ASSESSMENT OF CLIMATE CHANGE IMPACTS ON EXTREME FLOODS IN THE CHAMKHARCHU SUB-BASIN, BHUTAN

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ABSTRACT

The Chamkharchu sub-basin is located in the north-central region of Bhutan. It is highly vulnerable to hydro-meteorological hazards owing to variations in rainfall patterns triggered by climate change and has experienced floods. Socio-economic activities, infrastructure, and settlements are located along the flood plain, and lack of investment in scientifically designed flood protection measures along vulnerable areas could aggravate future flood risk. This study assessed the impact of climate change on extreme floods along the Chamkharchu River using recent advances in science and technology, including general circulation models (GCMs), considering the RCP8.5, scenario and rainfall-runoff-inundation (RRI) model for hydrological simulations. All selected GCMs projected an increase in extreme daily rainfall between 10% and 60%, inundation extent by 30%, and inundation depth by more than double, with an increase in the number of affected houses and population in the near future. This indicates that water resource sectors would be beneficial simultaneously, and there will be increased flood risk in human settlement areas, especially Choekhor Gewog (Chamkhar town).To overcome these effects, inundation maps were prepared for 100-year return period design floods and the number of likely affected houses and population were investigated, and two types of climate change adaptation measures were designed and estimated. Additionally, non-structural measures are recommended for effective flood management and decision-making.

Keywords: climate change, rainfall, return period, inundation, flood

1. INTRODUCTION

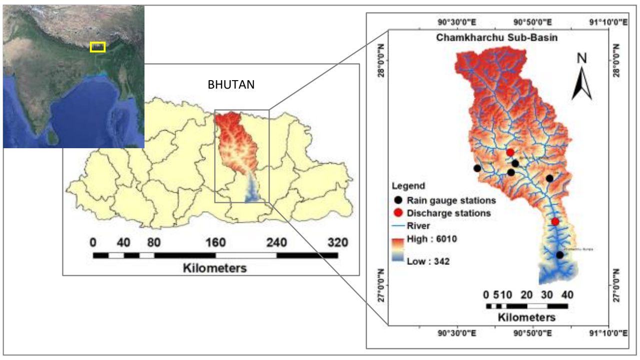

Figure 1. Study area

The Chamkharchu sub-basin(Chu Meaning River) is located in the north central region of Bhutan (90°45´18"E and 27°32´25"N), covering an area of 3,114 km^2 and covers the valley of Bumthang and part of Zhemgang. It is a sub-basin of the Manas River Basin. The elevation of the Chamkharchu sub-basin ranges from 342 m in the south to 6,010 m in the north. Chamkharchu is the main river flowing through Bumthang Valley. The length of the river is approximately 150 km. It meets Mangdechu, joins Manas and Bhramaputra Rivers, and finally reaches the Bay of Bengal. The minimum discharge recorded in the last decade was 9.43 m^3/s on February 7, 2010, and a maximum of 586 m^3/s on May 26, 2009, at the Kurjey hydrological station. Monsoon rainfall causes an extremely high increase in river flow.The annual average observed discharge at the Kurjey and Bemethang stations was 260 m^3/s and 320 m^3/s, respectively. Most of the settlements in the basin are located in Choekhor Gewog, especially in Chamkhar Town. Bhutan has experienced natural hazards,

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such as the glacial lake outburst flood of Lugge Tsho in 1994, the high-intensity Cyclone Aila in May 2009, which caused substantial damage in many parts of the country, and claimed 12 lives, in addition to causing damage of over US$ 17 million (DDM,2016). In July 2016, the rivers and streams in southern Bhutan washed away houses, farmland, and affected public infrastructure. Flash floods are one of the most common climate-induced hazards in Bhutan. Over 70% of the settlements, including infrastructure and fertile agricultural land, are located along the main rivers, posing a threat of flooding (NCHM, 2019). Choekhor Gewog, the most flood-prone area in the basin, is a major tourist hot spot and trading center in the region. Infrastructure has been built along the flood plains without proper scientific studies, and inadequate mitigation measures have increased flood risk through increased exposure and vulnerability to floods due to climate change. Therefore, this study assessed climate change impacts on extreme floods using currently available systems and models to support policymakers in the decision-making process. General circulation models (GCMs) are sometimes inaccurate because of their coarse resolution and different sensitivities to regional climates. Therefore, state-of-the-art technologies, such as the data integration and analysis system (DIAS) developed by the University of Tokyo, were used to process the high-volume data from GCMs and selected models that best represented regional performance for bias correction and downscaling. Additionally, to understand the basin characteristics, a rainfall-runoff-inundation (RRI) model capable of simulating rainfall-runoff and flood inundation simultaneously (*Sayama et al., 2012*) was used in the study.

