Analysis of Effective Flood Mitigation Measures in the Lower Shire River Basin, Malawi

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ABSTRACT

The low investment and inefficiency of existing structural measure such as Liwonde barrage to control flooding along the Shire River basin of Malawi, have exposed the area to flood disasters. This study focused on proposing effective countermeasures for reducing flood impacts based on a hydrological model and flood exposure assessment. Flood simulations were conducted using a Rainfall-Runoff-Inundation model with and without countermeasures to analyze flood inundation exposure and risk for different return periods using land cover maps, population, and building footprint data. The study findings showed that with the combined use of countermeasures such as two flood storage water dams and embankment, flood inundation area can be reduced from 1101 km^2 to 618 km^2 and 2017 km^2 to 1480 km^2 for 5- to 100-year return periods, and the number of affected buildings reduced from 30,380 to 18,716 and 80,454 to 63,093. Decrease in affected population was also confirmed using future projection of 2030 population and current 2020 population data. The study findings recommends that the Malawi government adopt construction of multiple countermeasures to reduce impact of flooding and strengthen resilience in the Lower Shire River Basin.

Keywords: Floods, Inundation maps, Return period, Exposure assessment, Effective countermeasures

INTRODUCTION

The Shire River Basin is the largest basin in Malawi, excluding Lake Malawi, with a coverage area of 31,965 km^2. As of 2018, the population was approximately 6,469,4421. The river has a length of 402 km^2, and it is the main outlet of Lake Malawi, which flows into the Zambezi River, Mozambique (Hanke, 2022). The basin is used for hydropower, irrigation, and water supply activities. Malawi experiences flood every year, particularly in the Nsanje and Chikwawa districts located in the Lower Shire River Basin. These lowland areas experience frequent floods that occur almost annually because the region experiences sudden onsets of extreme weather and climatological events that disrupt livelihoods, particularly for the poorest communities that are heavily reliant on rain-fed agriculture (Lumumba and Izadkhah, 2009). Flood mitigation measures in the Lower Shire mainly aim to reduce vulnerability (Gama et al., 2017). Despite government efforts to address the vulnerability challenge in this basin through the implementation of flood mitigation measures, such as the Liwonde barrage, which is used for flow regulation down the Shire River, the Lower Shire remains vulnerable to flood disasters that affect communities surrounding

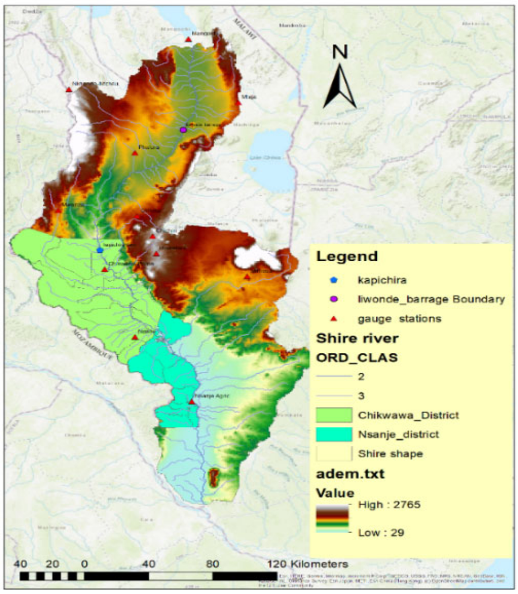

Figure 1: Location of Shire River Basin

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the basin. Floods have affected 406,113 households and resulted into 644 deaths during recent flood event 2023 (Malawi government, 2022). These floods disrupt livelihoods and contribute to the poverty cycle of affected communities. Notably, existing structures along the Shire River, such as the Liwonde Barrage and Kapichira hydropower dam, were not designed to store flood water during the rainy season because of limited storage capacity and operation rules of the barrage. Therefore, owing to the low investment and inefficiency of these existing structural measures along the river, river overflow is a challenge during the rainy season because there is no facility to maintain flow regulation and store flood waters, thereby exposing communities and croplands surrounding the river in the basin to flood disasters. Previous studies in the basin have focused on the impact of climate change and land cover change on flood risk to some extent (Hanke, 2022; Sam, 2018); however, none have focused on the quantitative analysis of flood preventive measures to reduce damage. Therefore, considering the negative impacts of floods, it is important to conduct exposure risk assessments with and without countermeasures, and propose effective measures to mitigate the impacts of floods. The proposed effective countermeasures will help to strengthen resilience and enhance preparedness activities of communities and improve the well-being of people living in the Lower Shire Basin using the Rainfall-Runoff-Inundation (RRI) model.

