ASSESSMENT OF INTEGRATED WATER RESOURCES MANAGEMENT UNDER CLIMATE CHANGE IN WANGCHU BASIN, BHUTAN

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ABSTRACT

Wangchu Basin, located in the western part of Bhutan, is an area of significant socio-economic importance. With 30% of Bhutan's population and most of its agricultural lands being located here, this basin is also the site for two major hydroelectric projects. Significant variability in precipitation patterns in the basin causes periods of flash floods and dry spells. We assessed the impact of climate change on the water resources of Wangchu Basin using general circulation models (GCMs) and hydrological simulations using the water and energy budget of rainfall-runoff inundation model (WEB-RRI). Analysis results project an increase in future rainfall and discharge, indicating that power generation and agricultural production can be enhanced. However, a pronounced increase in discharge during the rainy season also highlights the increased risk of flooding. To mitigate this risk, the implementation of both soft and hard components of flood countermeasures is necessary.

Keywords: climate change, general circulation models, WEB-RRI, hydropower

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1. INTRODUCTION

The Wangchu Basin is located in the western part of Bhutan (89°6'–89°46'E, 27°6'–27°51'N), covering approximately 4,596 km². The elevation of the basin (above mean sea level) ranges from 150 m in the south to 6,500 m in the north. 30% of the population of Bhutan lives this basin area, making it the most populated region of Bhutan. Wangchu Basin accounts for 10% of forest land, 12.1% of agricultural area, 9.2% of wetlands and 12.3% of livestock of Bhutan (Xue *et al.*, 2013), and it is a political, economic, and tourist hub of the country.

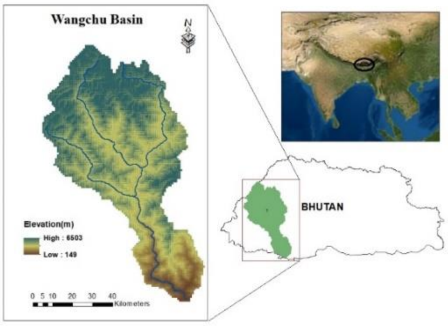

Figure 1. Study area

An assessment for the Wangchu Basin by NEC (2016) concluded that climate change would result in higher temperatures with more erratic and intensive rainfall during the monsoon (rainy) season. Bhutan's primary focus on economic development through hydropower and agriculture has overlooked the impact of climate change Owing to limitations in technical capacity and the unavailability of assessment tools, very few studies have investigated the impact of climate change on water resources. Seasonal shortages and degradation of water resources due to climate change have been observed in the Wangchu Basin (NEC, 2016). Flooding occurs whenever there is heavy and continuous rainfall in the basin, causing widespread damage. Climate change is expected to cause higher temperatures, thereby raising the mean annual average temperature. Significant changes in precipitation patterns, with erratic and variable rainfall during pre- and post-monsoon season has caused flash floods and dry spells. This has been detrimental to agriculture, hydropower, and domestic water supply, which are highly susceptible to seasonal changes in water availability, floods, and landslides. The Wangchu Basin feeds water to two hydropower plants: CHPC (315 MW) and Tala (1020 MW). During the rainy season there

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is sufficient flow to propel all turbines from June to October. From November to April, not all turbines can be operated, and around February, the flow may be insufficient to drive even one turbine (NEC, 2016), demonstrating that the high seasonal variability in streamflow limits the efficiency of power generation. Under climate change, the extremes in the river flow will determine the socioeconomic conditions and resilience of the nation.

This study assessed climate change impacts on water resources in the Wangchu Basin to support policymakers in decision-making. We employed the data integration and analysis system (DIAS) developed by the University of Tokyo to process the high-volume data from GCMs and identify models with the best regional performance for bias correction and downscaling. We used the WEB-RRI to simulate and project future hydrological processes and water availability. This model accepts additional inputs, such as radiation, temperature, humidity, wind speed, and leaf area index, in addition to precipitation and generates reliable estimates of the water budget variability as well as climate change scenarios that can be used for long-term simulation and assessing hydrological extremes in a catchment with high confidence.

2 DATA AND METHODOLOGY

The methodology consisted of four main sections (Fig. 2), as detailed below. Past climate assessment of rainfall and discharge was carried out in this section. Our main focus was to analyze the variations in past and projected future climates. For this assessment, we used rainfall and discharge data for the period 1996–2020 sourced from the NCHM, Bhutan. The hydro-meteorological data were examined for basic climate change signals.

