DEVELOPMENT OF INTEGRATED WATER RESOURCES MANAGEMENT FOR EASTERN DRY ZONE IN SRI LANKA UNDER CHANGING CLIMATE: THE CASE OF MUNDENI, MAGALAWADUWAN, AND ANDELLAOYA RIVER BASINS

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ABSTRACT

The eastern dry zone of Sri Lanka is susceptible to extreme floods and droughts due to climate variations, high-intensity rainfall, a lack of disaster preparedness, and a lack of a science-informed water resources management increase the vulnerability of the region to floods and droughts. This study has developed an end-to-end approach combining scientific, engineering, and socio-economic analyses to increase the confidence level in decision-making under climate change for sustainable Integrated Water Resources Management (IWRM) in the river basins. It was found that flood and drought conditions increased between 1991 and 2020 and are likely to increase in the future (2035-2060) under RCP8.5. The hydrological model was used to quantify the inflow conditions and to test the ability of dams and river widening to facilitate flood control and drought management for future scenarios, and the feasibility of enhancing the agricultural productivity of the basins. Compared to past observations, the river basins will experience more discharge in the future except in January. The water management model was developed using Dam Operation Model (DOM) and Crop Model (CM) to estimate the water budget during wet and dry seasons. Finally, policy implications are suggested in terms of disaster risk reduction and water management. This study provides evidence-based information regarding past and future climate, water resources, crops and cultivation patterns, and countermeasures for making decisions toward sustainable development.

Keywords: IWRM, DOM, climate change, productivity, sustainable development

INTRODUCTION

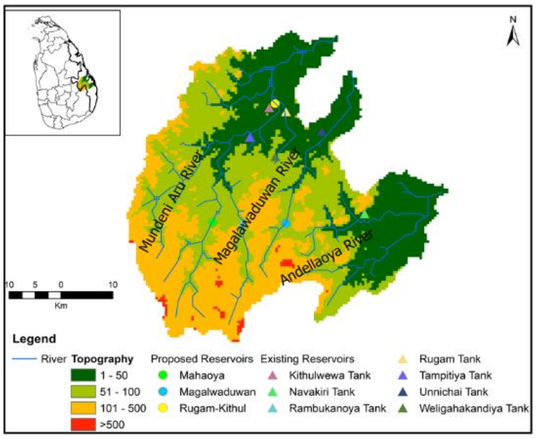

Figure 1. Location map

The dry zone covers 75% area of Sri Lanka. The zone receives an annual rainfall of between 1,200 mm and 1,750 mm. The economy is agriculture-based, contributing 5.8% to the National Gross Domestic Product (GDP). Approximately 27% of the national rice production is contributed by the eastern dry zone, where almost 47% of the population is predominantly engaged in cultivation. Floods and droughts are the most frequent and devastating disasters in the region, mainly due to the geographical location of the island and the tropical climate. As shown in Figure 1, the Mundeni, Magalawaduwan, and Andellaoya River basins are located in the eastern dry zone with a total catchment

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area of 2,193 sq. km. The annual average runoff to the sea is 1,421 MCM. The total storage capacity is 221 MCM, including the major, medium, and minor dams. These three river basins are the primary water resources in the Batticaloa district. Unnichchai is the largest dam in the district with a capacity of 68 MCM. The total available cultivable area is 26,370 ha within these basins. However, during the Yala cultivation in the dry season, only 60% (15,580 ha) of the total area can be irrigated from the dam storage due to water scarcity, and in the case of drought, the irrigation area decreases further. Ironically, the northeast monsoon causes rainfall in the wet season which may result in flood disasters. Both droughts and floods have resulted in severe damage to the socio-economic status of the people in the region. Significant flooding events occurred in 2011 and 2014. Recent droughts that occurred in 2016, and 2017 were recorded as severe drought years (FAO 2017). This study followed an end-to-end approach combining scientific, engineering, and socio-economic analyses by utilizing the latest science and technologies to reduce the climate model uncertainty arising due to coarse resolution and sensitivity by model selection and bias correction using the Data Integration and Analysis System of Japan (DIAS). Hydrological simulation also requires a reliable simulation of hydro-climatic variables. In this study, Water and Energy Budget-based Rainfall- Runoff- Inundation model (WEB-RRI) introduced a physical formulation using evapotranspiration fluxes, soil and vegetation interception, and soil moisture dynamics to sufficiently predict high and low flows.