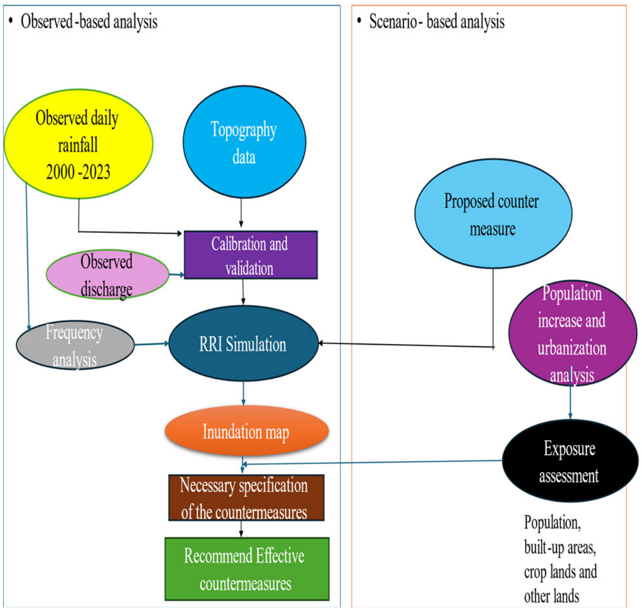


Figure 2. Flow chart for flood risk assessment

THEORY AND METHODOLOGY

The Methodology of this study was divided into two parts: observed-based and scenarios-based analyses (Figure 2). The RRI model developed by Sayama (2015) was used to simulate flood runoff and inundation. The model parameters were calibrated for the 2015 flood event and validated for the 2019 flood event. These flood events were selected because they are the worst in the Shire River basin, causing more damage to infrastructure, including houses and croplands. The simulated discharge from the RRI model was compared to the observed discharge for the 2015 and 2019 floods. Calibration and validation of the RRI model yielded superior results, indicating that it represents the condition of the basin well.

Using the rainfall Thiessen polygon method, the average basin rainfall was calculated to produce the basin-averaged annual maximum daily rainfall for 23 years using rainfall data from seven rain gauge stations. The basin-averaged annual maximum daily rainfall was used to conduct frequency analysis and estimate the rainfall intensity for each return period. The rainfall pattern of the 2015 flood event was used to design the rainfall for different return periods, including 5-, 10-, 20-, 50-, 80-, and 100-year return periods based on the Gumbel distribution function. The flood simulation was conducted using the RRI model with the design rainfall for each return period to produce inundation maps with and without countermeasures. For exposure assessment, the land cover maps (for years: 2010, 2015, and 2020), building footprint data, and population (current population in 2020 and projected data for 2030) were used. The flood inundation and exposure maps were analyzed in the Geographical Information System (GIS) (e.g., ArcMap 10.8.2) to estimate inundated area, affected population, affected buildings, and affected land cover classes, with and without countermeasures, and to propose effective countermeasure with necessary specifications to mitigate floods in the basin.

DATA USED

The Digital Elevation Model with 1-km spatial resolution from the Hydro-SHEDS (https://www.hydrosheds.org/) were used as the input into the RRI Model. The RRI model simulates the interactions between water flow on land and rivers at the basin scale using two-dimensional diffusive waves for flow simulation on slopes and one-dimensional diffusive waves for river simulation (Sayama, 2022). This study used daily rainfall data observed by the Department of Climate Change and Meteorological Services in the Malawi government (2010 – 2023) observed at 12 stations for input in the RRI model and historical daily rainfall data observed at 7 principal stations (2000-2023) for frequency analysis. Daily observed discharge at Chikwawa gauging station and Liwonde gauging station which is located downstream of Kamuzu Barrage was used as the boundary condition that we set in the model for the period 1 December 2014 to 27 January 2015 for calibration and 1 December 2018 to 23 March 2019 for validation of the model were obtained from the Malawi Government's Department of Water Resources Management. Land cover maps for 2010, 2015, and 2020 from https://storage.googleapis.com/earthenginepartners-hansen/GLCLU2000-2020/v2/download.html with (100 × 100 m per pixel) resolutions, basin building data from https://sites.research.google/open-buildings/ and population data from Malawi National Statistical office website (2018 Population census report) (https://finance.gov.mw/index.php/departments/national-statistical-office) and (settlement.emergency.copernicus.eu/ghs_pop2023.php) with 30-arcsec horizontal resolutions were used for exposure risk assessment, and finally recommended effective countermeasures.