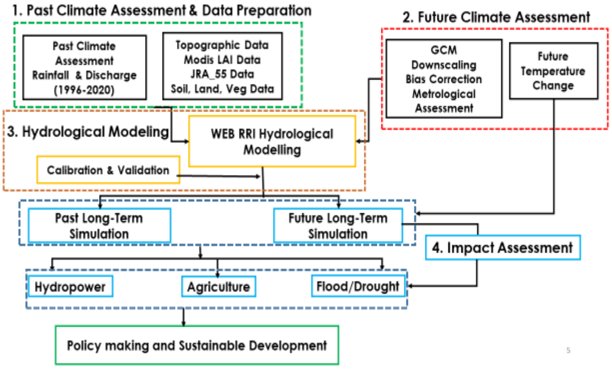

Figure 2. Methodology

Simulations of general circulation models (GCMs) are generally used to assess climate change (Khan *et al.*, 2018). To develop future climate projections, we selected appropriate GCMs using the platform on the Coupled Model Inter-comparison Project Phase (CMIP 5) data for the periods 1986–2005 and 2025–2044. Regional- or local-scale circulation studies require that the bias in GCMs be removed (Nyunt *et al.*, 2013). We therefore used the observed rainfall data for the period 1996–2020 for bias-correction and downscaling of the past (1986–2005) and future (2025–2044) climate projections. Accordingly, we selected four GCMs, namely, ACCESS1.0, CMCC-CMS, GFDL-ESM2M, and MPI-ESM-LR, for climate change assessment in the Wangchu Basin.

The WEB RRI model, which can estimate low flow, flood onset timing, peak flood discharge, and inundation extent, was used to simulate the observed and future climate scenarios (Rasmy *et al.*, 2019). The model was set up with inputs of the hydrological, meteorological, and topographical data from different sources (Table 1).

Table 1. Input Data for WEB-RRI

DATA	SOURCE	REMARKS
Discharge	NCHM, Bhutan	Period 1996–2020
Rainfall	NCHM, Bhutan	Period 1996–2020
Soil unit	FAO	-
DEM	USGS (http://hydrosheds.cr.usgs.gov/index.php)	2 km resolution
Land Use	GLCC (http://edc2.usgs.gov/glcc/glcc/php	1 km resolution
LAI/ FPAR	NASA (http://search.earthdata.nasa.gov)	500 m grid
JRA-55	JMA (Japan Meteorological Agency)	3h temporal resolution

For this study, we selected the time period 1/1/2006 to 1/1/2009 for calibration to capture the highest peak of discharge due to cyclone Aila, recorded on 05/25/2009. The model was also calibrated to capture the low flow values. The validation period of the model was selected as 2002–2006 for the same station. The model performed well within an allowable range of NSE 0.52 for calibration and NSE 0.61 for validation (Fig. 3). However, calibration was challenging owing to the localized rainfall and the time lag in melting of snow during the winter.

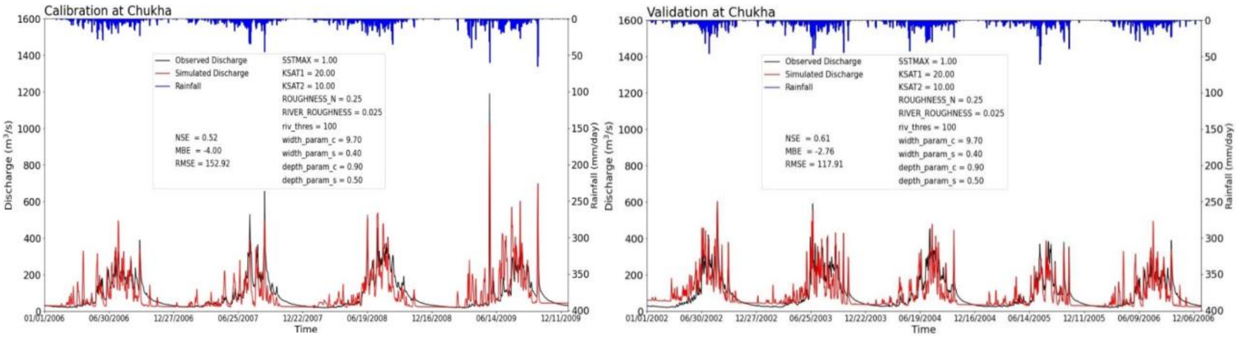

Figure 3. Calibration and Validation at Chukha Station

3. RESULTS AND DISCUSSION

3.1.1 Past Climate Change Analysis (Dry- and wet spell analysis):

Results suggest that the frequency of short-duration dry spells increase during the period 1996–2020, and the number of dry spells of medium- and long duration decreased (Fig. 4). This implies that in future, more rainy days and fewer longer-duration dry spells are likely to occur, indicating a reduction in drought events. The projected increase in the wet period indicates a greater possibility of flood events. This was further evidenced with the GCM climate model showing the number of extreme rain days compared with the observed (rainfall exceeding 20mm) also increase with double the fold (Fig.4a)

