DEVELOPMENT OF FLOOD RISK MITIGATION STRATEGIES CONSIDERING CLIMATE CHANGE IMPACT IN THE PARO RIVER BASIN, BHUTAN

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ABSTRACT

Paro valley, located in north-western Bhutan, has a population of 46,316, and the span of Paro river basin area is 1,167 square kilometers. The Paro river, crucial for irrigation, is prone to flooding due to climate change. The basin has faced hydro-meteorological hazards in the past decades due to climate change. The 2009 flooding event and increased river discharges highlight the area's vulnerability to flooding posing a risk to the town, infrastructure, and socioeconomic activity, especially in the airport area, which may further increase due to insufficient flood protection measures. The study assessed the impact of climate change on flooding in Paro valley using General Circulation Models (GCM) and Rainfall-Runoff Inundation (RRI) hydrological models. The past and future rainfall outputs were assessed with Data Integration and Analysis System (DIAS) demonstrating the potential benefits of preventative action. The selected GCMs predictions show a potential rise in extreme rainfall and discharge that could lead to dangerous flash floods in the basin. The study also indicates an increase in inundation areas affected by a large number of populations. Strategies for coping with the scenario were researched by developing inundation maps with a 100-year return period. In addition, mechanisms to assess the impact of floods were devised, and structural and non-structural measures were also recommended because disaster recovery costs are extremely high.

Keywords: climate change, rainfall, flood, damage, inundations.

1. INTRODUCTION

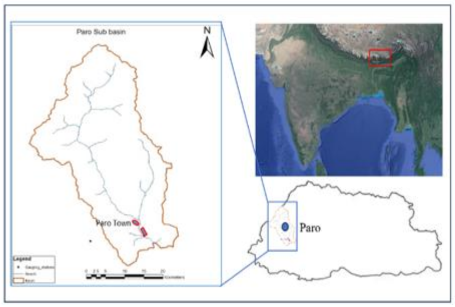

Figure 1. The location of the study area

Bhutan has experienced frequent flooding due to extreme rain, causing billions of dollars in property damage and loss of life. Besides causing fatalities and evictions of populations, floods can destroy buildings, infrastructure, and agricultural land. Floods like Cyclone Aila and monsoon have led to evictions and damage to public infrastructure. The Paro valley experienced flooding in 1968, 1973, 1993, and 2009, causing significant damage to infrastructure and crops (Emmer et al., 2022). In 1968, knee-deep floodwater swamped the town, while in 1993, paddy fields were severely damaged, causing crop loss and income loss. In 2009, Cyclone Aila caused extensive flooding and property damage, posing a threat to the operations of the international airport. Therefore, peak discharge and inundation simulations are essential to lower the risk of flooding. Additionally, damage assessment and socioeconomic evaluation are important for increasing public awareness and reducing mortality and property damage. According to Merz (2021), it is urgent to act now to reduce risks before disasters occur through awareness programs and assessing flood risks. This could involve creating emergency response plans, putting early warning systems in place, and constructing safety infrastructure like levees or dykes. The study was conducted with the following objectives: 1) to analyze extreme rainfall projections in the future as a result of climate change; 2) to assess the potential effects regarding flood-hazard extent; 3) to identify critical places so that risk assessment and socio-economic assessment can be done by giving valuable flood risk

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management insight, and 4) to propose and recommend proper flood mitigation strategies utilizing levees, dykes, and other engineering solutions, as well as the effects of mitigation measures.

