COMPREHENSIVE EVALUATION OF FLOOD MITIGATION MEASURES BASED ON CLIMATE CHANGE IMPACT ASSESSMENT IN THE WANGCHU BASIN

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ABSTRACT

The Wangchu basin in western Bhutan has almost 30% of the country's population, mostly settled along the rivers and streams in its sub-basins. The 2009 flood event and the unexpected increase in river discharge during the rainy season in recent times have illustrated the people of their vulnerability in the basin. This study assessed the impacts of climate change on rainfall intensity and flooding in the basin using general circulation models (GCMs). The rainfall-runoff-inundation model was employed in the study area to simulate past and future flooding as per the GCM rainfall outputs. The selected GCMs showed an increase in extreme rainfall, discharge, inundation area, affected population, and infrastructural damage cost in the future. Fewer inundation days but with increase in inundation area are predicted to occur in the future, indicating the high intensity of rainfall that could cause severe flash floods in the basin. Further, as huge recovery costs are incurred after a disaster, a method to evaluate the incentive for prior investment in flood preventive measures was developed. The evaluation will help to convince and explicate the decision-makers of the benefits of such early disaster preparedness works. The method is beneficial for the implementation of embankment works along the Haa sub-basin when considering future flooding.

Key words: *rainfall, discharge, damage, incentive, investment*

INTRODUCTION

Over the past few decades, Bhutan has experienced several types of hazards, including glacial lake outburst flooding, flash floods, landslides, and earthquakes. Flash floods are common in the country owing to the steep mountainous catchments and fragile geology. The threat of flooding arises whenever there is heavy and continuous rainfall in a basin. In the Wangchu basin, which has an approximate area of 4596 km^2 in the western part of the country, most of the settlements in Thimphu, Paro, and Haa districts are located along the river valleys downstream. Intense rainfall of more than 5 h to 6 h can easily increase the river discharge, thereby causing destruction along some highly vulnerable locations in the basin. According to many studies and reports, climate change is likely to intensify the magnitude of flooding. Several areas within the basin fall under the threat of flooding as per the report on the Wangchu Basin Management Plan (2016). Thus, the study was conducted with the following three main objectives: 1) to project future precipitation (rainfall)

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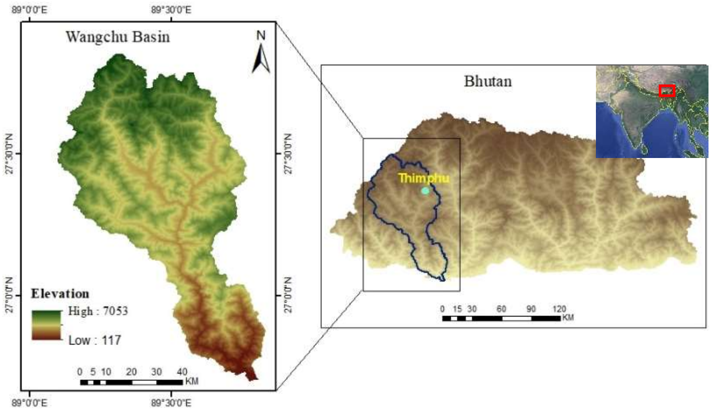

Figure 1. Study area

based on climate models, 2) to assess the impacts of climate change on flooding in the basin, and 3) to develop a methodology for evaluating the incentive in prior investment of flood preventive measures for decision-making and implementation.

THEORY AND METHODOLOGY

The approach of the research was framed to assess the impact of climate change on flooding and the benefits of undertaking early implementation of flood mitigation measures. A hydrological model was employed to generate accurate streamflow estimates. The general circulation models that best simulated the climate in the target area were selected to conduct the climate change impact assessment. The study was further expanded by assessing the significance of flood mitigation measures. The three main phases of the study are elaborated in detail below.

