MODELING THE IMPACT OF LAND COVER CHANGE ON FLOOD RISK IN THE LOWER SHIRE RIVER BASIN, MALAWI

Hanke Titus Lloyd Ndau[*]
MEE21730

Supervisors: **Professor OHARA Miho** [**]
Professor TAKEUCHI Kuniyoshi [***]
Professor FUKUI Hideo [****]

ABSTRACT

Severe poverty, dependence on rain-fed agriculture, and increasing population size in the Shire River Basin of Malawi have resulted in rapid conversion of forests to settlements and croplands along rivers. We quantify how land cover changes over a 30-year period, between 1990 and 2019, have affected the nature of floods and flood disaster damage in the lower Shire River Basin in Malawi, using the Rainfall-Runoff-Inundation Model. We found that forest depletion from 13,743 km^2 to 6,444 km^2, and cropland expansion from 6,311 km^2 to 13,776 km^2 caused an increase in flood inundation area from 817 km^2 to 1,164 km^2. We conclude that the conversion of land from forest to agricultural land, which was stimulated by agricultural development policies, increased the flood risk to communities in Chikwawa and Nsanje districts in the lower Shire Basin. Our recommendation is that development strategies should include specific measures to either maintain forest cover or offset the equivalent roughness and infiltration provided by forest cover.

Keywords: Risk assessment, Land-cover change, Floods

INTRODUCTION

The Shire River is the only outlet from Lake Malawi. The basin is the largest in Malawi, covering a total of 31,965 km^2 excluding Lake Malawi. The total basin population in 2018 was 6,469,442. The river flows southward into the Zambezi River in Mozambique. Nsanje and Chikwawa districts in the Lower Shire River Basin (Figure 1) accounted for most of the flood disaster damage in Malawi between 2015 and 2022 (Figure 2) (Malawi Government, 2022). Large-scale flood disasters have become more frequent (Gama et al, 2017; Kita, 2015), suggesting an increase in the severity of flood hazards (increased rainfall, inundation depth, and extent), vulnerability (policies, socioeconomic factors, and opportunities), and exposure (utilization of flood plains with insufficient countermeasures). Despite the high impact of floods on lives and economic development in the lower Shire River Basin, there is low investment in structural flood control measures. Flood mitigation measures in lower Shire mainly aim to reduce the vulnerability of people (Gama et al, 2017). The basin experienced rapid population growth between 1977 and 2018 (Figure 3). Poverty, population growth, and high dependence on charcoal for heating coupled with agricultural input subsidies (Chawawa, 2018) have resulted in large-scale deforestation (Palamuleni et al, 2010). This land use conversion will likely result in a change in the behavior of runoff and flood risk, as illustrated by Barasa et al. (2015). It is, therefore, important to understand the interactions between rainfall, runoff, inundation, exposure, and damage in the lower Shire River Basin to improve the people's welfare, with basin wide approaches for resilience and sustainable development.

[*] Disaster Mitigation Officer in Office of the President and Cabinet, Department of Disaster Management Affairs, Lilongwe, Malawi

[**] Adjunct Professor at National Graduate Institute for Policy Studies (GRIPS), and Senior Researcher at Int. Centre for Water Hazard and Risk Management (ICHARM), Public Works Research Institute (PWRI), Tsukuba, Japan

[***] Professor Emeritus at University of Yamanashi, Former advisor of ICHARM, PWRI, Tsukuba, Japan

[****] Professor at National Graduate Institute for Policy Studies (GRIPS), Japan

Our main aim is to assess the relationship between land cover changes, discharge, and flood disasters in the lower Shire River Basin using hydrological simulation. We quantify the major land cover changes in the river basin, identify the changes in discharge resulting from land cover changes, and identify the elements at risk under different land cover situations. Finally, we propose policy measures for development in other basins and reduction of flood risk in the lower Shire Basin.

