ASSESSMENT OF CLIMATE CHANGE IMPACTS ON EXTREME FLOODS AND LAND DEVELOPMENT IN THE KELANI RIVER BASIN, SRI LANKA

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Abstract:

This study focuses on the Kelani River Basin in Sri Lanka, which often experiences flooding owing to its geography and topography. This area is particularly at risk because it is close to Colombo, the capital city, and has considerable urban development. With the population expected to double in the next 20 years and the rapid urban growth in the lower basin, prioritizing flood defense in this area is crucial. This study proposes an approach to evaluate how rainfall may change in the future, addressing the limitations of current assessments of infrastructure development that rely on today's climate and land use pattern. It aims to determine flood exposure and potential risk using expected changes in rainfall patterns and land use. These findings suggest that heavy and prolonged rainfall events are expected to increase in the future, thereby increasing the risk of flooding. The study predicted that flooding is likely to worsen, with the percentage of buildings at risk of flooding possibly increasing by 25%, 33%, and 45% for 10-, 50-, and 100-year return periods, owing to climate change and changes in land use. These results provide valuable information for decision-making regarding the future use of land in river basins.

Keywords: Kelani River Basin (KRB); Climate change; land-use land cover (LULC); RRI flood simulation; land use planning

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INTRODUCTION

The Kelani River Basin, especially the lower region, faces annual flooding that impacts densely populated areas, including the city of Colombo. Covering 2340 Km^2, 35% of the area falls within the Colombo District, where the capital city is situated. Figure 1 shows a map of the Kelani River Basin. With a population of nearly three million, half of which is in the Colombo district, this represents approximately 12% of the country's total population.

The basin comprises two distinct topographical regions: a mountainous upper region and a flat coastal area. It can be divided into the Upper Kelani River Basin (UKRB) and the Lower Kalani River Basin (LKRB). The highest elevation in the river basin is 2500m above mean sea level (MSL). With annual rainfall ranging from 2500 to 5000 mm across the basin, the Kelani River Basin is classified as a wet-zone basin. The temperature of the upper basin varies between 15°C and 18°C, while the lower basin varies between 28°C and 30°C.

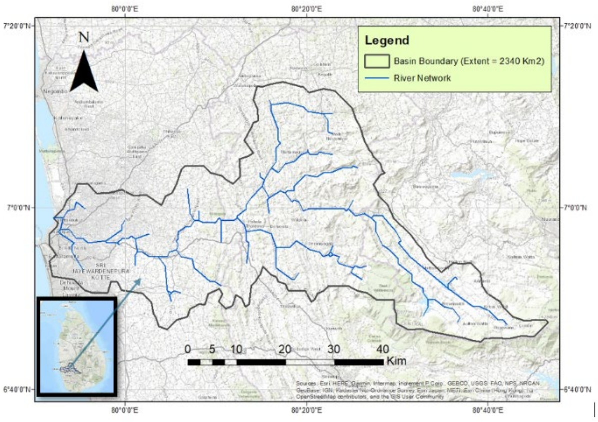


Figure 1. Basin and river network

Significant floods occurred in the Lower Kelani area in 1957, 1967, 1978, 1989, 2008, and 2016. The main causes of severe floods are high-intensity rainfall, rapid urbanization, and abrupt slope changes in rivers.

Despite ongoing development, there is a lack of comprehensive responses to the needs of the basin. Notably, land-use zoning maps and policy plans based on the comprehensive future flood response of the basin are lacking. Therefore, the current assessment of the impact of development is ad hoc. This often leads to the analysis of impacts based on individual development components without considering the entire basin. To effectively manage land use, it is crucial to evaluate a basin's flood behavior by considering future climate projections.

In this study, climate-projection data from general circulation models (GCMs) and a rainfall-runoff-inundation (RRI) model were used to assess the potential impact of floods under current and future climatic and land use land cover (LULC) conditions and to develop land use zoning maps to regulate future developments in the basin.

FRAMEWORK

The overall framework of this study is comprised of four key elements that will help achieve these objectives (Figure 2).

i.) Climate change analysis

Ground-based rainfall data from upstream and downstream gauging stations were used for the past climatology analysis. The innovative trend analysis (ITA) method of Sen (2017) was applied to examine the rainfall data series from 1980 to 2020.

