

Climate Change Impact Assessment on Water Resources: A Case Study of the Mulungushi River, Zambia

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ABSTRACT

Climate change is increasingly altering hydrological processes, posing serious threats to water resource sustainability, ecosystem health, and socio-economic development. This study assessed the impacts of climate change on the water resources of the Mulungushi River catchment in Central Province, Zambia, with the objective of evaluating long-term hydro-meteorological trends and predicting future river hydraulic conditions. Historical rainfall, temperature, evaporation, discharge, and water-level data covering the period 1993–2023 were analyzed using statistical trend analysis in Microsoft Excel and spatial analysis in QGIS. A hydraulic model of the Mulungushi River was developed in HEC-RAS using cross-sectional geometry, discharge records, and boundary conditions to simulate river flow characteristics under steady-flow conditions. The results revealed a persistent decline in regional rainfall, with an average trend of -3.0348 mm/year, indicating increasing climatic variability across the catchment. Analysis of observed stage records showed fluctuations in river water levels, while HEC-RAS simulations projected a reduction in average water levels from approximately 2.204 m to 1.602 m over the projected period. Hydraulic simulation further indicated subcritical flow conditions throughout the river reach, with maximum channel velocities below 1.27 m/s and Froude numbers less than one. The findings demonstrate that continued climatic variability is likely to reduce water availability and alter river hydraulics, with implications for irrigation, domestic water supply, and hydropower generation. The study provides a scientific basis for sustainable water resources management and climate adaptation planning within the Mulungushi River catchment and similar river basins in Zambia.

Keywords: Climate Change; Hydraulic Modeling; Water Resources; Climate Variability.

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1. INTRODUCTION

1. Introduction

Climate change has become one of the most significant environmental challenges affecting sustainable development worldwide. Among its most profound consequences is the alteration of the hydrological cycle, leading to changes in rainfall patterns, river flows, groundwater recharge, and the frequency of floods and droughts. These changes threaten water security, food production, hydropower generation, ecosystem integrity, and socio-economic development, particularly in developing countries where livelihoods depend heavily on climate-sensitive natural resources. Water therefore represents one of the primary pathways through which the impacts of climate change are experienced, making the assessment of river basin responses essential for sustainable water resources planning (Corinna & Ghazali, 2008).

Globally, numerous studies have demonstrated that increasing temperatures and changing precipitation regimes are altering river hydrology and reducing the reliability of freshwater resources. Climate-induced variability has intensified the occurrence of prolonged droughts, extreme floods, and seasonal shifts in rainfall, thereby increasing uncertainty in water availability. Meron et al. (2018) reported that climate change affects every component of the hydrological cycle, while Hamududu and Ngoma (2019) emphasized that sustainable water resources management now requires integrated, multidisciplinary approaches involving water, agriculture, energy, finance, and regional planning. These findings highlight the need for scientifically informed adaptation strategies capable of improving resilience to future climatic variability.

The impacts of climate change are particularly severe in Sub-Saharan Africa, where rapid population growth, dependence on rain-fed agriculture, and limited adaptive capacity increase vulnerability to water scarcity. Although the region contributes less than 1.6% of global greenhouse gas emissions, climate projections indicate that water resources will become increasingly stressed due to declining rainfall, rising temperatures, and increasing hydrological variability (Ribeiro et al., 2009; Bakker, 2010; Spore, 2008). These changes threaten food security, energy production, and sustainable economic development across the region.

In Zambia, climate change has become an important national development concern because the country's economy relies heavily on agriculture, hydropower generation, mining, and water-dependent industries. Previous studies indicate that Zambia's mean annual temperature has increased by approximately 1.3°C since 1960, while annual rainfall has generally declined because of changing climatic conditions and the influence of the El Niño Southern Oscillation (ENSO) (McSweeney et al., 2017; WARMA, 2022). These climatic changes have increased pressure on river catchments and reservoirs, affecting water availability for irrigation, domestic consumption, industrial use, and electricity generation. Sustainable management of water resources has therefore become central to achieving national development priorities and building climate resilience.

