Climate change and water resources in Bhutan

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Abstract
Bhutan is a carbon negative country; however, we are vulnerable to climate change and the impacts of climate change on water resources, agriculture, water hazards such as flash floods, incessant rainfall induces landslides are evident in the country. Water also plays a crucial role in driving some of the major economic sectors of Bhutan.

Hydropower is a climate-sensitive sector as it is completely reliant on water levels and flows in the rivers, which is variable depending on good monsoon years. Threats from climate change may impact the hydrological regime and electricity generation from hydropower. The agriculture sector consumes over 90% of the water resources and employs more than half of the population of Bhutan.

In line with global projections, wet regions will continue to get wetter and dry regions will continue to get drier in Bhutan. The already water-stressed areas may be expected to

further exacerbate in the future. An increase and shift in the overall snow and glacial melts is expected due to the implication of increase/ shift in temperature, this will in turn affect river flow. There will be a higher chance of reduced flow during warm and dry periods and flooding threats during monsoon season. Bhutan is highly vulnerable to the threats of GLOFs since most of the human settlements and major economic activities are located along the main drainage basins.
As Bhutan's way forward to a climate resilient society, numerous projects and policies are in place through proper planning and readiness which also proposes short-, medium-, and long-term adaptation measures for various key climate sectors. Agonisingly, they are few and far between leaving the country vulnerable to the threats of climate change leading to too little water in lean season and too much water in summer season.

Keywords: Bhutan, climate change, water resources, water hazard

1. Introduction

The Kingdom of Bhutan is a landlocked country bordered by China to the north and India to the south. Bhutan occupies an area of 38,394 km^2 and has a total population of 735,553 (NSB, 2017). The climate varies by altitude from alpine to subtropical and is strongly influenced by monsoons. Bhutan is endowed with enormous water resources, they are best described in terms of glaciers, glacial lakes, and high-altitude wetlands, rivers, and river basins, and groundwater and reservoirs. Bhutan has one of the highest per capita availability of water in the world, an average flow of 2,238 m^3/s.

Most of the main rivers and tributaries of these main rivers in Bhutan provide water for hydropower use, tourism/recreation, domestic water supply, industry, ecological needs, and irrigation. Water also plays a crucial role in driving some of the major economic sectors of Bhutan. The agriculture sector consumes over 90% of the water resources, employs 62.2% of the population (PHCB, 2017,) and contributes 15.82% to the country's GDP (NSB, 2020).

The hydropower plants contribute significantly to the overall GDP growth, it has contributed 19.45% of domestic revenue, 34.15% of total export earnings and 8% of GDP in 2016 (RMA, 2017). In 2019, the percentage share of GDP by electricity was 12.69 (NSB, 2020). With the development of hydropower, it has not only helped the domestic sectors with improved livelihoods, but the industrial sector has also been thriving rapidly. It has driven economic growth and greatly boosted progress in meeting many of the country's social-economic development objectives.

The Covid-19 pandemic has disturbed all import and export trades in the country but the country's biggest export, hydropower has not been affected. The overall generation of the DGPC power plants that include Tala, Chhukha, Basochhu, and Kurichhu has increased by 14%, 3,724 MU of hydropower was generated from January to July in 2020 as compared to 3,248 MU in the same period in 2019 (Kuensel, 2020, b).

1.1 River Basins and Water availability in Bhutan

Bhutan has five main river basins namely Amochhu, Wangchhu, Punatsangchhu, Mangdechhu and Drangmechhu as shown in Figure 1. The minor basins are Jaldakha, Aiechhu, Jomori, Merak-Sakteng chhu and Nyera Amari.

