DEVELOPMENT OF AN INTEGRATED WATER RESOURCES MANAGEMENT PLAN INCORPORATING THE CLIMATE CHANGE IMPACT ON THE MALWATHU OYA BASIN, SRI LANKA

Ranapura Dewage Thilini Kaushalya*
MEE22725

Supervisor: Professor MOHAMAD Rasmy **
Professor KOIKE Toshio***
Professor FUKUI Hideo****

ABSTRACT

The Malwathu Oya Basin is the second largest river basin in Sri Lanka and is vital for the country's agricultural production and economic sustainability. This basin is prone to frequent flooding and droughts because of temporal and spatial climatic variations. Although some studies have individually examined the prevalent issues in this basin, this study holistically adopts an end-to-end approach encompassing climate change analysis, hydrological modeling, dam operational analysis, and disaster risk reduction assessment. Future climatic variations from 2050–2075 were explored through climate change analysis, considering the representative concentration pathway 8.5, and utilizing selected general circulation models (GCMs). These results imply that the basin will be more wetter in the future and vulnerable to extreme hydrometeorological disasters. A water energy budget-based rainfall-runoff inundation (WEB-RRI) model was developed to assess the basin's hydrological response. The model results suggest that the increased inundation extends downstream, indicating potential flood risks. Socioeconomic damage analysis was used to evaluate building and agricultural damage under extreme past and future conditions. Future projections indicate a significant increase in building and agricultural damage, necessitating proactive measures. The dam operational analysis focused on managing reservoir storage through pre-release and diversion strategies to transfer flood risks from urban areas and address flood and drought conditions. The research framework provides evidence-based information encompassing scientific, engineering, and socioeconomic assessments for developing the integrated water resource management (IWRM) plan to support policymakers in making informed decisions for sustainable water resource management in the Malwathu Oya Basin, emphasizing the urgency in adopting proactive measures for a more resilient and sustainable future.

Keywords: Climate change, flood and drought, WEB-RRI, dam operational management, IWRM

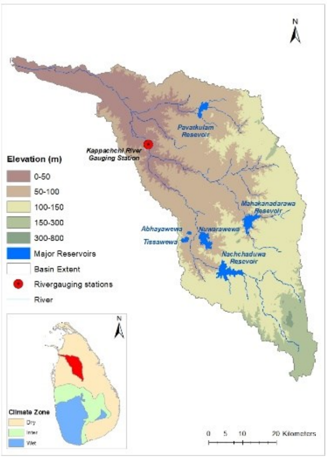

Figure 1: Malwathu Oya Basin.

INTRODUCTION

Malwathu Oya is the second-largest river basin in Sri Lanka, with a basin area of approximately 3,246 km^2, located in the dry zone, as depicted in Figure 1. It plays a vital role in the economy because of its significant contribution to the country's agricultural production. As a critical water resource in dry zone, it serves various purposes, including drinking, industry, irrigation, and environmental water supplies. However, despite the basin's well-established water resource system, frequent flooding and drought occur because of significant temporal and spatial variations in the annual climate. While several studies have been conducted that focused on specific regions of the Malwathu Oya Basin to address these issues individually, the need for a holistic approach covering the entire basin is recognized in this research. A conceptual framework is formulated to develop an integrated water resource management (IWRM) plan to

* Irrigation Engineer, Irrigation Department, Sri Lanka.
** Adjunct Professor GRIPS/ Senior Researcher, ICHARM
*** Executive Director of ICHARM/ Adjunct Professor GRIPS
**** Professor GRIPS

address flood and drought conditions subject to climate change in this basin to suggest proactive measures for creating future resilience.

THEORY AND METHODOLOGY

The research framework involves an end-to-end approach, encompassing various modeling and other assessments linking science, engineering, and socioeconomic considerations. This integrated approach provides evidence-based information that can support policymakers in making informed decisions and promote effective strategies for sustainable water resource management in the Malwathu Oya Basin. Figure 2 shows the overall research framework and methodology of this study, which is segmented into four main components.

(i) **Climate change analysis**: Appropriate general circulation models (GCMs) were selected to represent the regional climate of the Malwathu Oya Basin using global and observed climate data to generate future climate data through the downscaling and bias correction using past data.

(ii)**Hydrological modeling:** A hydrological model was developed to study the hydrological response of the basin using the water-energy budget-based rainfall runoff-inundation (WEB-RRI) software developed by Rasmy et al. (2019). Socioeconomic damage assessment and exposure assessments were conducted using model outputs to evaluate crop and building damage and flood-affected population concerning future and past extreme events.