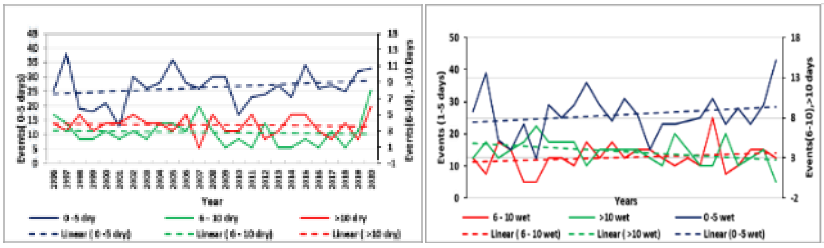

Figure 4. Dry spell and wet spell analysis for the Wangchu Basin

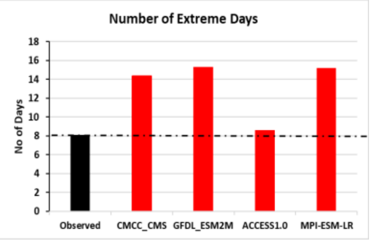

Figure 4a. No of extreme rainy days for GCMs

3.1.2 Innovative Trend Analysis

The innovative trend analysis represents the pattern of precipitation during the periods 1996–2007 and 2008–2020 for the Wangchu Basin (Fig. 5). Analysis was conducted with two equal-sized datasets representing the distant past and recent past, respectively. The results of the innovative trend analysis illustrate that there is no change in rainfall events of intensity ≤20 mm. However, the number of extreme rainfall events of high intensity is projected to increase, indicating more flood events.

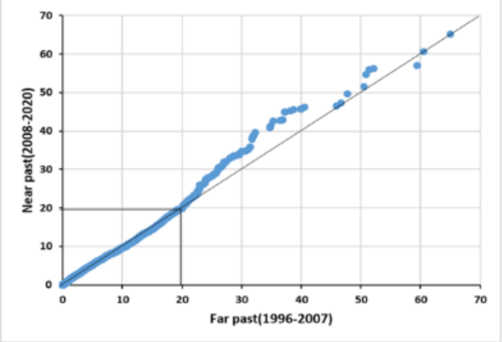

Figure 5. Innovative trend Analysis

3.2 Future Climate Assessment

3.2.1 Rainfall Analysis

We analyzed climate models with 20-year simulation periods both for the past (1986–2005) and future (2025–2044) for the RCP8.5 scenarios. By comparing the projected rainfall for each selected GCM, we found that three models (CMCC-CMS, GFDL-ESM2M, and MPI-ESM-LR) predicted a 22–30.31% increase in rainfall in the future (Fig. 6a). The ACCESS1.0 model predicted a slight decrease (-3.79%) in rainfall. Upon investigating in DIAS vis-a-vis the pressure field, we observed a domain fall under very high divergence in future, indicating that rainfall will decrease significantly (Fig. 6b). With regard to the meridional wind field, a domain fall in the south wind appears dominant in future, but only marginally, thereby indicating that rainfall will increase slightly (Fig. 6c). The combined effects of these factors based on GCM projections are considered to show a marginal decrease in rainfall. As per the past climate (wet- and dry spell) analysis, increased numbers of rainy days were estimated to occur in the recent past. We therefore conclude that on the whole, rainfall in the basin is likely to increase.

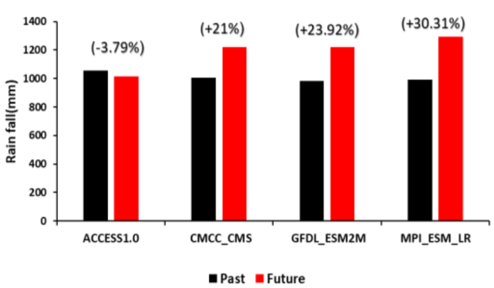

Figure 6a. Annual Average Rainfall for GCMs

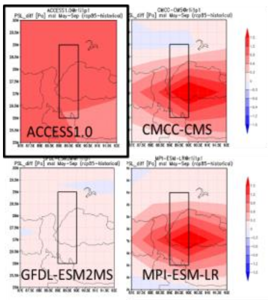

Figure 6b. Pressure field(future-past)