2. THEORY AND METHODOLOGY

The overall methodology adopted in this study consists of five components, as shown in Figure 2.

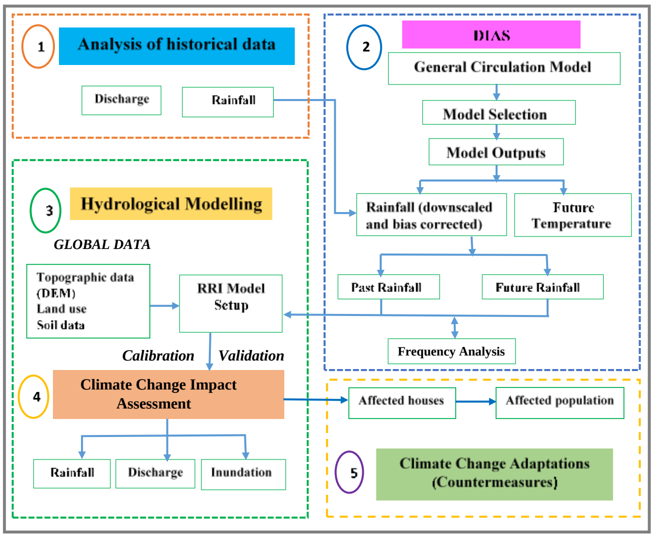


Figure 2. Methodology

1. Observed rainfall data from 1996 to 2021 were assessed to examine the basic climate change signals.
2. The selection of the GCMs was based on a historical simulation of daily rainfall. GCMs, that best represented the regional climate of the study area, were selected for future climate projections, that is, ACCESS1.3, CESM1(CAM5), CNRM-CM5, CMCC-CMS, and MIROC5. The selected climate models were then bias-corrected through statistical downscaling to provide accurate future projections.
3. To investigate the effects of climate change on extreme floods in the basin, the RRI model was calibrated and validated using observed discharge data from Bemethang Station. The historical maximum flood of Cyclone Aila in, 2009 was simulated in the RRI, for calibration. Model performance was evaluated using the Nash-Sutcliffe efficiency (NSE) and correlation coefficient (Correl). The RRI model was validated using the 2010 discharge at Bemethang Station.
4. The rainfall increase factors of each selected GCMs were calculated for different return periods of 10, 20, 50, 100, and 200 years with respect to the historical rainfall. The selected GCMs were further divided into two groups; Case 1 with a “large increase in rainfall” and Case 2 with a “medium increase in rainfall” (further explained in the results and discussion). Increased factors for design rainfall of the 100-year return period for the historical rainfall and, future Cases 1 and 2 were computed. The increased factors for each case were applied to the hyetograph, and future floods for each case were projected. Accordingly, the increase in inundation extent, inundation depth, affected houses, and affected populations were investigated.
5. Finally, climate change adaptation measures were proposed and simulated in the RRI. This assessment was particularly focused on Choekhor Gewog, which was affected by flooding in May 2009.