2. THEORY AND METHODOLOGY

2.1 The study consists of five steps as shown below to achieve the objectives

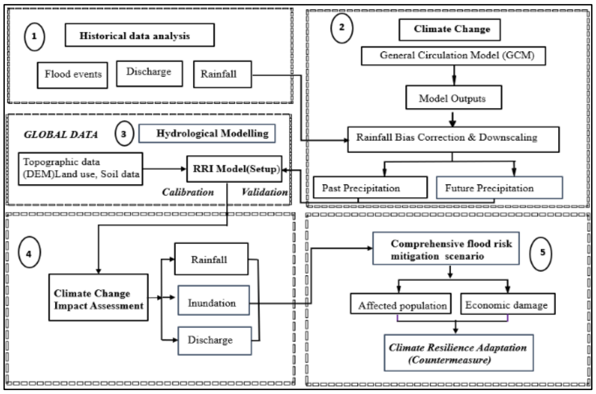

Figure 2. The research framework

1. The study analyzed histological data, including rainfall and discharge, to understand the hydrological behavior of the basin. This data is crucial for Data Integration and Analysis System (DIAS) to understand and process rainfall data. Different return periods are used to consider potential outcomes.
2. For the climate change assessment phase, 25-year rainfall data using DIAS for past and future examinations was assessed. Global circulation models are assessed using histological data, and bias-corrected future projections are used. The selected future projections, including CESM1 (BGC), CMCC-CMS, CNRM-CM5, ACCESS 1.3, and CCSM4, are bias-corrected through statistical downscaling for projection.
3. The study developed hydrological modeling for extreme flooding in the basin due to climate change by calibrating rainfall data of 2022 and validating rainfall data of 2018 and 2019 with the discharge data of Bondey Station.
4. The study calculated General Circulation Models (GCMs) for various return periods using historical rainfall data, applied increase factors to the hyetograph, and projected future floods to understand hydrological behavior in response to extreme weather events.
5. The final phase involved analyzing results and suggesting a Climate Resilience Adaptation (Countermeasure) to mitigate the impacts of climate change on the study basin's hydrological behavior. Identifying areas of vulnerability and developing appropriate adaptation strategies is essential for minimizing the impact of climate change on the area's long-term sustainability.

2.2 Data

One of the most important aspects of any research project is gathering reliable data. Table 1 shows data gathered from different Organizations.

Table 1. Data for the study

Sl. No	Data Type	Remarks	Source
1	Rainfall	1996-2022	NCHM, Bhutan
2	Discharge	2014-2022	NCHM, Bhutan
3	Settlements (Houses)	2019	DHS, MoIT, Bhutan
4	Soil		FAO
5	DEM	90-meter resolution	DHS, MoIT, Bhutan

3. RESULTS AND DISCUSSION

3.1. RRI model Calibration and Validation

The discharge data of Bondey DSC from March to November 2022 was calibrated using the rainfall-runoff-inundation (RRI) model. The simulations were further validated using the discharge data of the same station from March to November for the years 2018 and 2019, respectively. The result simulated was precise due to the model's ability to accurately reproduce the observed stream flow behavior with regard to calibration and validation periods. The NSE value for calibration was 0.712, and the validation values were 0.785 and 0.654, respectively**.** The calibration and validation results are shown in Figure 3.

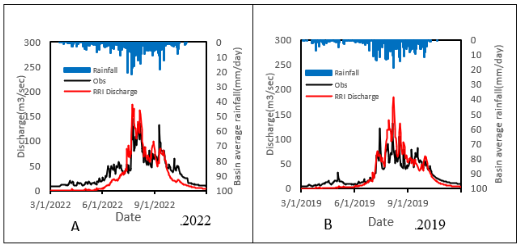

Figure 3. RRI model A) Calibration and B) Validation.

3.2. GCM selection and bias correction

The selection process for GCMs was based on their ability to simulate historical daily rainfall accurately, ensuring that the chosen models effectively represent the regional climate of the study area. The three models (CESM1 (BGC), CMCC-CMS, and CNRM-CM5) with high scores of six points each and two other models (ACCESS1.3 and CCSM4) with four points each were selected. A 43% increase in extreme rainfall for the period 2025–2050 has been recorded for ACCESS 1.3, which is the highest among all other climate models selected in this study for the near future.

3.3. Rainfall analysis

The following analysis was based on rainfall data collected.

1) Annual change in rainfall

Innovative trend analysis of the past rainfall (1996–2022) was done based on annual fluctuations and extremes. The highest annual maximum average rainfall of 104.1 mm/day was recorded in 2009, while 2018 saw the lowest. Annual maximum rain spells data analyzed for 1-day, 2-day, 3-day, 4-day, and 5-day events from 1996 to 2022 at Paro DSC Station recorded the highest rainfall of 107.4 mm/day in 2009 due to Cyclone Aila, with subsequent maximums of 122.4, 136.0, 137.2, and 137.8 mm/day for 2-day, 3-day, 4-day, and 5-day events for the same year. Cyclone Aila caused massive flooding in the Paro river basin in 2009. Thus, both trends indicate that extreme rainfall can cause lowland floods, landslides, and slope failures. Figure 4 shows the annual maximum daily rainfall (1996–2022), and Figure 5 shows the annual maximum rain spell for the Paro DSC Station.