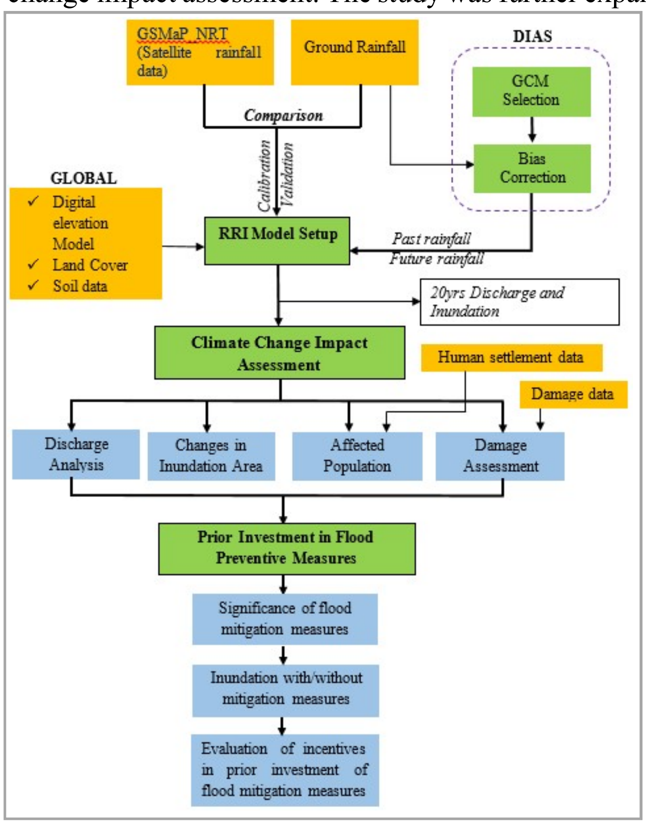

Figure 2. Framework of research work

1) Hydrological model setup

The rainfall-runoff-inundation (RRI) model, which is a two-dimensional hydrological model, was used for the study. The model was set up by calibrating with the 2009 flood event. The model performance was evaluated using the Nash-Sutcliffe Efficiency (NSE) and correlation coefficient (Correl). The model was validated using the 2007 and 2012 flood events.

2) Climate change impact assessment

GCM rainfall outputs were used to conduct the climate change impact assessment. The GCMs were selected from the Data Integration Analysis System integrated with the Coupled Model Intercomparison Project Phase 5. The selected models were then bias-corrected through statistical downscaling to provide proper projections. Assessments of extreme rainfall and discharge, inundation area, affected population, and damage costs were conducted using the output of the models. For damage cost assessment, frequency analysis for the observed discharge and past and future GCM discharge was performed at the Haa gauging station to determine the respective return period and draw the damage curves.

3) Prior investment in flood preventive measures

A method to evaluate the incentive for prior investment of flood preventive measures based on the expected utility theory (U) was developed. The incentive equation (I) was developed as a function of the time horizon

(i), probability of occurrence of a future flood (p), reduction in damage cost due to the preventive measure (R), construction cost of the preventive measure (C), and time discount rate (D) to convert the future value to the present value. If the preventive measure was constructed under a loan project, then an annual negative discount rate was applied to the cost of the evaluation. The incentive equation is written as follows:

$$I = \sum_{i=1}^{n} \frac{u(p*R)/(1+D_p)^i}{u(C)/(1+D_n)^i} \tag{1}$$

However, if the cost of the construction is from the government budget, then the incentive is calculated as follows:

$$I = \frac{\sum_{i=1}^{n} u(p*R)/(1+D_p)^i}{u(C)} \tag{2}$$

The equations were applied to determine the incentives for the construction of embankments along the Haa sub-basin. Embankments were considered for the purpose in the study as it is the most feasible and commonly used flood mitigation measures in Bhutan. An incentive of 1.0 or greater is often considered beneficial for adopting the plan of prior investment in mitigation measures.

DATA

The rainfall and discharge data were collected from the National Center for Hydrology and Meteorology. The GSMaP-NRT rain data were downloaded from the Japan Aerospace Exploration Agency website. Damage data were collected from the district offices and the Flood Engineering and Management Division of the MoWHS. The settlement data for the Haa and Paro sub-basins were from the Department of Human Settlement. The 15sec GRID conditioned digital elevation model, flow accumulation, and flow direction were downloaded from the USGS HydroSHEDS website.