THEORY AND METHODOLOGY

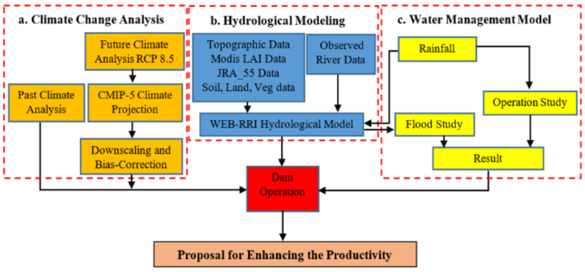

Figure 2. Methodology

The method used three main components (Figure 2): a) climate change analysis to understand the trends of climate signals in the past and future; b) hydrological modeling to study the hydrological responses of the basins for the past and future climate for effective decision making on IWRM; c) a water management model to study the water balance during wet and dry conditions in the basins.

a) Climate Change Analysis

Initially, the past observed 30-year climate records from 1991 were divided into two-time series 1991-2005 and 2006-2020 to identify climate trends respectively. Subsequently, the future climate was projected from 2035-2060 for understanding future hydro-climatic consistency using the Coupled Model Inter-comparison Project (CMIP5) in the DIAS tool. To increase the confidence level of the results, climate models were selected and statistically downscaled with bias correction by means of observed rainfall data from 1991 to 2016. GCMs evaluations were conducted based on key meteorological elements to represent reliable regional climate.

b) Hydrological Modeling

WEB-RRI hydrological model introduced by Rasmy et al. (2019) was used to study the hydrological responses of the basins. Observed rainfall data, elevation data, MODIS Leaf Area Index (LAI) and Photo-Synthetically Active Radiation (FPAR) data for dynamic vegetation, Japan Reanalysis incorporating 55 years of data, soil data, and land use data were prepared and used as input data for the model. The model was then calibrated and validated for each basin individually using the observed discharge data. Subsequently, Mean Bias Error (MBE), Root Mean Square Error (RMSE), and Nash-Sutcliffe Efficiency (NSE) were used as indices to evaluate the model performance.

c) Water Management Model

A water management model was developed to optimize flood control during the wet season and to optimize irrigation to enhance agricultural productivity in the dry season. It contains two sub-models namely, Dam Operation Model (DOM) and Crop Model (CM). The DOM was developed for all dams in the river basins to predict changes in dam storage during the flood. The inflow to the dams was estimated by WEB – RRI models for the past and future, whereas the outflow of the dams was quantified using the hydro data of the dams such as Full Supply Level (FSL), High Flood Level (HFL), Spill Crest Level (SCL), and sizes of the radial, sluice and scour gates. The CM was used to estimate the crop water requirements for different crops such as paddy, chili, green gram, soya bean, big onion, red onion, and ground nut and in different cultivation patterns.

DATA

Daily rainfall data for all three river basins were collected from both, Irrigation and Meteorological Departments. Thirty years of data were collected from the Meteorological Department for Batticaloa station and from the Department of Irrigation, the same 30 years of data were collected since 1991 for the other stations, Navakiri, Unnichchai, and Rugam.