RESULTS AND DISCUSSION

Hydrological Modeling: The RRI model was calibrated and validated for the Shire River basin by comparing calculated discharge with observed discharge at Chikwawa gauging station. The calibration of the RRI model for 2015 resulted in NSE = 0.77, MBE = −461.09 and RMSE = 564.02 m^3/s, as shown in (Figure 3). Figure (4) shows the performance of RRI model for 2019 flood in the case of validation, in which NSE = 0.6, MBE = −1152.69, and RMSE = 1429.39 m^3/s. The calculated discharges for 2015 flood were reasonably agreeable with observed discharge. Although there are some discrepancies between calculated and observed discharge for 2019 flood, which is possibly due to boundary condition discharge data at Liwonde barrage and observed discharge data at Chikwawa gauging station. Overall, as per the NSE values obtained from calibration and validation, the performance of the RRI model was acceptable with adjusted parameters, suggesting that the model represents the actual conditions of the basin hence the model parameters were used to analyze the effective flood mitigation measures in the Lower Shire River basin, Malawi.

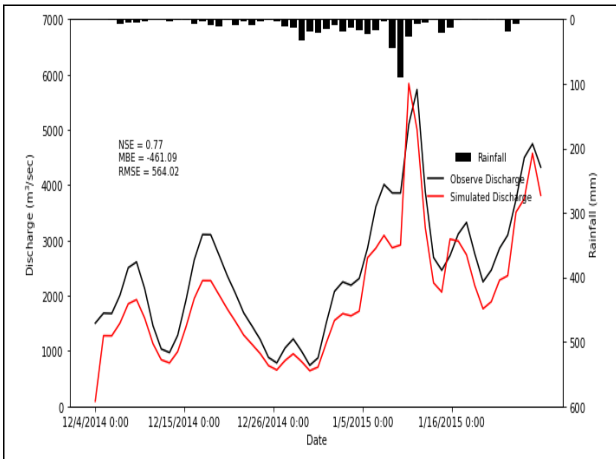


Figure 3: Comparison of calculated and observed discharge for 2014-2015 flooding

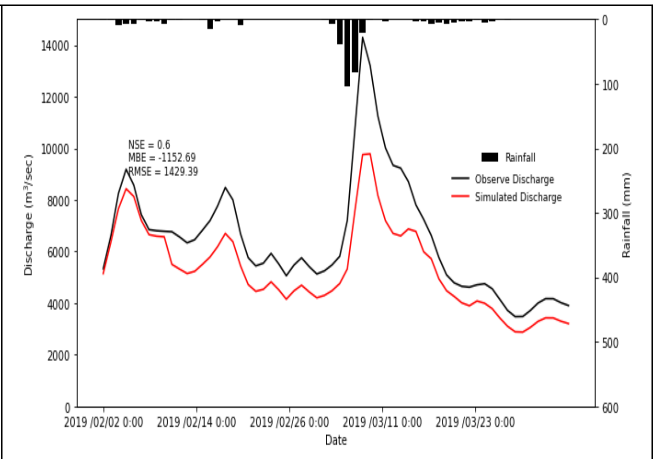
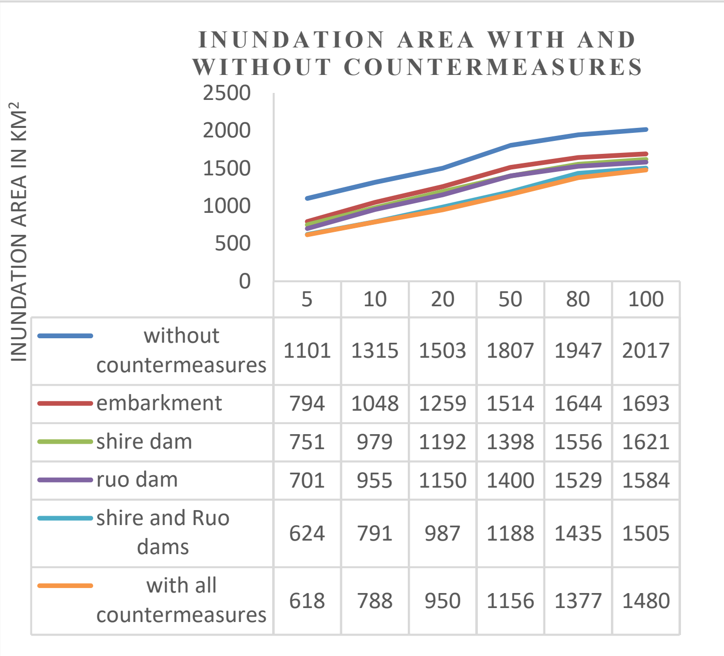


