A STUDY ON CLIMATE CHANGE IMPACTS ON EXTREME RAINFALL AND FLOOD EVENTS IN THE KALU RIVER BASIN, SRI LANKA

ARUNA Samarathunga[1]
MEE21731

Supervisors:
Prof. RASMY Mohamed[2]
Prof. KOIKE Toshio[3]
Prof. SUGAHARA Masaru[4]

ABSTRACT

Frequent flooding in the Kalu River basin causes numerous damages to lives and properties every year. Though there are several flood mitigation proposals, none of them has been implemented to date. High-intensity and frequent rainfall enhanced by global warming, rapid development, lack of evidence-based information, and absence of disaster mitigation plans are expected to boost the severity of these damages in manifold and additional pressures to sustainable development of the region. This study investigated the climate change impacts on extreme rainfall and flood events using *in-situ*, selected, and bias-corrected General Circulation Models' (GCM) outputs and rainfall-runoff-inundation model in the Kalu River basin, Sri Lanka. The results showed that the annual (13%–26%) and extreme rainfall intensity (53%–62%) will increase in the mid (2050–2075) and far (2075–2100) futures. The results coincided with the recorded increasing climate signals of extreme rainfall. The well-calibrated and validated hydrological model was used to drive the basin responses to projected rainfall from GCMs. The results showed that the flood discharge may increase by 20%–30% and the flood water levels in the far future may rise by 1.5m, compared to that in the past (1980–2005). The simulation of proposed dry dams as flood mitigation measures showed that they can reduce the flood inundation area by ~16%. The evidence-based information obtained in this study can support the preparation of future flood mitigation measures and decision-making for the sustainable development of the basin.

Key Words: Climate Change, Kalu River, Extreme Rainfall, Flood Mitigation

1. INTRODUCTION

The floods in the Kalu River have caused many deaths and millions of dollars' worth of damage. Major floods occurred in 2003 and 2017. In 2017, the flooding caused 86 deaths and affected 60,080 people. Damage to homes, schools, public buildings, roads, irrigation systems, and businesses that costed over 10 billion dollars (Disaster Management Center, Sri Lanka). In the current state, no structural or non-structural countermeasures have been implemented for controlling or mitigating these floods in the basin, except for water-level-based early warning for the upstream area (www.rivernet.lk).

In the past, the Kalu River basin has been studied for flood management and water use for hydropower and irrigation (Table 1). In these studies, the feasibility of building a dam upstream of Ratnapura town at Malwala was investigated for hydropower generation, irrigation water supplies, flood management, water storage, and

Table 1: Past Flood Mitigation Proposals

Year, Study done;	Proposals
1968, ECI, Engineering Consultants, Inc, USA	Multi-purpose Kukule Dam, 1850 MCM
	Multi-purpose Ratnapura Dam, 308MCM
	A Levee, 55Km
1989, TAMS Consultants, Binnie & Partners, and CECB-Sri Lanka	Single purpose hydropower Ratnapura Dam, 505MCM
	Multi-purpose scheme on the Kukule River, 400MCM
1999, Gezhouba Construction, China	Ratnapura Dam Project, 500MCM
2004, Irrigation Department, Sri Lanka	Ratnapura Dam, 278 MCM
2009, JICA Study, Japan	Ratnapura Dam, 278 MCM
	Flood Bunt, 62Km
	Levee at Ratnapura, 13Km
	Bypass at Ratnapura, 9Km
2014, TAHAL Group, Netherlands	Ratnapura Dry Dam I, 115MCM
	Dela Dry Dam II, 66MCM
	Dela Dry Dam III, 66MCM

[1] Civil Engineer, Irrigation Department, Sri Lanka
[2] Adjunct Professor, GRIPS (Senior Researcher, ICHARM)
[3] Adjunct Professor, GRIPS (Executive Director, ICHARM)
[4] Professor, GRIPS

inter-basin water transfer. It was hypothesized that a large dam at Malwala would be a successful flood control strategy. However, due to several political and economic reasons, the proposal had been changing over time and finally, a dry dam system (Ratnapura I, Dela II, and Dela III) was proposed as a structural flood countermeasure (Table 1).

Moreover, climate change is likely to speed up the water cycle as high temperatures due to global warming increase the rate of water evaporation worldwide. As a result, it is expected to increase floods, reduce lead time, and increase the vulnerability to extreme events in the basin. Previous studies in the basin have not investigated the climate change impacts on extreme rainfall and flooding conditions. Therefore, obtaining evidence-based information for the future climate projections and their impacts on extreme floods to understand the future risk is very important at this time, for sound policy making and developing plans for Disaster Risk Reduction (DRR).