RESULTS AND DISCUSSIONS

(a) Climate change analysis: Innovative Trend Analysis (ITA) was applied to analyze the trends and extreme rainfall for both time intervals in the past. The results for annual occurrences of rainy, wet, and dry days were then obtained. In this study, a day with a rainfall of more than 100 mm was considered a rainy day, and a day with a minimum of 1mm of rainfall was considered a wet day otherwise, it's a dry day. In addition, the wet and dry spells study consisted of short (0-5 days), medium (6-10 days), and long (more than 10 days) spells. Identical results were obtained for both time sequences except for long wet spells. The analyses indicated that; extreme rainfall (Figure 3) and medium wet spell increased, likewise dry days also increased. The results stated that, there was an increasing trend in flood and drought conditions in the past. After the bias correction, future rainfall data were analyzed as the same as the past analyses for selected five GCMs, (ACCESS1.3, CNRM-CM5, CanESM2, GFDL-ESM2G, and MPI-ESM-LR). The results revealed that; monthly average rainfall and extreme rainfall (Figure 4) will increase; rainfall will increase with the return period; the medium wet spell will increase; dry days (Figure 5) and the long dry spells (Figure 6) will increase. Thus, both past and future analyses highlight consistent results and indicate an increasing trend of floods and droughts.

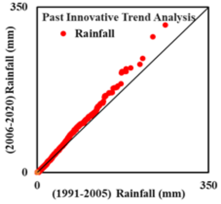

Figure 3. I TA for Past

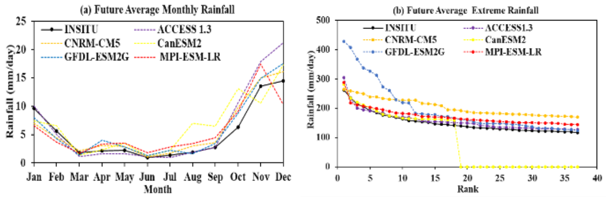

Figure 4. Future rainfall

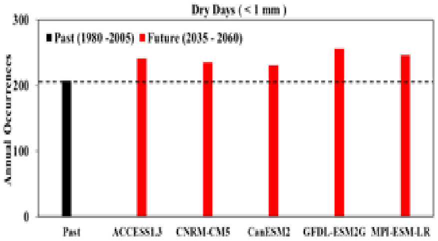

Figure 5. Dry days

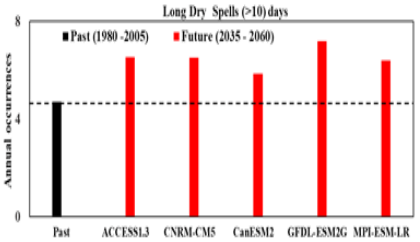

Figure 6. Long dry spells

(b) Hydrological modeling

As shown in figure 7, the observed daily discharges were compared to the WEB-RRI model simulated discharges for calibration of each river basin separately. The model was calibrated for the Mundini River basin at the Tempitiya discharge location using discharge data from 1992 to 1993. Also, the models were calibrated for the Magalawaduwan River at Unnichchai discharge location and the Andellaoya River at Navakiri discharge location using inflow data from 2014 to 2015. The three calibrated models satisfactorily represented the base flow and peak flood with NSE equal to 0.77, 0.86, and 0.85 for Mundeni River (a), Magalawaduwan River (b), and Andellaoya River (c), respectively. The calibration parameters were validated at the same discharge locations, and Model performance indices were obtained with acceptable values as shown in Figure 8.