The Mulungushi River, located in Zambia's Central Province as shown in Figure 1, it is a strategically important river system that forms part of the Lunsemfwa River Basin. The catchment covers approximately 4,200 km² and supports agriculture, domestic water supply, and hydropower generation. The river also supplies water to communities served by the Lukanga Water Utility Company while contributing to electricity production through the Lunsemfwa Hydropower Scheme. Recent observations have shown declining river water levels, with peak water levels decreasing from 1111.8 m in 2015 to approximately 1110.24 m in 2024, raising concerns regarding long-term water availability and the sustainability of water-dependent socio-economic activities within the catchment.

Despite growing concern over climate variability in Zambia, relatively few studies have integrated long-term hydro-meteorological trend analysis with hydraulic modelling to quantify climate change impacts on individual river systems. Most existing studies have focused on national or regional climate trends, while limited attention has been given to catchment-scale assessments that combine historical climate observations with hydraulic simulations capable of projecting future river behaviour. Furthermore, there remains limited evidence on how projected climatic changes may influence the hydraulic characteristics of the Mulungushi River and its capacity to sustain water supply, irrigation, and hydropower generation. Addressing this knowledge gap is essential for developing effective climate adaptation strategies and improving evidence-based water resources management in Zambia.

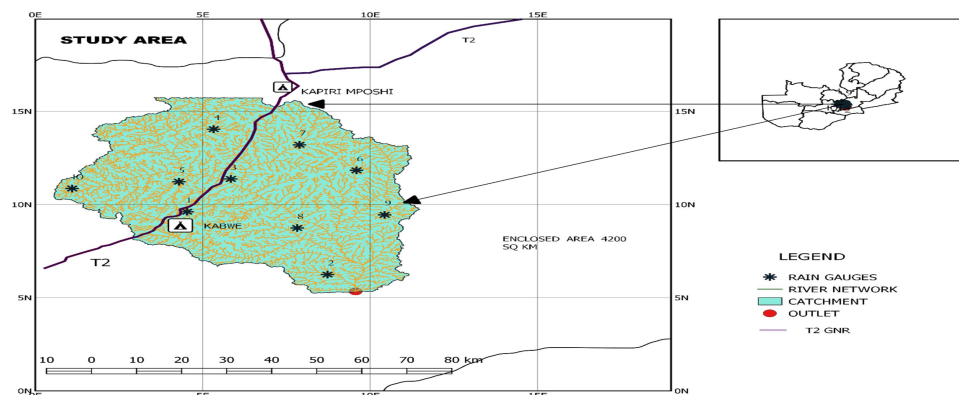


Figure 1. shows the localized map of the study area

Hydraulic modelling has become an indispensable tool for evaluating river responses to changing climatic conditions. The Hydrologic Engineering Center's River Analysis System (HEC-RAS), developed by the United States Army Corps of Engineers, has been widely applied for river hydraulics, floodplain analysis, drought assessment, reservoir operation studies, and climate impact assessments because of its capability to simulate water-surface profiles, flow velocities, channel hydraulics, and river stage under different hydraulic conditions. Previous applications have demonstrated its effectiveness in supporting water resources planning and climate adaptation, particularly when combined with Geographic Information Systems (GIS) and long-term hydro-meteorological datasets.

This study addresses these gaps by integrating statistical analysis of historical hydro-meteorological data (1993–2023), GIS-based spatial analysis, and HEC-RAS hydraulic modelling to assess the impacts of climate change on the Mulungushi River. Specifically, the study aims to:

1. Analyse historical rainfall and temperature data (1993–2023) to determine long-term climatic trends affecting the Mulungushi River catchment.
2. Develop and apply a hydraulic model using HEC-RAS to simulate river flow characteristics and evaluate the potential impacts of climate variability on future water levels.
3. Provide scientific evidence to support sustainable water resources management and climate adaptation planning for the Mulungushi River catchment.

The study contributes to ongoing efforts to strengthen climate resilience in Zambia's water sector and directly supports Zambia Vision 2030, which recognises sustainable environmental and natural resource management as a prerequisite for achieving inclusive socio-economic development. Furthermore, the research aligns with the conference theme on climate resilience and sustainable infrastructure by demonstrating how hydraulic modelling and hydro-meteorological analysis can provide evidence-based solutions for managing water resources under changing climatic conditions. The findings are expected to inform policymakers, water managers, hydropower operators, and local communities in developing adaptive strategies for sustainable river basin management.

