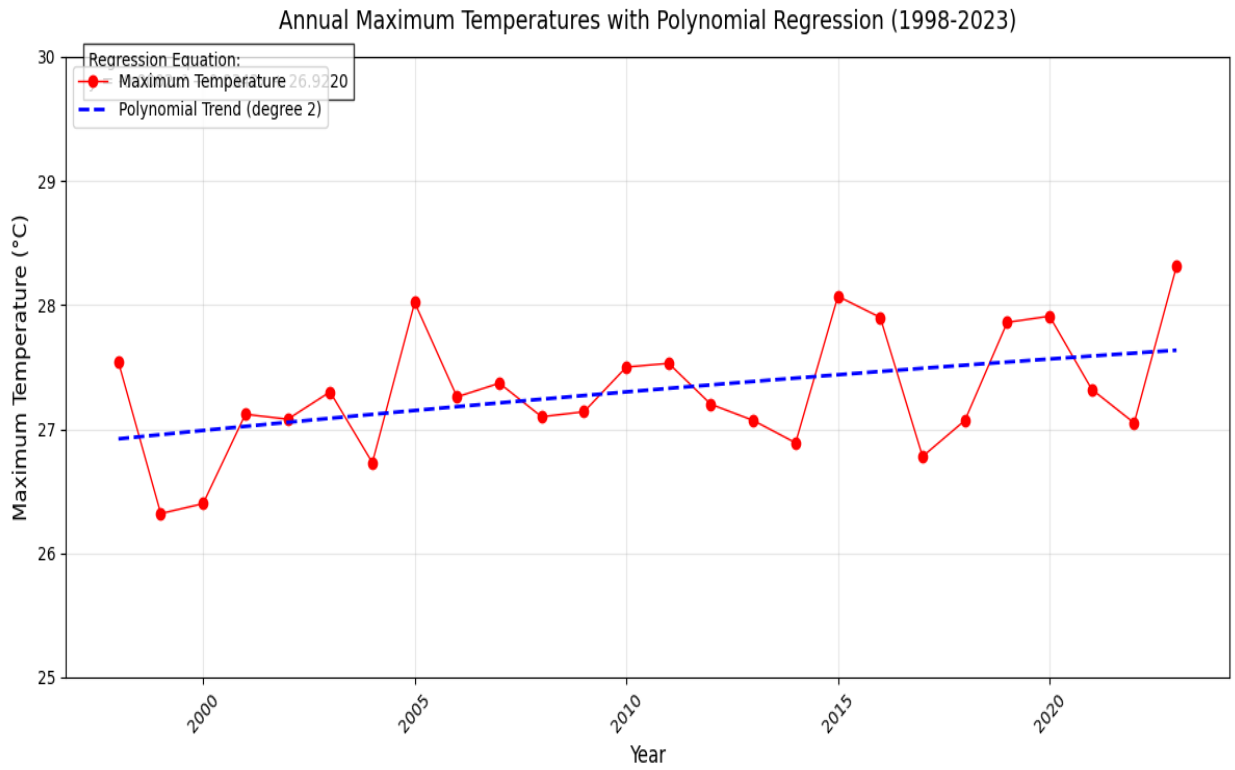


Figure 7: Annual maximum temperature trend

The regression line, which depicts both the general warming and a possible acceleration in recent years, shows a distinct increasing trend in the graph's annual maximum temperatures. With values ranging from about 26°C to 28.5°C, the actual temperature data show a considerable amount of interannual variability. The lowest values, such as 26.32°C in 1999, occur in earlier years, while the greatest values, such as 28.31°C in 2023, occur in more recent years. With the sharpest rises seen in the past ten years (2015–2023), the polynomial fit points to a non-linear warming pattern that is consistent with more general climate change evidence. This tendency is quantitatively supported by the regression equation (seen in the graph), where a positive quadratic term indicates an increasing rate of temperature rise. These results highlight the need for adaptation measures in susceptible sectors and are in line with trends in global warming. They also highlight the increasing

frequency of extreme heat events. Although short-term fluctuations may be caused by natural climate variability, the finding of a significant monotonic trend would be strengthened by additional statistical validation using the Mann-Kendall test (not shown here). This analysis emphasizes how urgent it is to address temperature increases brought on by climate change and the effects they have on society.