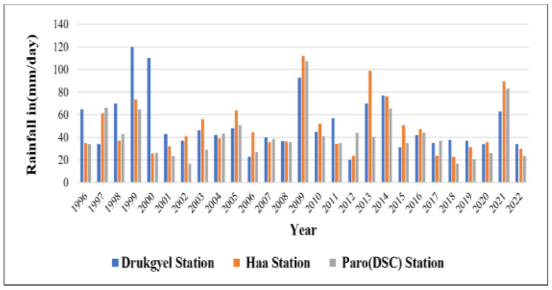

Figure 4. Annual maximum daily rainfall (1996-2022).

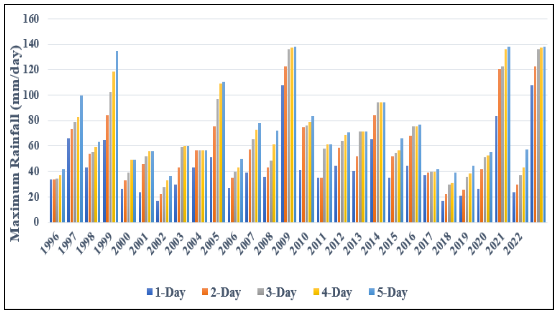

Figure 5. Annual Maximum Rain Spells (Paro DSC)

2) Extreme daily and maximum average rainfall

Figure 6 shows the extreme daily rainfall at Paro DSC for the past and future. Two selected Global Climate Models (GCMs), ACCESS1.3 and CNRM-CM5, were used to compare the changes in extreme daily rainfall for the past and future. The analysis projected an increase in rainfall from 2025 to 2050. The range of increases was 43% for ACCESS1.3 and 13% for CNRM-CM5 Paro DSC station. Trend analysis of past rainfall also revealed an increase in extreme rainfall, increasing the likelihood of flooding in the near future. The ACCESS1.3 model showed an increase of 12%, while the CNRM-CM5 model showed a rise of 11% maximum annual rainfall of the basin, which suggests a trend toward more intense rainfall events in the coming years. Though there is a slight variation in the

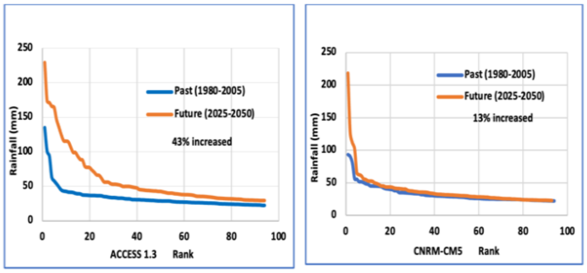

Figure 6. Paro DSC station extreme daily rainfall for past and future

magnitude of the projected increase between the two models, both model results point to an increase in the maximum annual rainfall for the studied stations in the near future. Figure 7 shows the Average annual rainfall for Access 1.3 and CNRM-CM5. The findings indicate possibilities of flooding in the future, which can pose significant hydrological risks, including flash floods, urban floods, and landslides. Effective mitigation and non-mitigation measures are needed to reduce exposure.