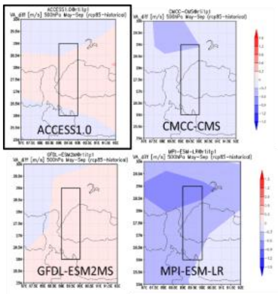

Figure 6c. Meridional wind field(future-past)

3.2.2 Extreme Rainfall Analysis

We analyzed rainfall extremes based on past climate data and the model-projected future rainfall. Three climate models CMCC-CMS, GFDL-ESM2M, and MPI-ESM-LR, predicted increases in extreme rainfall events in the future, with as much as 130–240 mm of rainfall per day. Contrarily, the ACCESS1.0 model predicted a decrease in extreme events due to decreased rainfall. However, past climate analysis and innovative trend analysis also suggest an increase in extreme rainfall events in the basin, signifying more frequent floods in the future.

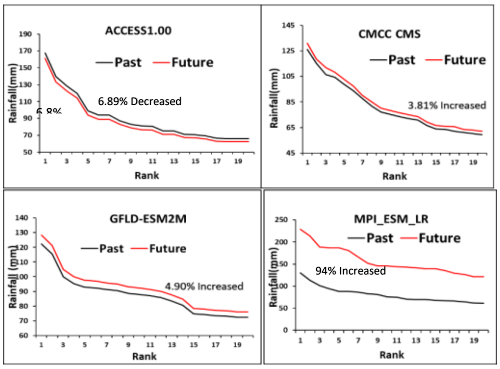

Figure 7. Extreme rainfall for GCM models

3.2.3 Monthly Average Rainfall Analysis

The projected change (future minus past) in monthly average rainfall varied among the climate models selected for analysis (Fig. 8). While all models predicted an increase in rainfall, the patterns varied in each. There was no consistency in the increase in rainfall throughout the monsoon, and a seasonal variation was predicted. The increase in the rainfall during the monsoon will benefit the rain-fed Agriculture in the basin since Bhutan is a mountainous country with rough topography and agriculture is being practiced

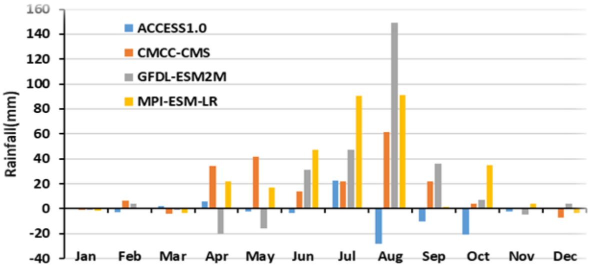

Figure 8. Monthly Average. Rainfall for GCMs difference(Future minus Past)

on the slop depending on rain-fed irrigation. Excessive water during peak monsoon can be harvested and used during pre and post-monsoon for rain-fed agriculture

3.2.4 Discharge Analysis We compared the river discharge values projected by the climate models with the actual discharge observations recorded at the Chukha station (Fig. 9a). All the models predicted that discharge will increase by 14–30%, corresponding to the projected increase in rainfall in the future. However, the ACCESS model predicted an 8.77% decrease in discharge corresponding to a decrease in rainfall. All models predicted increase in discharge during the pre-monsoon (low flow), monsoon, and post-monsoon (low flow) seasons, except ACCESS1.0, which predicted decreases during peak and post-monsoon (low flow). Hence, we can conclude that the discharge will likely increase in the future, and changes in the seasonal pattern of increase in discharge during the month preceding the post-monsoon period will enable to enhance the agricultural activities and the Hydropower energy in the basin.