The "Data Integration and Analysis System" (DIAS) was used to project future climatology, including GCM selection, bias correction, and downscaling. The data necessary for climate projection were obtained from the "Coupled Model Inter-Comparison Project-5" (CMIP-5).

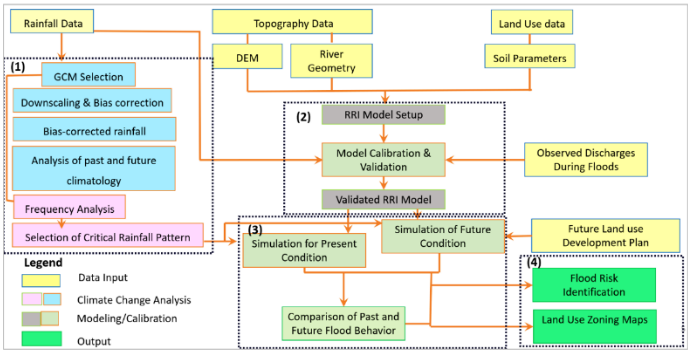


Figure 2. Methodology flowchart

Two time periods, namely, the near future (2025-2050) and mid-future (2050-2075), were chosen for the climatology projection. Three domains were selected based on Koike et al. 's (2014) approach. This approach used seven parameters to select the best GCMs for regional climatology. Future climatological analyses should also include innovative trend analyses.

ii.) Rainfall run off and inundation modeling

The RRI model was used to assess the flood behavior of the basin under past and future climate and land use/land cover (LULC) conditions. The rainfall runoff and inundation (RRI) model was employed for modeling run-off and inundation in this study. The RRI model simultaneously simulates rainfall runoff and inundation using a two-dimensional (2D) numerical simulation process (Sayama et al. 2015). The RRI model employs a 2D diffusive wave model to capture the flow on slopes and a 1D diffusive wave model to capture the flow on rivers. Additionally, the model simulated lateral subsurface flow and vertical infiltration using the Green Ampt Model. The model was calibrated using the 2016 extreme flood event, and validated using the 2017 event. The observed and modeled hydrographs were compared using the Nash–Sutcliffe efficiency (NSE), mean bias error (MBE), and root mean square error (RMSE).

iii.) Flood simulation for present and future conditions

The study involved fitting the basin in-situ and bias-corrected rainfall series from the GCMs to the Gumbel distribution to obtain past and future rainfall intensities for various return periods. Incremental factors obtained from the GCM-projected annual maximum rainfall were used. The findings of this study are based on extreme scenarios that represent the most adverse future conditions. Future flood responses corresponding to climate change effects were simulated with and without land use land cover (LULC) change. For future land use land cover (LULC), the RRI land cover was modified according to the National Physical Plan 2040 proposed by the National Physical Planning Department in 2019.

iv.) Inundation maps and land use zoning

Finally, land-use zoning maps were created considering factors such as inundation depth, occurrence probability, and expected damage level. Following this assessment, two land-use zones were identified: a land development restricted zone and land development regulated zone. These zones aim to regulate future land development and urbanization within the basin.

DATA

Daily rainfall data from 14 gauging stations (1980–2020) were obtained from the Meteorological Department. River discharge data for extreme events were obtained from the Irrigation Department. Building footprint data was downloaded from the Microsoft Global Building Footprint Database.

RESULTS AND DISCUSSION

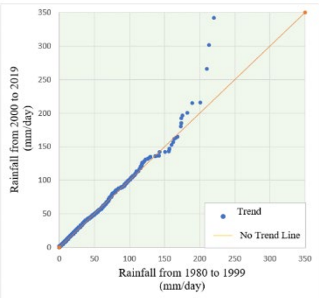


Figure 3. Past rainfall trend

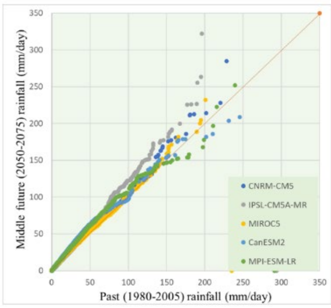


Figure 4. Future rainfall trend

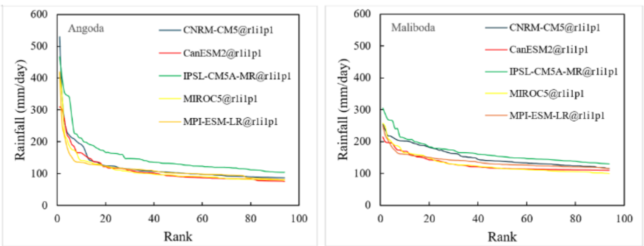


Figure 5. Future extreme rainfall variation (Left-Lower basin, Right-upper basin)