A mann kendall test was conducted on the maximum temperature data to determine if there is a trend in the behavior of the maximum temperatures over the years

```
Mann-Kendall Test Results for Maximum Temperatures:
------------------------------------------------
Kendall's tau (τ): 0.216
p-value: 0.1228

Interpretation:
• No statistically significant trend detected (p ≥ 0.05)
• The data doesn't show clear evidence of increasing or decreasing maximum temperatures

Linear trend slope: 0.0285 °C/year
Estimated change over period: 0.71 °C from 1998 to 2023
```

Figure 8: Maximum temperatures Mann Kendall test

The results of the test indicated that the p-value = 0.216 which is above therefore there is no statistically significant trend in the maximum temperatures.

4.2.1.1. Maximum Temperature and Dam Volumes Correlation

In order to draw and understand the correlation and determine if there is a relationship between the average maximum temperature trend and dam volumes, a scatterplot was produced using the average annual maximum temperatures and average annual dam volumes using jupyterlab. The result of the plotting was as follows:

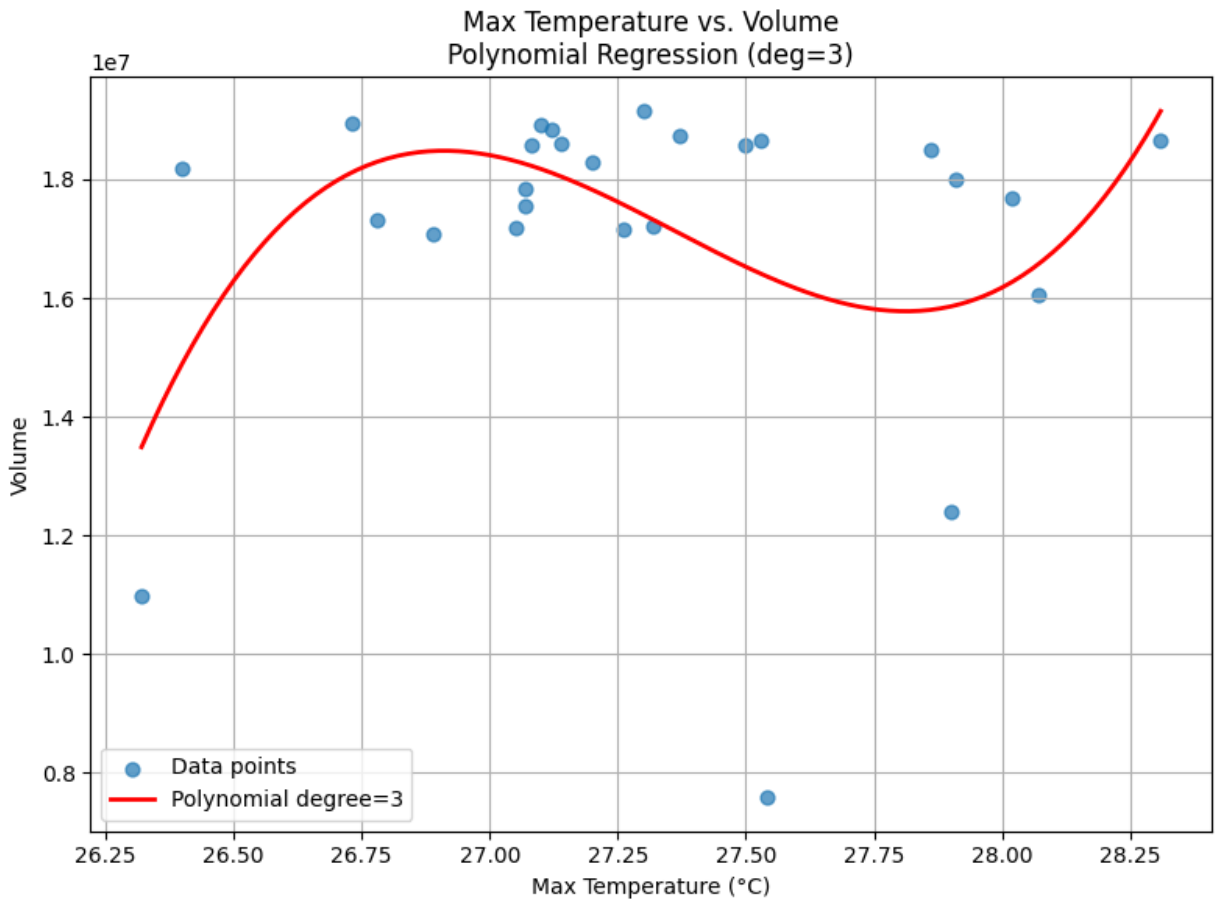


Figure 9: Maximum temperature vs dam volumes scatterplot

Based on a third-degree polynomial regression, the graph shows a nonlinear relationship between the maximum temperature and volume. A higher growth in volume occurs in the mid-temperature range (27.00–27.50°C), while at lower temperatures (26.25–26.75°C), volume remains relatively steady or grows gradually, according to the fitted curve. The graph points to a probable plateau or drop in volume above about 27.75°C, which suggests a potential threshold or saturation effect.