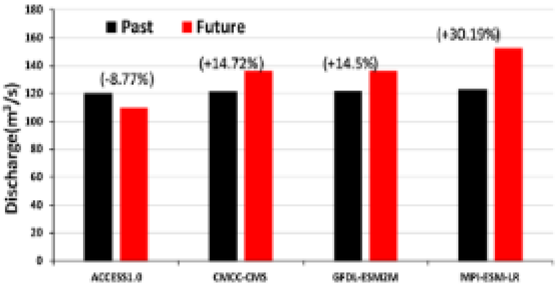

Figure 9a. Annual Average Discharge for GCMs

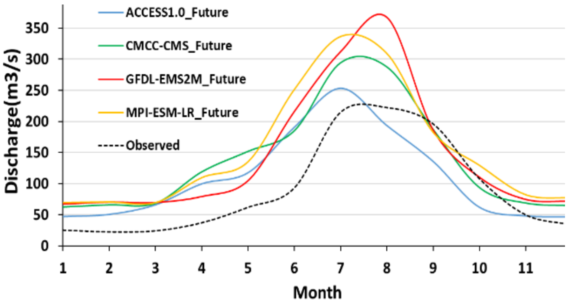

Figure 9b. Seasonal Discharge for GCMs

3.3 Investigations on Dam Operations

The hydropower projects at Chukha and Tala, based in the Wangchu Basin, generate 336 MW and 1020 MW power, respectively. Only 40% of the total flow is utilizing under the current climatic condition, which can generate only 60% of the total capacity due to seasonal variation of discharge (low discharge during per and post monsoon). Under the climate change condition, the future discharge of the climate model(GFDL-EMS2M) predicts to increase the inflow stream discharge by 40% and the power generation can be increased from 60% to 80% without intervention due to an increase in the low flow (Ref fig. 10a & 10b). To generate a full capacity of both the power plants, additional water storage of 720MCM and 1234MCM will be required for Chukha and Tala Dam, respectively. Due to challenging topography, it is proposed to investigate the feasibility to construct the additional dam with a capacity of 720MCM, which will help Chukha Dam to generate power to its 100% capacity and increase the power generation of Tala hydropower by 25% from existing power generation. This proposal will not only enhance the revenue of the country in the future, but it will also control flood disasters in downstream areas bordering with India.

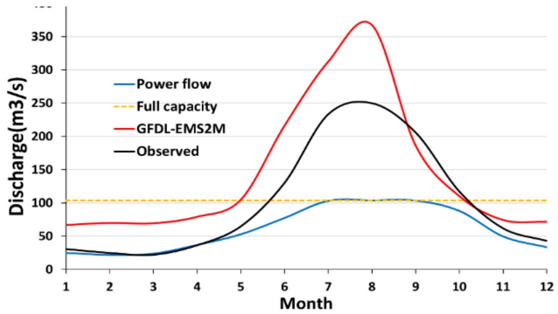

Figure 10a. Chukha Dam Inflow and power flow

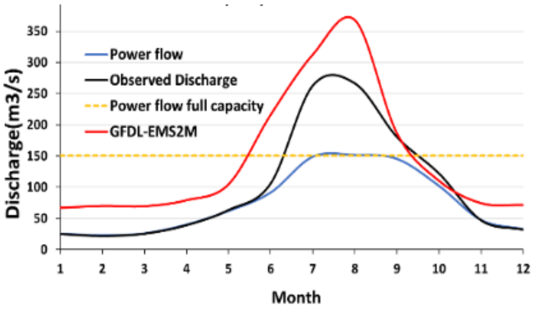

Figure 10b. Tala Dam Inflow and Power flow

3.4 Scientific Evidence-based Data for Policy and Decision-making

The basin-scale annual assessments of rainfall and discharge are summarized below. Policymakers can utilize this information to make decisions regarding disaster risk management. Increases in extreme rainfall and floods will cause increases in disasters and water resources availability in the future. The volume of excess water during the monsoon period will increase and potentially cause damage downstream through dam spillage. Hence, it is advisable to utilize the excess spillage to generate additional hydropower and, simultaneously implement both soft and hard countermeasures against floods to minimize the damage and increase the efficiency of water usage.

Table 2 likelihood annual assessment of rainfall and discharge

Assessment for future	Level of confidence
Rainfall	Likely to increase
Extreme Rainfall	Likely to increase
Discharge	Likely to increase
Floods	Likely to increase
Temperature	Extremely likely to increase

4. CONCLUSIONS AND RECOMMENDATIONS

This study incorporated recent advancements in science and technology by using selected GCMs based on their regional performances and developing a WEB-RRI model to simulate the basin-level hydrological response under climate change. This will enable evidence-based decision-making and sustainable utilization of water resources in the Wangchu Basin. Analysis of past rainfall patterns indicates an increase in the number of wet days and a reduction in the number of dry days. Bias-corrected results from the future climate change model indicates increases in average annual temperature (+1.2°C) and annual rainfall (130–160 mm). Policymakers should therefore strategically plan and review the rain fed irrigation practices. Analysis results project an increase in future rainfall and discharge, indicating that power generation and agricultural production can be enhanced. However, a pronounced increase in discharge during the rainy season also highlights the increased risk of flooding. Hence, policymakers should plan disaster-mitigation measures through soft and hard countermeasures such as utilizing excess water through additional reservoirs to harness hydropower, which would simultaneously help control downstream floods.

5. ACKNOWLEDGMENT

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