ASSESSMENT OF CLIMATE CHANGE IMPACTS ON EXTREME FLOODS IN RUO RIVER BASIN, MALAWI

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ABSTRACT

The Ruo River Basin in southern Malawi, vital for its socio-economic role, faces escalating flood risks escalated by tropical cyclones. This thesis examines the impact of climate change on flood risks and vulnerabilities, focusing on improving hazard mapping and vulnerability assessments. Using advanced hydrological modeling, remote sensing, and the Rainfall-Runoff-Inundation (RRI) model calibration with Sentinel data, the study enhances flood risk evaluation. Bias-corrected General Circulation Models (GCMs) forecast a 29% rise in inundated areas, a 33.9% increase in affected agricultural land, a 38.5% rise in building damage, and a 42.5% greater population risk during a 100-year flood event. These increases suggest significant financial strain on households and the government. The Pressure and Release (PAR) model highlights key vulnerabilities, including land tenure issues, rainfed agriculture reliance, and insufficient early warning systems. The study proposes practical countermeasures, including engineering solutions, community strategies, and policy reforms to improve safety & resilience and align with global sustainability goals.

Keywords: Flood risks, Extreme rainfall, General Circulation Models, vulnerability, countermeasures

INTRODUCTION

The Ruo River Basin in southern Malawi is a region of critical socio-economic importance, renowned for its agricultural productivity and ecological value (GoM,2017). However, the basin faces escalating flood risks, worsened by climate change, which increasingly threatens its socio-economic stability and environmental health. Historical records indicate that extreme flood events have caused widespread damage, loss of lives, displacement and significant economic losses, placing the basin among the top three most affected regions in all these major flood events (GoM, 2023, 2022, 2019, 2015). These events highlight the urgent need for robust flood risk management strategies. Flooding in the Ruo River Basin is driven by a combination of factors, including the topographical challenges of its mountainous and lowland regions, intense rainfall events, and socio-economic conditions such as high population density and reliance on subsistence rainfed farming. These floods not only have caused immediate physical destruction but also exacerbate poverty, impeding sustainable development in the basin.

Despite the evident impact of flooding, there is a notable lack of localized, comprehensive studies that analyze the interaction between climate change, extreme flood risks and vulnerabilities in the basin area. Previous research, such as that by Kachaje et al. (2016) and Kleynhans et al. (2018), focused on

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current climate conditions and flood hazards. Kleynhans et al.'s hydrodynamic modeling provides insights into levee design under current conditions but overlooks a broader range of countermeasures. Consequently, existing flood risk management approaches in the basin fall short, as they do not integrate climate projections, socio-economic vulnerabilities, or high-resolution hazard mapping.

This thesis seeks to address these critical gaps by employing advanced remote sensing, future climate projections, and hydrological modeling to develop an integrated flood hazard map and vulnerability assessment. The research aims to uncover the root causes of flooding and propose practical, sustainable solutions to enhance flood risk management and resilience in the Ruo River Basin.

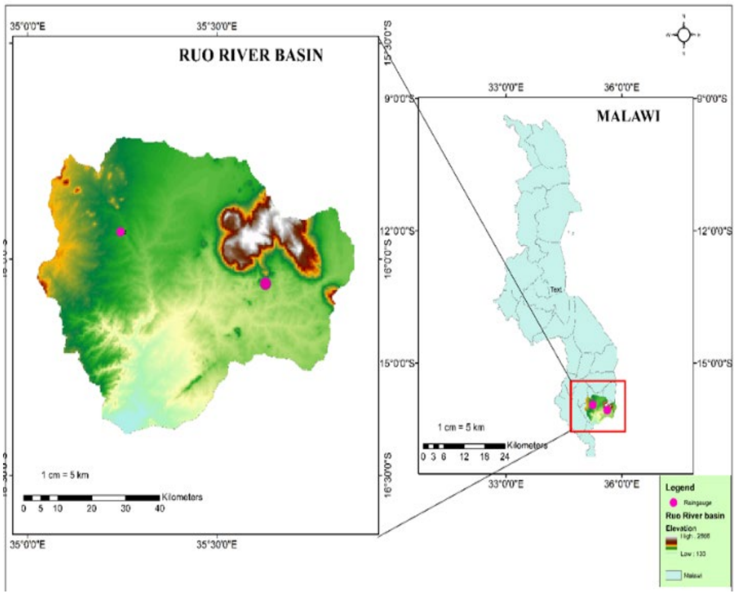


Figure1. Location of Ruo river basin.