Therefore, this study aimed to obtain evidence-based information from past and future climate model outputs. In addition, this study investigated the effects of three dry dams on the Kalu River floods as proposed by the Irrigation Department as one of the flood mitigation measures, especially to protect the upstream urban area (Ratnapura). However, there are two major challenges when using General Circulation Models' (GCM) outputs for assessments of basin-scale climate change impact. GCM outputs cannot be used directly in basin-scale assessment due to coarse spatial resolution and the model's climate sensitivity to global warming scenarios may vary depending on the type of model. This study used Data Integration and Analysis System (DIAS) to address these two issues and chose three models with better regional performances and bias-corrected GCM outputs to reduce biases due to coarse resolution. Furthermore, this study used the water and energy budget rainfall-runoff inundation (WEB-RRI) model to simulate peak discharges and inundation seamlessly for different climate models outputs for the future climate.

2. THEORY AND METHODOLOGY

The subparagraphs listed below illustrate Figure 1, which consists of four primary sections.

2.1. Assessment of past climate conditions for rainfall

Rainfall (Figure 2) and flow data from 1980 to 2015, were taken into account. These hydro-meteorological data were evaluated for climate-related indicators.

2.2. Assessment of future climate conditions for rainfall

The future climate was analyzed using the Coupled Model Inter-comparison Project Phase 5 (CMIP-5) and precipitation data from 1980 to 2005 was used for bias-correction and downscaling of far future climate projections using the DIAS climate change prediction tool. Using performance indicators based on their capacity to simulate regional climate, GCM models were chosen for the study area based on their competence to simulate regional climate (Koike et al., 2014).

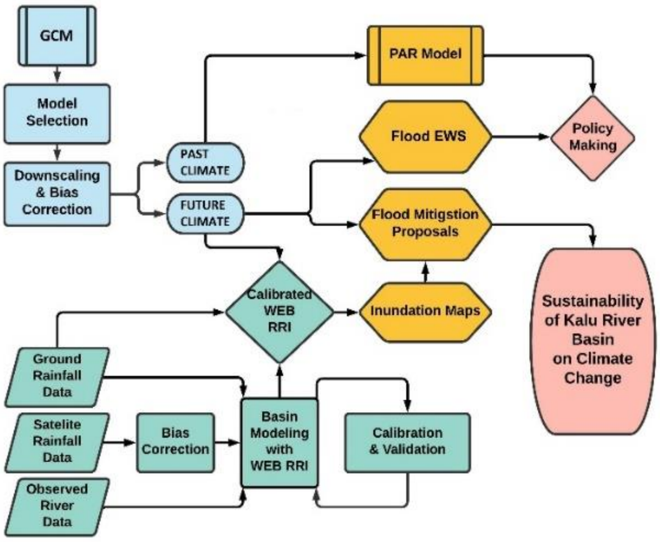

Figure 1: Flow Chart of Methodology

2.3. Hydrological modeling (WEB-RRI)

WEB-RRI modeled basin-scale hydrological responses to past and future climatic conditions. WEB-RRI is an enhanced version of the RRI model that is more suitable for river management. Topography, MODIS LAI and FPAR satellite data, Japanese 55-year Reanalysis, soil, land use, vegetation, and precipitation data were used to set up the model. WEB-RRI can identify low flow, flood onset, peak discharge, and inundation (Rasmy et al., 2019).

2.4. Assessments of the influence of climate change on flood prevention proposals

To prevent flood inundation in the basin, effective structural solutions for flood mitigation and flood control management are required. The findings of the model were used to investigate the feasibility of dry dam operations taking into account the effects of climate change on the management of water-related disasters.

