INVESTIGATION OF RIVER-LAGOON-FLOOD NEXUS UNDER CLIMATE CHANGE:

THE CASE OF BATTICALOA LAGOON AND CONNECTED RIVER SYSTEM, SRI LANKA

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ABSTRACT

Lagoons encompass approximately 13% of the coastline worldwide. They are coastal reservoirs fed by rivers and serve as a natural system to mitigate flooding in coastal areas. However, torrential rainfall events could inundate a lagoon to its capacity, blocking outflow to the sea and causing rivers and lagoons to overflow, thereby exacerbating flood damage in nearby cities (e.g., the 2024 floods in Rio Grande do Sul, Brazil). Additionally, global warming may aggravate these damages because of more frequent and intense rainfall events in the future. Previous studies have mainly focused on rivers when studying floods, ignoring the feedback from the river–lagoon system because of its complex nature. This study proposes a framework to investigate the river–lagoon–flood nexus in the context of climate change in the Batticaloa Lagoon in eastern Sri Lanka. This research implemented an end-to-end (i.e., scientific, engineering, and economic) approach using climate model predictions, a hydrological (WEB-RRI) model, and the pressure and release (PAR) model to provide evidence-based information and suggest policy changes for sustainable disaster management in the Batticaloa district. The results revealed that total annual rainfall and 4-day extreme rainfall will increase under all RCP scenarios. The extreme flood situation will raise the lagoon water level by 0.64m in the future compared to the water extreme level in 2011. Creating new outlets and operating a new reservoir could lower the future lagoon level by 0.92m and reduce the impacted cropland by 3,560 hectares. Currently, no flood hazard map exists for the region or an identified authority for integrated river–lagoon system management. Implementation of the proposed mitigation measures and policy changes will promote sustainable development in the Batticaloa district.

Key Words: **Climate Change, WEB-RRI, Lagoon, Reservoir operation, PAR model**

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INTRODUCTION

Coastal lagoons are shallow water bodies partially or totally isolated from the open sea by natural or mechanical barriers but linked to the sea by one or more inlets. These natural ecosystems are most valuable for the fishing and aquaculture industries, attracting substantial human settlement along the lagoon. These natural systems receive water from rivers. The lagoon level remains constant for extended periods owing to discharge from natural or mechanical outlets. As a result of increasing rainfall and outflow limitations, the lagoons rapidly attain the maximum level, which creates a critical situation for nearby cities. The island nation of Sri Lanka is situated in the Indian Ocean near the Equator. Batticaloa, situated in the eastern part of Sri Lanka, is known for its lagoons. Currently, climate change-induced lagoon floods pose a serious threat to the area. This study aims to analyze the lagoon system alongside the major river basins that flow into the Batticaloa and Valaichennai lagoons as a combined system. The Batticaloa district is most severely impacted by floods, as evidenced by the 2011 flood that affected 31634 people (desinventar.lk).

Research on the individual river basins has not fully addressed the actual situation in the district. Human inhabitation is primarily along the lagoon—a crucial fact overlooked by previous studies. Therefore, combining the lagoon and river system study is significant to understand the actual flood situation in the area.