Figure 4: Comparison of calculated and observed and discharge for 2018-2019 flooding event

Flood exposure analysis with and without countermeasure

The results showed that without the use of flood structural control measure there is tremendous increase in exposed inundation area from 1101 km^2 for 5 years to 2017 km^2 for 100 years return period (Figure 5). Increase in number of affected buildings (Figure 7) from 30,380 to 80,454 for 5 year and 100- year return periods. In addition, there is substantial increase on number of affected populations from 93,100



	5	10	20	50	80	100
without countermeasures	1101	1315	1503	1807	1947	2017
embarkment	794	1048	1259	1514	1644	1693
shire dam	751	979	1192	1398	1556	1621
ruo dam	701	955	1150	1400	1529	1584
shire and Ruo dams	624	791	987	1188	1435	1505
with all countermeasures	618	788	950	1156	1377	1480

Figure 5: Affected inundation area with and without countermeasures

to 253,847 using 2020 population data and 124,527 to 330,382 for future projection using 2030 population data (Figure 8). Flood intensity exposes many buildings, population and areas in communities to flood disasters because of a lack of structural measures. The inundated area continues to rise and becomes exposed to disasters if proper action is not taken to reduce the flood impacts in the basin as shown in the inundation map in Figure 7. To reduce the impact of flooding, the study proposed the construction of two storage water dams and a 5-meter-high embankment. Flood simulations were conducted for different scenarios such as a 5- to 100-year return periods to reduce peak discharge of the hydrograph at the proposed dam location. Storage volume was estimated using simulation discharge data at the proposed dam locations such as Chikwawa Mkulumadzi forest area in the Shire River main channel and Sakhulani area in the Ruo major Shire River tributary. To set dam conditions in the RRI model, 2000 m^3/s starting discharge was selected as a threshold for flood storage volume capacity of 1 billion m^3 at Chikwawa dam, 3500 m^3/s for Ruo dam with 522 million m^3 (Figure 6) to reduce 5-years most frequents occurring floods and 100-years extreme floods in the basin. The study also considered the topography, elevation and calculated inundation areas for the proposed dam location. Therefore, with the use of proposed two flood storage water dams located at (Mkulumadzi forest area, Chikwawa district in the Shire main channel and the other at Sakhulani area in the Ruo River main tributary) flood can be reduced. Additionally, construction of embankment in the disaster-prone areas of the Nsanje district such as Bangula and Nsanje Boma flood exposure risk and its impact can be reduced in the Lower Shire River basin. Study findings show reduction in the flood inundation area from 1101 km^2 to 618 km^2 for the 5-year return period and 2017 km^2 to 1480 km^2 for 100-year return period (Figure 5). Decrease in the number of affected buildings (Figure 7) from 30,380 to 18,716 and 80,454 to 63,093 for a 5- and 100-year return period.