a.) Climate change analysis

An innovative analysis examining past rainfall trends indicated no distinct trend in low-intensity rainfall. However, the frequency of extreme rainfall events increased (Fig. 3). The GCMs MPI-ESM-LR, CanESM2, CNRM-CM5, IPSL-CM5A-MR, and MIROC5 were selected for downscaling and bias correction to represent the future climatology in the basin. Three of the models showed an increasing trend in intensity above 90 mm/d, except for CanESM2 and MPI-ESM-LR, as shown in Figure 4.

Significant increases in future extreme precipitation were observed at the Angoda station lower basin and the Maliboda station upper basin, as shown in Figure 5.

b.) RRI model calibration and validation

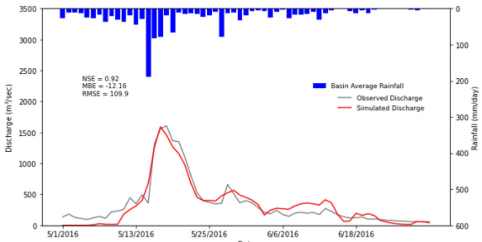


Figure 6. RRI model calibration results

The Rainfall Runoff Inundation (RRI) model was calibrated according to rainfall data between May and June 2016 and discharge data from the Hanwella River gauging station during the same extreme event. The model was calibrated until the simulated and measured discharges matched well, with a performance index of NSE = 0.92.

An extreme event that occurred in 2017 was selected for validation. When comparing the discharge for this event in May 2017, an NSE of 0.78 was obtained. In addition, the assessment of the extent of inundation for the extreme event in May 2016 yielded a fit value of 64.8%, indicating a reasonable fit between the observed and model-provided flood extents. Figures 6 and 7 show the corresponding hydrographs and inundation extent maps.

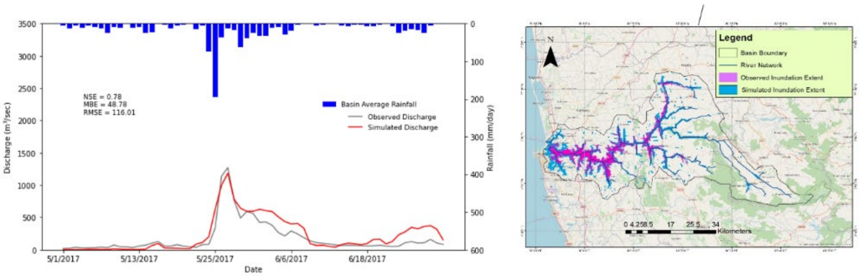


Figure 7. RRI model validation results
(Left- Hydrograph of 2017 extreme event, Right- Flood extent of 2016 extreme event)

c.) Flood behavior, and flood-exposed buildings according to future conditions of climate and land use

Rainfall intensities for various return periods were determined by conducting a frequency analysis. The average rainfall of the basin from the selected GCMs was utilized for this frequency analysis, and rainfall intensities for 10-year, 50-year, and 100-year return periods were obtained. Extreme increasing factors were then calculated and applied to represent future climate change and inundation maps. Table 1 summarizes the rainfall intensities for the different return periods and increasing factors.