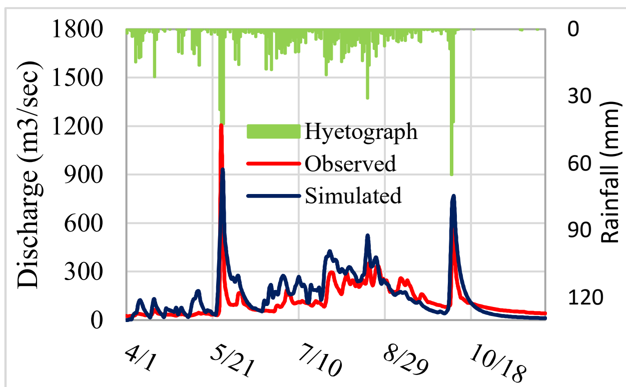

Figure 3. Rainfall-runoff-inundation model calibration for 2009

RESULTS AND DISCUSSION

1) RRI model setup

The calibration and validation results are shown in Figures 3 and 4. The RRI model showed good performance in assessing basin hydrological responses. It tended to slightly overestimate the low flows, but the peak flows matched well. Acceptable values of NSE = 0.657 and Correl = 0.695 were obtained for the calibration process. The model provided better validation results for the 2007 event with NSE and Correl values of 0.686 and 0.939, respectively, and 2012 event with values of 0.674 and 0.856, respectively.

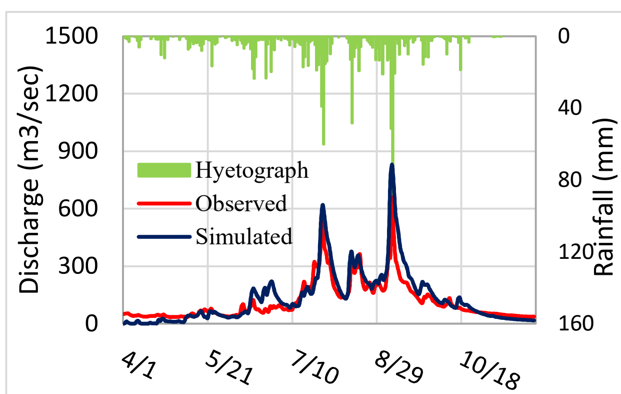

Figure 4. Rainfall-runoff-inundation model validation for 2007

2) Climate change impact assessment

(i) GCM selection and bias correction

ACCESS1.0, GFDL-ESM2G, CESM1(CAM5), and CMCC-CMS models were selected based on the evaluation of their performances for the past simulation against a reference dataset over the area of interest and region(s) closely climatologically related to the target area. Bias correction of the selected GCMs was performed with the observed rainfall data. Each models provided past (1986–2005) and future rainfall (2041–2060) outputs.

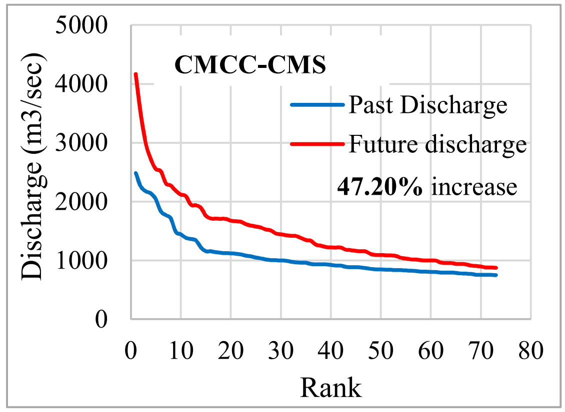

Figure 5. Change in extreme daily rainfall

(ii) Extreme daily rainfall and discharge

Models showed an increase in extreme daily rainfall in the future. While ACCESS1.0 model showed an increase of 6.16%, the other three models predicted a rise of more than 40%. Similarly, an increase in extreme daily discharge of up to 30% was predicted by the models. The changes in rainfall and discharge for the CMCC-CMS model are shown in Figures 5 and 6.