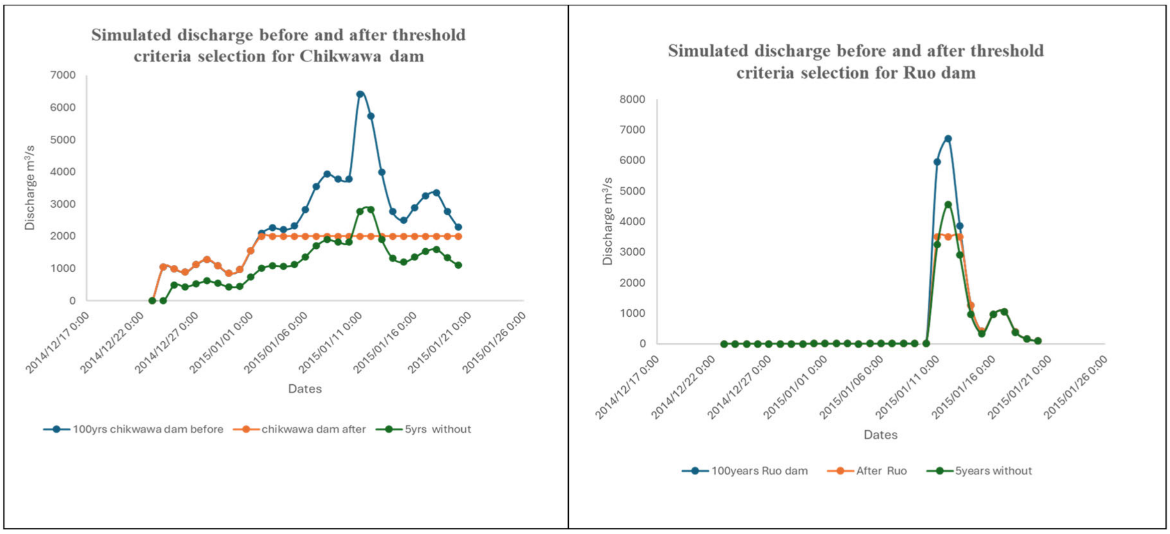


Figure 6: Simulated discharge before and after threshold criteria selection for Chikwawa and RUO dams

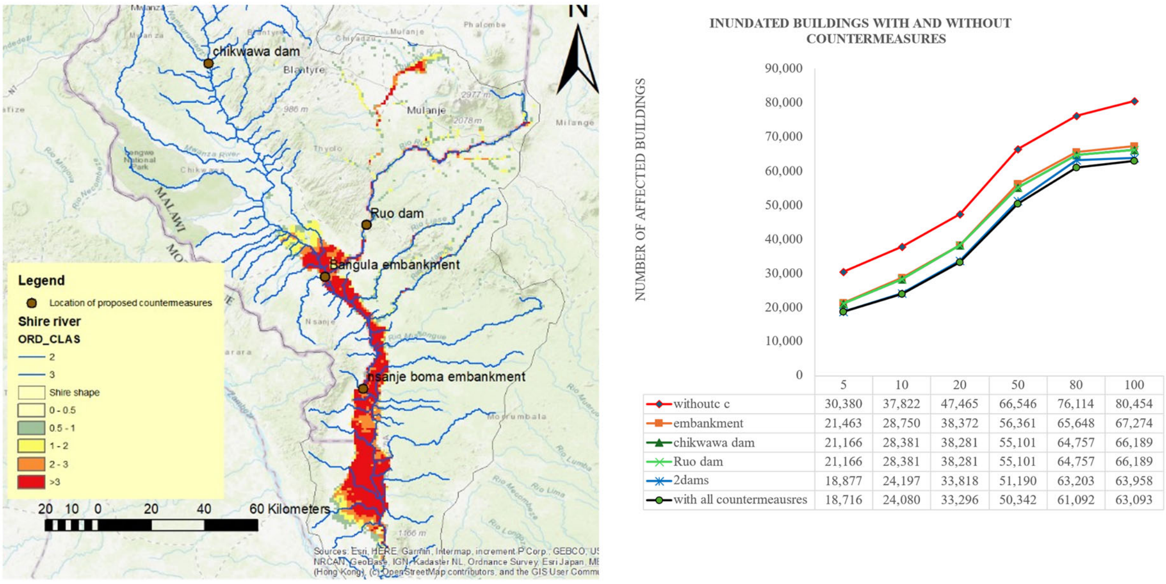


Figure 7: Locations of proposed countermeasures and number of affected buildings

Further decrease in affected population (Figure 8) from 93,100 to 60,607 and 253,847 to 192,747 using 2020 population data and from 124,527 to 80,284 and 330,382 to 250,104 using 2030 population data (future projections). These results demonstrate that with the use of multiple effective countermeasures, the exposure risk in the basin is reduced. This is because embankments help to reduce flood risk by stabilizing the flow of water and diverting water away from spilling to vulnerable areas. Furthermore, flood storage water dams help to regulate water flow during heavy rainfall by controlling the release of water. They mitigate downstream flooding, protecting communities and infrastructure, creating reservoirs to store water and regulate water levels in rivers, reducing peak flows and velocities, thus minimizing the impact of sudden floods.