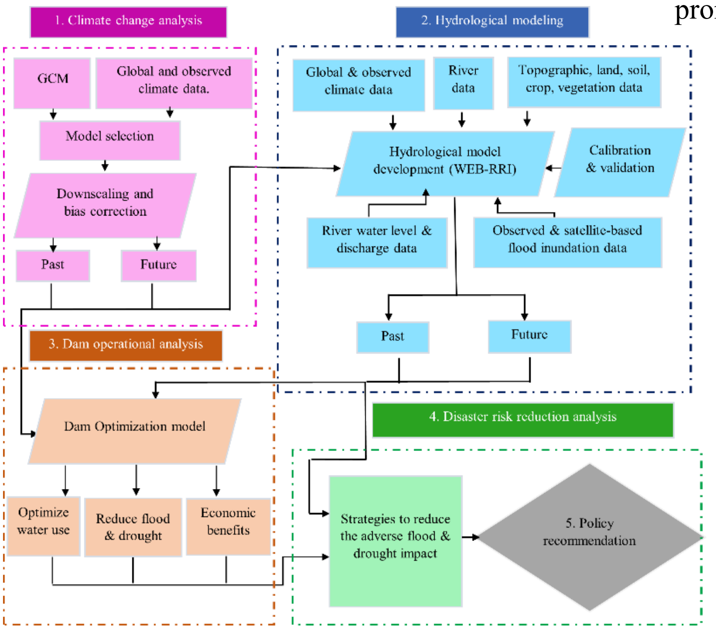

Figure 2: Research framework.

(iii) **Dam operational analysis**: A dam operational analysis was conducted to manage the Nachchaduwa reservoir storage, prioritizing flood and drought water management requirements while maximizing economic benefits. The ability to transfer flood risk to less-urbanized areas through flood bypass channels/tunnels was analyzed. A crop model was developed to identify suitable agricultural patterns during dry years for effective water management.

(iv) **Disaster risk reduction analysis:** A vulnerability assessment was conducted using the pressure and release (PAR) model (Wisner et al., 2004) to identify the root causes, dynamic pressures, and unsafe conditions prevailing in the Malwathu Oya Basin. Strategies for mitigating flood and drought impact were assessed based on the research findings and PAR model framework. Appropriate policy recommendations were suggested to support evidence-based decision-making.

DATA

Daily rainfall, discharge, flood inundation extent, land use, population, and economic data were obtained from the respective government organizations in Sri Lanka. The required topographic and global land-use data were obtained from the United States Geological Survey archives. The soil type distribution data were extracted from the Food and Agriculture Organization archives. Leaf area index and fraction of photosynthetically active radiation data were acquired from NASA's data archives. Atmospheric forcing inputs such as air temperature, wind speed, shortwave and longwave radiation, specific humidity, and surface pressure data were collected from Japanese 55-year reanalysis (JRA-55) data.

RESULTS AND DISCUSSION

(a) Climate change analysis: This analysis was conducted to study the variations in past and future climatology in the basin to assess the occurrence of extreme climatic events in the future period from 2050–2075. The ACCESS1.3, CMCC-CESM, CNRM-CM5, CanESM2, and GFDL-ESM2G GCMs were selected, downscaled, and bias-corrected to represent the Malwathu Oya Basin climatology. The climate change impact on mean annual and north east monsoon (NEM) rainfall was analyzed, as shown in Figure 3.

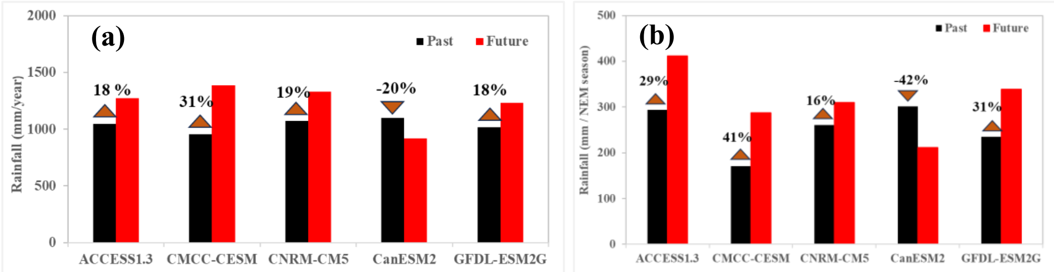

Figure 3: Past and future comparison of model-predicted basin average (a) annual rainfall and (b) seasonal rainfall.