2. MATERIALS AND METHODS

This study applied remote sensing and GIS tools to process and generate prerequisite maps such as rainfall maps for better analysis of climate change impacts on Mulungushi River's water resources. Water levels were collected from the gauge station for the past 4 years in order to carry out the linear trend analysis for Mulungushi River, Data Description are shown in Table 1.

Table 1. Data sources and data types used in the study

SN	Data Description	Data Type	Year	Source	Purpose
1	Rainfall	Numerical	1993–2023	Kabwe Meteorological Station	Historical climate data analysis
2	Temperature	Numerical	1993–2023	Kabwe Meteorological Station	Historical climate data analysis
3	Evaporation	Numerical	1993–2023	Kabwe Meteorological Station	Historical climate data analysis
4	Discharge	Numerical	2013–2023	Lunsemfwa Hydropower Station (LHPS)	River flow simulation
5	Satellite imagery	Spatial	2003, 2013, and 2023	QGIS / GIS database	Land Use/Land Cover (LULC) analysis

2.1 GIS-Based Rainfall Mapping

Spatial rainfall distribution across the Mulungushi River catchment was determined using the Thiessen polygon method implemented in QGIS 3.18. This method was selected because it provides

a reliable estimate of areal precipitation by assigning weights to rainfall stations according to their area of influence within the catchment. A total of 30 years of rainfall records (1993–2023) were collected from ten rain-gauge stations, designated P1, P2, P3, P4, P5, P6, P7, P8, P9, and P10, located within and around the Mulungushi River catchment as illustrated in Figure 2.

The rainfall mapping procedure involved several sequential GIS operations. First, the Mulungushi River watershed was delineated in QGIS 3.18 using the Mulungushi Dam outlet as the drainage outlet point. The geographic coordinates of the ten rainfall stations were then imported into QGIS as an XY dataset and converted into a point shapefile. Using the Vector Geometry Tools function, Thiessen polygons (Voronoi polygons) were generated from the station shapefile, creating polygons that defined the area of influence associated with each rainfall station.

The generated polygons were subsequently processed to determine the contribution of each station to the overall catchment rainfall. Polygon areas were calculated within the attribute table, and the weighted areal precipitation for the Mulungushi River catchment was estimated using the Thiessen polygon weighting approach. The resulting spatial dataset was used to produce a rainfall distribution map for the catchment and to compute the regional mean annual precipitation, which formed the basis for the subsequent hydro-meteorological trend analysis.

2.2 GIS-Based Rainfall Mapping

Historical climate data was analyzed to identify trends in temperature and precipitation affecting Mulungushi River from 1993 to 2023 using Excel and QGIS. Precipitation data set from points 1 to 5 were analyzed in Excel. Statistical methods were used to interpret the data and determine patterns or changes over the specified period.

2.3 Model Setup and Simulation in HEC-RAS

Hydraulic modelling of the Mulungushi River was carried out using the Hydrologic Engineering Centre's River Analysis System (HEC-RAS) to simulate river flow behaviour and evaluate the potential impacts of climate variability on river water levels. A steady-flow hydraulic model was developed based on historical river geometry, discharge, and water-level observations. The modelling process began by importing the catchment and river shapefiles generated in the GIS environment into HEC-RAS. The river geometry was established using the river centerline and cross-section data extracted from terrain information processed in Global Mapper and QGIS. Cross-sections were interpolated where necessary to improve the spatial representation of the river channel and floodplain.

Hydraulic resistance within the model was represented using Manning's roughness coefficients (n values) assigned to the river channel and adjacent floodplain areas according to observed terrain characteristics, vegetation cover, and channel conditions. Appropriate roughness values were selected to represent the hydraulic behaviour of different land-cover types within the study reach.

Boundary conditions were then specified using the available upstream and downstream water-level and discharge records collected from the Mulungushi River gauge station and the Lunsemfwa Hydropower Station database. These boundary conditions were used to simulate the hydraulic behaviour of the river system under observed hydrological conditions.

Historical discharge records were entered into the model as steady-flow inputs, together with representative flow conditions corresponding to reduced rainfall and reduced river discharge observed within the historical hydro-meteorological record. These climate-related flow scenarios were used to evaluate the sensitivity of river water levels and hydraulic characteristics to continued climatic variability.

The HEC-RAS simulations generated outputs including water-surface elevations, flow velocities, hydraulic depths, Froude numbers, and longitudinal water-surface profiles for each cross-section along the modelled river reach. These outputs formed the basis for assessing projected changes in river water levels and hydraulic conditions within the Mulungushi River catchment.

