# IMPACT ASSESSMENT ON EXTREME FLOODS DUE TO CLIMATE AND SOCIAL CHANGES IN THE AMOCHU BASIN, BHUTAN

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## ABSTRACT

Phuntsholing Town, located within the transboundary Amochu River Basin in Bhutan, has experienced recurrent flood damage historically. Besides the impact of climate change, ongoing urbanization along the Amochu River flood plains, due to limited inhabitable flatlands, could exacerbate future flood risk. Therefore, this study aims to assess the impacts of climate change and social change on extreme floods over time. Bias-corrected rainfall outputs from the general circulation models (GCMs), considering the representative concentration pathway (RCP8.5) scenario, are fed into the rainfall-runoff-inundation (RRI) hydrologic model to simulate changes in extreme discharge, inundation, and affected populations. The results show that climate change increases flood inundation and affects the population in the future, but social change aggravates flood risks. The mitigation of flood risk by embankment construction is demonstrated to be effective; however, inland inundation and overflow from extreme floods necessitate integrated flood management. While an adequate drainage system is proposed for the future town, the study highlights the need for proper consideration of the impact of social change on building a more flood-resilient society.

**Keywords:** rainfall-runoff-inundation model, general circulation model, inundation, return period, transboundary

## INTRODUCTION

The abundant water resources in Bhutan are of crucial economic importance through the export of clean hydropower electricity to India. However, the unimodal annual distribution of rainfall concentrated within the summer monsoon months from June to September increases the risk of hydrological disasters such as floods, flash floods, and landslides. A notable flood impact was experienced in 2009 when tropical cyclone Aila forced its way into the Himalayan country through India, inflicting losses of 12 lives and incurring US$70 million in damages (Lotay, 2015). Glacier lake outburst floods are also characteristic of a country with a glacier cover of 1.64% in the northern frontiers. Under the impacts of climate change due to global warming, daily extreme rainfall and extreme floods are projected to become more frequent. Small mountainous catchments, such as those in Bhutan, could face tremendous floods and flash floods regularly.

The study area of the Amochu Basin (Figure 1), covering approximately 3798 km$^2$ of westernmost Bhutan, is the smallest of the four major river basins in the country. However, it shares approximately 39% of its catchment with China, and recurrent significant floods have been recorded in the last three decades, causing

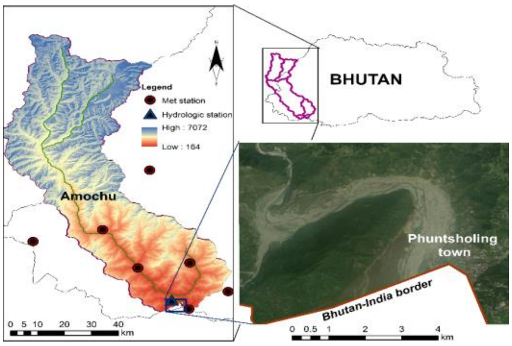

*Figure 1: Location of study area*

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damage to lives and properties. With the rising population in the border town of Phuntsholing, and due to the topographically limited expansion area, flood plains along the Amochu River are explored for land reclamation to support township development.

The development of a new town might incur new flood risks through increased exposure and vulnerability, besides the impact of climate change on flood magnitude and frequency. Therefore, the objectives of this research are to assess and compare the impacts of climate and social changes on extreme floods, evaluate the transboundary flow contribution, and propose additional countermeasures to mitigate flood risks.

## THEORY AND METHODOLOGY

This study focuses on understanding and assessing the impacts of climate change and social change on extreme flood risks. Figure 2 shows the research framework and the overall methodology followed during the study. The major components are climate data processing, hydrological modeling, climate change impact (CCI) assessment, social change impact (SCI) assessment, and transboundary flow contribution analysis before proposing an effective countermeasure for a flood-resilient town.