A likely increasing trend in the future compared with the past is indicated by four models, except for the CanESM2 model. A comprehensive assessment was conducted to determine the reasons for this discrepancy by comparing the model outputs with the reanalysis products and conducting statistical and graphical analyses. Two significant variations were identified, as shown in Figure 4.

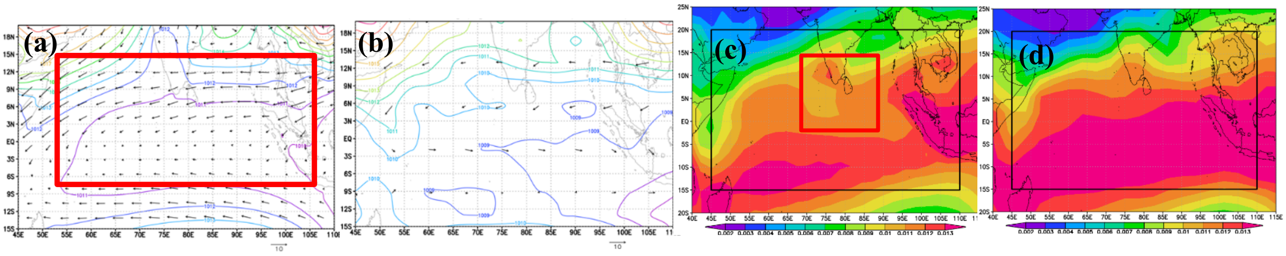

Figure 4: (a) wind vector abnormal variation during the NEM season predicted by ACCESS 1.3 (b) wind vector normal variation predicted by CMCC-CESM (c) future specific humidity reduction predicted by CanESM2 (d) future specific humidity increment predicted by CMCC-CESM.

The abnormal interpretation of NEM in the future can be attributed to the ACCESS 1.3 model when compared to other models. Compared with the reanalysis outputs and other models, a significantly reduced estimation of specific humidity and future rainfall was observed in the CanESM2 model. Variations in results can occur owing to variations in model parameterization and the uncertainties associated with each GCM. Therefore, considering the inability to reproduce the NEM wind vector and specific humidity correctly, the ACCESS 1.3 and CanESM2 models were excluded from the hydrological analysis.

Climate change effect on future rainfall extremes and droughts were assessed using four precipitation indices: the annual average occurrence of wet days, dry days, rainy days that exceed 50 mm of daily rainfall, and non-rainy days. The results are summarized in Table 1. In the future, an increase in medium and long wet spells and extreme rainfall events are likely to occur. The annual average occurrence of short, medium, and long dry spells shows a virtually certain increase in the future. By contrast, the annual average occurrence of non-rainy days is expected to decrease. This implies a reduction in frequent water shortages during the dry season and the occurrence of prolonged dry spells. These results imply that the Malwathu Oya Basin will face increased vulnerability to severe floods and reductions of water shortages in the future.

Table 1: Climate change effect on future rainfall extremes and droughts.

Annual average occurrence of climate indices	Level of confidence
Short wet spells	Likely decrease
Long and medium wet spells	Likely increase
Dry spells	Virtually certain
Extreme rainy days	Very likely increase
Non-rainy days	Very likely decrease

(b) Hydrological modeling: The WEB-RRI model was developed to analyze the Malwathu Oya Basin hydrological responses. The model was calibrated by considering the natural river flow conditions and dam operations of the Nachchaduwa and Mahakanadarawa reservoirs as the boundary conditions. The model was validated using observed discharges of the years 2008 and 2014. The inundation extent was validated using a ground-surveyed flood map of the 2011 event, yielding a critical success index of 0.782. The model showed good agreement with base and peak observed discharges and inundation extent, as shown in Figure 5.