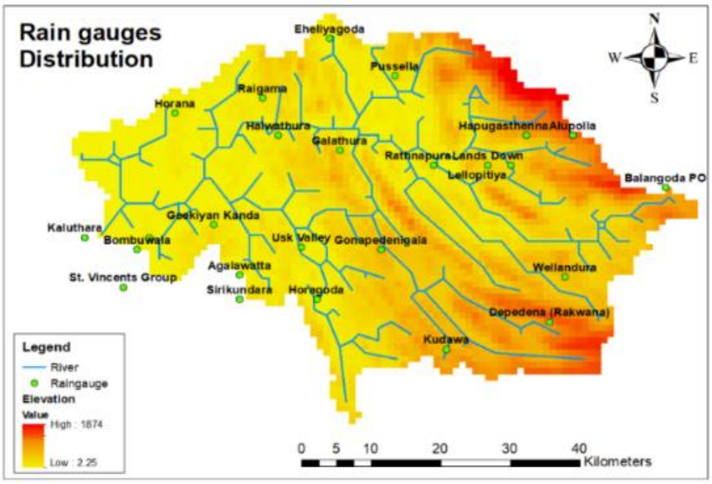

Figure 2: Rain Gauges Distribution Map of Kalu River, Sri Lanka

3. STUDY AREA & DATA AVAILABILITY

Daily rainfall data (1980–2015) from 25 rain gauging stations located within the Kalu River catchment were used in this study. Figure 2 depicts the spatial distribution of these stations. They were reviewed for correctness before being used in the analysis. Visual detection is used for the initial rough screening. It was verified whether the observations were consistently or mistakenly linked to the incorrect day, whether they contained serious errors, or whether the decimal points were missing. Gaps in the availability of data in years that had less than 365 days were noted. Gaps were filled up by the closest station.

4. RESULTS AND DISCUSSION

4.1. Past Climatology Analysis

4.1.1. Wet Spells

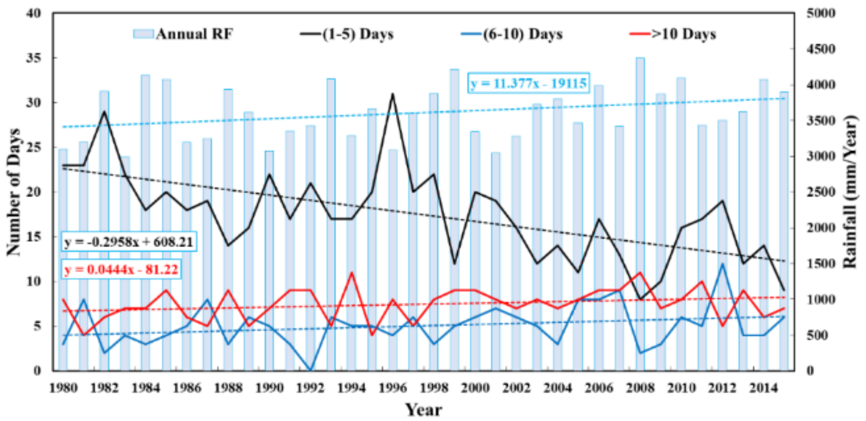

Figure 3: Basin Average Wet Spells

As depicted in Figure 3 (based on data from 25 stations), the average trend for short wet spells (1–5 days) has been falling over the past 36 years, whereas the average trend for medium and long wet spells has been rising. Meanwhile, Thiessen polygon's average precipitation over the Kalu River basin has increased significantly over the past 36 years (1980–2015).

4.1.2. Innovative Trend Analysis

The Innovative Trend Analysis was utilized to examine the climatic trends of the past by analyzing the change in precipitation at two equal, consecutive historical scales (Sen, Z., 2017). Figure 4 shows that over the last 36 years, precipitation of more than 100 mm has been increasingly common. The pattern of precipitation throughout the far past (1980–1997) and near past (1998–2015) periods is illustrated by trend analysis. The analysis revealed that there was no significant variance in the pattern between the two time periods. However, the increasing pattern of heavy rainfall events during the last decade signals major flood damage.

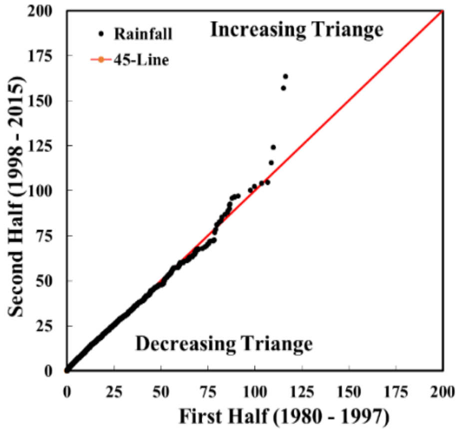

Figure 4: Innovative Trend Analysis

4.2. Future Climatology Analysis

Two sets of GCM outputs, the past and future climates were examined in this study. The historical model simulation window (1980–2005) included 26 years for the past climate analysis, and the RCP 8.5 scenario included 26 years from 2075 to 2100 for the future climate analysis. For this research, the following GCMs were found to be the most suitable: MPI-ESM-LR@ens_mean, ACCESS1.0@ens_mean, and CMCC-CESM@ens_mean.

