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DEVELOPING A MULTIVARIATE FLOOD RISK INDEX FOR THE KELANI AND KALU RIVER BASINS IN SRI LANKA USING FUZZY LOGIC

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In Sri Lanka, rapid urbanization in recent years has intensified flood risks in vulnerable areas. Since assessments based solely on climate change factors may reduce the accuracy of evaluations, this study develops a Multivariate Flood Risk Index (MFRI) using fuzzy logic, integrating both climate-related and land-use factors. As a case study, flood risk is evaluated in three regions Hanwella, Ratnapura Town, and Kalawellawa-Molkawa covering the Kelani and Kalu river basins, which experience recurrent annual flooding. The MFRI integrates hazard risk factors, Rainfall Intensity (RI), Rainfall Season (RS), and River Level (RL), which are considered for all three regions. Additionally, Soil Moisture (SM) is included for Hanwella, and Reservoir Dam Status (RD) is included for Kalawellawa-Molkawa. Population Density (PD) and Dependency Ratio (DR) are considered as vulnerability risk factors. The Linguistic Ordered Weighted Averaging (LOWA) operator computes the hazard risk, while the Mamdani Fuzzy Inference System (MFIS) assesses vulnerability. Final flood risk combines both hazard and vulnerability risks using LOWA, with factors categorized as Low, Medium, or High. Three linguistic quantifiers were tested, with the '*mean*' quantifier being the most effective. Analysis of five-year data revealed RI and RL as dominant hazard factors in Hanwella and Ratnapura, while RI, RL, and RD were most critical in Kalawellawa-Molkawa. Flood risk outputs indicated that high levels of RI and RL typically produced medium to high risk, while low levels led to consistently low risk. In the rainy season (on-season), even moderate levels of RI or RL were enough to trigger high risk, whereas in the off-season, both needed to exceed medium levels to yield comparable risk. Validation with the Irrigation Department's flood level data confirmed the model’s accuracy. The MFRI offers an adaptable framework for flood risk assessment, aiding targeted mitigation strategies in flood-prone regions.

Keywords: flood risk index, fuzzy logic, LOWA operator, hazard assessment, vulnerability

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INTRODUCTION

In recent years, population density and land use in Sri Lanka have changed significantly due to rapid urbanization. As a result, combined with the impacts of climate change, flood risk has increased in vulnerable regions. However, most existing flood risk assessment models focus mainly on climate factors, which may not fully capture these changes. Therefore, this study employs fuzzy logic to assess flood risk by integrating several climate-related and land use factors. Flood risk is assessed by combining hazard risk, the likelihood of flood occurrence, and vulnerability risk, the degree of societal impact. As a case study, the model is applied to the Kelani and Kalu river basins, which are prone to annual flooding and affect nearly 200,000 people during major flood events occurring every two to three years [1,2]. The resulting flood risk is categorized into three levels—low, medium, and high—for comparison purposes.

METHODOLOGY

The hazard risk factors considered in this study include rainfall, river, and soil-related variables. Rainfall factors comprise **Rainfall Intensity (mm/day)** and **Rainfall Season (on/off)**; river-related factors include **River Water Level (m)** and **Reservoir Dam Status (open/closed)**; and the soil-related factor is **Soil Moisture**, which represents the degree of soil saturation with water. Both Rainfall Season and Reservoir Dam Status are binary variables: the season is classified as on-season (March to November) or off-season (December to February), while the dam status is either open or closed. The vulnerability risk factors are **Population Density (PD)** and **Dependency Ratio (DR)**, the latter defined as the number of people under 20 years and over 55 years per 100 individuals in the total population.

The final Flood risk was obtained by integrating Hazard and Vulnerability risks, developed separately using the **Linguistic Ordered Weighted Aggregation (LOWA)** operator [3,4] for hazard assessment and the **Mamdani Fuzzy Inference System (MFIS)** [5] for vulnerability assessment, with integration performed through the LOWA operator. When applying the LOWA operator to assess Hazard Risk, three linguistic quantifiers—*mean*, *at least half*, and *most*—were used for analytical purposes. However, only the *mean* quantifier was employed when combining hazard risk and vulnerability risk. Figure 01 shows the flow chart of the methodology.

This study focuses on three regions: **Hanwella** in the Kelani River Basin, **Ratnapura Town,** and **Kalawellawa–Molkawa** in the Kalu River Basin. Table 01 presents the considered hazard and vulnerability factors for each area. The numerical data of these factors were categorized into three linguistic levels—Low, Medium, and High—using triangular and semi-trapezoidal fuzzy membership functions, as illustrated in Figure 02. Accordingly, hazard risk and vulnerability risk were obtained as Low, Medium, or High linguistic levels. Finally, hazard risk and vulnerability risk were combined using the LOWA operator to generate the final flood risk (Flood Risk Index), which classifies flood risk into three levels: Low, Medium, or High.