The hydraulic model was calibrated using observed water-level measurements obtained from the Mulungushi River gauge station. Calibration involved iterative adjustment of Manning's roughness coefficients and boundary-condition parameters until the simulated water levels showed satisfactory agreement with the observed stage records. Model validation was subsequently performed by comparing simulated water levels with an independent portion of the available observation dataset to confirm that the model reproduced the hydraulic behaviour of the river under conditions different from those used during calibration.

Although the modelling approach provides a useful representation of river hydraulic behaviour, uncertainty remains because of the limited duration of available water-level observations, interpolation of some missing hydro-meteorological records, and the assumption of steady-flow conditions in HEC-RAS. Nevertheless, the model provides a robust basis for evaluating the likely hydraulic response of the Mulungushi River to continued climate-related reductions in rainfall and discharge.

3. RESULTS AND DISCUSSION

To analyze and find the regional rainfall for the entire catchment, the Thiessen polygon method was used:

$$P_{av} = \sum_{i=1}^m \frac{A_i}{A} P_i \quad (1)$$

Where:

- P_{av} = the areal mean precipitation
- P_i = rainfall observed at the i-th station inside or outside the basin
- A_i = in region portion of the area of the polygon surrounding the i-th station
- m = the number of areas (Akintug, n.d.) .

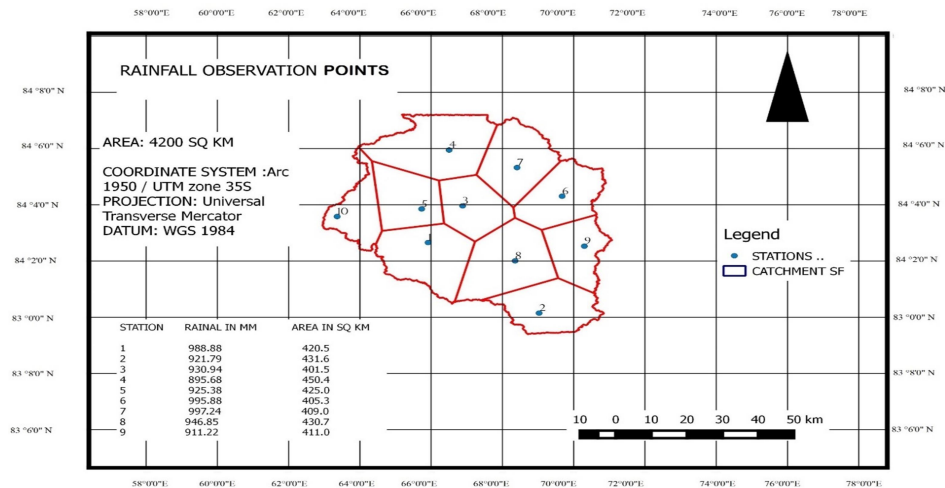


Figure 2. shows rainfall observation points and associated areas.