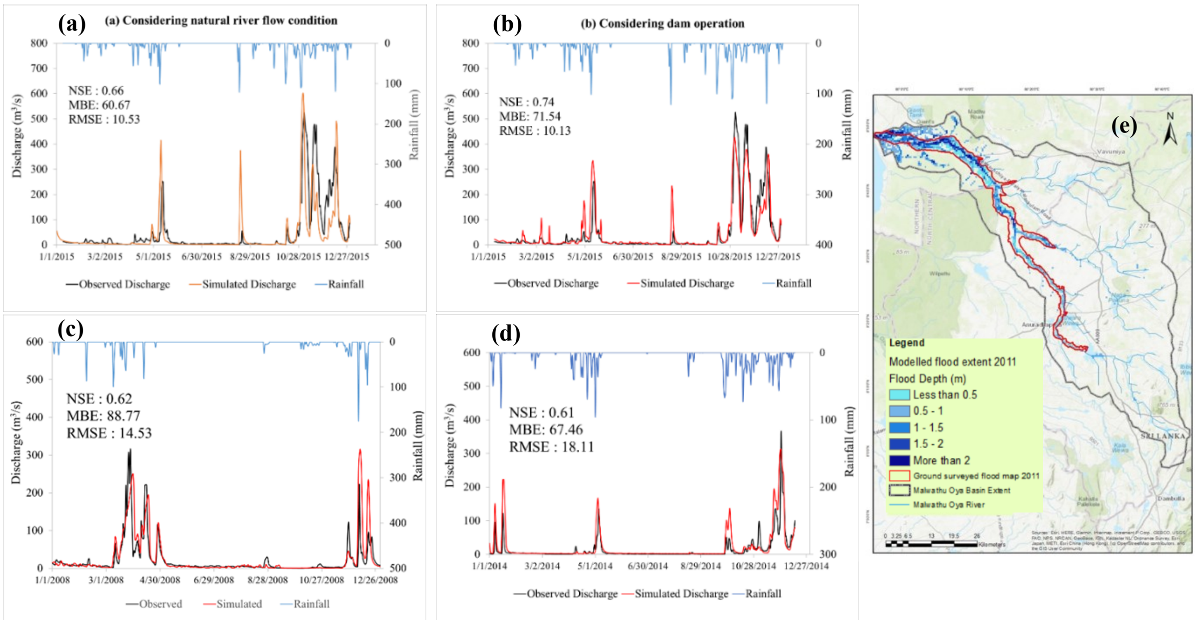

Figure 5: Comparison of observed and simulated discharges for (a) model calibration considering natural river flow conditions and (b) considering dam operations. (c and d) Model validation for years 2008 and 2014 (e) inundation validation using ground surveyed flood map for 2011 event.

The all-time maximum inundation depth produced by each GCM for the past and future extreme climates was derived from the WEB-RRI model, as shown in Figure 6. It was observed that all models predicted an increase in the future inundation extent, estimating 30% to 40% increment compared to that of past inundations.

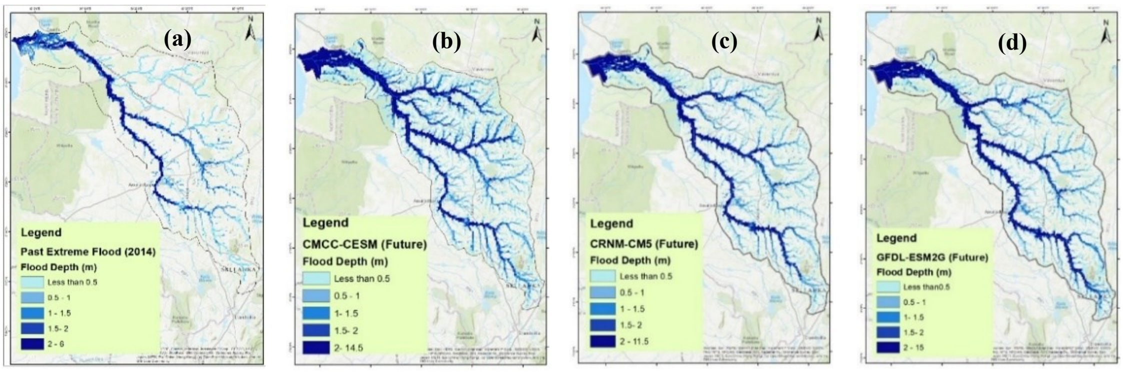

Figure 6: All-time maximum flood depth corresponding to (a) past extreme (b) CMCC-CESM (c) CRNM-CM5 (d) GFDL-ESM2G future scenarios.

(c) Socioeconomic damage analysis: Building and crop damage, and the corresponding economic losses were calculated using the all-time maximum flood depth for past and future extreme scenarios. Owing to the unavailability of future land-use changes, future damages were calculated based on the present data.