THEORY AND METHODOLOGY

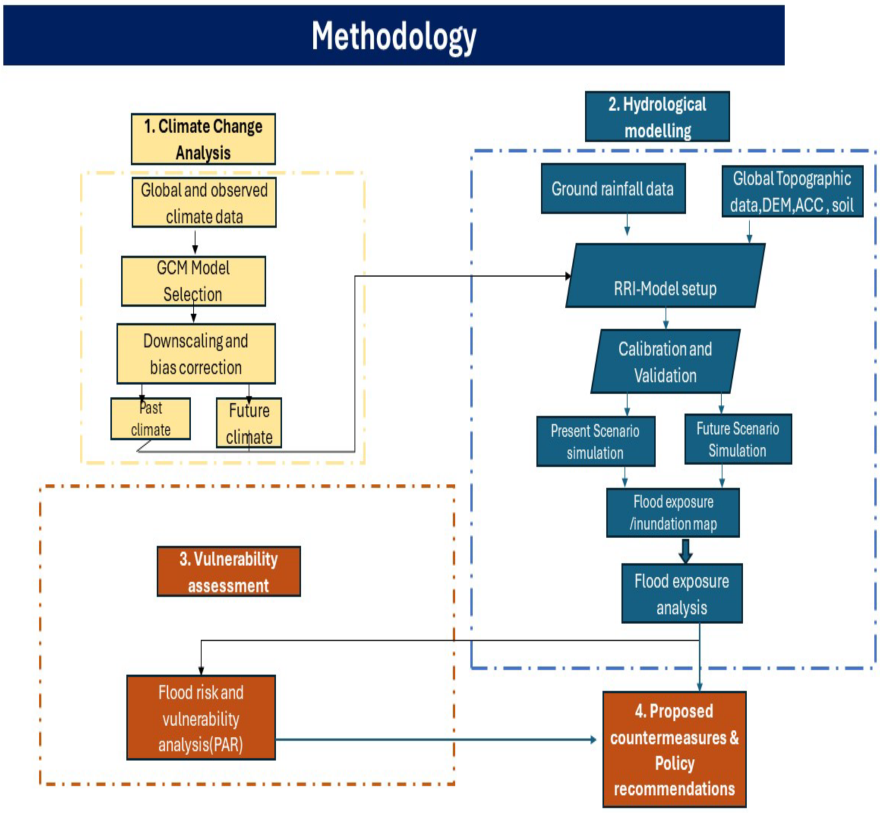


Figure 2. Methodology framework

This study adopts a holistic approach to assess flood risks in the Ruo River Basin including:

1. Climate change analysis

This study examines both historical and future climatology. Historical rainfall data from ground stations were analyzed for past trends, whereas future projections for 2040–2060 were obtained from GCMs in the CMIP-5 archive with bias correction using the observed data. GCMs were selected by comparing key meteorological variables with global and regional reanalysis products.

2. Hydrological modelling

An RRI model for the basin was developed to assess the hydrological response of the basin under past and future climatic conditions using diffusion wave approximation (Sayama, 2022). Calibration and validation were conducted using data from extreme events in 2019 and 2023, respectively. The model performance was evaluated using Nash–Sutcliffe efficiency (NSE) for discharge comparisons at the Sankhulani River gauging station.

3. Flood Behavior, Exposure, and Frequency Analysis

This study assesses extreme flood events in the Ruo River Basin by analyzing both past and future scenarios. Using a four-day rainfall period, it estimates rainfall intensities for 5, 20, 50, and 100 years return periods and applies GCM-projected rainfall data to predict future flood risks. The resulting flood hazard maps are evaluated for their impact on inundation extent, agricultural areas, population exposure, and building damage, considering socio-economic vulnerabilities under current and future climate.

4. Vulnerability assessment

The vulnerability assessment for the basin employed the Pressure and Release (PAR) model to evaluate the susceptibility of communities, agriculture, and infrastructure. This study examines the progression of vulnerability from root causes through dynamic pressure to unsafe conditions. The analysis involved reviewing previous studies, government and non-governmental reports, demographic and socioeconomic profiles of the area, publications and academic research.

DATA

Daily rainfall records from 2002 to 2023 were collected from two gauging stations through the Meteorological Department, while the Department of Water Resources provided corresponding river discharge data for extreme flood events. A LiDAR-based digital elevation model (DEM) was used to generate inputs for the Rainfall-Runoff-Inundation (RRI) model, including river networks and slopes. Building footprint data was sourced from the Microsoft Global Building Footprint Database, and population data were obtained from the National Statistics Office.