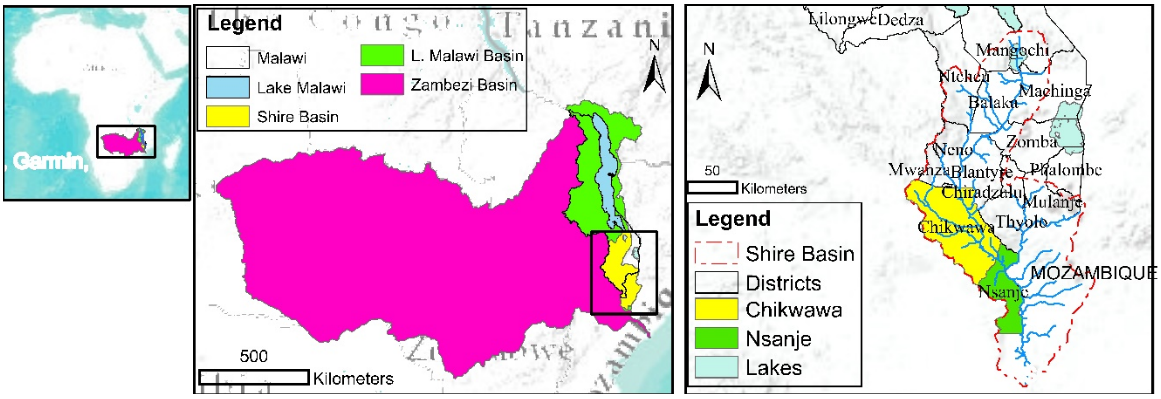


Figure 1: Location of Shire River Basin

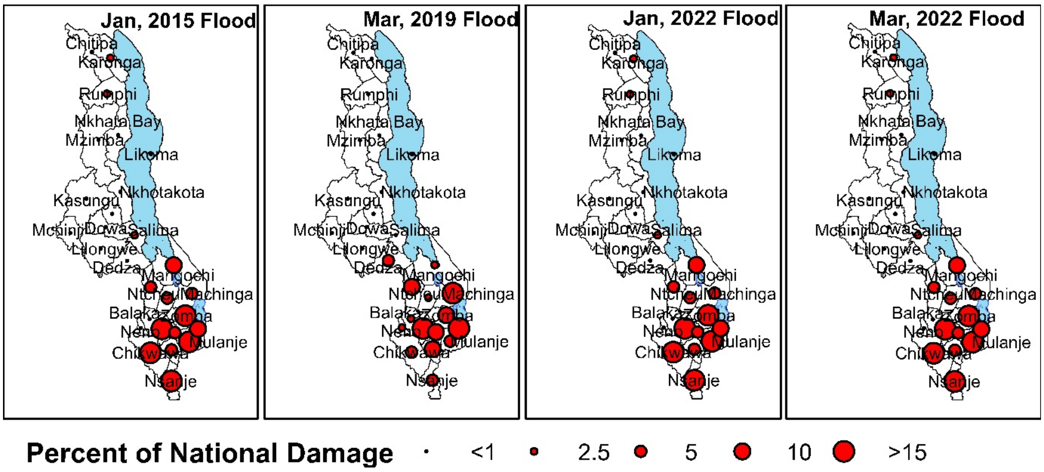


Figure 2: Flood impacts in Malawi from 2015 to 2022

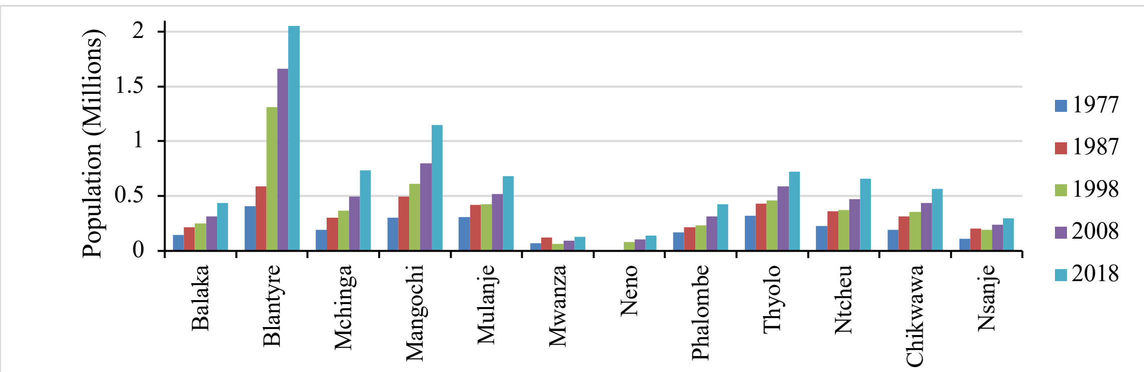


Figure 3: Population Growth in the Shire River Basin

THEORY AND METHODOLOGY

We use the Rainfall Runoff Inundation (RRI) model to compare flood behavior under 1990 and 2019 land cover. Figure 4 summarizes the methodology of the analysis. The hydrological responses of a basin to precipitation are greatly influenced by the basin's soil and land cover. In the RRI model, the influence of land cover is expressed through slope roughness and infiltration. It is expected that with high infiltration in forests and low infiltration in built-up areas and cropland, the proportion of each land class will influence the behavior of discharge and the extent of inundation.

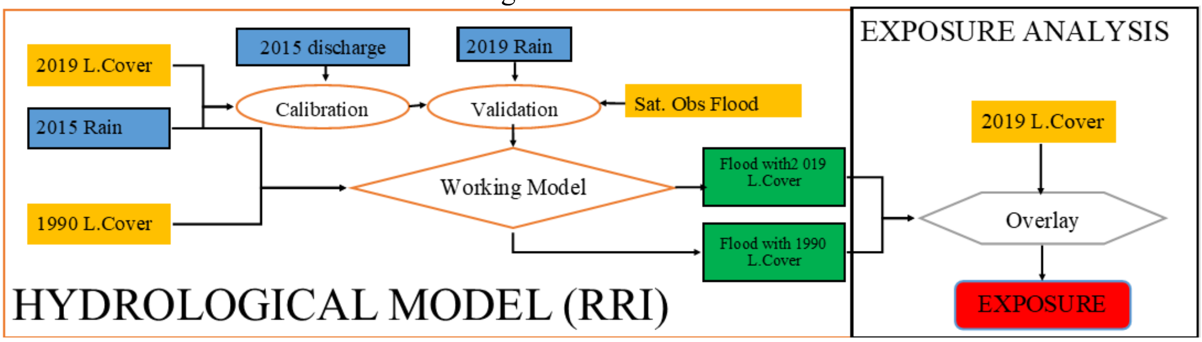


Figure 4: Summary of the research methodology

Data

Land cover data: We use high resolution land cover maps (30 × 30 m per pixel) produced by the Department of Surveys in the Malawi Government. The 1990, 2000 and 2010 land cover classes are used to quantify changes in land cover. The analysis is limited to basin areas within the borders of Malawi, because high-resolution maps for Mozambique were not available. Coarse-resolution global land cover maps have a higher estimation error and therefore are not reliable for analyzing small-scale changes (Li, Samat, Liu, Lin, & Bai, 2019). Therefore, the 100 m resolution global land cover map, which includes the Mozambican area of the basin, is not used to analyze land cover changes. However, it is used as input for the model calibration.

Data for hydrological simulation by RRI model: Land cover maps with moderate resolution (100 × 100 m per pixel) for 2019 obtained from the Copernicus Global Land Service are used for the RRI model. Daily rainfall observed by the Department of Climate Change and Meteorological Services in the Malawi government at ten stations, and a Digital Elevation Model (DEM) with 450 m resolution from hydro-sheds are used as the main input into the hydrological simulation model. We use the mean daily discharge observed at Chikwawa for the period 1 December 2014 to 20 January 2015 for calibration and 1 December 2019 to 30 April 2020 for validation of the model. Both sets of data are obtained from the Malawi Government's Department of Water Resources Management. The inundation is verified using satellite-observed inundation by Modis Tera (MODQ09A1) surface reflectance.