4.2.1 Changes in annual climatology of rainfall

Figure 5 shows the results of the analysis of annual average rainfall changes between the past and the future in the selected GCMs. Owing to increased global warming rates, CMCC-CESM and MPI-ESM-LR predict higher rainfall increase rates (10% and 7%, respectively) in the near future (2025–2050), but ACCESS1.0 predicts a decreased rate (-8%). However, ACCESS1.0, CMCC-CESM, and MPI-ESM-LR show significant rainfall increases in the mid (2050–2075) and far future (2075–2100). It is noticeable that the ACCESS1.0 model keeps the rainfall increment below 10%, whereas the other two models predict rainfall increases of 20% and 40% in the mid and far future, respectively.

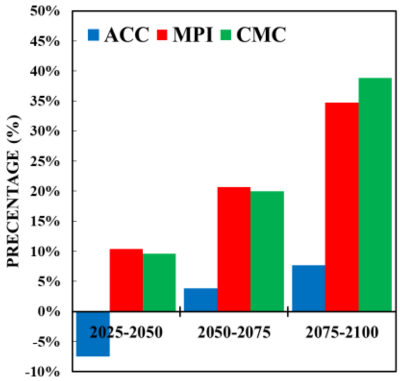

Figure 5: Percentage of Change of Past & Future annual Rainfall

The spatial distribution of changes in annual average rainfall for the GCMs is compared in Figure 6 (a) to (c). All three models show that in near future (2025–2050), as the climate gets warmer, the western part of the Kalu River basin will likely get more rain while the area upstream will get lesser. Furthermore, it is important to note that the geographical changes in rainfall projected by GCMs may reverse in the far future (2075–2100) and occur at a significantly larger scale than those projected by GCMs in the near future.

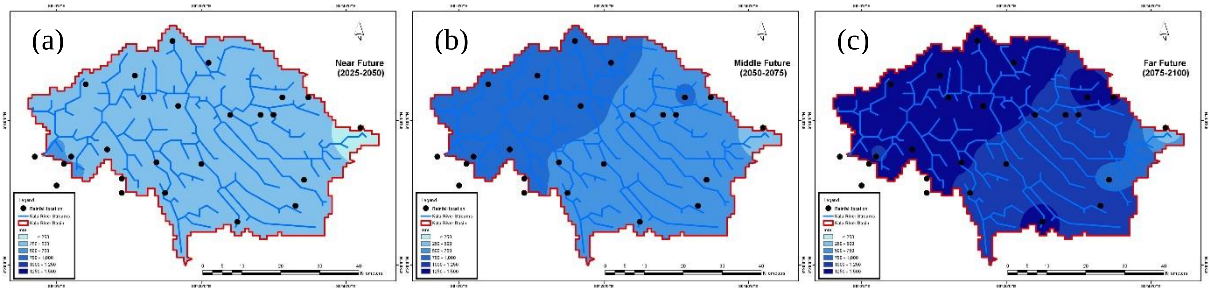

Figure 6: The Comparison of Annual Average Rainfall Differences (Future- Past) in mm/year for (a) Near Future, (b) Mid Future, and (c) Far Future all GCMs Ensemble Mean

4.2.2. Heavy Rainfall Prediction

In the simulations for the years 2075 to 2100, the top 25 daily rainfall occurrences were compared with the previously observed records for the past 26 years (Figure 7). ACCESS1.0, CMCC-CESM, and MPI-ESM-LR models predict an increment in the intensity of daily extreme rainfall of 54%, 80%, and 53% respectively. Therefore, there is a great probability of extreme rainfall occurrences becoming even more intense. As a result of these occurrences, new indicators will be generated.