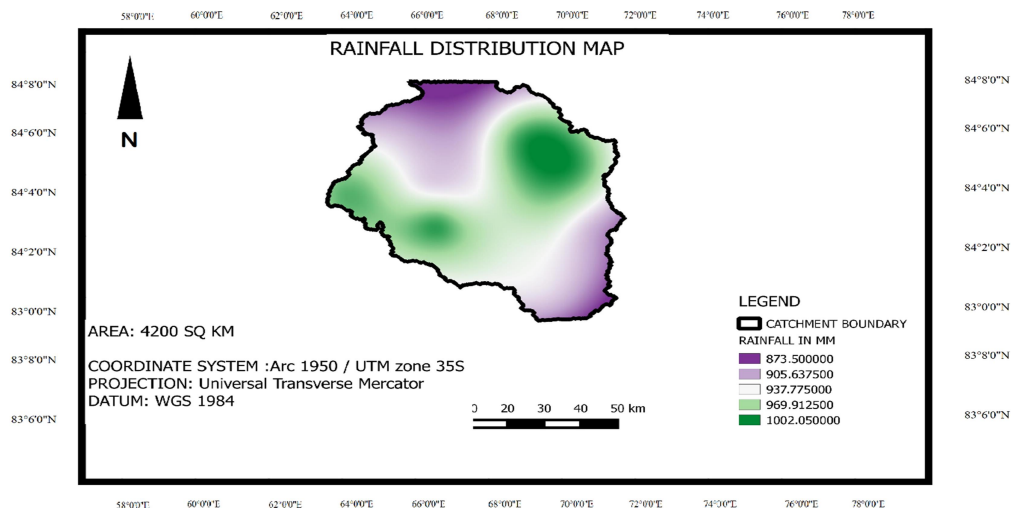


Figure 3. Rainfall Distribution Map

During the categorization system, very higher rainfall value was reclassified as class five (>1002 mm/year), high ranked to class four (1002-970 mm/year), moderate ranked to class three (970-938 mm/year), low ranked to class two (938-906 mm/year) and very low ranked to class one (<874 mm/year).

The analytical study was carried out to check annual variability and trend in rainfall over the past three decades with raw data from five out of ten observation points namely P1, P2, P3, P4 and P5. The linear regression method was used to find and analyze variation trends in time series of yearly rainfall using a statistical tool in Excel as Illustrated in Figure (4, 5, 6, 7, and 8). Positive values of the slope indicate increasing trends while negative values refer to decreasing trends.