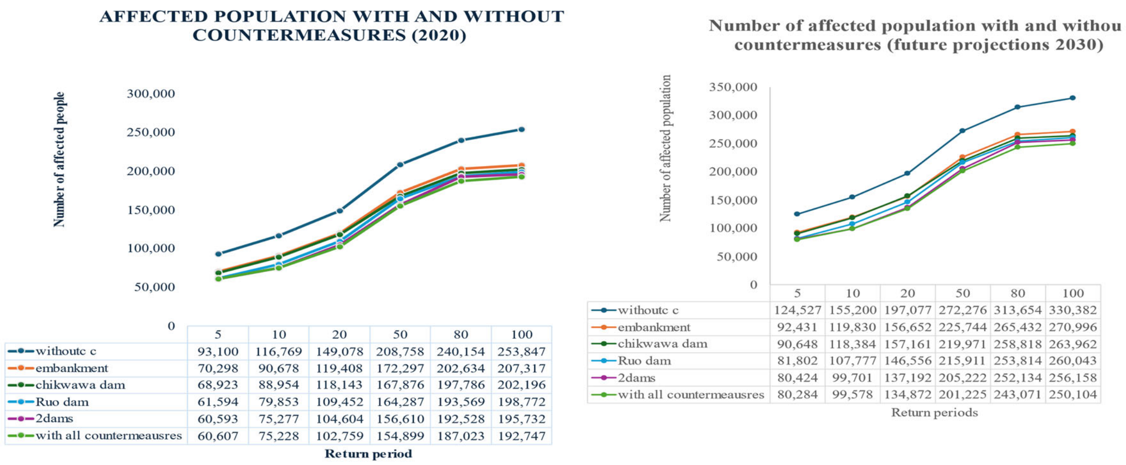


Figure 8: Affected population with and without countermeasure

Land cover change analysis

The study also evaluated changes in different land-cover classes using land-cover maps for 2010, 2015, and 2020. The results showed that forest cover was depleted from 12239 km^2 to 11305 km^2 with a -3.71% to -4.39% increase in built-up areas from 1074 km^2 to 1760 km^2 by 15.08% to 28.10% (Table 1) and a slight change in cropland expansion from 4784 km^2 to 5133 km^2 by 4.39% to 2.52%. This is due to unsustainable land use practice such as deforestation and increase in population growth which have contributed to increased runoff and flood exposure risks in the study area.

Table 1. Percentage of land cover change

Land cover	Area 2010	Area 2015	Area 2020	% (2010-2015)	% (2015-2020)
Vegetation	13355	13338	13325	-0.13	-0.10
forest	12239	11801	11305	-3.71	-4.39
cropland	4784	5004	5133	4.39	2.52
built-up	1074	1265	1760	15.08	28.10
Open water surface	505	549	435	8.10	-26.28

RECOMMENDATION

With low investment and inefficient structures to control flooding waters along the Shire River, has resulted in increase in number of affected flood inundated areas, population, buildings, and land cover classes being exposed to flood disasters, especially in the Lower Shire River Basin. To mitigate flood impact, Malawi government requires comprehensive flood control measures which involves a holistic and transdisciplinary approach. This involves implementation of scientific knowledge-based decisions by involving engineering works and policies on designing and planning of effective flood control measures to be used in reducing the flood impacts. Therefore, study findings recommend Malawi government to put priorities in disaster risk reduction by investing in effective structural countermeasures which involves engineering works to reduce the impacts of floods in the Shire River Basin. The government can adopt construction of two dams to store flooding water during rainy season and embankments to maintain flow regulation in the main channel and diverting water from spilling over to vulnerable areas. The countermeasures will help to reduce flood exposure risks by strengthening resilience to communities living in these areas from climate related hazards and natural disasters such floods and enhance preparedness activities in the Lower shire River basin. Finally, the study recommends policy implementation on land use planning to reduce the impact of flooding in the basin.

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REFERENCES

Sayama, T. (2022). *Rainfall Runoff Model (Manual)* ver. 1.4.2.5. Tsukuba: International Centre for Water Hazard Management, Public Research Institute (PWRI), Disaster Research Institute, Kyoto University.

Gama, S., Koike, T., Yoshihiro Shibuo, A., & Rasmy, A. (2017). *FLOOD HAZARD AND RISK ASSESSMENT UNDER CLIMATE CHANGE IN THE LOWER SHIRE BASIN, MALAWI*. Retrieved from www.masdap.mw.

Malawi Government. (2022). *Malawi Disaster Damage Profile. Lilongwe*: Department of Disaster Management Affairs.

Hanke, T., Miho, O., Kuniyoshi, T., & Hideo, F., (2022). *Modelling the impact of land cover change on flood risk in the Lower Shire River Basin, Malawi*.

Lumumba Mijoni, P. and Izadkhah, Y.O. (2009). *Management of floods in Malawi: case study of the Lower Shire River Valley. Disaster Prevention and Management, Vol. 18 No. 5, pp. 490-503.* https://doi.org/10.1108/09653560911003688.