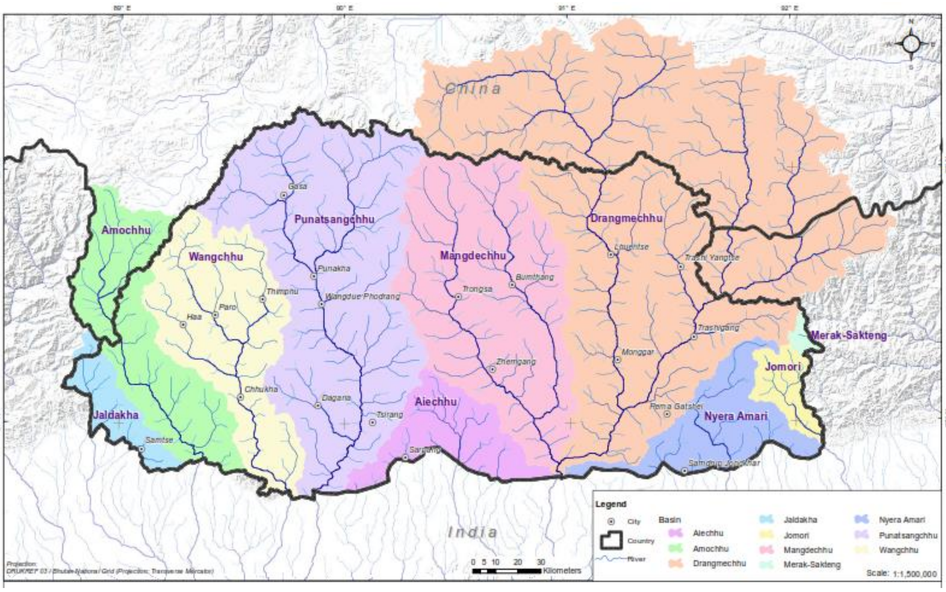

Figure 1 River Basins of Bhutan

The Punatsangchhu is the largest basin in Bhutan with an area of 9,645 km^2 and encompasses the rivers of Phochhu, MoChhu, Dangchhu, and Dagachhu. The Drangmechhu basin has an area of 8,457 km^2 within Bhutan. It has two trans-boundary tributaries of Kurichhu from China and Gongri from China and India in the North. The main tributaries are Khomachhu, Sherichhu, Kholongchhu, and Gamri rivers. The river basins of Nikachhu, Durchhu, Mangedechhu, and Chamkarchhu in the districts of Bumthang, Trongsa, Zhemgang, and parts of Wangduephodrang form the Mangedechhu basin. The total area of the basin is 7,380 km^2. The Wangchhu basin has an area of 4,596 km^2, the rivers include Parochhu, Thimphuchhu, Haachhu, and Pippingchhu. The Wangchhu is considered one of the most important basins in the country with the highest population and economic activities. The Amochhu is the smallest of the main basins with an area of 3,252 km^2. It consists of the transboundary Amochhu river that originates from China and other rivers such as Jaldakha, Tendu, and Bindu Khola. The Aiechhu basin has an area of 1,937 km^2 and it is considered part of the Punatsangchhu management basin.

Bhutan has abundant water resources, which are mostly in the form of rivers. Bhutan has around 3,182 rivers and rivulets with a total length of 4,741 km. The average flow in Bhutan is 2,238 m^3/s while the total annual water volume is 70,576.02 MCM (Million Cubic Meter) and per capita, water availability is 94,500 m^3/capita/annum, the highest in the region (NEC, 2016). The maximum extra flow is in the month of July, while the minimum is in between the months of December, January, and February. The total annual flow generated in the Amochhu basin is 9,375.07 MCM, Wangchhu basin is 5,209.06 MCM, Punatsangchhu basin is 19,129.79 MCM, Aiechhu basin is 6,989.14 MCM, Mangdechhu basin is 11,797.24 MCM and the combination of Nyera Amari chhu with Jomori and Merak-Sakteng basin has an annual flow of 4,506.57 MCM (NEC, 2016). Some 88% of annual precipitation from monsoon and pre-monsoon make up the major portion of water

Table 1 River basin flows of Bhutan (NECS, 2016)