Methodology

Land cover change analysis: Using the Tabulate-area tool in ArcMap 10.8, we calculate the change in land cover between 1990, 2000, and 2010. We focus on the changes between eight land classes: bare land, forest, cropland, herbaceous wetland, built-up areas, water bodies, shadow, cloud cover, and unknown. We only consider the macro-scale changes that are likely to have a significant impact on runoff for the full basin, and mesoscale changes are calculated for the Nsanje and Chikwawa districts to estimate exposure. Using the maximum likelihood classifier tool in ArcMap 10.8, we reclassify "shadow," "cloud cover" and "unknown" land classes into the adjacent land cover class, since the RRI treats all classes in the input file as land surface features. The 30 m land cover maps are merged with the 100 m land cover maps to fill the Mozambique area of the basin. The assumption is that land cover change is negligible in the Mozambique area of the basin.

Hydrological modeling: The RRI model simulates the interactions between water flow on land and rivers at the basin scale using 2-dimensional diffusive wave for flow simulation on slopes and 1-dimensional diffusive waves for river simulation (Sayama, 2022). The Nash-Sutcliffe coefficient (NSE), mean bias error (MBE), root mean square error (RMSE), probability bias (PB), and r-squared are used to evaluate the model's prediction. These indices summarize the performance of the model by comparing the simulated discharge with the observed discharge. By adjusting the soil porosity, depth, and surface roughness in the RRI model, we calibrate the basin conditions for the flood in January 2015 to obtain a simulated discharge similar to the observed discharge at the Chikwawa Horological Station. The model performance is then validated by simulating the flood from 1 December 2018 to 31 March 2019. We calculate the Land Surface Water Index (LSWI) from the Modis satellite image to detect inundation for the 10 January 2015, and 8 March 2019, thereby verifying the extent of the flood.

Measuring the impact of land cover change on flood disaster: To evaluate the impact of land cover change, we compare the model's peak discharge and inundation areas under different land cover conditions. We simulate the January 2015 flood under the same basin conditions as the final calibrated model but using the 1990 land cover. Using the cross-tabulation tool in ArcMap 10.8, we compare the changes in the inundation area. We also compare the exposure to elements at risk in 1990 and 2010 using the respective land-cover maps.

RESULTS AND DISCUSSION

Land cover change

Figure 5 shows that forest cover decreased 13,747km^2 in 1990 to 6,444 km^2 in 2010, and cropland increased from 6,311 km^2 in 1990 to 13,776km^2 in 2010. Most of the forest area was converted to cropland and settlements although the proportion of the built-up area remained small compared to the size of the basin. In Chikwawa and Nsanje districts, built up areas and cropland appear to be increasing near riverbanks, which leads to an increased exposure risk.

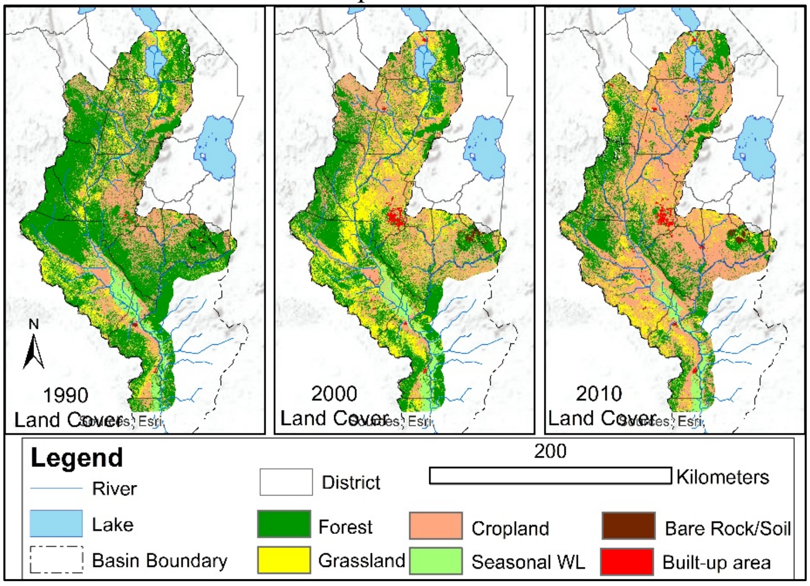


Figure 5: Land Cover in 1990, 2000 and 2010

Hydrological modeling

Using the model parameters in Tables 1 and 2 we obtained the discharge illustrated in Figure 6 during calibration and validation. The indices show that the model can simulate flood conditions efficiently with an NSE of 0.65, with a slight underestimation of discharge (Table 3). As the indices exceeded the thresholds of acceptable simulation, we used the model parameters listed in Table 1 to examine the impact of land cover change on discharge and inundation.