(i) Building damage assessment: Microsoft building footprints, damage factors, and the corresponding economic data were used to estimate building damage. Flood-affected buildings were classified as partially damaged if the flood depth was between 0.3 –3 m and fully damaged if the flood depth exceeded 3 m. Accordingly, the economic loss was calculated considering both building and content damage, and the results are shown in Table 2. The estimated losses (LKR Billion 1.41) were compared with the actual annual average flood damage (LKR Billion 1.48) (CRIP, 2019), revealing a favorable agreement. The projected building damage is expected to increase by an average factor of three under extreme future conditions. The GFDL-ESM2G model projected a maximum building damage of LKR Billion 6.64.

(ii) Agricultural damage assessment: Agricultural damage and the corresponding economic losses were assessed by conducting a similar analysis. The dominant crop type in the basin is paddy, which reaches the mid-growth stage during the flood season. The agricultural damage was classified as partially damaged if the flood depth was between 0.3–0.9 m and fully damaged if the flood depth exceeded 0.9 m. Accordingly, the economic losses were calculated, as shown in Table 2. A comparison is made between the annual average agricultural damage (CRIP, 2019) of LKR Billion 1.44 and the estimated past agricultural damage (LKR Billion 1.78). This demonstrates a reasonable agreement. Under extreme future conditions, projected agricultural damage is expected to double.

Table 2: Economic loss due to building and agricultural damage.

Scenario	Past	CRNM -CM5	CMCC -CESM	GFDL - ESM2G
Building damage				
Partial damage	1,964	7,298	6,601	9,111
Full damage	0	66	1,759	1,647
Loss (LKR Billion)	1.41	3.58	5.28	6.64
Agricultural damage				
Partially damaged area (km^2)	143	190	212	189
Fully damaged area (km^2)	132	249	331	284
Loss (LKR Billion)	1.78	2.97	3.74	3.25

(d) Dam operational analysis: Reservoir storage management for the Nachchaduwa reservoir was analyzed to develop balanced operations for addressing flood and drought conditions. The analysis was conducted for the 2014 flood event, considering the receipt of an accurate meteorological forecast three days before the extreme rainfall occurred. The developed reservoir storage management rule was based on reservoir storage pre-release from 0–100% in 20% increment levels before the flood event and refilling to the full supply level (FSL) after the flood event. Accordingly, five cases were analyzed, as shown in Table 3. This analysis suggests that considerable flood depth reduction, particularly in urban downstream areas, can be achieved when the pre-release quantity exceeds 60% of reservoir capacity. However, the developed reservoir operation is an ideological management scenario because of the uncertainty range associated with the quantitative information provided by rainfall forecasts. Therefore, it is necessary to quantify the uncertainties associated with rainfall and suitably incorporate them into reservoir operational analyses using weather forecast models.

Table 3: Reservoir pre-release analysis results.

Scenario	Pre-release as a % of reservoir capacity	Flood depth reduction (m)
Case 1	100%	0.84
Case 2	80%	0.57
Case 3	60%	0.37
Case 4	40%	0.20
Case 5	20%	0.05
Baseline (FSL)	0%	-

The possibility of diverting excess flood water to reduce urban flood risk was analyzed as a potential flood mitigation strategy. Two diversion scenarios were considered in the analysis: (i) 50 –100 m^3/s and (ii) 100 –150 m^3/s of water diverted from the Nachchaduwa reservoir, starting three days before the flood event. To facilitate this diversion strategy, it is necessary to improve the existing diversion infrastructure from Nachchduwa to the Nuwarawewa reservoir, and diverted water can be channeled back to the

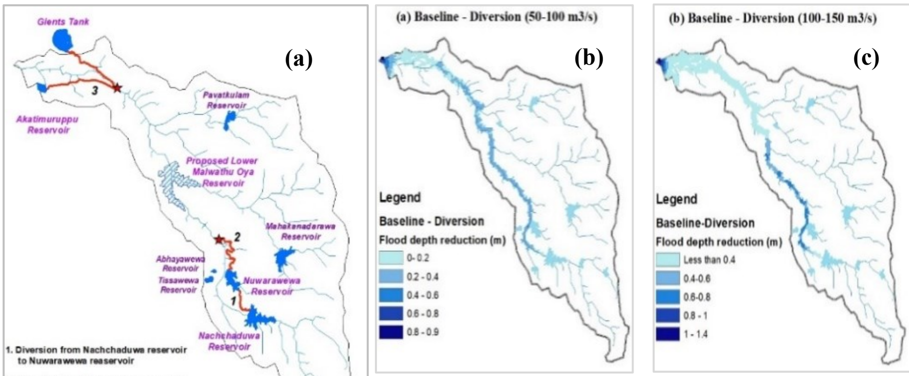

Figure 7: (a) Proposed diversion path (b) and (c) flood depth reduction corresponds to 50–100 m^3/s and 100–150 m^3/s diversion capacities.