Management Basin	**Area (km²)**	**River Basins**	**Area (km²)**	**Annual flow (MCM)**
Amochhu	3,252	Jaldakha	942	2,715.64
		Amochhu	2,310	6,659.36
Wangchhu	4,596	Wangchhu	4,596	5,209.06
Punatsangchhu	11,582	Punatsangchhu	9,645	19,129.79
		Aiechhu	1,937	6,989.14
Mangdechhu	7,380	Mangdechhu	7,380	11,797.24
Drangmechhu	11,584	Drangmechhu	8,457	13,569.14
		Nyera Amari	2,348	3,383.89
		Jomori	642	925.24
		Merak - Sakteng	137	197.44
Total	**38,394**	**Total**	**38,394**	**70,576.01**
		Population		**746,773**
	Per Capita Water Available		**94,508.04 m^3/ Annum**	
	Flow		**2,238.0 m^3/s**	

volume in the basins. Table 1 shows the net outflow per basin annually.

2. Climate change in Bhutan

An analysis of trends in climate parameters using Climate Research Unit (CRU) data for the country from 1976 to 2005 showed an increasing trend in temperature and decreasing trend in rainfall at mean annual scales with high variability. The mean annual temperature has increased by 0.8 degrees Celsius. The seasonal temperature has increased as well, with the highest increase during the winter months by 1.3 degrees (NCHM, 2019). The seasonal rainfall trends reveal a wet summer monsoon and dry winter season. The spatial variation between the regions has been observed with much higher rainfall in the southern belt of the country.

Under the RCP 4.5 scenario, the climate projection for surface temperature indicates an increase of about 0.8°C – 1.6°C during 2021-2050 and about 1.6°C – 2.8°C towards the end of the century (2070-2099). Overall, the climate projection of surface temperature under the RCP4.5 scenario indicated an increase of about 0.8°C – 2.8°C during 2021-2100. Larger warming is indicated during March, April, May, and December, January, February seasons. The country is expected to experience an increase in temperature with a larger increase projected in the high lands. Under the RCP 8.5 scenario, the climate projection for surface temperature indicated an increase of about 0.8°C – 2.0°C during 2021-2050 and an increase of about 3.2°C towards the end of the century (2070-2099) (NEC, 2020).

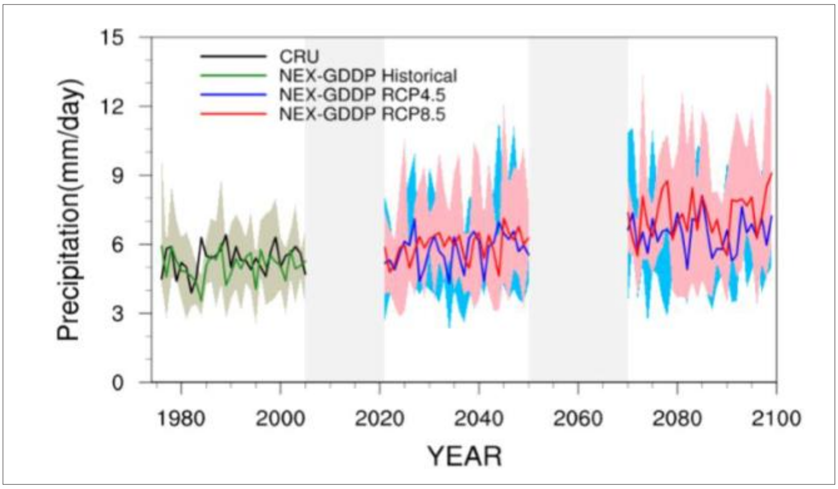

Figure 2 Historic and future precipitation trends based on the NEX-GDDP and CRU data (NCHM, 2019)