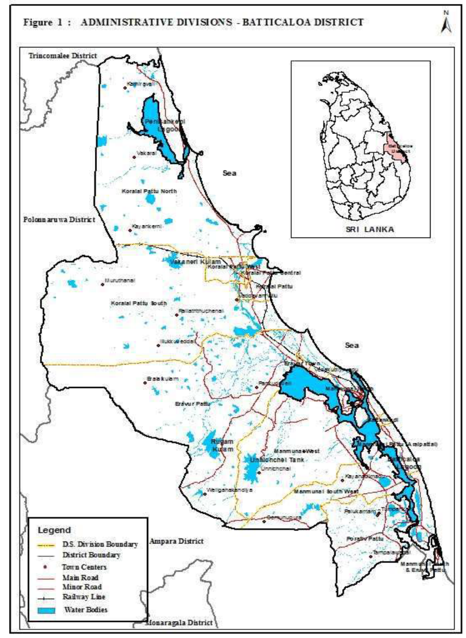

Figure 1: Batticaloa district

METHODOLOGY

This study conducted four main analyses to derive evidence for making policy recommendations. The first is climate analysis, where past data were analyzed to ascertain the actual trend of rainfall in the study area. GSM models were applied to predict future rainfall in the study area, and various scenarios of future predictions were proposed in the IPCC with different carbon emission scenarios. The best GSM model predicted for the study area was selected for future analysis. Past data of the model, along with the observed rainfall in the study area, were utilized for bias correction. The bias-corrected future prediction of the model was employed for future analysis. The Web-RRI Hydrological model was applied to model the study area and analyze the hydrological process in the lagoon and the river system as the second analysis. A digital elevation model (DEM) was created with individual river basins and lagoons. Future rainfall from the climate analysis was used for the future analysis, and the lagoon water level was obtained. As the study area is extremely shallow and tidal wave changes are insignificant around Sri Lanka, the WEB-RRI model is applied to the hydrological model (Rasmy *et al*.2019). Dam operation methods and

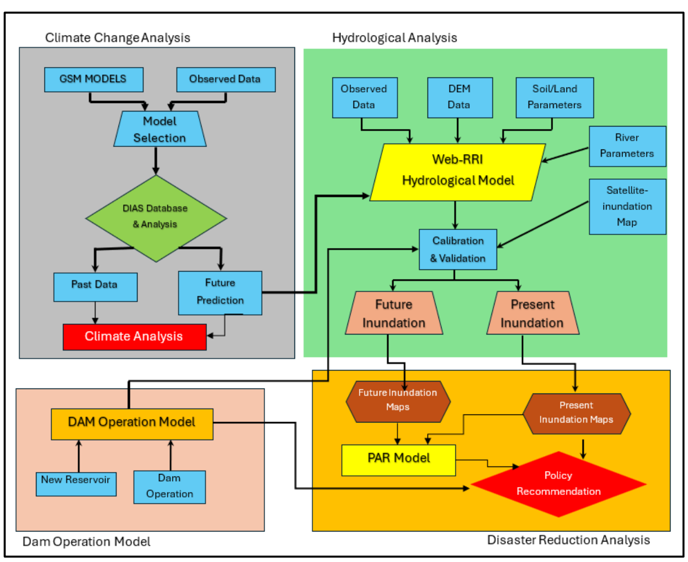

Figure 2: Research framework

lagoon operation were incorporated into the hydrological model as the third analysis. Additionally, new reservoirs, river basin diversion, and new lagoon outlets were included in the models, and the results were analyzed. The PAR model was created for the study area to identify the root cause of the unsafe situation as the final analysis. Root causes were identified using the PAR and Release models (Wisner et al.,2004). Based on these analyses, evidence-based policy recommendations were derived.

DATA

The climate analysis utilized the daily rainfall data from meteorological stations in Batticaloa, Ampara, Trincomalee, and Polonnaruwa. The river gauge data from the Mahaoya station in Mundeni Aru were employed for hydrological modeling. Additionally, the model relied on the digital elevation model from "Hydro SHEDS." The economic analysis employed the global land use data from the European Space Agency (ESA) and the global population data from the Copernicus Program.

RESULTS AND DISCUSSION

Climate change analysis

Rainfall observation indicates that annual rainfall has not significantly increased. However, extreme events (more than 70mm Daily rainfall) show an increasing trend. Additionally, 4-day total rainfall exhibits an increasing trend. Monthly total rainfall has not significantly changed.

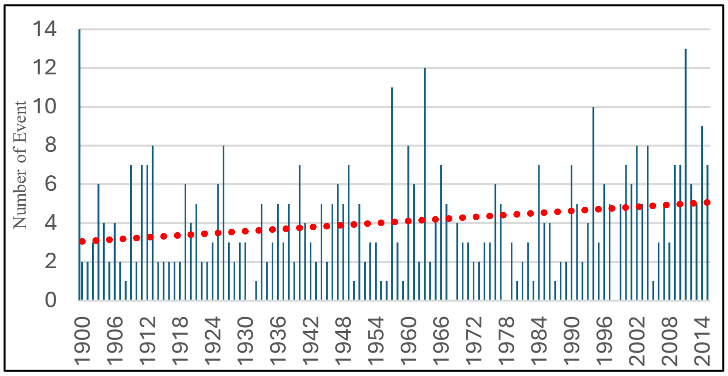

Figure 3: Extreme events from climate analysis

Future climate analysis

The analysis of past and future climate indicates that the annual total rainfall in the study area is projected to increase significantly in subsequent years. Additionally, extreme events—that is, more than 70mm daily rainfall—are expected to increase significantly in the future.