RESULTS AND DISCUSSION

1. Climate change analysis

The analysis of rainfall trends in the Ruo River Basin reveals a significant increase in extreme rainfall events, particularly those exceeding 100 mm/day, in recent years (2002–2023) compared to earlier periods (1980–2000), as illustrated in Figure 2. The basin average rainfall was considered for future rainfall innovative trend analysis, and the different GCM relevant trends are shown in Figure 2. All four Global Climate Models (GCMs) used for future projections indicate a continued rise in rainfall intensity, with the Access model predicting the highest increase, especially for events exceeding 200 mm/day.

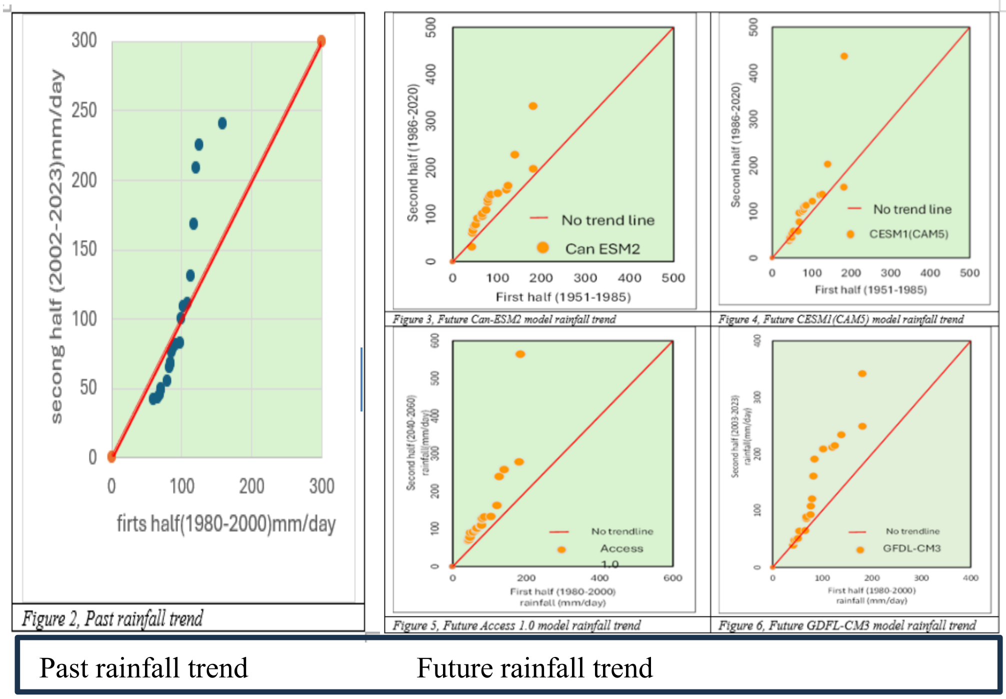


Figure 3. Past and future GCM extreme rainfall

Historical data shows that rainfall intensities above 200 mm/day have consistently triggered severe flooding, leading to widespread damage to infrastructure, agriculture, and communities (GoM, 2023).

2. RRI model calibration and validation.

The RRI model was calibrated using the March 2019 flood event and validated with the 2023 event by integrating Sentinel-1 data. This integration notably enhanced the model's flood simulation accuracy. The calibration resulted in significant improvements, with the model's NSE increasing to 0.75, and further validation reaching an NSE of 0.88. These results underscore the effectiveness of high-resolution satellite data in refining flood simulations, in remote areas lacking extensive ground-based measurements.

3. Flood Behavior, Basin Exposure, and Inundation Intensities Across Return Periods

Figure 4 compares current and future climate inundation extent and depth over 20,50- and 100-year return period from RRI simulation. The analysis highlights that climate change-driven precipitation is causing more severe and widespread flooding in the Ruo River Basin.