Data

Table 1. Data for the study

Sl.No	Data Type	Remarks	Source
1	Rainfall	1996 – 2021	NCHM, Bhutan
2	Discharge	1996 – 2021	NCHM, Bhutan
3	Settlement (Houses)		DHS, MOWHS, Bhutan
4	Soil		FAO
5	DEM	15 sec grid	USGS(http:hydrosheds.cr.usgs.gov/index.php

3. RESULTS AND DISCUSSION

3.1 Rainfall Analysis:

Past observed rainfall was assessed on the extremes, with innovative trend analysis and annual fluctuations. The trend analysis represents the rainfall pattern during two periods: (1996–2008) and (2009–2021), as shown in Figure 3. The analysis showed that the rainfall intensity remained the same until ≤ 20-mm. At the end of the second period, the number of extreme events with high rainfall intensity showed an increasing trend, which is an indication of more flood events in the future. Figure 4 shows that the highest annual average rainfall of 1,108 mm/year was observed in 2013, whereas lowest annual average rainfall of 537mm/year was observed in 2018. Interannual variation exists; however, all annual rainfall patterns show an increasing trend.

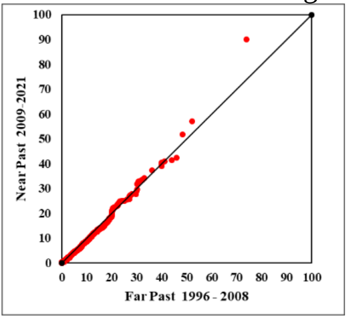


Figure 3. Innovative trend analysis

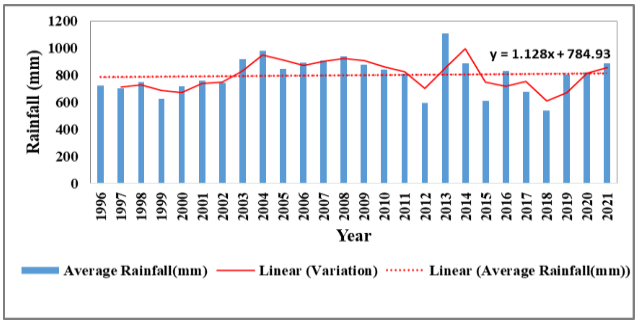


Figure 4. Trend of annual rainfall since 1996

Future climate models with twenty-five-year simulation periods for the past (1980 – 2005) and near future (2025 – 2050) were simulated for the RCP8.5 scenario.The ACCESS1.3 GCM projected the highest increase in annual rainfall of 32.55% (286mm/year) among the GCMs, while the CMCC-CMS showed the smallest increase of 5.76% (51mm/year). As shown in Figure 5, all climate models agreed that rainfall will increase in the near future. An increase in annual rainfall is an indicator of climate change.

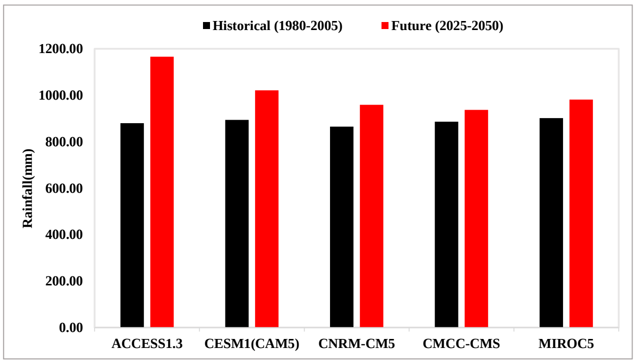
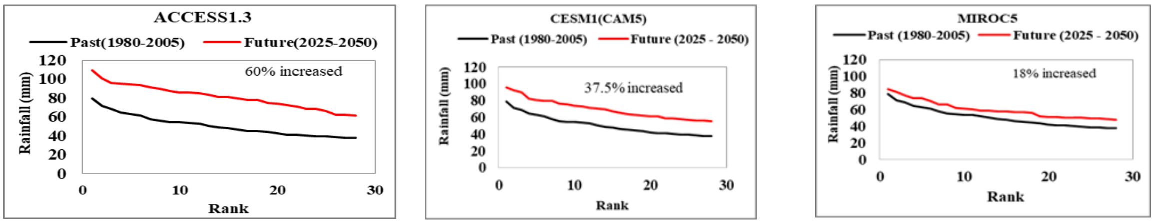