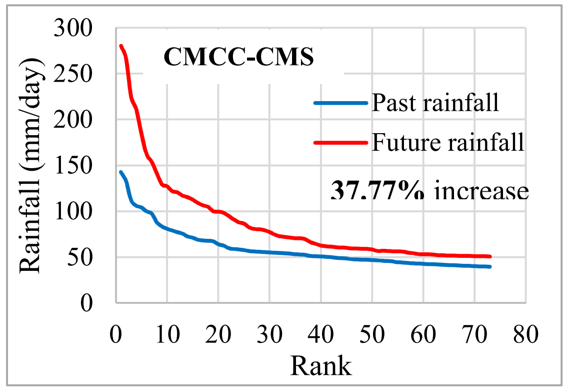

Figure 6. Change in extreme daily discharge

(iii) Changes in inundation area and duration

The area and volume of the inundation were observed to increase in the future as a result of extreme rainfall and discharge. The inundation map of the CMCC-CMS model in Figure 8 shows an increase in inundation depth and area in the future along the low-lying valley of the Paro, Haa, and Thimphu sub-basins. The number of inundation days for both the past and future ranged from to 4–6 d/y. However, three of the models provided relatively fewer inundation days in the future, as shown in Table 1. Such results with a lesser duration of inundation but increased inundation area indicates a high intensity of rainfall, which could trigger flash floods in the valley.

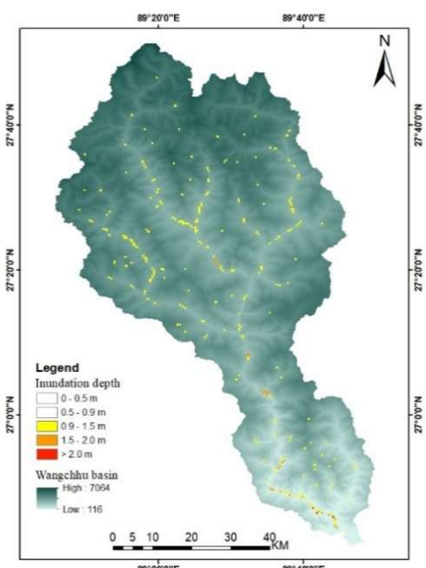

Figure 7. Inundation map of the CMCC-CMS model (Past)

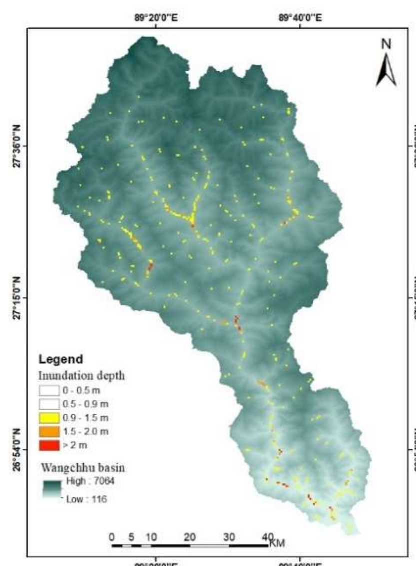

Figure 8. Inundation map of the CMCC-CMS model (future)

Table 1. Change in inundation area and duration

Model	Inundation area (ha)		Duration (d)	
	Past climate	Future climate	Past climate	Future climate
ACCESS1.0	650	994	6	4
GFDL-ESM2G	950	1800	4	6
CESM1-CAM5	760	1350	6	5
CMCC-CMS	975	2070	5	4

(iv) Affected population

The affected population was determined by laying the settlement data over the past and future inundation maps of each model in the Haa sub-basin. The increase in the inundation area along Haa Chhu indicated a larger number of people to be affected in the future, as presented in Table 2.

Table 2. Affected population in the basin as per the selected models

Model	Past climate condition		Future climate condition	
	Affected population	Percentage of population affected	Affected population	Percentage of population affected
ACCESS 1.0	400	2.93%	996	7.29%
GFDL-ESM2G	1045	7.97%	1500	10.98%
CESM1_CAM5	440	3.22%	1480	10.83%
CMCC-CMS	1112	8.14%	1820	13.33%

(v) Infrastructural damage cost

The likely damage cost due to flooding in the future was derived from the damage curves that were drawn based on damage data of the 2007, 2009, and 2012 flooding events in the Haa sub-basin (Figure 9).