The significant dispersion of data points around the regression line suggests that volume fluctuation cannot be entirely explained by temperature alone, emphasizing the role of other unmeasured factors. However, it is difficult to assess the trend's behavior at temperature extremes (>28°C) due to the scant data. The results highlight how crucial nonlinear modeling is for temperature-dependent systems because linear approximations would miss these crucial turning points.

In order to establish a relationship between the maximum average temperatures and dam volumes, a Pearson Correlation Analysis was conducted in Excel spreadsheet:

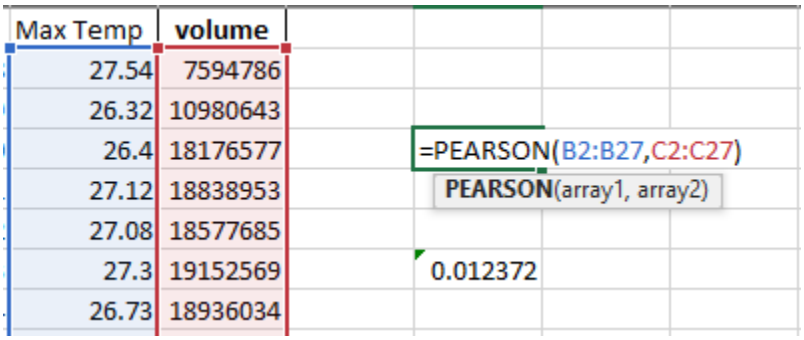


Figure 10: Annual maximum temperature Pearson analysis

A very weak linear relationship between maximum temperature and volume is indicated by the Pearson correlation analysis, which yields a coefficient of 0.012372. This near-zero value suggests that there is essentially no meaningful linear association between temperature changes and volume fluctuations in the dataset. A tiny propensity for volume to slightly rise with higher temperatures is implied by the coefficient's positive sign, although this influence is so tiny as to be essentially insignificant. Without more data, it is extremely unlikely that this indicates a statistically or practically meaningful relationship because the correlation value is so near to zero.

The interpretation of this dataset is significantly impacted by the absence of a significant linear association. First, it implies that a straightforward linear model cannot accurately forecast volume changes based solely on maximum temperature. Given the limited link, it is likely that other unmeasured factors influence volume more significantly than temperature. This result is consistent with the data points' apparent scatter, which lacks a distinct linear trend. The slight correlation in this case emphasizes the necessity of taking into account more intricate, possibly nonlinear interactions between these variables, even if the Pearson coefficient only evaluates linear associations.