Figure 5. Annual average rainfall for GCMs



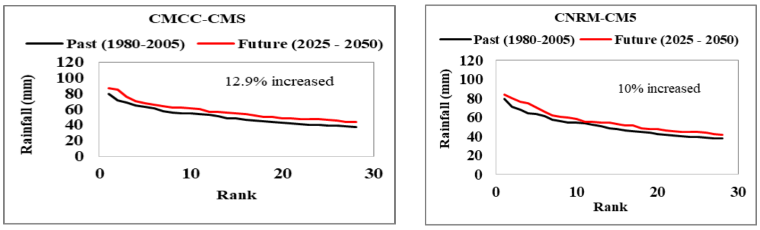


Figure 6. Extreme rainfall for GCMs

Figure 6 shows the changes in extreme daily rainfall for all five GCMs. All models show an increase in heavy rainfall in the near future (2025-2050), but the increased rate has some ranges of uncertainties. The increase rate ranged between 60% for ACCESS1.3 and 10% for CNRM-CM5. Past innovative trend analysis also showed an increase in extreme rainfall events, which signifies that more frequent floods are likely to occur in the future. Such increases in extreme rainfall will pose serious hydrological hazards such as flashfloods, urban floods, and landslides aggravated by the steep sloped mountain topography in the basin.

3.2 Return Period Analysis

Figure 7 shows the flood frequency analysis of the historical rainfall and adopted GCMs, which reveals that, as the return period increases, the magnitude of rainfall also increases, for both historical and GCM simulated rainfall. The outputs of ACCESS1.3 are the highest among the GCMs, and other four GCMs were close to each other. The increase factors for each GCM were computed with respect to the historical rainfall. Two cases were used, based on the increase in rainfall magnitude. Case 1 involved a large increase in rainfall (ACCESS1.3) and Case 2 involved a medium increase in rainfall CESM1(CAM5), CMCC-CMS, CNRM-CM5, and MIROC5). The increase in rainfall magnitude was shown to increase by factors of 2.12,2.13,2.13,2.14,and 2.14 for Case 1 and 1.58,1.55,1.52,1.50, and1.49 for Case 2 for the 10 ,20 ,50 ,100 and 200-year return periods, respectively. Basin-scale design rainfall (100-year return period) for the historic and future scenarios (Case 1 and Case 2), was computed, and the factors increased by 2.4 and 1.70 for future Case 1 and 2, respectively. They were then applied for climate change impact assessment.

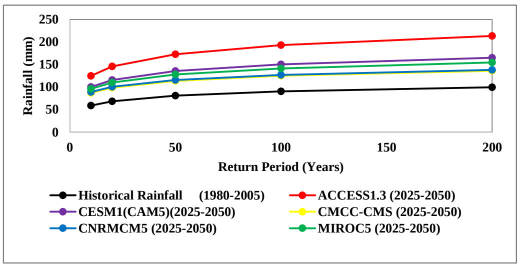


Figure7. Return period rainfall

3.3 Hydrological model development

The calibration of the RRI model was performed using the 2009 (January – December) discharge data from Bemethang Station and validation using the discharge data of 2010 (January – December) from the same station. The simulation results are shown in Figure 8. The Nash-Sutcliffe efficiency (NSE) values for calibration and validation were obtained within the acceptable range of 0.76 for the calibration, and 0.75 for the validation.The simulated hydrograph tended to agree with the observed peaks, but slightly under-estimated base flow.

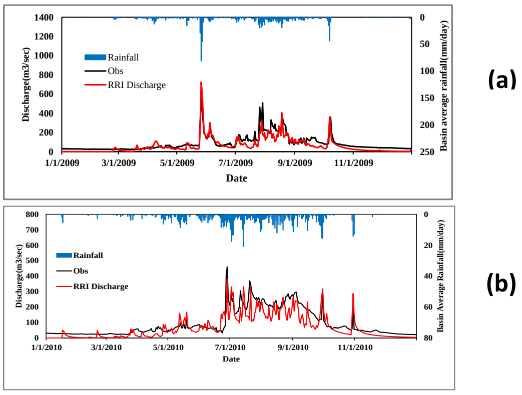


Figure 8: Simulation of RRI model
(a) Calibration (b) Validation

3.4 Flood simulation for selected return period

This study assessed the changes in inundation extent, depth, number of houses, and population affected by past and future floods in the Choekhor Gewog (Chamkhar area). A greater inundation extent and depth can be seen along the Chamkhar area, where there are concentrated settlements, infrastructure developments, and agricultural activities. The inundation depth increased because of the limited low-lying flat areas along the river. This indicates an increased future flood risk in low-lying areas. Figure 9 shows the inundation extent and depth changes for the past and future floods.