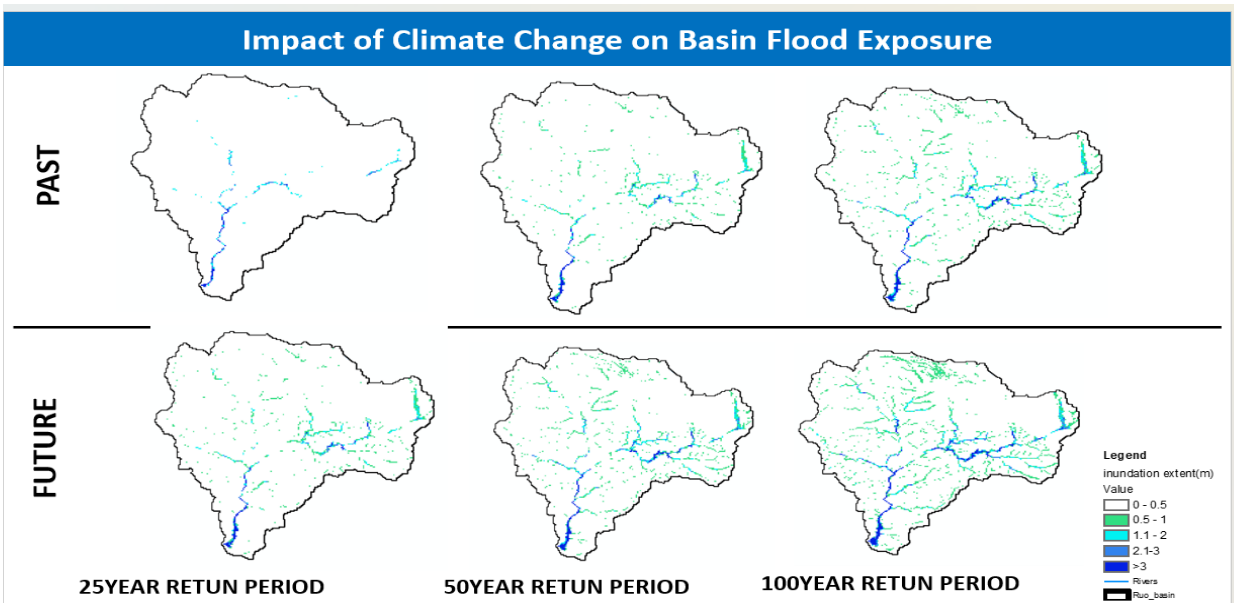


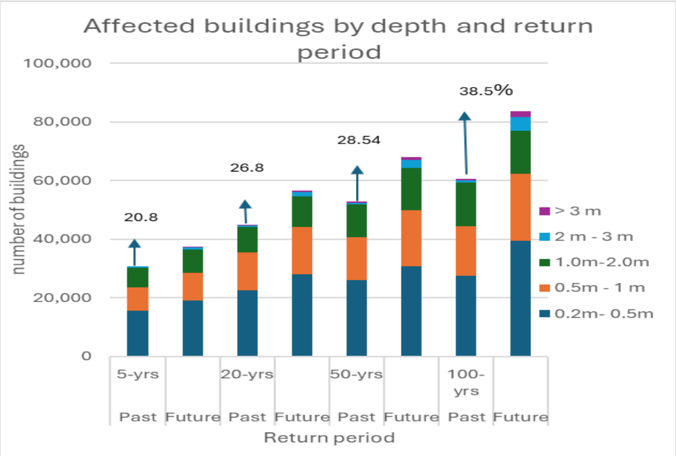
Figure 4. Past and future climate inundation

Under current conditions, inundation depths for a 20-year return period mostly range between 0-1 meter, with flooding. However, future scenarios show higher depths, typically 1-2 meters, with flooding extending across a broader area of the basin. For 50- and 100-year return periods, future conditions predict deeper inundation, with some areas experiencing more than 3 meters of flooding. The basin's flat terrain increases its vulnerability, making flood risk-based land use planning crucial to mitigate the impact on low-lying areas and guide safer development.

Flood Damage Assessment

Future climate projections for the Ruo River Basin predict a 33.3% increase in inundated areas over the next 100 years, significantly impacting land availability for agriculture and housing. With nearly 90% of the local population dependent on agriculture, this increase threatens productivity and could worsen poverty. Additionally, a 40.55% rise in affected agricultural land will further strain household food security and economic stability, leading to increased disaster response costs for the government.