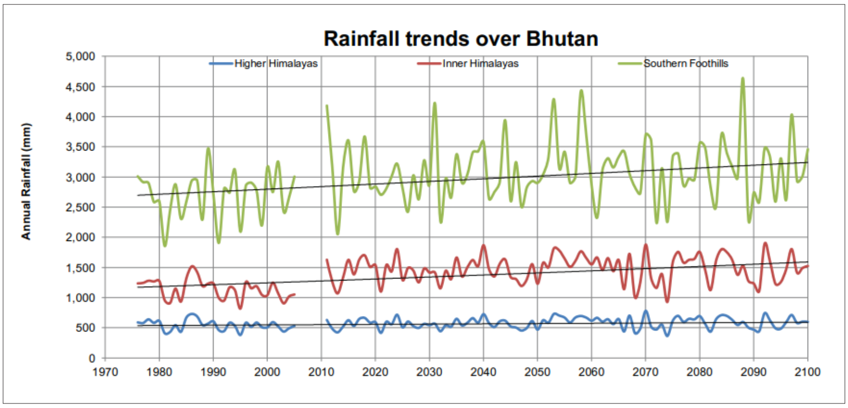

Figure 3 Historic and future temperature trends based on the NEX-GDDP and CRU data (NCHM, 2019)

Precipitation trends for mid-century indicate a potential increase of 5-15% (RCP4.5) or 10-20% (RCP8.5). A marginal decrease towards the end of the century (2070-2099) in rainfall can be expected under the RCP4.5 scenario, while under the RCP8.5 scenario a 30% increase all over Bhutan towards the end of the century may be expected. The projections suggest increasing rainfall during the summer (June, July, August, and September) and winter (December, January, and February) seasons are likely to receive a decrease in rainfall in some parts of the country, in the northwestern region of Bhutan (NEC, 2020).

Although the underlying data are quite uncertain the emerging trends and spatial and temporal patterns are suggesting that the wet regions will continue to get wetter and dry regions will continue to get drier, which is in line with global projections. Hence the already water-stressed areas may be expected to further exacerbate in the future.

2.1 Water sources

The trends of total annual rainfall in almost all the stations are showing a negative slope indicating a decrease in total rainfall which confirms cases of drying up of water sources across the country (ADB, 2016).

A total of 6555 water sources were mapped during the recent nationwide water source inventory to measure the extent of the water sources drying phenomenon across the country by the Watershed Management Division (WMD) in collaboration with the field offices in 2019. About 35 % (2317) of the water sources are in drying condition and 2 % (147) in dried-up condition. The remaining 63 % (4091) are in similar condition as previous years (no changes in the status of the water sources). The water sources are used mainly for drinking, irrigation and hold spiritual and religious importance for communities. 50 listed water sources mainly springs are used for drinking and 39 for irrigation purposes. 14 water sources are used for both drinking and irrigation which are a mixture of springs and streams. No clear structural assessment of the reasons for drying was presented although in most assessed springs mismanagement seems to be the main problem, like deforestation.

A lake in Sarpang had dried up which was mainly due to the alignment work of power transmission lines (WMD, 2020). Examples of springs drying up exist in Lower Shaba, Shaba, and Lholing villages of Shaba Gewog, Paro was attributed to the forest fire and excessive use of forest resources, climate change, or developmental activities (NEC, 2020).

Drying of water sources is one phenomenon of watershed degradation that result in the loss of value over time, including the productive potential of land and water, accompanied by marked changes in the hydrological behavior of a river system resulting in inferior quality, quantity, and timing of waterflow (FAO, 1990). The Trashi Yangtse Dzongkhang has the highest area of degraded watershed (1209 km^2) followed by Thimphu Dzongkhang (855 km^2) while Dagana Dzongkhag has the least area of degraded watershed (81.7 km^2). Figure 4 shows the status of watersheds in the districts of Bhutan.