4.2.2. Minimum Temperature Trend

The computation using jupyterlab of the average annual minimum data gave the following graph and trend:

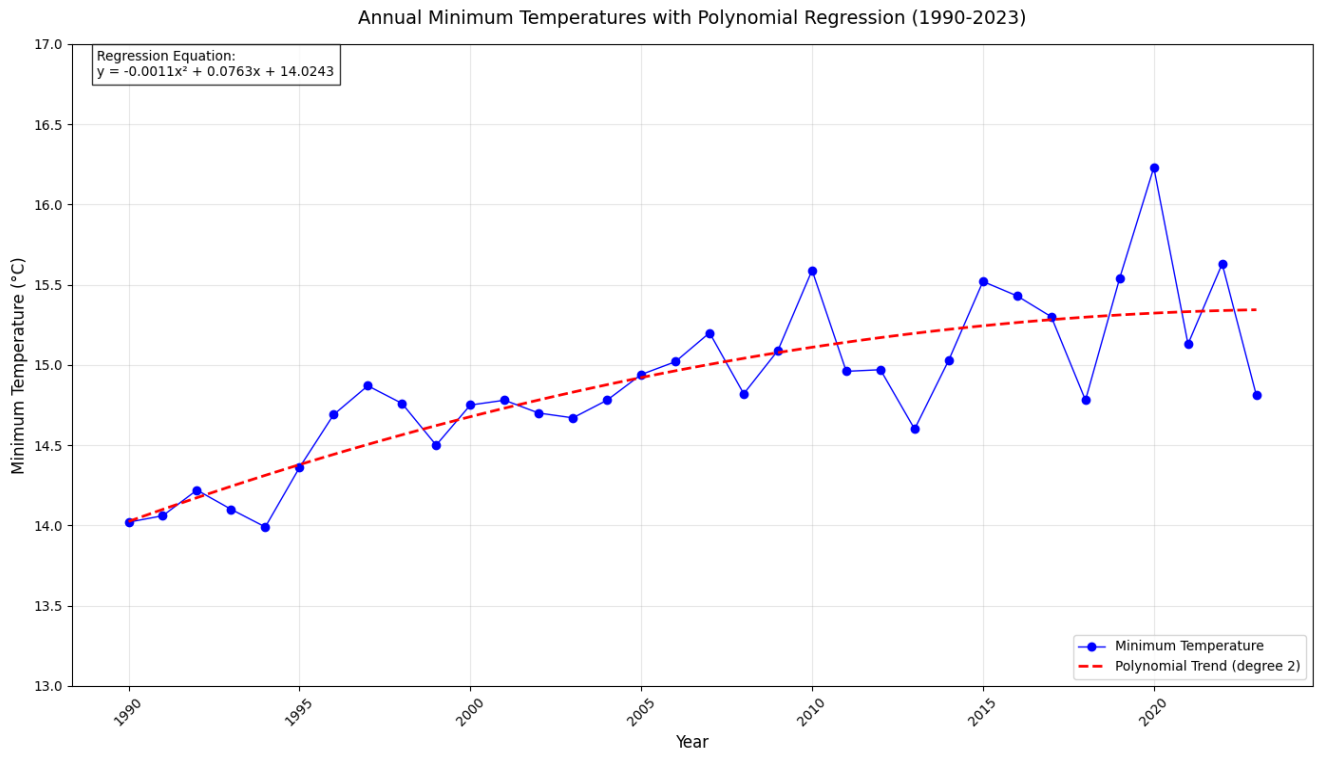


Figure 11: Annual minimum temperature trend

This figure represents the annual minimum temperatures recorded from 1990 to 2023, with a second degree polynomial applied to capture the underlying trend. The observed values show interannual variability, with the minimum temperatures ranging approximately between 14.0°C and 16.3°C. The polynomial trend is described by the following regression equation:

$$y = -0.0011x^2 + 0.0763x + 14.0243$$

where y represents the estimated minimum temperature and x denotes the year. The positive linear coefficient (0.0763) suggests an overall upward trend in minimum

temperatures over the study period, while the negative quadratic coefficient indicates a slight deceleration in this warming trend in the recent years.

The analysis of annual minimum temperature data over the 34-year period from 1990 to 2023 reveals a statistically significant warming trend as evidenced by the polynomial regression model. The general increase in minimum temperatures is consistent with global patterns of climate change.