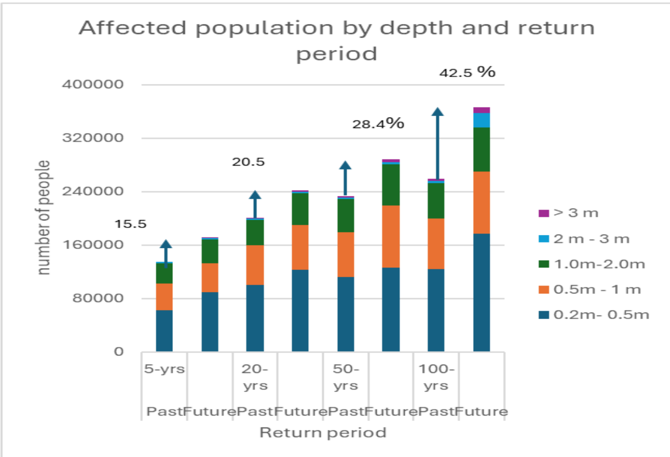
Damage assessment on Buildings damage



The analysis shows a clear trend of increasing damage to buildings as flood return periods lengthen, indicating more severe and frequent floods under climate change. For the 5-year return period, most buildings are inundated at depths of 0.2-1 meters, leading to moderate structural damage. However, for the 50- and 100-year return periods, flood depths of 1-2 meters pose a high risk, especially since almost all buildings are single-story and would face extensive damage or complete submersion. This suggests a significant threat to property and habitability in the Ruo River Basin.

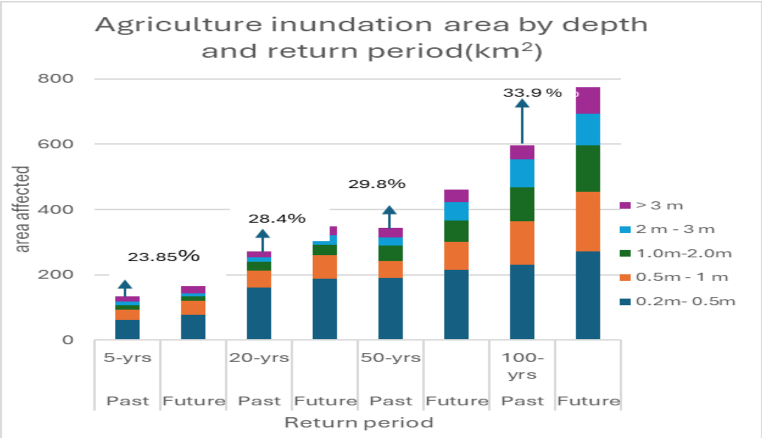
Damage assessment on population at risk

As return periods extend from 5 to 100 years, the number of people affected by floods increases by 15.5% to 42.5%. Moderate flooding impacts many, especially in shorter return periods, while deeper floods affect more people in longer return periods. Extreme flooding affects fewer individuals but poses severe risks. Greater flood depths lead to higher health and safety risks and significant damage, placing additional strain on recovery efforts and local economies.



Agriculture damage assessment

Future agricultural inundation is projected to rise by 23.85% to 33.9% over 5 to 100-year return periods. For 5 and 20-year periods, most inundation is within the 0.2-0.5 m range, with some in the 0.5-1 m



range. In the 50 and 100-year periods, inundation increases significantly across all depths, indicating severe flooding. Floods of 0.5-1 m will damage crops through waterlogging, while 1-3 m floods lead to crop rot and livestock drowning. This increase threatens food security, reduces crop yields, livestock supplies, significantly affecting household incomes and increasing poverty.

4. Vulnerability Analysis

Application of PAR model reveals key factors increasing vulnerability in the basin including land tenure issues, reliance on rainfed agriculture, settlement in flood-prone areas, economic pressures, and inadequate early warning systems. Addressing these hazards and vulnerabilities is crucial for enhancing resilience against climate-driven flood risks.

CONCLUSION AND RECOMMENDATION.

This study utilizes advanced methodologies including climate change analysis, hydrodynamic modeling, and vulnerability assessment to provide a comprehensive understanding of the Ruo River Basin's extreme flood risk. The calibration and validation of RRI model with high-resolution Sentinel satellite data significantly enhanced flood simulation accuracy, underscoring the importance of precise data in flood prediction. Future projections from bias-corrected GCMs indicate intensified extreme rainfall, necessitating proactive measures to address escalating flood risks. Application PAR model reveals key vulnerabilities, such as land tenure issues, dependence on rainfed agriculture, settlement in flood-prone areas, economic pressures, and inadequate early warning systems. Addressing these vulnerabilities is crucial for building resilience against climate-driven flood risks. To address both hazards and vulnerabilities against rising flood risks driven by climate change, the study recommends a multi-faceted approach: implementing engineering solutions like multipurpose dams and flood embankments, adopting community-based strategies including early warning systems and afforestation, and enacting policy reforms such as land tenure adjustments, improved building codes, and subsidies for building and irrigation materials. A synergistic combination of structural and non-structural measures is essential to safeguard both people and property, enhancing safety and resilience in the Ruo River Basin.

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