Table 1. Increasing factors for future climate scenarios according to return periods

GCM/ Climatic scenario	10-year return period			25-year return period			50-year return period			100year return period		
	Past (mm/day)	Future (mm/day)	Increasing Factor	Past (mm/day)	Future (mm/day)	Increasing Factor	Past (mm/day)	Future (mm/day)	Increasing Factor	Past (mm/day)	Future (mm/day)	Increasing Factor
CNRM-CM5	194.5	246.1	1.27	224.6	295.4	1.32	247.0	332.04	1.34	269.1	368.4	1.37
IPSL-CM5A	199.8	243.0	1.22	236.4	284.8	1.20	263.6	315.8	1.20	290.5	346.5	1.19
MIROC-5	182.8	217.4	1.19	211.6	263.9	1.25	233.0	298.3	1.28	254.3	332.5	1.31
Scenario												
Mild			1.19			1.20			1.20			1.19
Average			1.22			1.26			1.27			1.29
Extreme			1.27			1.32			1.34			1.37

This study assessed the impacts of climate change and land use and land cover (LULC) changes on flood behavior in the Kelani River Basin. To simulate future floods, modifications were made to the RRI land cover data based on the future development plan of the National Physical Plan 2040 proposed by the National Physical Planning Department (NPPD). Figure 8 shows the current land use map and Figure 9 shows the future land use map utilized in the RRI model.

The changes in inundation depth and increment for the 10-, 50-, and 100-year return periods are illustrated in Figure 10, comparing past and future conditions.

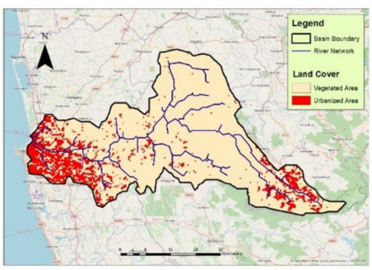


Figure 8. Current land use map

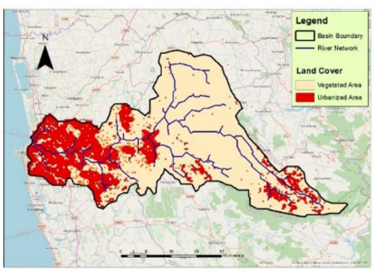


Figure 9. Future land use map

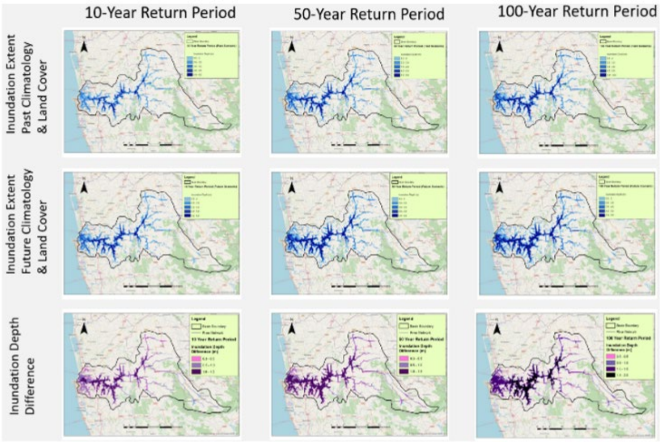
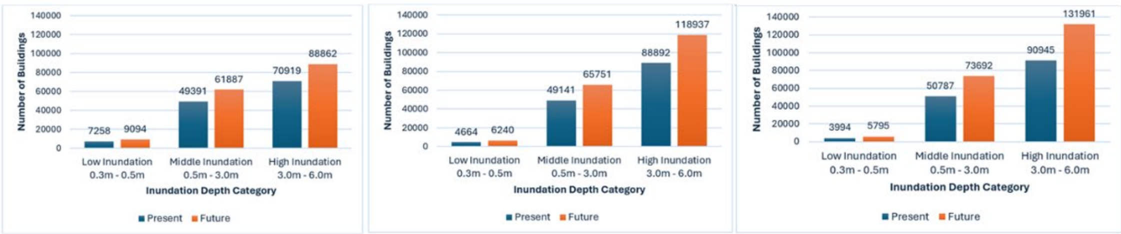


Figure 10. Inundation comparison of different scenarios

A notable increase in the inundation extent of 9.7, 13.9, and 16.3 km^2 for 10-, 50-, and 100-year return periods was observed when compared to the present and future land use conditions.

Further, flood-affected buildings were analyzed by classifying them into three categories (low, middle, and high inundation) based on present and future climate and LULC conditions. The bar charts in Figure 11 show the number of buildings affected in each inundation category. The flood damage to buildings is summarized in Table 2. The flood damage of buildings was projected to increase by 28.4%, 37.3%, and49.2% for 10-, 50-, and 100-year return period floods The flood damage to buildings will increase by 2446 million, 12436 million, and 22669 million LKR for the 10-, 50-, and 100-year return periods, respectively. These findings underscore the future flood vulnerability of the basin and emphasize the importance of reducing flood exposure through land-use zoning for future development.