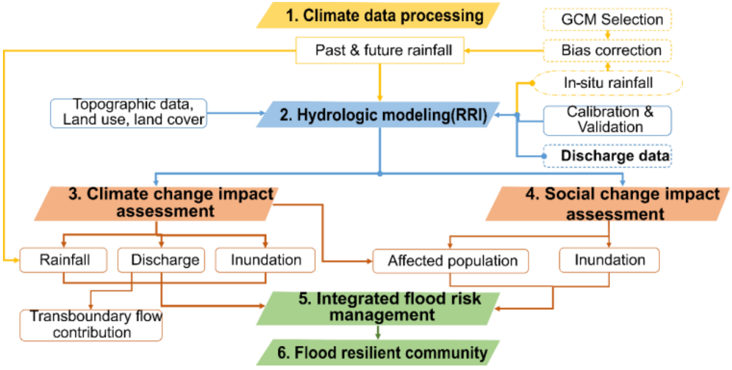


*Figure 2: The research framework*

### 1. Climate data processing

The crucial processes for the selection of general circulation models (GCMs), statistical bias correction and downscaling, are handled in this step. The Coupled Model Inter-comparison Project Phase 5 (CMIP5) data analysis tool integrated into the Data Integration and Analysis System (DIAS) was utilized. The selection is based on the method developed by "Nyunt *et al.* (2016)," which uses a scoring scheme based on the climatological monthly long-term mean spatial correlation (Scorr) and root mean square error (RMSE) for each of the seven key meteorological elements. The combined highest-scoring GCMs for the annual and rainy seasons (May to September) were adopted and then statistically bias corrected for rainfall in the DIAS, which followed the three-step method (Nyunt *et al.*, 2013). The bias-corrected historical rainfall (1980–2004) and future rainfall are utilized in the subsequent sections.

### 2. Hydrologic modeling

The rainfall-runoff-inundation (RRI) hydrologic model developed by "Sayama *et al.* (2012)" was used in the present study. The model was calibrated using the discharge data of Doyagang Station for 2007 and validated using data from 2008 to 2010. The RRI performance was evaluated in terms of the Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), and RMSE. PBIAS measures the average tendency of the simulated discharge values to be larger when negative (-ve) or smaller when positive (+ve), than the observed discharge values. Using the bias-corrected rainfall outputs from the adopted GCMs, RRI simulations were carried out for discharge at the basin scale and inundation for both the basin and the local scale. For the local-scale inundation simulation, a separate RRI model was established with the calibrated parameters of the basin-scale model.

### 3. Climate and social change impact assessment

The impacts of climate change are assessed in terms of the change in extreme daily rainfall, annual and monsoon rainfall, extreme daily discharge, flood return periods (RPs), inundation, and affected population between the past and the future. In this study, the past is 1980–2004 and the future is 2076–

2100. For the climatological change assessment, bias-corrected rainfall from the adopted GCMs is analyzed. The top one percent of the daily rainfall and discharge are considered for the extreme event analysis. Frequency analysis to determine the change in flood RPs employs the L-moment distribution fitting method of the Gumbel distribution, which is one of the three generalized extreme value (GEV) methods.

However, the impact of social change on flood risk analysis is assessed only for the local scale of Phuntsholing Town considering the affected population between the past and the future climate and town conditions. The change in inundation extent, by the intervention of a 2.81 m high embankment and river width of 300 m as undertaken by the Phuntsholing township development project (PTDP), is determined using the RRI model.

### 4. *Transboundary flow contribution*

The present study investigates the ratio of flow at the China–Bhutan border to Doyagang Station, located near the downstream end of the Amochu River, approximately 9 km upstream of the India–Bhutan border. The flow contribution from the upstream transboundary catchment was analyzed for annual flow, monsoon flow from June through September, and low flow from December through March using the RRI simulated discharges of the four adopted GCMs.

## DATA

The study required hydro-meteorological, topographical, land use and land cover, and social data such as settlement and population. Local data sets such as the observed hydro-meteorological time-series data and social data are available from the National Center for the Hydrology and Meteorology (NCHM), National Statistics Bureau (NSB), and Department of Human Settlement (DHS), Bhutan.

Free topographical data obtained from HydroSHEDS, provided by the U.S. Geological Survey were used in the RRI model. A spatial resolution of 30 arc-second (approx. 925 m) and 1 arc-second (approx. 30 m) were utilized for the basin and local scales, respectively. Soil and land cover data inputs were from free global datasets from the Food and Agriculture Organization (FAO).