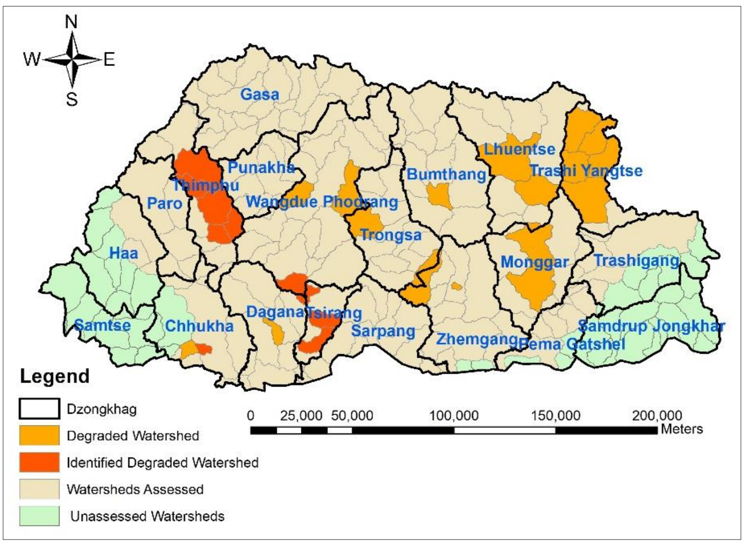

Figure 4 Map showing critical watersheds in Bhutan

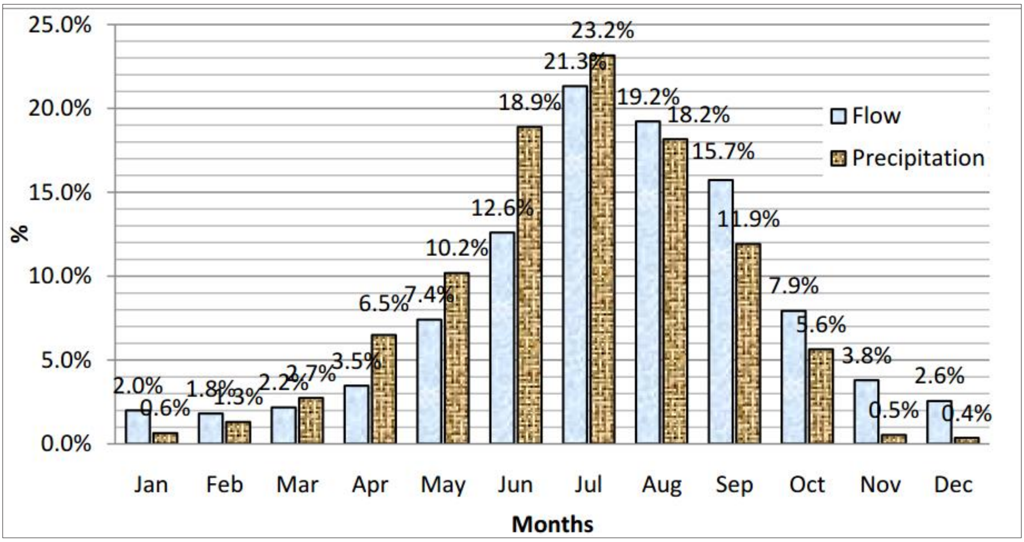

Figure 5 Comparison of average observed seasonal flows and precipitation in Bhutan (NEC, 2016, a)

2.2 Trends of river flows

The average total monthly rainfall in Bhutan is least in the month of December (5 mm), while the highest is in July (425 mm). The maximum annual total rainfall is received at Samtse with 5,461 mm of rainfall in a year whereas, Thimphu received the least annual total rainfall, a rainfall of 602mm in a year (ADB, 2016). Figure 5 shows the comparison of average observed seasonal flows and precipitation in Bhutan.

The trends of total annual rainfall in almost all the stations are showing a negative slope indicating a decrease in total rainfall and decreasing trend of river discharges. All the stations across the country show a negative trend of decreasing average annual flows except for four stations, the Parochhu at Paro, Punatsangchhu at Wangdi Rapids, Khomachhu at Sumpa, and Wangchhu at Tamchu. The highest negative trend can be identified for the Punatsangchhu River at Kiribati station with a considerably significant R^2 of 0.76 as compared to other stations (ADB, 2016).