The fitted quadratic model not only confirms the upward trajectory of minimum temperatures but also reveals a potential moderation in the rate of increase in recent years. This is reflected in the curve's subtle flattening after the mid-2010s. Such behavior could be attributed to short-term climate variability or regional climate feedback mechanisms. While individual years (e.g., 2020) show sharp peaks, the overall trend supports the conclusion that minimum temperatures have increased since the early 1990s.

Upon a Mann-Kendall trend test

```
[14]: mk_result = mk.original_test(min_temps)

[15]: print(f"Test Statistic (S): {mk_result.s}")
      print(f"Variance (Var(S)): {mk_result.var_s}")
      print(f"Z Statistic: {mk_result.z}")
      print(f"P-value: {mk_result.p}")
      print(f"Trend: {mk_result.trend}")

      Test Statistic (S): 358.0
      Variance (Var(S)): 4546.666666666667
      Z Statistic: 5.2944598388633795
      P-value: 1.1936871824325124e-07
      Trend: increasing
```

Figure 12: Annual minimum temperature Mann-Kendall test

The results of the test gave a near 0 value ($1.19*10^{-7}$). The very low p-value confirms the robustness of this trend, suggesting that the observed changes are highly unlikely to have occurred by chance. This indicated a high confidence that the trend is indeed increasing.

4.2.2.1. Minimum Temperature and Dam Volumes Correlation

In order to draw and understand the correlation and determine if there is a relationship between the average minimum temperature trend and dam volumes, a scatterplot was produced using the average annual maximum temperatures and average annual dam volumes using jupyterlab. The result of the plotting was as follows:

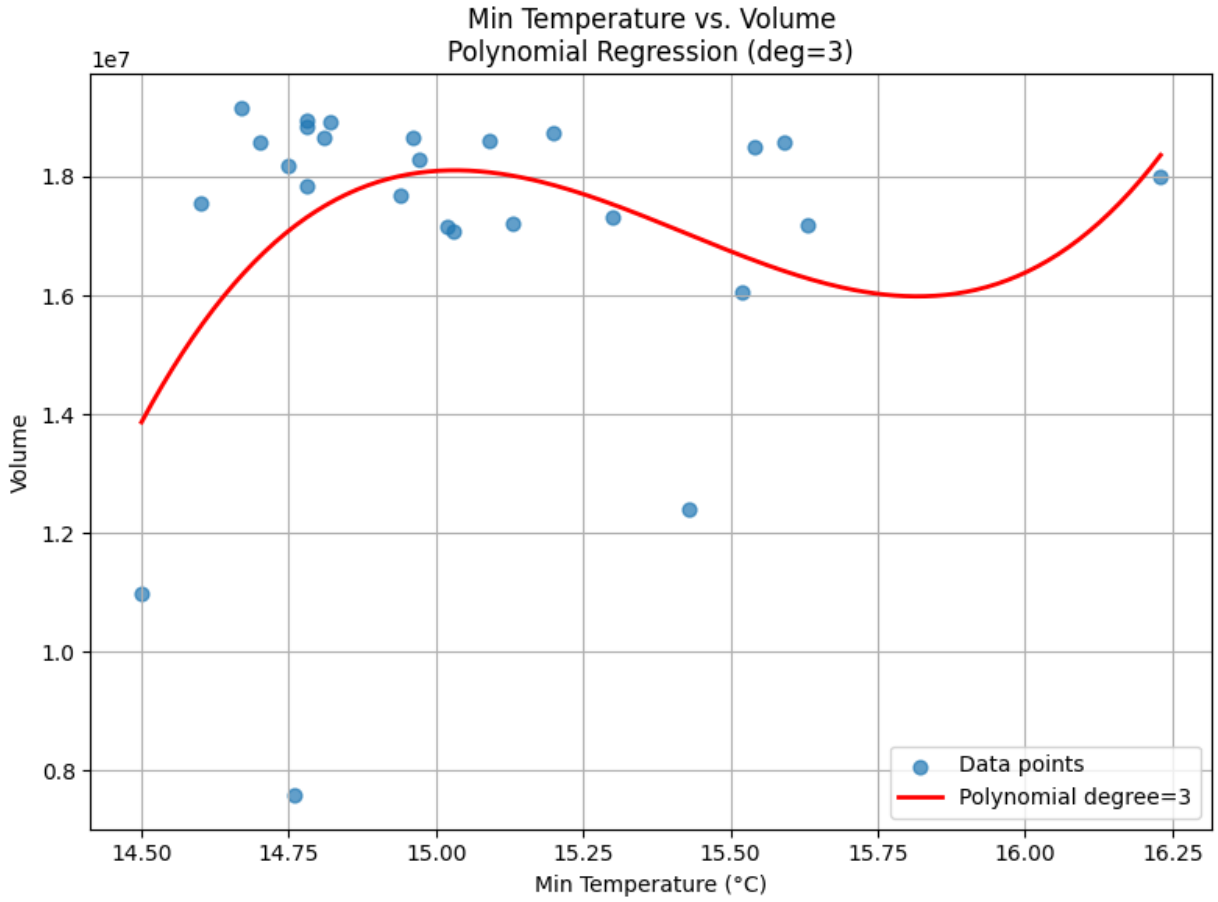
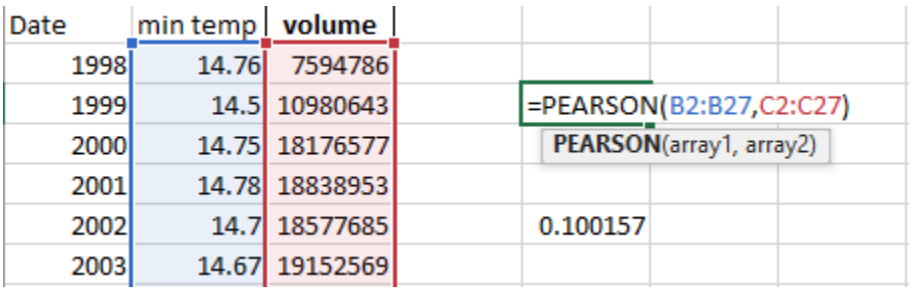