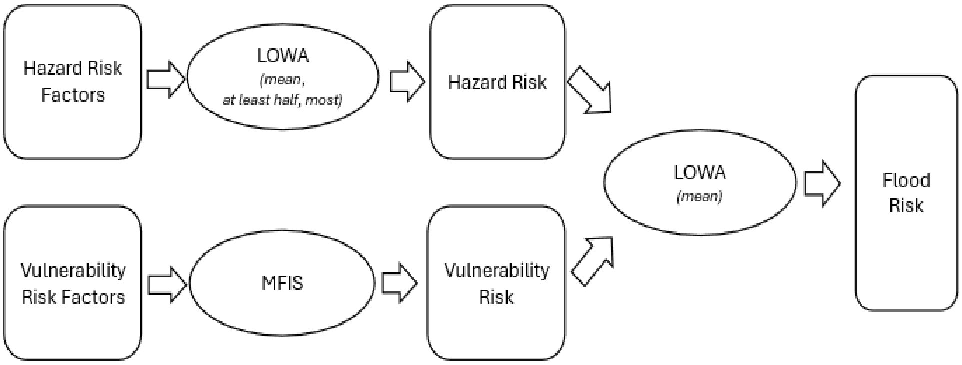

Figure 049: Flow chart of proposed methodology

Area	Hazard Factors	Vulnerability Factors
Hanwella	Rainfall Intensity (RI)	Population Density (PD)
	Rainfall Season (RS)	Dependency Ratio (DR)
	River Level (RL)	
	Soil Moisture (SM)	
Ratnapura Town	Rainfall Intensity (RI)	Population Density (PD)
	Rainfall Season (RS)	Dependency Ratio (DR)
	River Level (RL)	
Kalawellawa-Molkawa	Rainfall Intensity (RI)	Population Density (PD)
	Rainfall Season (RS)	Dependency Ratio (DR)
	River Level (RL)	
	Reservoir Dam Status (RD)	

Table 034: Hazard and vulnerability risk factors for each region.

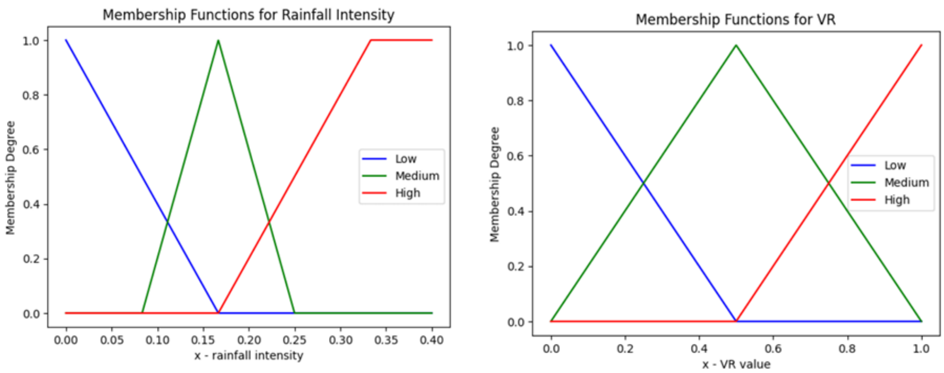

Figure 050: Membership functions for RI (input) and vulnerability risk (output)

RESULTS AND DISCUSSION

Daily data from the past five years has been used to calculate the Flood Risk (FR) for each area. To present the daily flood risk more clearly, the results are organized by season. As an example, Table 2 shows the flood risk for **Ratnapura Town** during the first 15 days of a selected on-season month, indicating the **linguistic quantifiers** used to assess the hazard risk. Additionally, daily flood level data issued by the Irrigation Department for each study region is provided for validation purposes. The flood level data includes four categories: **No Flood, Alert Level, Minor Flood,** and **Major Flood**. No Flood means no floods occurred, while 'Alert Level' signifies a heightened risk of flooding. 'Minor Flood' indicates a low-level flood event, and Major Flood' indicates a severe flood event.

As observed, the final Flood Risk calculated for all areas using the *mean* linguistic quantifier closely aligns with the flood level data used for validation. For Ratnapura and Hanwella, analysis of the risk output results from the past five years indicates that Rainfall Intensity (RI) and River Level (RL) are the most significant factors influencing flood risk. For the Kalawellawa-Molkawa area, analysis of the last five years' data shows that RI, RL, and Reservoir Dam Status (RD) are the most significant factors affecting flood risk.

The model results indicate that in all three study regions, during the off-season, both rainfall intensity (RI) and river level (RL) must exceed medium levels for the flood risk to rise to medium or high; otherwise, the risk remains low. In contrast, during the rainy season (on-season), even if only one of RI or RL reaches a medium level, it is sufficient to trigger a high flood risk, while low values in both maintain a low-risk outcome.

Date	Quantifier			Flood Level
	Most	Mean	At least half	
1/6/2024	medium	medium	high	No Flood
2/6/2024	low	medium	high	Minor Flood Level
3/6/2024	low	medium	high	Minor Flood Level
4/6/2024	low	medium	high	Alert Level
5/6/2024	low	medium	medium	No Flood
6/6/2024	low	medium	medium	No Flood
7/6/2024	low	low	medium	No Flood
8/6/2024	low	low	medium	No Flood
9/6/2024	low	low	medium	No Flood
10/6/2024	low	low	medium	No Flood
11/6/2024	low	low	medium	No Flood
12/6/2024	low	low	medium	No Flood
13/6/2024	low	low	medium	No Flood
14/6/2024	low	low	medium	No Flood
15/6/2024	low	low	medium	No Flood

Table 02: On-season; Ratnapura Flood Risk Levels for June 2024.

CONCLUSIONS/RECOMMENDATIONS

In the study areas, Rainfall Intensity (RI) and River Level (RL) were identified as the most significant risk factors. The final Flood Risk (FR) levels are determined based on the observed behavior of RI and RL, where flood risk increases when both exceed medium levels, with heightened sensitivity during the rainy season. Future studies could include additional region-specific risk factors to improve the accuracy of the Flood Risk Index. Triangular and trapezoidal membership functions were used to reduce computational complexity, though more advanced or adaptive functions could enhance precision. Fuzzy rules in the MFIS were defined without expert input; involving domain specialists in future work is recommended to further improve assessment quality and reliability.

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