Table 1: Parameters used for different land cover categories

	Forest	Bare soil	Seasonal wetland	Cropland	Built up area	Permanent water
ns-slope	0.35	0.1	0.5	0.3	0.2	0.4
Soil depth	2.6	2.6	2.6	2.6	2.6	1.0
gamma-a	0.463	0.479	0.475	0.463	0.475	0.408
ksv	9.27×10^{-6}	2.78×10^{-7}	1.27×10^{-6}	9.170×10^{-7}	1.0×10^{-8}	0.0
faif	8.89×10^{-2}	6.13×10^{-2}	3.163×10^{-1}	1.89×10^{-2}	1.668×10^{-1}	1.980×10^{-1}

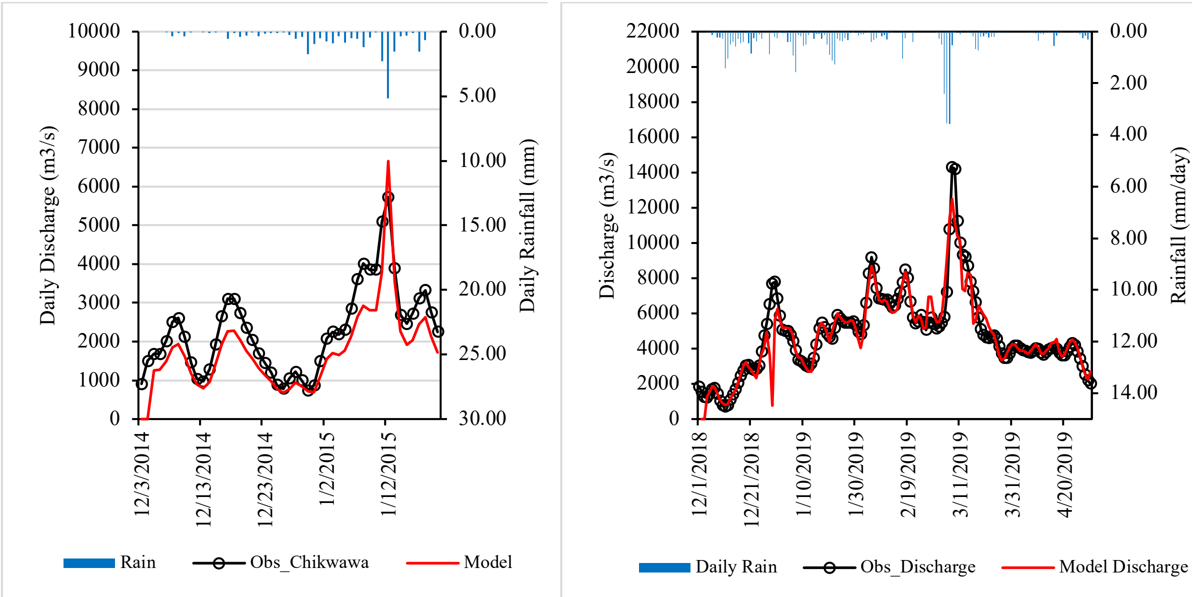
Where: ns-slope: Manning's roughness coefficient for slope
ksv: vertical saturated hydraulic conductivity GA Infiltration Parameter
gammaa: Effective porosity
faif: suction at the wetting front

Table 2: River Parameters

River threshold		80
Width parameter	C_W	5.00d0
Width parameter	S_w	3.50d-1
Depth parameter	C_d	9.50d-1
Depth parameter	S_d	2.00d-1

Table 3: Model Performance indices

	Calibration	Validation
NSE	0.65104	0.856628
MBE	-556.932 m^3/s	-253.159
RMSE	658.1954 m^3/s	1076.123
RB	-0.24551	-0.07567
RSQ	0.903039	0.682886
P-Bias	-24.5511	-7.56669