Malwathu Oya Basin after passing the Anuradhapura city limits. The diverted and pre-released water can be stored in the proposed Lower Malwathu Oya multipurpose reservoir which is currently under construction. Furthermore, it is proposed that excess flood water be diverted into the Giants Tank and Akatimuruppu reservoirs in highly water-stressed regions. Therefore, the proposed diversion would contribute to the IWRM in this basin by enhancing the flood management system and supporting drought management. Flood depth reduction due to diversion was analyzed using the WEB-RRI model. It suggested that both diversion scenarios significantly reduce flood depth in downstream areas, attributed to a maximum flood depth reduction of 0.9 m for scenario 1 and 1.4 m for scenario 2. The proposed diversion paths and flood depth reductions corresponding to the two scenarios are shown in Figure 7.

(e) Water management assessment using a crop model: A crop model was developed to analyze suitable crop patterns during a dry year, considering the Nachchaduwa reservoir storage and irrigable area. The Maha cultivation season, which spans October to February, benefits from NEM rainfall. Thus, 100 % of paddy cultivation is possible during this season. The Yala cultivation season extends from April to July and usually suffers from a water deficiency during dry years. Thus, three probable options for changing the cultivation crop were analyzed: (i) 100% paddy, (ii) 100 % green gram, and (iii) 50 % paddy + 50% green gram. Accordingly, 100 % green gram cultivation is the most favorable crop pattern during dry years, generating an 11% increase in the economy compared to the usual paddy cultivation.

(f) Disaster risk assessment and policy recommendations: Based on the basin's socioeconomic conditions, a vulnerability assessment was conducted using the PAR model and relevant policies were suggested. The recommended policies are: 1) stakeholder collaboration for disaster management and decision making; 2) develop balanced reservoir operational rules to improve the current water resources system; 3) shift to modernized irrigation practices; 4) capacity and infrastructure development; 5) enact regulations to protect flood reservation zones and retarding areas; and 6) prepare and implement guidelines for disaster management.

CONCLUSIONS AND RECOMMENDATIONS

The Malwathu Oya Basin is important to Sri Lanka's agricultural and economic sustainability. This study gathered evidence-based information through an end-to-end approach that combined scientific, engineering, and socioeconomic assessments to formulate policy recommendations for IWRM. Climate change analysis projected an increased vulnerability of the basin to extreme future rainfall and prolonged dry periods. Hydrological modeling revealed a significant increase in future downstream inundation extent, indicating potential flood risks. Socioeconomic damage analysis demonstrated that building and agricultural damage is projected to rise substantially under extreme future conditions, necessitating proactive measures. Dam operational analysis proposes reservoir storage management strategies to address flood and drought conditions by pre-releasing and diverting excess floodwater to less urbanized areas to reduce flood risk, while effectively utilizing diverted water in water-stressed areas. Furthermore, assessing suitable crop patterns during dry years emphasizes the importance of adaptive water management practices for agricultural sustainability. Finally, this study outlines vital policy implications derived from the research findings, aiming to strengthen climate change mitigation and adaptation measures and enhance IWRM in the Malwathu Oya Basin. By implementing these policy recommendations, the Malwathu Oya Basin can enhance its water resource management capabilities, adapt to climate change challenges, and achieve a more resilient and sustainable future.

ACKNOWLEDGEMENTS

I wish to express my heartfelt appreciation to Professor Mohamad Rasmy and Professor Toshio Koike for their invaluable advice, guidance, and exceptional supervision throughout my Master's degree program.

REFERENCES

CRIP. (2019). *Flood and Drought Risk Assessment for the Malwathu Oya Basin - Volume 1*.

Rasmy, M., Sayama, T., & Koike, T. (2019). Development of water and energy Budget-based Rainfall-Runoff-Inundation model (WEB-RRI) and its verification in the Kalu and Mundeni River Basins, Sri Lanka. *Journal of Hydrology*, *579*. *https://doi.org/10.1016/j.jhydrol.2019.124163*

Wisner, B., Blaikie, P., Cannon, T., & Davis, I. (2004). AT RISK. In *AT RISK*. Taylor & Francis. https://doi.org/10.4324/9780203428764