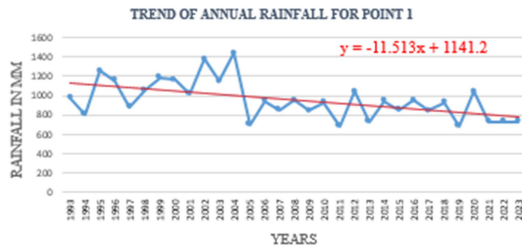


Figure 4. Annual rainfall for point 1

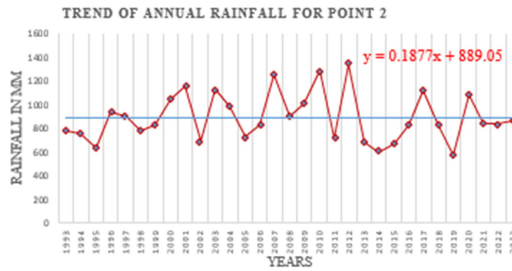


Figure 5. Annual rainfall for point 2

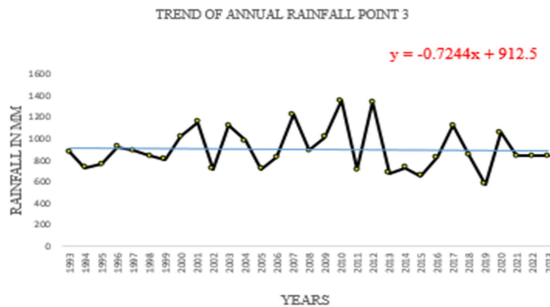


Figure 6. Annual rainfall for point 3

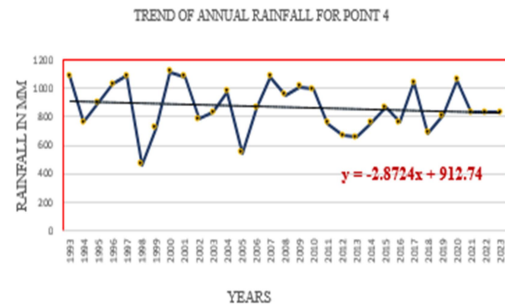


Figure 7. Annual rainfall for point 4

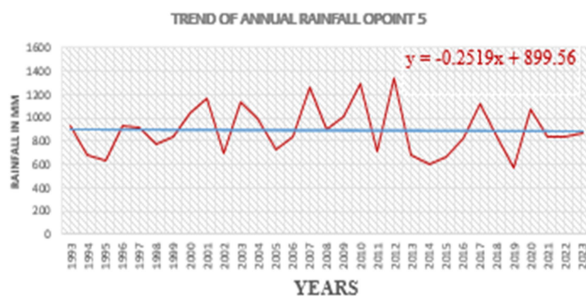


Figure 8. Annual rainfall for point 5

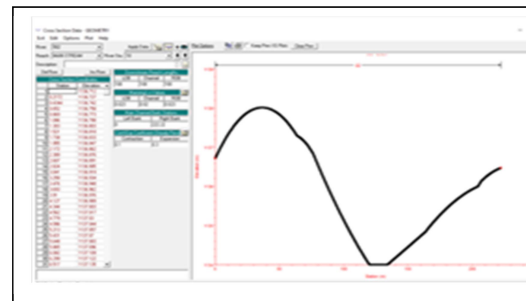


Figure 9. Geometry Data

Statistical analysis of rainfall series data highlights that the occurrence of rainfall is unpredictable and irregular. The annual rainfall trend appeared negative (downward) for climatological station one, three, four and five while for station two the trend was positive. The annual rainfall increased at a rate of -11.513 mm/year, 0.1877 mm/year, -0.7244 mm/year, -2.8724 mm/year and -0.2519 mm/year respectively.

River flow simulation was done in HEC-RAS 4.1 with the help of Global Mapper, which was used to come up with cross section data as shown in Figure 9. The software is used for drought and flood projections, but in this research the focus was to assess the impact of climate change on the river by projecting water levels as well as discharges.

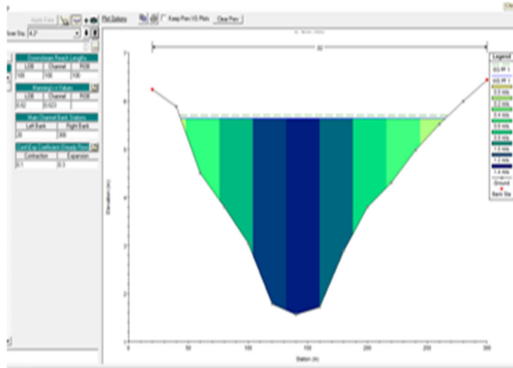


Figure.10 HEC RAS Results velocities.

Profile Output Table - Standard Table 1

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HEC-RAS Plan 02 River M1 River

Reach	River Sta	Profile	Min Ch Elevation (m)	W.S. Elev (m)	E.G. Slope	Vel Chnl (m/s)	Flow Area (m ²)	Top Width (m)	Froude # Ch
REACH 10	PF 1		1.50	5.96	0.000269	1.27	395.09	205.88	0.29
REACH 9.8"	PF 1		1.46	5.95	0.000226	1.17	425.84	218.06	0.27
REACH 9.6"	PF 1		1.42	5.93	0.000188	1.08	461.17	231.75	0.25
REACH 9.4"	PF 1		1.38	5.92	0.000152	1.00	500.79	242.33	0.22
REACH 9.2"	PF 1		1.34	5.92	0.000121	0.92	542.74	249.41	0.20
REACH 9	PF 1		1.30	5.91	0.000096	0.85	586.07	254.75	0.18
REACH 8.8"	PF 1		1.36	5.90	0.000092	0.84	598.06	259.43	0.18
REACH 8.6"	PF 1		1.42	5.89	0.000087	0.82	612.95	264.34	0.17
REACH 8.4"	PF 1		1.48	5.89	0.000081	0.79	629.60	269.47	0.17
REACH 8.2"	PF 1		1.54	5.88	0.000075	0.77	649.20	274.84	0.16
REACH 8	PF 1		1.60	5.87	0.000069	0.74	671.39	280.44	0.15
REACH 7.8"	PF 1		1.60	5.86	0.000071	0.74	671.40	280.51	0.16
REACH 7.6"	PF 1		1.60	5.85	0.000075	0.75	670.75	280.47	0.16
REACH 7.4"	PF 1		1.60	5.85	0.000075	0.75	669.32	280.15	0.16
REACH 7.2"	PF 1		1.60	5.84	0.000077	0.75	667.16	279.31	0.16
REACH 7	PF 1		1.60	5.84	0.000079	0.75	664.95	302.26	0.16

Table 2. shows river flow simulated with velocities.

After a simulation for steady state was run, the results obtained in Table 2 and Figure 10 consists of water levels, velocities, and Froude numbers for all ten sections of the cross sections. The water levels showed water levels being less than 1.7 m, channel velocity not exceeding 1.27 m/s and no section has a Froude number above 1 implying that the flow is be subcritical.

Rainfall occurrence was unpredictable and irregular, according to a statistical examination of Rainfall series data. The trend analysis in Figure 11 revealed an overall downward trend for the past three decades whose first derivative of annual rainfall with respect to time (years) indicated negative as can be seen from the linear regression equation on Figure 11.