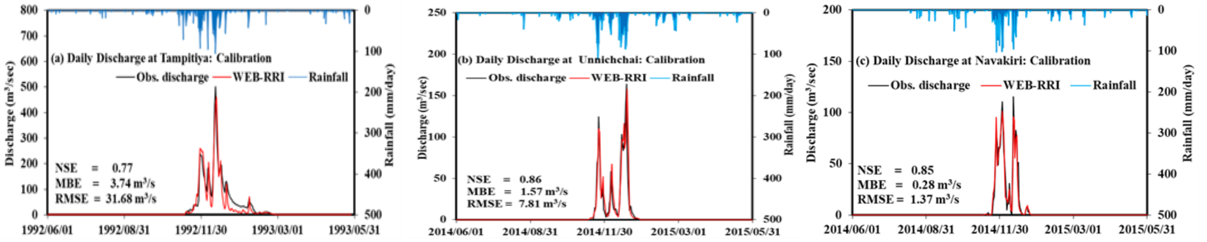

Figure 7. Calibrations of the WEB-RRI models

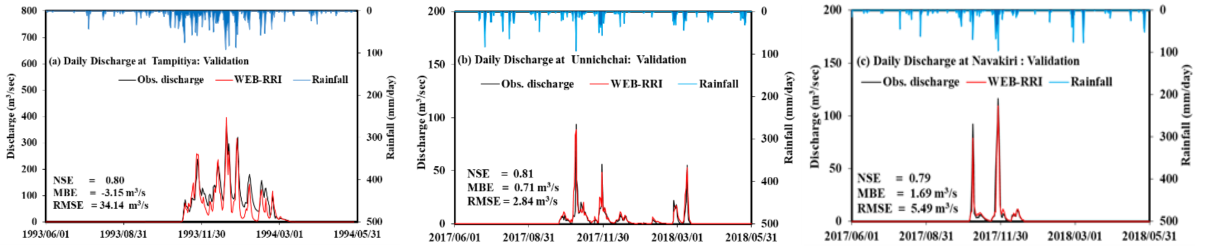

Figure 8. Validations of the WEB-RRI models

(c) Hydrological assessment for future river discharges: To understand the probable changes in past and future discharges in the river basins, trend analyses were performed based on past (1991-2016) and future (2035-2060) daily discharges according to GCMs output data.

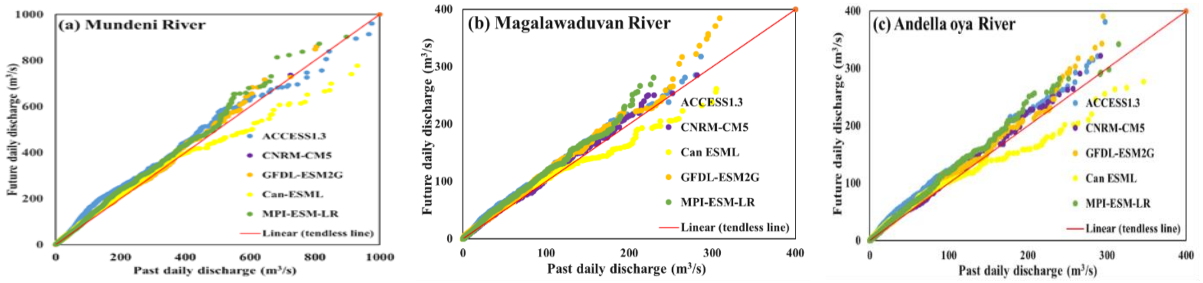

Figure 9. Trend analysis of past (1991-2016) vs future daily discharges (2035-2060)

An increasing trend in the future daily discharges in all river basins can be observed in Figure 9 for all GCMs, except Can ESML. The ACCESS1.3 model indicates a noticeable non-monotonic increasing trend in extreme discharge in the Mundeni River basin. The similarities in the assessment results of river basins predict that more discharge can be expected in the future. Figure 10 clearly demonstrates the climatological differences in the monthly discharges of three basins between the future (2035-2060) and past (1991-2016). The mean discharge from all GCMs indicates that all three basins will exhibit a higher discharge in the future between September and December, and a lower discharge in January, compared to the past with variability in the changes between GCMs. Historically, basins receive more rainfall from October to January with the effect of the northeast monsoon. Thus, the high discharge period in the future is likely to begin before October. These results positively support wet cultivation in October due to a sufficient supply of water for cultivation while reducing the risk of inundation during the harvesting period in January. However, countermeasures should be adapted to manage extreme flood events during wet seasons. The future increase in discharge from February to May represents an advantage for Yala cultivation during the dry season. Also, due to the increase in monthly discharge, it can be expected that all dams will be in full storage capacity prior to the dry season.