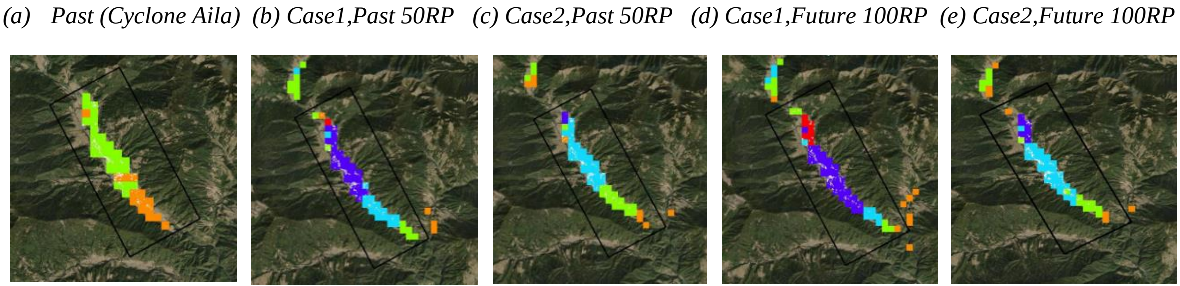


Figure 9. Changes in inundation *Legend : depth in meter* 🟩 0–0.5 🟧 0.5–1 🟩 1–2 🟦 2–3 🟪 3–4 🟥 4 – 4.5

Inundation extent increases from the past to future floods, ranging from 6.75 km^2 in the past to 8.78 km^2 in the future for the 50-year return period past floods and the 100-year return period future floods. The inundation areas for the past 50-year return period and future 100-year return period floods are the same because of the limited flood plain areas surrendered by the mountain slopes; however, the depth changes.

3.5 Affected houses and population change

Figure 10 shows the results of the analysis of the number of affected houses and people under the Choekhor Gewog (Chamkhar Town) for past and future floods. The number of affected houses increased from 469 in the past to 529 in the future, while the number of affected people ranges from 1,876 in the past to 2,116 in the future.

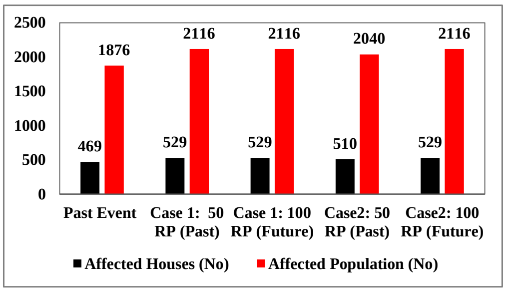


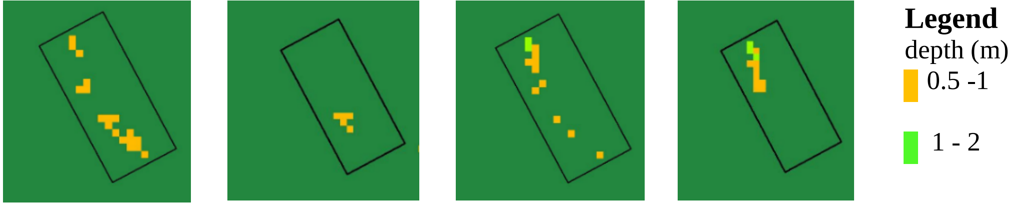
Figure 10. Affected houses and population

3.6 Characteristics of the inundation

Owing to the topographical characteristics of Choekhor Gewog (Chamkhar Town), the inundation depth will increase dramatically, while a relatively smaller increase is predicted in the affected area, meaning not so large increase in the number of the affected houses and population. Early warning systems that have already been established should be strengthened and ensure that societies at risk are aware of these systems. For a rapid reaction, safe evacuation areas within the shortest possible distance from the settlement should be identified, with good road and footpath access.