Figure 13: Minimum temperature vs dam volumes scatterplot

The graph indicates that at lower temperatures (around 14.5°c-15.25°c), increase in temperature corresponds to decrease in volume. In mid range temperatures, the curve bottoms out near 15.25 which suggests that this temperature represents a critical point where volume is minimized.

After the minimum point (~15.25), the trend reverses and the volume begins to increase with temperature. The significant dispersion of data points around the regression line suggests that volume fluctuation cannot be entirely explained by temperature alone, emphasizing the role of other unmeasured factors. The results highlight how crucial nonlinear modeling is for temperature-dependent systems because linear approximations would miss these crucial turning points.

In order to solidify the presence of a relationship between minimum temperatures and dam volumes, a Pearson Correlation Analysis was conducted between the two variables in Microsoft Excel:



Date	min temp	volume
1998	14.76	7594786
1999	14.5	10980643
2000	14.75	18176577
2001	14.78	18838953
2002	14.7	18577685
2003	14.67	19152569

Figure 14: Minimum temperatures vs volumes pearson analysis

The Pearson correlation coefficient came to 0.100 which indicated an extremely weak, positive linear relationship between the two variables. This means that while there is a slight tendency for dam volumes to increase with increasing minimum temperatures, the association is minimal. Given that that the r is very close to 0, it is unlikely that minimum temperature is a strong predictor of dam volume changes.

4.3. TREND RESULTS FOR DAM VOLUMES

This section provides an analysis of the dam volumes obtained from the LWB in Lilongwe. The data for dam volumes ranged from 1998-2025. The time-series for the dam volumes was computed using hydrological years which are recorded from November- October. A trend of dam volumes was computed using python script in jupyterlab which produced the following output:

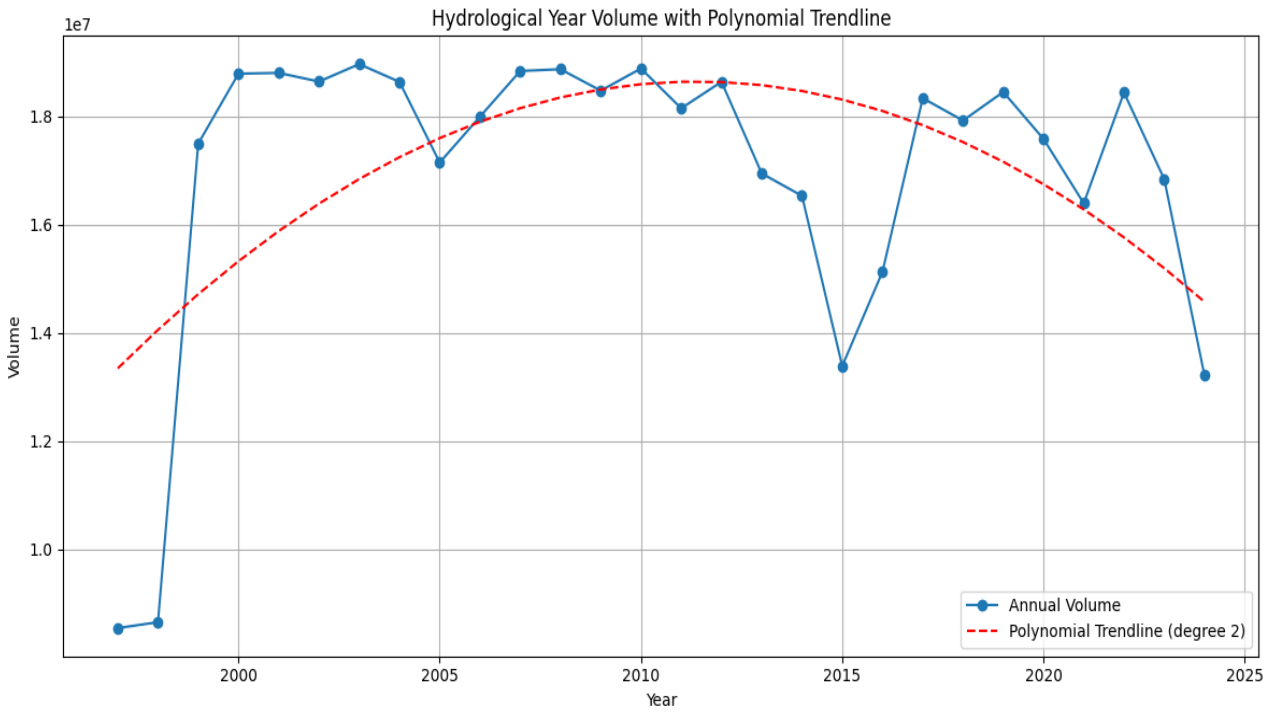


Figure 15: Dam volumes trend

The analysis of the hydrological trends (1997-2025) using a second-order polynomial regression revealed that distinct temporal patterns in the dam volumes. The fitted trendline ideintifies three characteristic phases:

- An initial rapid increase from the extreme El Nino induced drought conditions in 1997-1998 (Reliefweb, 1997) from 8.54 million units to peak volumes of 18.7-18.9 million units during the 2000-2004.
- A subsequent decade long plateau (2004-2014) with stable high volumes exhibiting minor interannualfluctuations
- A recent period (2015-2025) marked by heighteined volatility, including an extreme drought in 2015-2016_also induced by an El Nino event_ which was followed by partial recovery with notable interannual oscillations.

Upon conducting the Mann Kendall trend test:

```
[10]: mk_result = mk.original_test(df["volume"])

[11]: print(f"Test Statistic (S): {mk_result.s}")
      print(f"Variance (Var(S)): {mk_result.var_s}")
      print(f"Z Statistic: {mk_result.z}")
      print(f"P-value: {mk_result.p}")
      print(f"Trend: {mk_result.trend}")

      Test Statistic (S): -78.0
      Variance (Var(S)): 2562.0
      Z Statistic: -1.5212520009101793
      P-value: 0.12819661046060982
      Trend: no trend
```

Figure 16: Dam volumes Mann-Kendall trend test

The p-value came up 0.128 which is above the $p<0.05$ threshold which means that there is no significant trend in dam volume variation.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