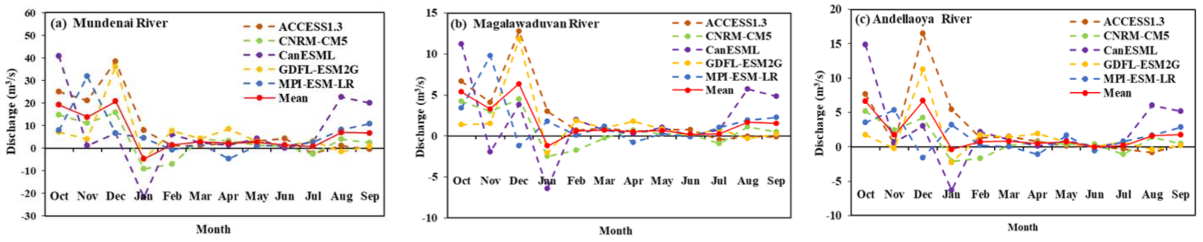

Figure 10. The climatological differences in monthly discharges of GCMs between future and past

(d) Dam optimization and countermeasures for future extreme climatic projection

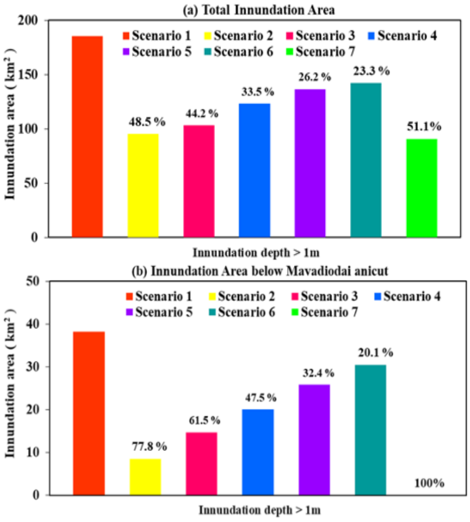

Figure 11. Probability of inundation area with depth greater than 1m

Extreme future discharge according to the climate model MPI- ESM-LR output data was used to optimize the dams operation for an extreme flood event. Existing dams, Unnichchai (68 MCM), Navakiri (65 MCM) and Rambukanoya (56 MCM) and proposed dams Mahaoya (80 MCM), Rugam-Kithul (58 MCM) and Magalawaduwan (58 MCM) were considered in this study. Figure 11 illustrates the probability of a flood inundation area with a depth greater than 1m for a projected extreme flood event in November-December 2035. Scenario 1 is modeled without the use of dams, and scenarios 2, 3,4,5 and 6 are based on dams with initial storage before the flood of 0%, 20%, 40%, 60% and 80% of the dam capacity respectively. The results revealed that the inundation area increased with an increase in dam storage. Dams showed a significant performance in downstream flood reduction when the dam storage was very low. Due to the uncertainty in the prediction and operational difficulties in conventional practices, it is not possible to significantly reduce dam storage prior to flooding. Maintaining at least 20% of storage capacity is also necessary for the ecosystem to function sustainably. Thus, scenario 6 was selected for the optimal dam condition similar to the present conventional practices during the monsoon season, and for more flood reduction, the river widening proposal was applied in scenario 7 by 30m. River widening was proposed from Mavadiodi anicut which is located in the Mundinai River below the proposed-Rugam Kithul dam. Scenario 7 expressed a successful reduction in the downstream inundation of the Mundenai river by widening from Mavadiodai anicut. This study proposes dam optimization and river widening due to the scarcity of suitable earth materials for the construction of levees and river dredging increases the risk of intrusion of high salinity water from Batticaloa Lagoon and the Indian Ocean.

(e) Analysis of cultivation (Yala) in the dry season: Three possible scenarios were analyzed to optimize the productivity of agriculture (Table 1). In scenario 1, cultivation starts on April 5th and the crop is pady as per present practices. For scenario 2 (changing cultivation calendar), cultivation starts on March 5th and the crop is paddy. For scenario 3 (introducing other field crops), cultivation starts on March 5th and the crops are 80% paddy and 20% other field crops as given in Table 1. The crop water requirement was computed for the maximum cultivable extent of 26,370 ha in the basins.