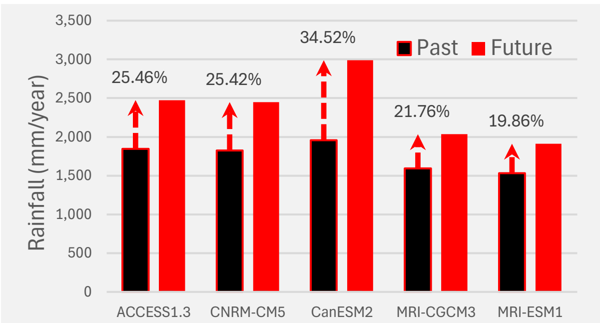

Figure 4: Annual rainfall from model

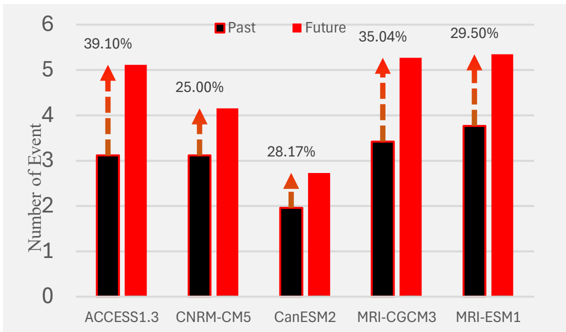

Figure 5: Extreme events from model

Future return period

The following scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) predict future events using models. The changes in extreme events in the future are calculated, and the coefficients of the return periods are as follows: RCP 2.6 shows a 3% increase, RCP 8.5 shows a 28% increase in the 100-year return period, and RCP 4.5 is predicted to decrease by 7% in the future.

3-day and 4-day total rainfall

The 3-day and 4-day total rainfall for RCP 2.6, RCP 4.5, and RCP 8.5 scenarios were calculated. RCP 8.5 showed an increase of more than 11% in all models. Conversely, RCP 4.5 indicated a decrease in the return period but a significant increase in 3-day and 4-day total rainfall in three models, with only two models showing a decreasing trend in the future for the RCP 4.5 scenario.

Hydrological modelling

The Web-RRI model prepared for the lagoon and river basin is shown in Figure 6. The 2011 flood event was used to calibrate and set parameters for NSE 0.751 and MBE -3.083. The same parameters were applied for the 2014 flood and inundation area used for validation.