3.7 Climate change adaptation measures

Two types of structural measures, embankment and bed lowering (dredging), were introduced and simulated in the RRI for Future Cases 1 and 2. Regarding the embankment, the river width increased from 63 m to 80 m and the bank height increased to 6 m and 5 m, for future Cases 1 and 2, respectively. For bed lowering (dredging works) river width increased from 63 m to 80 m, and depth increased from 4.01 m to 7 m and 6 m, for Cases 1 and 2, respectively. The inundation depth was reduced significantly after placing the embankment and dredging work, as shown in figure 11.



(a) Case 1: with embankment
(b) Case 2 with embankment
(c) Case 1 with dredging
(d) Case 2 with dredging

Figure 11. Inundation depth changes after placing structural measures

Infrastructure for effective and sustainable flood management is required to protect the properties, human lives and other infrastructure along the banks of the river. The design and drawing of these structures were carried out. Figures 12 (a) and (b) show climate-resilient countermeasure drawings for embankments and bed lowering (dredging works).

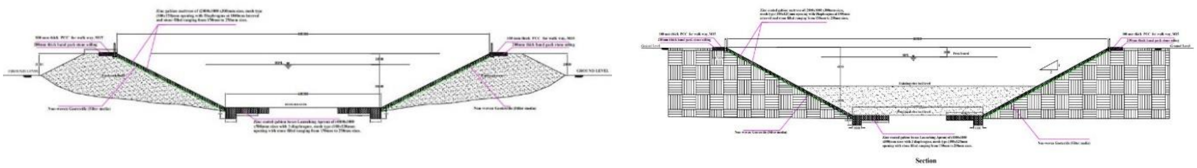


Figure 12. (a) Embankment (b) Bed lowering (dredging works)

3.8 Sediment management

To accommodate additional (flood) water, a wider riverbed was proposed in the design. This will decrease flow velocity and the sediment will be deposited. River bed levels should be monitored by measuring cross-sectional profiles, and a sediment management plan should be prepared.

4. CONCLUSIONS

This study assessed the impact of climate change by incorporating recent advancements in scientific and technological tools and models. The DIAS and, CMIP5 platforms were used to select the GCMs and RRI model to simulate the basin-scale hydrological response under climate change scenarios. A climate change impact assessment showed an increased flood risk in the basin, particularly in the Chamkhar area. Bias corrected results from future climate models showed an increase in extreme daily rainfall between 60% and 10%, which indicates the possible occurrence of severe flash floods in the future. The annual average rainfall is also projected to increase between 51 mm and 286 mm. Inundation depths were observed to double in the future, with an increase in the number of affected houses and population. The extent of inundation is projected to increase by at least 30% (2.05 km$^{2)}$. Two types of effective flood mitigation measures were designed and estimated along areas of high vulnerability (specifically, Chamkhar Town). A cost estimate was carried out for the embankments design, estimated at Nu. 59,173.00 (US$ 740) and Nu.52,468.00 (US$ 650) per meter length for Cases 1 and 2, respectively. For dredging, costs arrived at Nu. 83,427.00 (US$ 1049) and Nu.71,244.00 (US$ 896) per meter length for Cases 1 and 2, respectively.

5. RECOMMENDATIONS

The frequency and intensity of flood hazards are likely to increase in the future due to climate change, which needs to be addressed through an end-to-end approach. Non-structural measures such as flood zoning, capacity development of relevant stakeholders, preparedness, forecasting, insurance, hazard maps, and evacuation, should be strengthened. The best combination of both structural and non-structural measures need to be applied, in which science and technology play an essential role. Policymakers should plan strategically, and give priority to investments into the climate-resilient mitigation measures, considering the extreme scenarios due to climate change.

6. ACKNOWLEDGEMENT

I sincerely thank my main supervisor, Prof. Toshio KOIKE for his continuous advice, and generous expert guidance throughout my master's studies at ICHARM. I am also thankful to Prof. Mohamed Rasmy Abdul Wahid for his support, and guidance. I extend my deep appreciation to Dr. Katsunori TAMAKAWA for his guidance on climate change and the DIAS system.

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