The slope, which is the most important statistical parameter in regression analysis, is the very indicator that quantifies the pattern of temporal change during the time period under consideration. Negative values of the slope indicate decreasing trend at the rate of -3.0348 mm/year respectively. For the entire catchment area, the year 2004 saw the highest regional rainfall amounts in 30 years, corresponding to 1229 mm. The linear regression line predicts a decrease over the next 10 years.

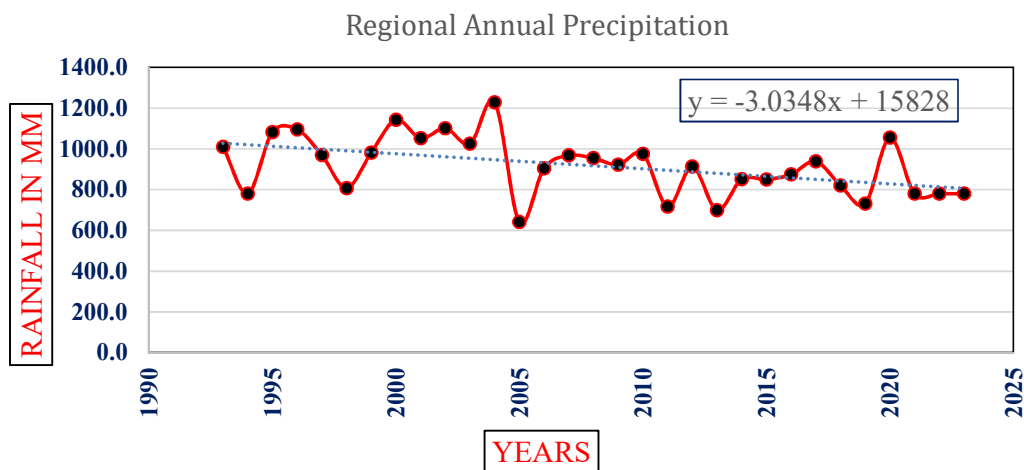


Figure 11. Regional annual trend of all stations

The analysis of trend in surface runoff (water level) of Mulungushi River was carried out for almost four (4) years and two (2) months from 21/11/2018 to 15/02/2022 whose data was collected every after two (2) hours from the logger that was installed as illustrated in Figure 12 and 13.

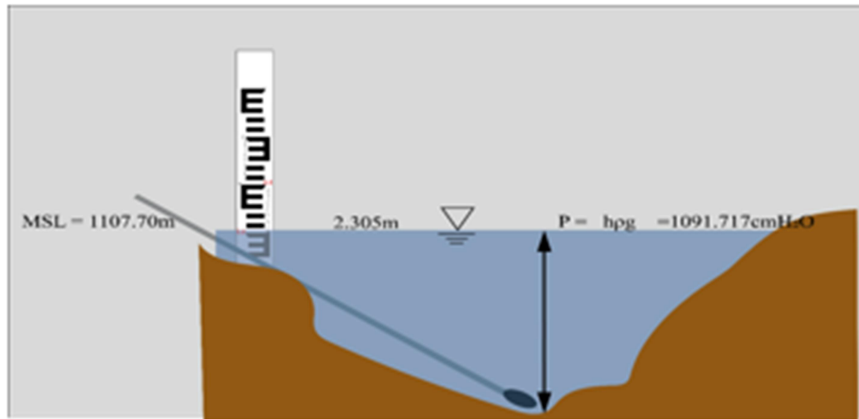


Figure 12. shows the water level calibration tool.

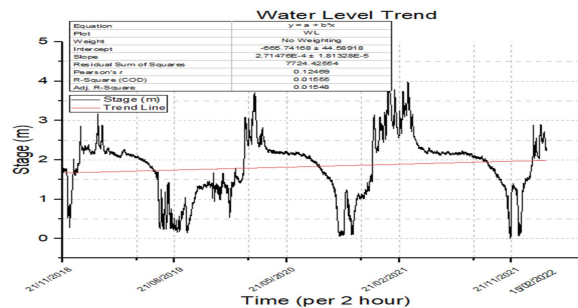


Figure 13. shows water levels for four years two months from 2018 to 2022.