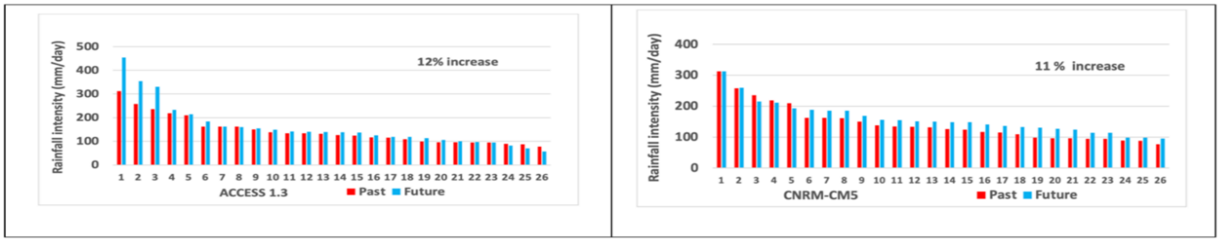

Figure 7. Average annual rainfall for ACCESS1.3 and CNRM-CM5

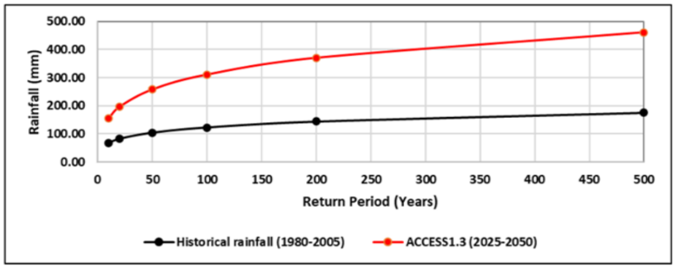

Figure 8. Return period historical and future rainfall

3) Return period

Flood frequency analysis using the Gumbel Extreme Value (GEV) distribution for historical and near-future rainfall for different return periods of 10, 20, 50, 100, 200, and 500 years between the past and future climatic conditions showed an increased magnitude and frequency of rainfall for both ACCESS 1.3 and historical rainfall with an increase in the return periods. The extreme rainfall outputs of ACCESS 1.3 were the highest among all the GCMs, so flood frequency analysis was computed for this climate model to predict future flood events. Increase factors for ACCESS 1.3 showed significant increases in rainfall magnitude for different return periods, as shown in Figure 8. 100-year return periods were used to implement flood prevention measures and adjusted for rainfall models of both historical and future periods. The findings indicated a rise of 1.14 for the historical rain and 1.35 for the near-future climate ACCESS 1.3 model, as illustrated in Table 2, which serves as an important indicator for the preparation of flood inundation maps, socio-economic analysis, and climate change adaptation measures.

Table 2. Design rainfall for historical (1980−2005) and future climate (2025−2050) return period in order

Return Period	Historical Rainfall (1980-2005)	Increase Factor	Future climate (2025-2050)	Increase Factor
50	107.40		229.34	
100	122.54	1.14	310.80	1.35

3.4 Flood simulation for an inundation area.

The study employed RRI simulation to create inundation maps for future events with a 100-year return period. The model was developed by analyzing historical and projected rainfall data, focusing on the international airport area, with a focus on investigating flooding and inundation levels due to climate change. The study indicated inundation in lower-elevation valleys, especially in airport areas, due to flat, low-lying areas near the river, as shown in Figure 9. The occurrence of inundation could be due to the increase in rainfall intensity and river discharge, which could trigger flash floods in the basin that can have adverse effects on daily activities and cause socio-economic losses.

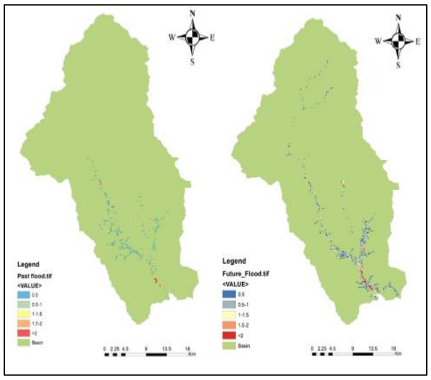

Figure 9. Inundation map of Paro River basin for past and future (100 Return period)

3.5 Damage assessment

Damage was computed using Wisconsin guidelines. The study revealed that floods in the past have significantly impacted airport and town center as illustrated in Figure 10. Further, 7.7 km of roads were damaged, which is projected to increase to 12.28 km in the future; 823 houses in the rural were inundated in the past and the number is expected to increase to 1823 in the future; and 329 hectares of agricultural land were affected, which will increase to 597.42 hectares. This entails a need for mitigation measures such as flood protection infrastructure and emergency response plans for the community's safety, particularly the airport. Flood damage assessments are also key for raising awareness of flood risks and closing the gap between perceived and actual risks (Driessen et al., 2018). Therefore, prioritized flood protection areas are identified, and necessary recommendations are made based on national significance, initial development costs, and flood inundation extent.