Calibration Results Validation Results

Figure 6: Result of RRI model calibration output

Impact of land cover change on discharge and inundation

In the 20 years from January1990 to December 2010, the land use of 25,165 km^2 in the lower Shire changed remarkably with forest cover decline from 13,743 km^2 to 6,444 km^2 and cropland increase from 6,311 km^2 to 13,776 km^2. By this change, the flood inundation area in the lower Shire basin identified by RRI simulation using the rainfall Dec. 3, 2014-Jan 21, 2015 increased from 817km2 to 1164.173km^2 (Figure 7). This increase exposes 240km^2 of cropland to floods from the higher inundation, and only 90km^2 is at risk with the lower inundation area. These results indicate that land cover change throughout the basin has increased the flood risk in the lower Shire River Basin. With the dominant national development agenda aimed at improving food security (Malawi Government, 2021a) and commercializing the agricultural sector (Malawi Government, 2021b), it is likely that flood risk will also increase.

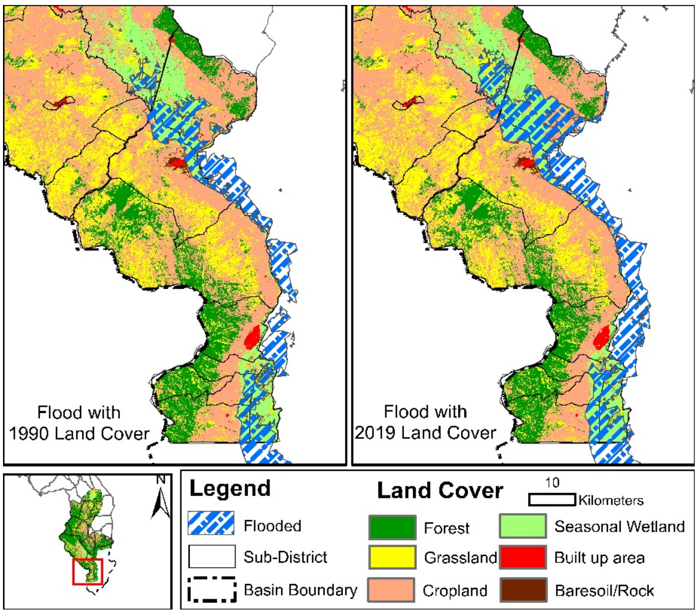


Figure 7: Flood inundation simulated with 1990 land cover and simulated with 2019 land cover

Policy implications

It is widely accepted that floods are among the major hindrances to national development and are likely to derail development agendas, and achieving the Sustainable Development Goals, considering climate change. Therefore, development policies should include specific provisions for maintaining or increasing current forest cover alongside the agricultural initiatives. In river basins that still have large forests, a larger proportion of forest cover relative to other land use should be maintained. Agricultural expansion as stipulated in the Malawi Vision 2063 should have mandatory water retention or infiltration enhancing mechanisms. Where this is not possible, investment should be made for structural countermeasures such as river diversions to protect the critical infrastructure downstream. Government should subsidize flood friendly crops such as rice and sugarcane for Chikwawa and Nsanje, instead of maize, to improve food security in the flood prone areas.

CONCLUSION

We evaluated the relationship between land cover change and flood risk in the lower Shire Basin using hydrological simulations. Our findings showed that land cover change increased the inundation area and discharge in the lower Shire River Basin. As the risk is further exacerbated by the utilization of land along the riverbank, we concluded that development, while paramount in reducing vulnerability, has increased exposure to floods in the basin. Therefore, we recommend that development policies include the financing of flood countermeasures to curb short- and medium-term risk.

Our research focused on the numerical relationship between rainfall, runoff, and inundation as influenced by to land cover change in a large basin. High resolution land cover maps for Mozambique are required to explain land cover changes in the Mozambique section of the basin and evaluate how these have influence the floods. Our study explained the relationship between daily rainfall and one flood event. The lower Shire River Basin is also prone to flash floods, which were not included in our analysis. Due to unavailability of data, we did not conduct flood frequency analysis, neither did we estimate damage. Future research should therefore consider flood frequency and climate change, as well as potential damage resulting from exposure.

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