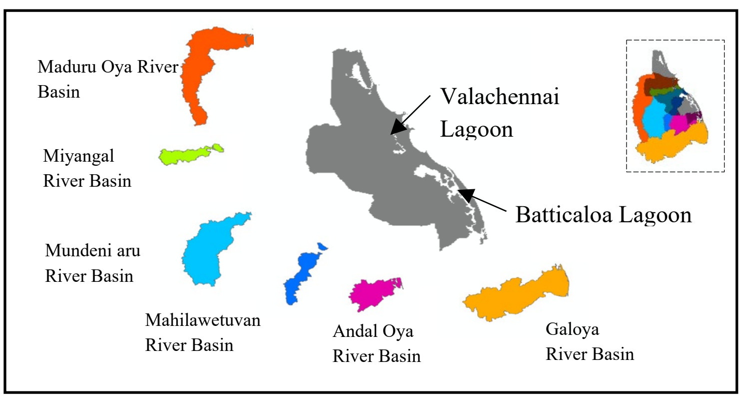

Figure 6: Hydrological model with six river basins with lagoon

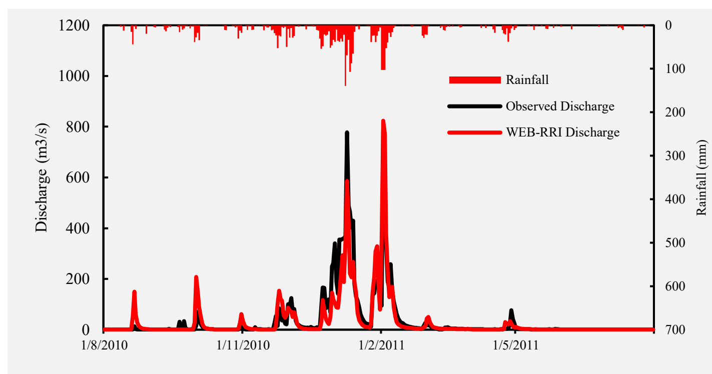

Figure 7: Calibration results from the model

Lagoon and reservoir operation

Three types of lagoon and river operations were tested to reduce flooding in the system. These include river diversion to adjust river basins, additional lagoon outlets, and reservoir operation or new reservoirs. Maduruoya and Galoya are the river systems in the northern and southern parts of the study area. A model was created by diverting 500m^3 and 800m^3 from the Maduruoya and Galoya Rivers, respectively, during the flood season. However, the lagoon water level did not significantly change. When two additional lagoon outlets were used, the model showed a 0.63m reduction in the peak lagoon level. Seven scenarios of reservoir operations were studied in the model, and the following reductions were observed in the peak lagoon level.

Table 1: Reservoir operation analysis and effect on lagoon water level

	Sennayaka (Galoya)	Maduruoya	Unnichchai	Navakiri	Rambukanoya	Rugam-Kithl	Mahaoya	Reduction in the Peak (m)
Case1	80 % full	80 % full	80 % full	80 % full	80 % full	Nil	Nil	**0.18**
Case2	50 % full	50% full	50% full	50% full	50% full	Nil	Nil	**0.39**
Case3	50% full	50% full	20% full	20% full	20% full	Nil	Nil	**0.53**
Case4	100% full	100% full	100% full	100% full	100% full	20% full	20% full	**0.13**
Case5	100% full	100% full	100% full	100% full	100% full	50% full	50% full	**0.08**
Case6	80 % full	80 % full	80 % full	80 % full	80 % full	50% full	50% full	**0.36**
Case7	80 % full	80 % full	50% full	50% full	50% full	20% full	20% full	**0.42**

Present and future flood analysis was performed based on the reservoir operation and additional lagoon mouth model. The more convenient options of Case 6 of the reservoir operation and the additional lagoon outlet were considered as future countermeasures for economic analysis.

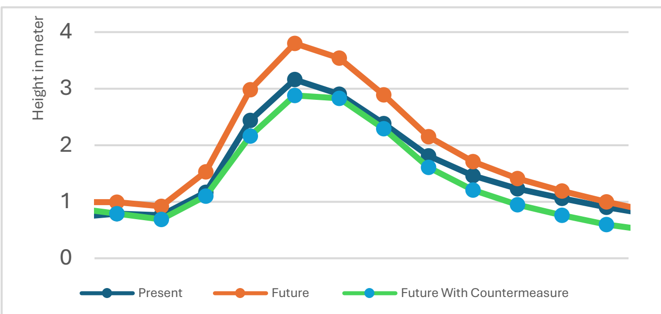

Figure 8: Lagoon level for present and future climate situations

Figure 8 illustrates that without any countermeasures, the lagoon water level is projected to increase from 3.16m to 3.8m in the future, which represents a 0.64m increase. However, by implementing countermeasures, we can reduce the future lagoon water level to 2.88m, resulting in a 0.92m reduction.

Disaster risk reduction

The analysis of the crop area indicates that future rainfall will lead to increased crop damage, from 43,456Ha to 55,210Ha. However, implementation of countermeasures could reduce the damage to 51,644 Ha. Additionally, the rural population will be significantly impacted by floods in the future, and the evacuation population is expected to increase by 232%. Specifically, village, town, and city evacuation will increase by 37%, 24%, and 11%, respectively. Overall, the evacuation population will increase by 73% in future flood events. Percentage of fully damaged buildings will increase by 64% in the future. Additionally, a flood map of the study area for the present and future was created, identifying a critical area. The water level in the lagoons near Kalmunai, Valaichennai, and Chenkalay will be more critical in the future.