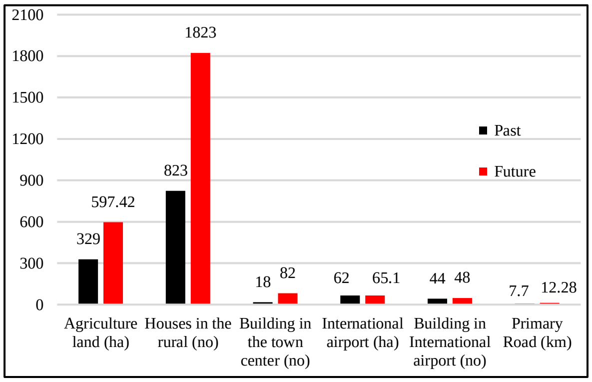

Figure 10. The inundation graph of Paro basin

3.6 Socio-Economic Impact Assessment

A socioeconomic impact assessment was conducted, with the assumption of four people in the rural area per house. As per the National Statistics Bureau -2017 survey, 44 people were found occupying one building in town centers, with a 0.02% annual growth rate in Paro. Based on these statistics, the affected population was estimated. Table 3 shows the affected population in the basin.

Table 3. Affected population in the basin as per the flood inundation map

Sl. No	Inundation information (threshold of 0.5m)	Affected by past flood	Amount (USD)	Affected by future flood	Amount (USD)
1	Agriculture land	329	117,433.26	597.42	213,182.15
2	Houses in the rural	823	10,721,141.71	1823	23,897,262.90
3	Building in the town center	18	417,072.16	82	1,899,995.44
4	Building in the airport area	44	1,643,011.57	48	1,396,559.84
5	Primary road	7.7	10,626.00	12.28	16,946.40

Figure 11 illustrates the impact of flooding on population and buildings in the past and future based on a 100-year return period. The analysis found that floods had the greatest impact on the international airport, both in the past and in the future. On the other hand, the impact of floods in the town center will be nearly four times greater than in the past, and twice as great in the rural area. As a result, the analysis indicates that the cost of impact due to flooding in the river basin will be twice as high as the initial expenditure. Floods are the costliest natural hazards, causing up to 50,000 deaths and affecting 75 million people annually (Mwape, 2009). The study highlights the importance of robust structures upstream of the airport, a levee for the primary road, and an aesthetic design mitigation structure for the town center. Discontinuing levees on rural residential and agricultural land is recommended for economic viability and cost-effectiveness. Revetment structures, made from concrete, stones, or geotextiles, are recommended for flood control and erosion prevention along riverbanks.

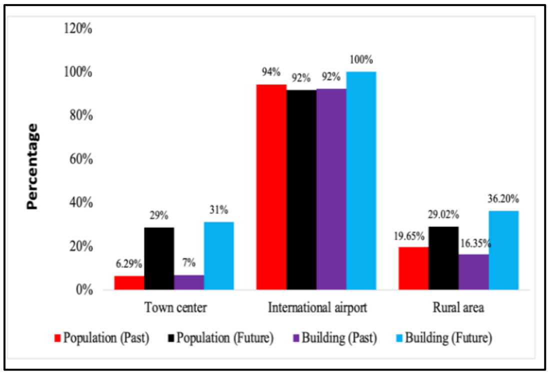

Figure 11. Impact on population and buildings for past and future floods.

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 models to simulate the basin-scale hydrological response under climate change scenarios. Paro district has experienced significant urbanization and socioeconomic development in the past decade. However, the climate change impact assessment showed an increased risk of flooding and subsequent consequences in the basin. Increases of at least 43% in extreme daily rainfall and 12% in the maximum annual rainfall of the basin were presented by most of the GCM outputs. The high intensity of the rainfall was indicated by the observation of the inundation areas, which would double over time as the afflicted population in the Paro river basin increased. Effective flood mitigation measures are recommended along the basin's most vulnerable sections, which will alert the communities of the potential occurrence of major flash floods upstream. Structural damage costs are also expected to increase twice in future floods for the same return period. Climate change is expected to increase the flood risk, therefore, necessitating an end-to-end approach like flood protection structures, flood zoning, stakeholder capacity building, and awareness programs is essential to reduce dangers and ensure safety.

5. RECOMMENDATIONS

The limited time prevented intricate structures from being included, necessitating extra modeling exercises. Further study can be conducted to evaluate the effectiveness of flood protection structures and their effects on inundation levels, thereby providing insights into suitable structures for specific areas. Future researchers can assess the efficacy of flood protection technologies and identify the best structures for study-area locations. Moreover, it is critical to strengthen non-structural safeguards such as flood zoning, stakeholder capacity building, forecasting, and evacuation. Policymakers should prioritize climate-resilient mitigation measures and invest in disaster prevention strategies using incentives to reduce natural and man-made disasters.

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