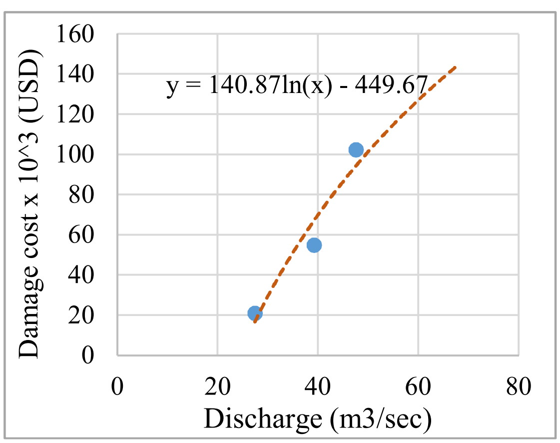

Figure 9. Damage cost against discharge of past events

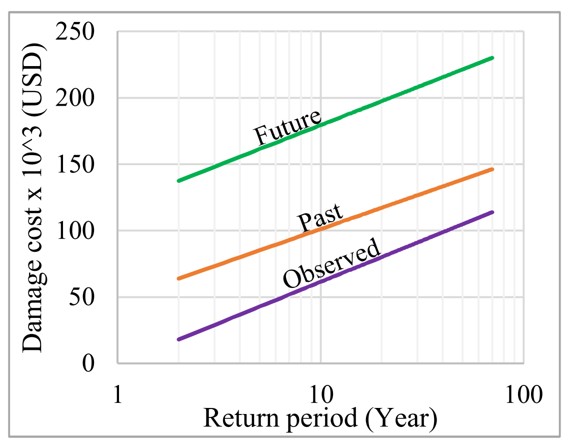

Figure 10. Damage curve for deriving the damage cost

The return periods of the observed events and model's past and future discharge were determined through frequency analysis. According to Figure 10, the infrastructural damage cost in the future is almost twice as high as that of the past with the discharge of the same return period. A 10 y return period flood will have a damage cost of $189 393 USD in the future, while the cost in the past was only $101 146 USD.

3) Prior investment in flood preventive measures

The incentive for prior investment of preventive measure was evaluated considering future flooding according to the CMCC-CMS model in the Haa sub-basin. The probability of flooding was 0.013, and damage reduction totaling $205 210 USD was calculated after intervention of the embankment. An initial construction cost of $472 500 USD was calculated for the embankment. A positive discount rate (D_p) of 20.3% and negative discount rate (D_n) of 10.4% were determined through a questionnaire form circulated to officials of the Flood Engineering and Management Division in Bhutan. As shown in Figure 11, both the loan and government budget had an incentive (I>1) for undertaking prior construction in the embankment along the Haa Chhu River. Government-funded projects provide faster benefits/incentives than loan projects. The cost of construction plays a significant role in the evaluation whereby loan projects have a long year of repayment.

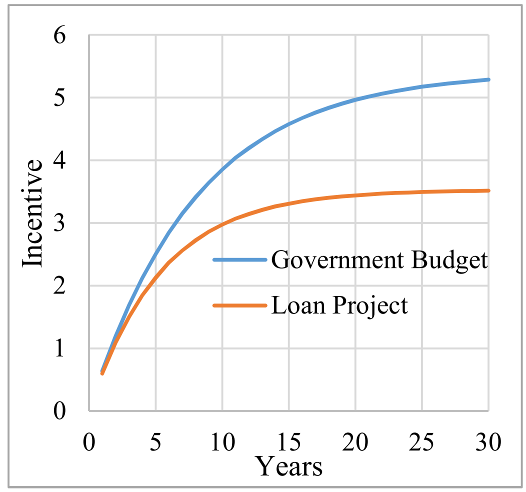

Figure 11. Incentive for flood preventive measures

CONCLUSIONS AND RECOMMENDATIONS

The climate change impact assessment showed an increased risk of flooding and subsequent consequences in the basin. Increases of at least 40% in extreme daily rainfall and 30% in discharge were presented by most of the GCM outputs. Inundation areas were observed to double in the future with an increase in the affected population along the Haa sub-basin of 35%. Lower number of inundation days but with increased inundation areas were observed in the future predictions, which indicates the high intensity of the rainfall. As these are signs of the possible occurrence of severe flash floods, effective flood mitigation measures are suggested along the highly vulnerable areas in the basin. Infrastructural damage costs were observed to be twice as high as those in the past with floods of the same return period. Use of a more number of past flooding events is recommended to draw the damage curves in order to obtain accurate future damage costs. A method to evaluate the incentive as a basis for decision-making for prior investment in flood protection measures was developed. Countries are often reluctant to invest in early disaster prevention measures, but spend a large amount of money on recovery activities. The concept of incentive is encouraged to convince and explicate the relevant agencies and decision-makers of the economic benefits of prior investment. The study observed a high incentive for investment along the Haa Chhu flood-prone areas.

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