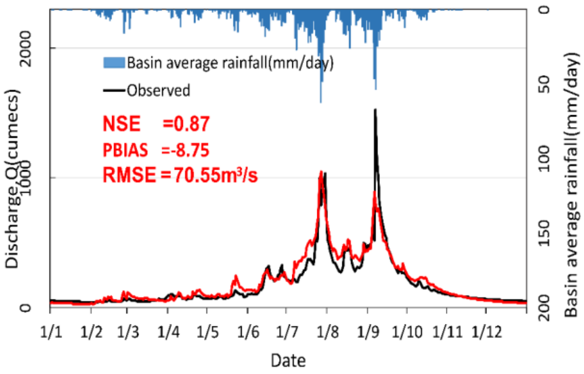
## RESULTS AND DISCUSSION

### 1. *Climate data processing*

Four GCMs with high scores were adopted from the 44 GCMs. The GCMs that best represented the study area climate were CESM1 (CAM5), ACCESS1.0, GFDL-ESM2G, and CMCC-CMS. Bias correction using ground-level rainfall was subsequently performed, and past rainfall for 1980–2004 and future rainfall for 2076–2100 were modeled.

### 2. *Hydrologic modeling*

The calibration of the RRI model using observed discharge data of 2007 resulted in NSE = 0.87, PBIAS = -8.75, and RMSE = 70.6 $m^3/s$ as shown in Figure 3. Figure 4 shows the performance of RRI during validation, using discharge data from 2008 to 2010, in which NSE = 0.76, PBIAS = -3.15, and RMSE = 107.4 $m^3/s$. The simulated discharges fit well with the observed discharge, according to the NSE values but were slightly overestimated based on the PBIAS values. However, the hydrograph peaks were not well simulated due to the unequal distribution of ground rainfall gauges in the basin and the questionable accuracy of the rainfall data. The rainfall distribution using GSMaP and TRMM_3B42RT rainfall data showed that during the second peak in September, rainfall exceeded the first peak in July, which is opposite to the observed data of 2007.



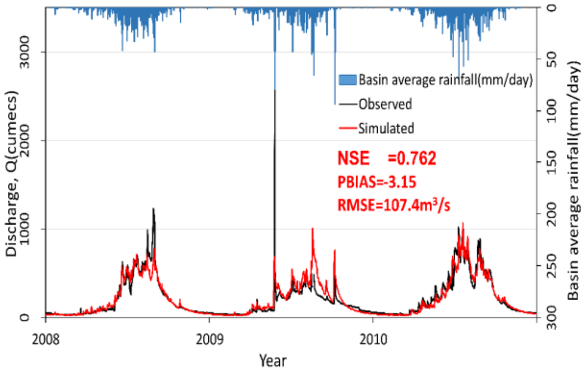


*Figure 3. RRI calibration using 2007 observed discharge data*

*Figure 4. RRI validation using 2008 to 2010 observed discharge data*

## 3. *Climate change impact assessment*

### 3.1. Changes in extreme rainfall and discharge

The best scoring GCM, CESM1 (CAM5), shows an increased extreme daily rainfall and discharge in the future by 82.8% and 54.4%, respectively, as shown in figures Figure 5 and Figure 6. The other three adopted GCMs also showed similar increases. This implies that the flood hazard, and thus flood risk, will increase.

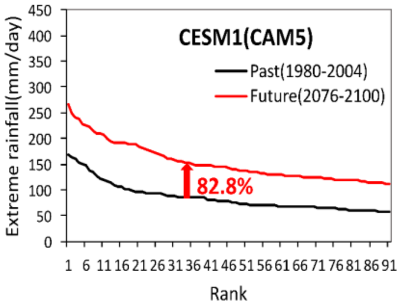


*Figure 5. Extreme daily rainfall change*

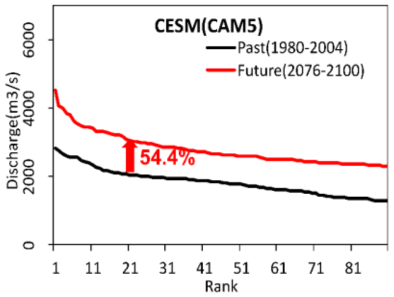


*Figure 6. Extreme daily discharge change*

### 3.2. Flood return period changes

The magnitudes of extreme floods with 10, 50, 100, 200, and 500 year RPs increased by 1.74, 1.67, 1.65, 1.64, and 1.62, respectively. Moreover, the analysis showed that the respective past floods will recur every 1.1 years, 1.7 years, 4 years, 9.1 years, and 16.7 years in the future. The increase in flood magnitudes due to climate change suggests a heightened flood hazard.