Although there was no statistical significance, the study's conclusions offer important new information about the connection between Kamuzu Dam II's water availability and climate variability. The polynomial regression analysis showed significant nonlinear patterns, even if the Mann Kendall tests failed to identify significant trends in in rainfall ($p = 0.350$), maximum temperatures ($p = 0.216$), or dam volumes ($p = 0.128$) although an increasing trend was identified in the minimum temperatures. In line with global warming trend, maximum temperatures showed an overall increased tendency especially after 2015, rising from about 26°C to 28.5°C (IPCC, 2021). Despite not being statistically significant in trend tests, this warming is consistent with predictions for southern Africa where rising temperatures worsen water stress and evaporation (Niang, Ruppel, Abdrabo, & Leary, 2014). Volumetric patterns of the dam revealed periods of stability (2004–2014), recovery (1998–2004), and recent volatility (2015–2025), including sharp drops during the El Nino drought in 2015-2016, evidenced by lower rainfall amount in the graphs which was associated with lower inflows throughout Malawi (Government of Malawi, 2016). These patterns imply that climate variability may still pose a danger to water security through extreme occurrences such as these even in the absence of statistical trends.

In conclusion, while climate variability in deed affects the Kamuzu Dam 2 through rainfall and temperature changes to some extent, the impact is small as evidenced by the mann kendall, pearson and moving average tests. Therefore, there needs to be further research on what has been leading to the increasing water challenges experienced in Lilongwe through other disciplines such as demographic trends, LULC and governance competency.

5.2. RECOMMENDATIONS

5.2.1. Enhance Water Conservation Measures

To mitigate the effects of declining water volumes in Kamuzu Dam II, targeted water conservation strategies should be implemented. Public awareness campaigns can encourage residents and industries in Lilongwe to adopt water-saving practices, such as fixing leaks and using water-efficient appliances (Lilongwe Water Board, 2024). Additionally,

incentives for rainwater harvesting and greywater recycling could reduce dependence on the dam, particularly during dry seasons (Trenberth, 2011).

5.2.2. Improve Dam Management and Sediment Control

Proactive dam management is critical to maintaining storage capacity. Adaptive water release policies should be introduced to balance supply during periods of low rainfall and high evaporation (Dam, 2003). Regular sediment removal and dredging are also essential to counteract sedimentation, which reduces the dam's effective volume (Hydroplus, n.d.).

5.2.3. Strengthen Climate Monitoring and Early Warning Systems

Expanding meteorological stations in the Dzalanyama catchment area would improve data collection on rainfall and temperature trends (Roger & Chorley, 2010). Integrating ENSO (El Niño-Southern Oscillation) forecasts into water resource planning could help anticipate extreme weather events, such as the 2015–2016 El Niño that severely affected Malawi (Care Climate Change, 2024).

5.2.4. Promote Sustainable Land Use Practices

Reforestation and soil conservation programs in the catchment area can reduce erosion and sedimentation while enhancing groundwater recharge (Rasha et al., 2023). Regulations to prevent deforestation and unsustainable agriculture should be enforced to protect the dam's watershed (Times News, 2023).

5.2.5. Diversify Water Sources

Reducing reliance on Kamuzu Dam II requires investment in alternative water sources. Groundwater extraction and inter-basin transfers could supplement supply during droughts (Oludhe, 2017). Small-scale reservoirs or check dams could also capture runoff during high rainfall periods, improving water security (Hadiza et al., 2021).

5.2.6. Policy Integration and Stakeholder Collaboration

A Climate Adaptation Plan for Kamuzu Dam II should be developed in collaboration with the Lilongwe Water Board, DCCMS, and local communities (Louis et al., 2007). Policymakers must prioritize climate-resilient infrastructure and long-term water security in national strategies (Arnout, 2013).

5.2.7. Further Research

An important recommendation to make would be inducing further this research into the impact of climate variability as there is limited studies that have looked into this topic. Further studies also need to be conducted to determine other possible causes of the water deficiencies experienced in Lilongwe such as demographic trends, LULC trends and policy and governance issues.

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