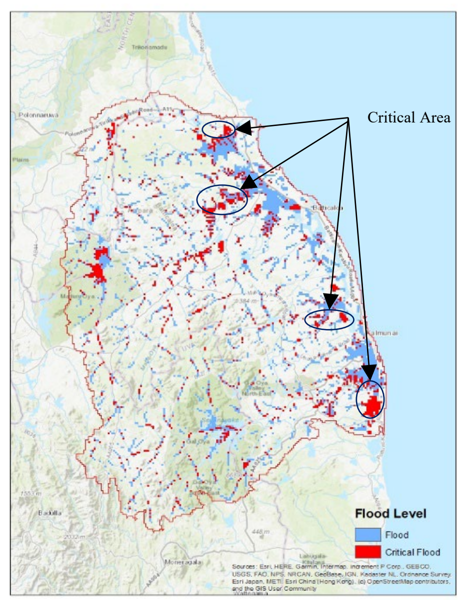

Figure 9: Future critical area for flood

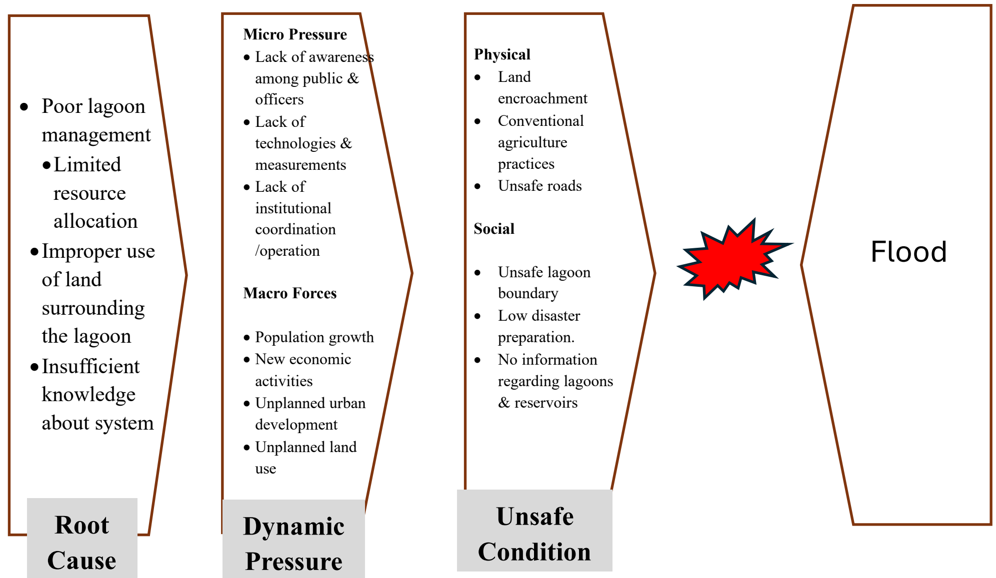

Figure 10: PAR model for the system

CONCLUSIONS AND RECOMMENDATIONS

The climate analysis explicitly indicates that the flood situation in the study area will exacerbate in all IPCC scenarios in the future. This will result in greater economic loss to the existing lagoon river system. Two additional lagoon outlets and reservoir operations could reduce the flood damage in urban areas. In addition to structural countermeasures, the following policy and soft measures should be implemented for sustainable development of the Batticaloa district:

- Establishing a new operating management entity for the lagoon and river system.
- Proposing a land use policy for considering the entire system as one system.
- Identifying critical areas from the model, prioritizing them for countermeasures implementation, and developing internal roads for better accessibility during floods.
- Creating a detailed model to produce highly accurate flood maps for each village, identifying unsafe areas and better escape routes for inhabitants.
- Educating the population and providing support for lagoon system research.
- Updating reservoir operation rules including flood retaining capacity.
- Improving rainfall predictions and creating more hydro metrological stations in the study area.

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