### 3.3. Inundation extent changes

The change in inundation extent in the Amochu flood plain in Phuntsholing showed increases of 108%, 84%, 68%, and 49% for 50, 100 (Figure 7), 200, and 500 year RP floods, respectively. Conforming with the increase in flood magnitudes in the future, the inundation extent is also increasing, but the rate of increase decreases with increasing RP, indicating that the flood plain is relatively small and surrounded by mountains, thereby naturally limiting the spread of flooding. More than 1 m inundation depth is considered for the impact assessment of inundation extent and affected population.

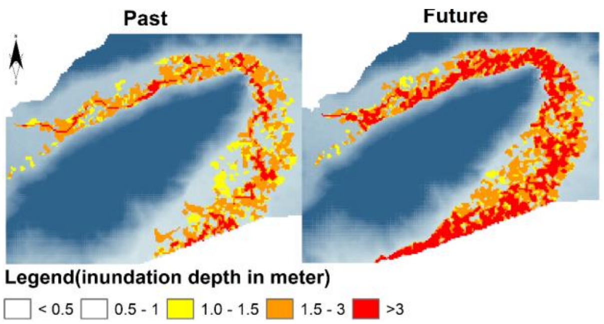


*Figure 7. Change in inundation extent for the 100 year RP flood*

### 3.4. Affected population change

With the increasing extent of inundation, the affected population for the present town will also increase in the future. Table 1 shows the results of the analysis of the number of people affected by different RP floods for the past and future. The increase in affected people ranges from 31% for a 500 year RP flood to 122% for the 50 year RP flood period. This suggests that climate change can have adverse impacts on society due to augmented flood hazards.

*Table 1. Affected population change with the present town conditions*

| Flood | Affected population (nos.) | | |
|---|---|---|---|
| RP | Past climate | Future climate | % Increase |
| 50 | 231 | 513 | 122.08 |
| 100 | 286 | 525 | 83.57 |
| 200 | 340 | 540 | 58.82 |
| 500 | 428 | 563 | 31.54 |

## 4. *Social change impact assessment*

### 4.1. Change in inundation extent with the embankment

The introduction of an embankment in the RRI model resulted in the reduction of the inundation area by 46% for a 500 year RP flood and up to 83% for a 50 year RP flood for the past climate, while in the future climate, the reduction was 23% for a 500 year RP flood and up to 38% for a 50 year RP flood. Figure 8 shows the inundation extent changes for the past and future 100 year RP floods with embankment, resulting in reductions of 69.9% and 25.4%, respectively. This indicates that the embankment cannot fully prevent inundation. However, inland inundation increases in the future, as depicted in Figure 9 with the change in inundation depth in the downstream part of the right bank exceeding 1 m.

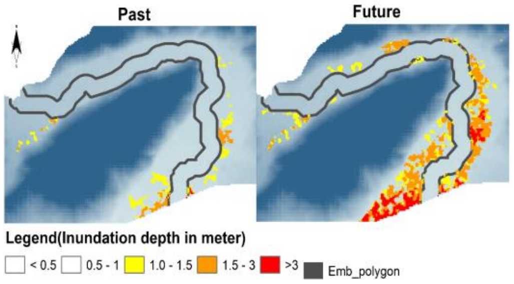


*Figure 8. Inundation extent changes for the past and future 100 RP floods with embankment of height 2.81 m and river width of 300 m*

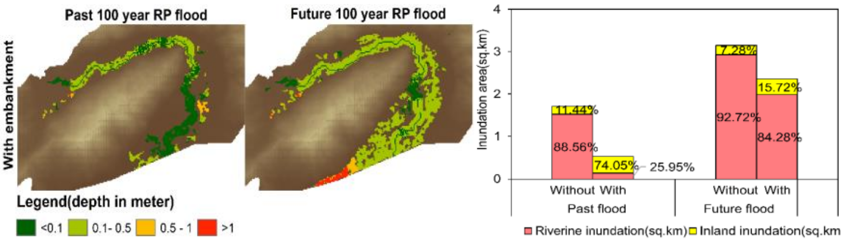


*Figure 9. Inland inundation change between the past and the future with embankment*