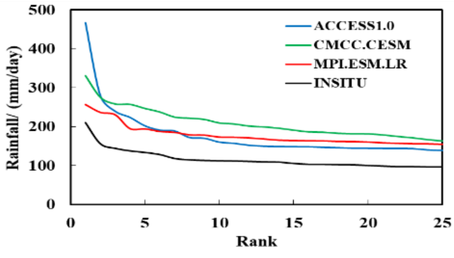

Figure 7: Extreme Rainfall

4.3. Retune Period

Figure 8 compares the observed basin average *in-situ* retune period of rainfall to the future basin average GCMs rainfall retune period. As a result of this, future projected values seem sufficiently reliable. The graph shows that the majority of the models predict a significant increase in rainfall throughout the return period. For example, 200mm/day basin average rainfall has a retune period

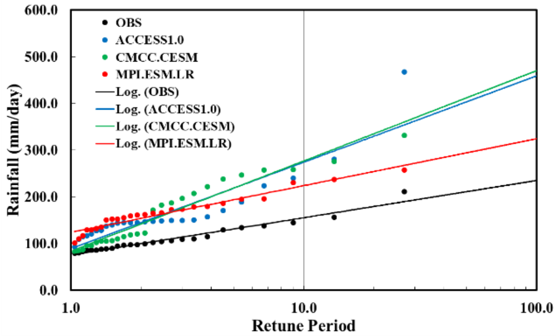

Figure 8: Frequency Analysis of Kalu River

of 36 years in the current climate, but it will rapidly decrease to 5 years in the MPI-ESM-LR model and 3 years in other models as the climate changes occur in the future.

4.4. Calibration and Validation of WEB-RRI Hydrological Model

WEB-RRI model calibration was performed from 01.01.2010 to 31.12.2010 and it was successfully calibrated during both high and low flow values. Ratnapura, which is upstream of the flood mitigation structural proposals, was the selected model discharge location (Figure 9). The model was then used for the validation run from 01.01.2013 to 31.12.2013.

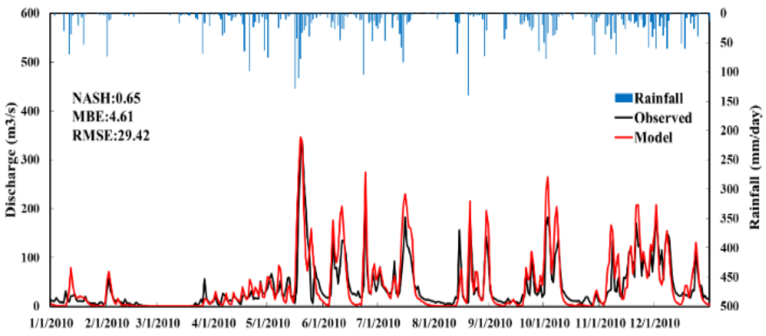

Figure 9: Simulation Vs Observed Results of WEB-RRI Model during Calibration

4.5. Comparison of Extreme Discharge (Past & Future)

Table 2 summarizes the corresponding upstream discharge (Ratnapura) for three selected extreme precipitation events in the basin from the GCM past and far future precipitation data set. The ACCESS1.0 and CMCC-CESM models estimated that by the end of this century, the discharge will increase by 30% and 20%, respectively. However, the MPI-ESM-LR model predicts no such discharge increase.

4.6. Inundation Difference (Future - Past)

Figure 7 shows that the majority of GCM models and their values predict that the river basin's extreme precipitation will increase in the future (2075–2100), compared to the past (1980–2005). In addition, when compared to other GCMs, the CMCC-CESM has a higher ranking for intense rainfall. Figure 10 shows the difference in inundation depth between future (2075–2100) and past (1980–2005) increases, based on the CMCC-CESM extreme scenario case model. It is clear that there will be a significant increase in the future inundation depth.

Table 2: Comparison of Extreme Discharge; GCM Past & Far Future in Upstream (Ratnapura)

MODEL	Extreme Events Discharge/ (m3/Sec)	1st Extreme	2nd Extreme	3rd Extreme
ACCESS 1.0	GCM Past (1980-2005)	1009.8	796.3	736.2
	Far Future (2075-2100)	1353.7	901.6	1106.6
	Ensemble Increment	1.3		
CMCC. CESM	GCM Past (1980-2005)	1038.3	698.8	713.9
	Far Future (2075-2100)	1091.5	1062.5	725.7
	Ensemble Increment	1.2		
MPI. ESM.LR	GCM Past (1980-2005)	1113.1	945.5	688.7
	Far Future (2075-2100)	737.9	800.2	1062.3
	Ensemble Increment	1.0		

4.7. Inundation Difference (With & Without Dry Dam System)

Figure 11 illustrates how the Kalu River basin's inundation varies with and without dry dam systems. It predicted that the use of flood mitigation strategies would significantly reduce upstream flooding of the basin. However, the dry dam system had no influence on the mitigation of downstream flooding.