Table1.Crops details

Dams	Scenario 1	Scenario 2	Scenario 3						
	Paddy (ha)	Paddy (ha)	Paddy (ha)	Chili (ha)	Green gram (ha)	Soya bean (ha)	Big onion (ha)	Red onion (ha)	Ground nut (ha)
Unnichchai	6224	6224	5187	166	166	166	124	207	207
Navakiri	9544	9544	8714	166	166	166	124	124	83
Rugam-Kithul	6224	6224	4896	207	207	207	207	207	290
Mahaoya	3465	3465	1452	332	290	332	332	353	373
Rambukanoya	913	913	913	0	0	0	0	0	0

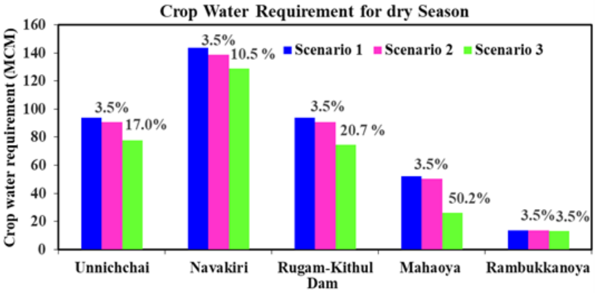

Figure 12. Crop water requirement for Yala season

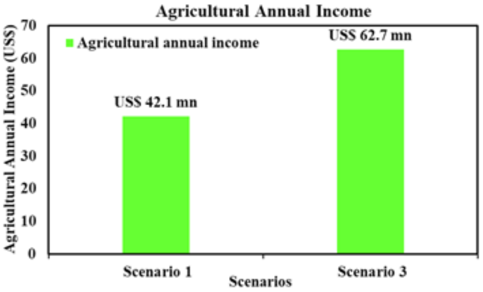

Figure 13. Agricultural annual income

According to Figure 12, the total crop water requirement was reduced by 3.5% and 19.2% in scenarios 2 and 3 respectively in comparison to scenario 1 in the basins. A minimum of 320 MCM crop water requirements are highlighted in scenario 3 and it is feasible to implement based on a planned future irrigation storage facility of 380 MCM in the basins. Also, in this study, the water balance computation considered only the storage capacity of the dams. It should be noted that, in addition to dam storage, river discharge and small streams also greatly contribute to water demand. Moreover, for successful IWRM a diversion channel is necessary to share water from the Mundeni River to other basins during cultivation in the dry season. Figure 13 indicates the agricultural benefit comparison between scenarios 1 and 3. In scenario 3, the annual economic benefit in the basin was increased by US$ 20.6 million.

(f) Policy Implication: Based on the findings of this study, the following policies are recommended for short-term implementation: 1) farmers in the basin areas should diversify their crops so as to increase economic gains and moderate the dry season water demand; 2) cultivation for the dry season should start from March instead of April; 3) real-time rainfall and discharge measuring gauges are essential for effective water management; 4) additional discharge control measures such as radial gates are also necessary to ensure the safety of the Navakiri dam. Long-term policies include, 1) structural countermeasures in the form of river widening and increasing storage capacity for effective flood management; 2) a diversion canal interconnecting the basins is ideal for water sharing; 3) an accurate weather prediction system is essential for successful future dam operations; 4) the spill tail canal capacity should be increased to accommodate future discharge requirements.

CONCLUSIONS & RECOMMENDATION

This study revealed that the main river basins in Batticaloa district will experience the impacts of floods and droughts in the future. Possible mitigation measures must be taken using evidence-based information through an end-to-end approach. Structural measures coupled with crop diversification and rescheduling the cultivation calendar of the dry season are the better options for reducing floods and managing the demand for water in the dry season which apparently increase the economic benefit of the farming community. Improving the dam operation system through the use of clear forecasting will reduce the inundation area. However, additional countermeasures are crucial to reduce the impact of flood disasters. Finally, this study also summarizes the essential policy implications based on the results to enhance the productivity of the basins by improving IWRM under climate change.

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