### 4.2. Comparison of climate change impact and social change impact

The changes in flood-affected population as per the analysis results are shown in Figure 10 based on the increase in the future population due to Phuntsholing Town expansion, and with and without the construction of embankments. This shows that, for a 100 year RP flood, SCI will affect 46.9% of CCI’s 51.2% without the embankment. With the embankment, it will be 17.9% and 80.6%, respectively; however, the total number of affected people is reduced. It also shows that the proportion of CCI decreases with an increase in the RP, which is caused by the decrease in the percentage increment of flood magnitude and inundation area, in the future as the RP increases. This reveals that the possible extent of inundation in the study area is limited by the increasing flood magnitude due to topography, where the flood plains are surrounded by mountain slopes. This indicates that a certain extreme flood magnitude will inundate to the maximum possible extent, causing maximum damage. Therefore, the need to properly and

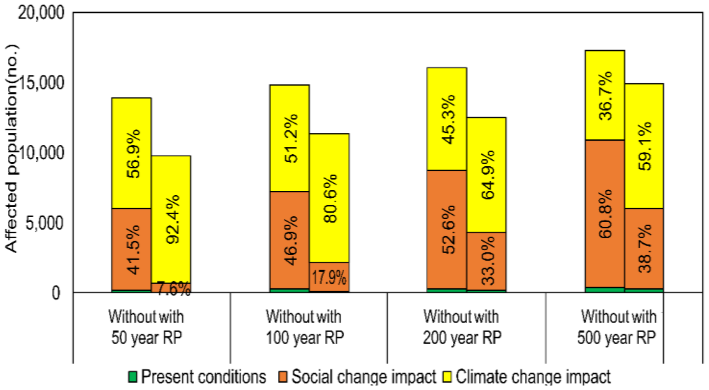


*Figure 10. Comparison of climate change impact and social change impact in terms of affected population*

adequately consider integrated flood risk management under climate and social change scenarios is critical.

### 5. *Transboundary flow contribution*

The average flow contribution from the upstream transboundary catchment in China is 37.3% for annual flow, 36.2% for monsoon flow, and 50.3% for lean flow, as shown in Figure 11. Because the monsoon flow contribution is less than the corresponding catchment area proportion of 50.2%, it indicates that the in-country catchment of 49.8% contributes 63.8%. Thus, flood risk management within an in-country catchment has greater significance. From the hydropower generation perspective, high transboundary flow contribution to low flow is of great significance, which will require transboundary cooperation to manage water resources more efficiently.

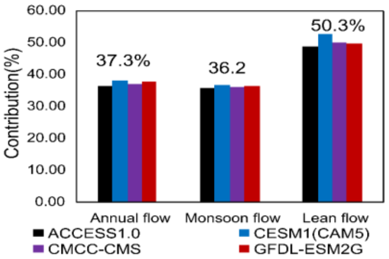


*Figure 11. Flow contribution from the upstream transboundary*

## CONCLUSION AND RECOMMENDATIONS

This study assesses the impacts of climate change and social change on extreme floods in the Amochu Basin in Bhutan. RRI simulations, with bias-corrected rainfall from the four adopted GCMs under the RCP8.5 scenario, resulted in a drastic increase in extreme daily rainfall and discharge in the future compared to the past. The magnitudes of extreme floods with RPs of 10, 50, 100, 200, and 500 years are shown to increase by 1.74, 1.67, 1.65, 1.64, and 1.62 times, respectively. The inundation extent and affected population also subsequently increase in the future due to climate change. Social change further increases the affected population even though the embankment minimizes it. For instance, without the embankment for the 100 year RP floods, 46.9% of the affected population is the result of social change, and 51.2% is due to climate change. On the contrary, embankment reduces the total number of the affected population, which is the effect of the reduced SCI. However, social change still impacts 17.9%, while CCIs increase to 80.6%. From the results, it can be inferred that under the stressed climate, the flood risk will increase in the future for Phuntsholing because of the increased flood hazards and vulnerability. The findings also suggest that a certain extreme magnitude of flooding might inundate almost the entire area. Even though the embankment is effective in mitigating the impact of social change, an adequate drainage system and soft countermeasures such as an early warning system are required to reduce flood risk due to inland inundation. Improved basin rainfall estimation and the use of a more realistic projected population are recommended for a similar SCI assessment of flood risk.

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