Table 3 highlights the flood reduction levels which can be determined for both livable and non-livable inundation depths as well as the impact of structural countermeasures and future climate change. Furthermore, it gives a quick summary of flood types (major and critical) followed by a difference in GCM model outputs.

A flood early warning system can play a key role in mitigating flood disasters in the Kalu River basin and reducing casualties in the future.

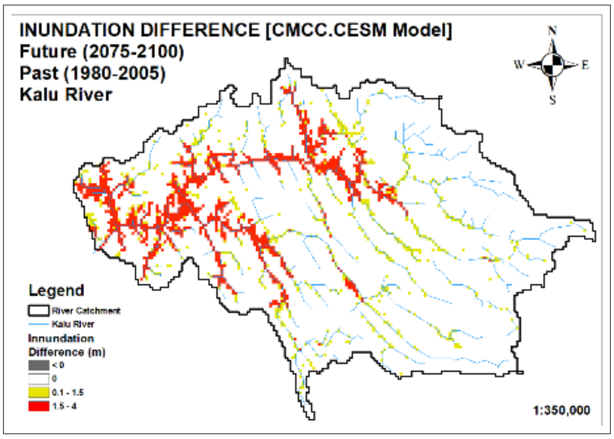

Figure 10: Inundation Differences (Future- Past)

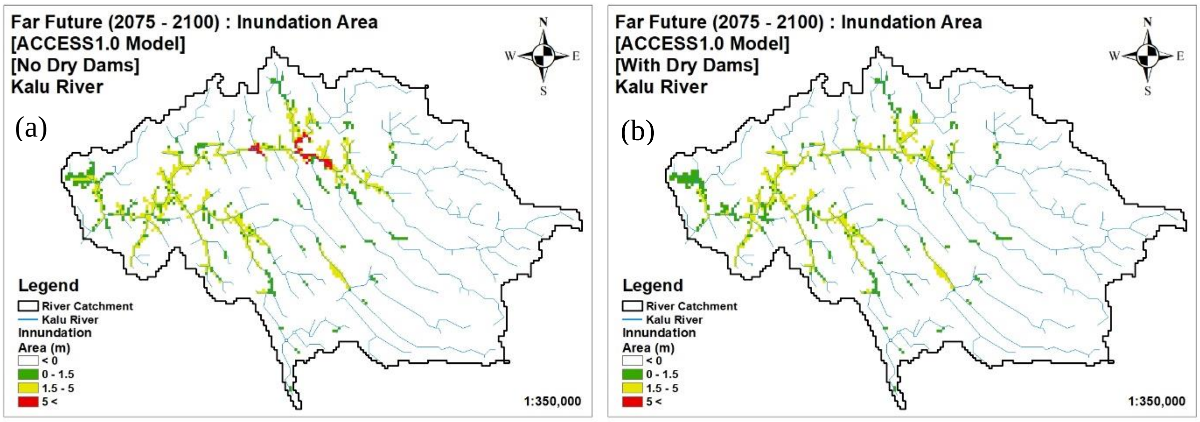

Figure 11: Inundation Difference (a) Without Dry dam System: (b) With Dry dam System; for ACCESS1.0 Model (3rd Extreme Case, Far Future)

Table 3: Flood Reduction Levels in Difference GCM

FLOOD REDUCTION LEVELS	ACC	CMC	MPI	Ensemble
Total Inundation Reduction	5%	6%	6%	6%
"Major Flood" Inundation Reduction (>1.5m)	14%	20%	14%	16%
"Critical Flood" Inundation Reduction (>5.0m)	63%	99%	61%	74%

5. CONCLUSION AND RECOMMENDATION

This study examined the impact of climate change on the latest flood mitigation proposal (Dry Dams System) in the Kalu River basin. Based on innovative trend analysis and studies of average wet spells, an increasing trend in extreme rainfall has been observed. In the past 36 years, there has been an increase in annual rainfall. The simulated discharge analysis was conducted to understand how the flood would move from the upper catchment and to assess the increment of future discharge. ACCESS1.0 and CMCC-CESM models predicted that the discharge increment at the end of this century will be 30% and 20%, respectively. The difference between past and future flooding showed that water levels will rise by more than 1.5m. As a result, there will be lesser inhabitable land in the basin. The developed WEB-RRI model can be used for real-time flood forecasting for the Kalu River basin. However, the software is needed to incorporate ground data and upload results. In order to address mitigation strategies for flood disasters in the Kalu River, a policy plan for the implementation of a sound disaster management plan at the basin scale was designed utilizing the Pressure and Release model (PAR model).

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