10-Year Return Period 50-Year Return Period 100-Year Return Period

Figure 11. Flood-affected buildings of different scenarios

Table 2. Flood damage to the buildings

Return Period	Total Damage (Millions LKR)		Damage Increment (Millions LKR)
	Present	Future	
10 Year	8612	11058	2446
50 Year	33340	45776	12436
100 Year	46075	68744	22669

d.) Land use zoning according to flood risk assessment

This study highlights the possibility of severe floods in the future due to climate change and changes in land use and land cover in the river basin. Flood risk maps according to current and future climate and LULC conditions are shown in Figure 12.

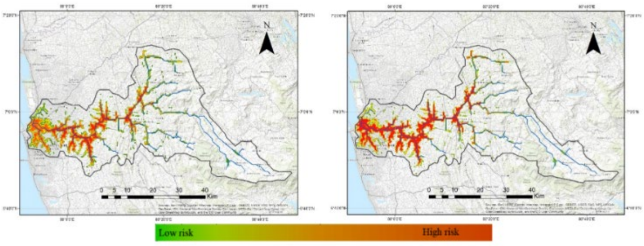


Figure 12. Flood risk maps (Left - Present climatic condition, Right – Future climatic condition)

According to the risk maps, flood risk will extend under future conditions to areas without flood risk. Land-use zoning is essential for implementing policies based on flood risk. Accordingly, future land development zones were classified into two categories:

The first zone, Land development restricted zone is defined as area in which expected inundation is over 3.0m for a 100-year return period flood based on future climatology. Activities such as reclamation of low-lying, marshy, and swampy lands are not allowed in this zone. Human settlement is also not allowed in this zone. However other high-priority urbanization activities are allowed under close supervision as the land cover changes are minimized. This zone can also be used for cultivation, recreational areas, and wetland parks. In contrast, this zone should be preserved as a flood retention area.

The other zone is the land development-regulated zone. In this zone, the expected inundation is over 0.5m for a 10-year return period flood based on future climatology. Developmental work is regulated in this zone. However, reclamation of marshy and swampy lands is still not allowed in this zone. Human settlements and other urbanization activities such as elevated roads, elevated buildings, and elevated houses can be allowed. Nevertheless, all the developments should be closely monitored by the relevant authorities. Additionally, this zone can be used for the development activities described under the land development restricted zone. These two zones are illustrated in Figure 13.

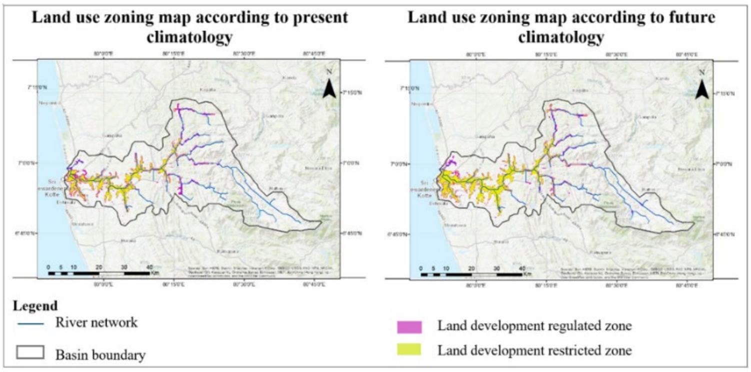


Figure 13. Land use zoning maps (Left-According to present climatology, Right-According to future climatology)

Implementing a land-use policy plan will be challenging, but integrating scientific, social, and economic aspects through an end-to-end approach can be much more effective in implementing a policy.

CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the impacts of climate change and land-use changes on flood behavior in an urbanized area. This study proposes a scientific approach to emphasize the necessity of land-use policies for basin management. The analysis revealed an increasing trend in high-intensity rainfall and predicted a higher frequency of future floods. Hydrological and hydrodynamic modeling successfully predicted the flows of the river basin, and future flood simulations indicated a significant increase in flood extent and depth. This study suggests the adoption of a land-use policy framework to preserve lowlands as flood retention areas to improve resilience against floods.

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