From the figure 12 shown, 2.305 was the reading from the staff gauge, 1107.70 m reading above sea level and 1091.717 cm H₂O was the reading from the logger that was installed just near Mulungushi Bridge. The logger works on the principle of pressure on a submerged body and that pressure displays the head. All other readings obtained from the logger were converted using this calibrating tool.

The occurrence of water level was unpredictable and irregular, according to a statistical study of stage series data. The results revealed an upward trend in stage level with the first derivative of water level with respect to time was positive. The year 2021 witnessed the highest water level amounts in four years for the Mulungushi River at the bridge, with 4.23641 m.

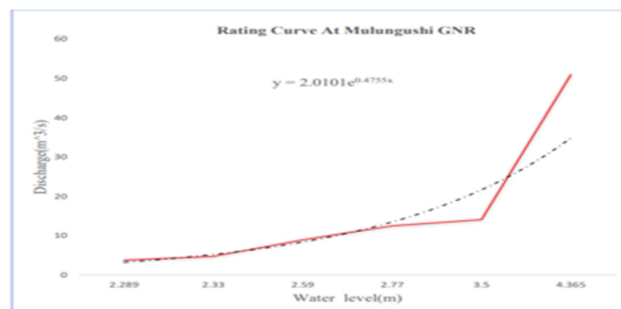


Figure 14. presents the rating curve for Mulungushi River at Great North Road.

This work considered the problem of river floods and droughts and presented a computer solution that is used to predict such a threat. The basic tool, called Hydrologic Engineering Centers for River Analysis System (HEC-RAS), created by the US Army Corps of Engineering, is well developed; and the models created in the system HEC-RAS are quite realistic. To solve practical drought and flood problems, simplified static models of Mulungushi River cross sections were created in the system HEC-RAS. The averages for water levels in the next 4 years is projected to be at 1.602 m.

4. CONCLUSION AND POLICY RECOMMENDATIONS

This study assessed the impacts of climate change on the water resources of the Mulungushi River catchment by integrating historical hydro-meteorological trend analysis with GIS-based spatial analysis and hydraulic modelling using HEC-RAS. The findings provide important evidence on the response of the catchment to long-term climatic variability and support sustainable water resources planning in Central Province, Zambia.

The analysis of rainfall records for the period 1993–2023 revealed a persistent decline in regional precipitation across the 4,200 km² Mulungushi River catchment. The catchment exhibited an overall rainfall trend of –3.0348 mm/year, indicating increasing climatic variability and a gradual reduction in rainfall over the past three decades. This declining rainfall trend has important implications for river runoff, agricultural productivity, and water availability within the catchment.

Hydraulic simulation using a 2D steady-flow HEC-RAS model further indicated a projected reduction in river water levels, with average water levels decreasing from 2.204 m in 2024 to 1.602 m over the subsequent four years. The simulated results suggest that continued reductions in rainfall and discharge are likely to alter the hydraulic behaviour of the Mulungushi River and reduce water availability for downstream users.

Overall, the study demonstrates that climate variability is already influencing the hydrological regime of the Mulungushi River and highlights the importance of integrating hydro-meteorological analysis with hydraulic modelling to support climate adaptation and sustainable water resources management. The findings are particularly relevant for agricultural planning and hydropower operations, where informed water allocation and efficient resource management are essential for improving resilience to future climatic conditions.

4.1 Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Long-term hydro-meteorological monitoring: Continuous collection of rainfall, discharge, and water-level data should be strengthened within the Mulungushi River catchment to improve trend detection and enhance the accuracy of future hydraulic and hydrological models.

2. Integrated climate–hydrology analysis: Further research should investigate the scientific relationship between declining regional precipitation and observed variations in river stage and discharge using integrated hydrological and hydraulic modelling approaches.
3. Advanced climate change modelling: Future studies should incorporate climate projection scenarios (e.g., CMIP6 or regional climate model outputs) together with hydrological models such as HEC-HMS or SWAT coupled with HEC-RAS to evaluate the long-term impacts of climate change under different emissions scenarios.
4. Water resources management and adaptation: The results should be used by water resource managers, irrigation planners, and the Lunsemfwa Hydropower Station to develop adaptive water allocation strategies, improve reservoir operation planning, and support climate-resilient agricultural practices within the Mulungushi River catchment.

Implementing these recommendations will enhance understanding of climate change impacts on the Mulungushi River and contribute to sustainable water resources management and climate adaptation planning in Zambia.

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