In connection with warming, an increase and shift in the overall snow and glacial melts is expected. This will in turn affect river flow, resulting in a decline in stored water from glaciers and snow cover. There will be a higher chance of reduced flow during warm and dry periods. However, during monsoon, this imposes a major flooding threat to almost 70% of the Bhutanese population living by the riverside (NSB, 2005). Floods have claimed many lives and caused a multitude of socio-economic, cultural, and environmental damages to Bhutan. The most devastating flood in the recent history of Bhutan happened during Cyclone Alia in May 2009, it caused damage of Nu.719 million to the Nation (DDM, 2015).

2.3 Changes in glaciers and glacier lakes

There are a total of 700 glaciers with an area of 629.55±0.02 km^2 in Bhutan (NCHM, 2019). This is about 1.64% of the total land cover of the country. The Punatsangchhu basin has the highest number of glaciers (341) while the Wangchhu Basin has the lowest number of glaciers (47). The largest glacier in Bhutan with an area of 45 km^2 is in the Mangde Chhu sub-basin. Bhutan has 2,674 glacial lakes covering an area of about 107 km^2. The Pho Chu, Mangde Chu, and Chamkhar Chu Sub-basins consist of more than 500 glacial lakes each. Manas Chhu basin has 1,383 glacier lakes covering an area of 55.51 km^2 followed by Punatshangchhu basin with 980 glacier lakes covering 35.08 km^2.

The Bhutan Glacier Inventory 2018 represents a lesser surface area than the earlier GAMDAM (Glacier Area Mapping for Discharge in High Asia Mountains) inventory of 2015 by 12%. However, in comparison with the ICIMOD inventory of 2014, the current inventory shows less surface area by 2%. The ICIMOD inventory of 2014 presented 886 numbers of glacier lakes, GAMDAM inventory of 2015 showed 864 numbers of glacier lakes whereas, the Bhutan Glacier Inventory of 2018 shows only 700 glacier lakes in the country (NCHM, 2019).

The two benchmarked glaciers, Ganju La and Thana have lost massive surface area according to the Glaciologist with the NHCM. The Ganju La glacier, located at the Phochhu sub-basin has retreated at an average retreat rate of 11.4 m per year with a total shrinkage of 0.081 km^2 between 2004 and 2019, while the Thana glacier located in the Chamkharchhu basin has lost a total area of 1.49 km^2 from 1980 until 2019, losing a surface area of 28.6 percent. The total retreat at the glacier's terminus from 2004-2019 was 182 m. While comparing the glacier mass added and mass loss, the total cumulative loss is -28.5 m, which means the glacier loss is more than the glacier-formed (Kuensel, 2020, a).

2.3.1 PGDLs and GLOF

Climate induced GLOFs could cause immense human and economic devastations to the population, economic activities, and infrastructures concentrated in large river valleys. There are also hydropower projects which are under construction and planned in these basins. Bhutan's glaciers are at risk because of present and future changes in climate. Warmer temperatures induce snowmelt and with the onset of monsoon, the rain intensifies creating high flow period. Bhutan is highly vulnerable to the threats of GLOFs since most of the human settlements and major economic activities are located along the main drainage basins.

There are 17 glacier lakes identified as potentially dangerous in Bhutan (NCHM, 2019). These potentially dangerous glacial lakes (PDGL) need constant monitoring because their feeding glaciers are changing regularly and also because of their lake's morphology.

The Phochhu and Mochhu sub-basins of the Punatshangchhu basin have the highest number of glaciers in Bhutan than any other river basins, make it the most vulnerable basin. The Phochhu sub-basin has 9 PDGLs and the Mochhu sub-basin has 2 PDGLs. potentially dangerous glacial lakes. The two largest under-construction hydropower projects namely Punatsangchhu I (1200 MW) and Punatsangchhu II (1020 MW) are located in this basin. The Mangdechhu basin has 3 PDGLs, Chamkharchhu sub-basin has 2 PDGLs and Kurichhu sub-basin has 1 PDGL. Figure 6 shows the overlay of location of glaciers and glacier lakes on the map of Bhutan.

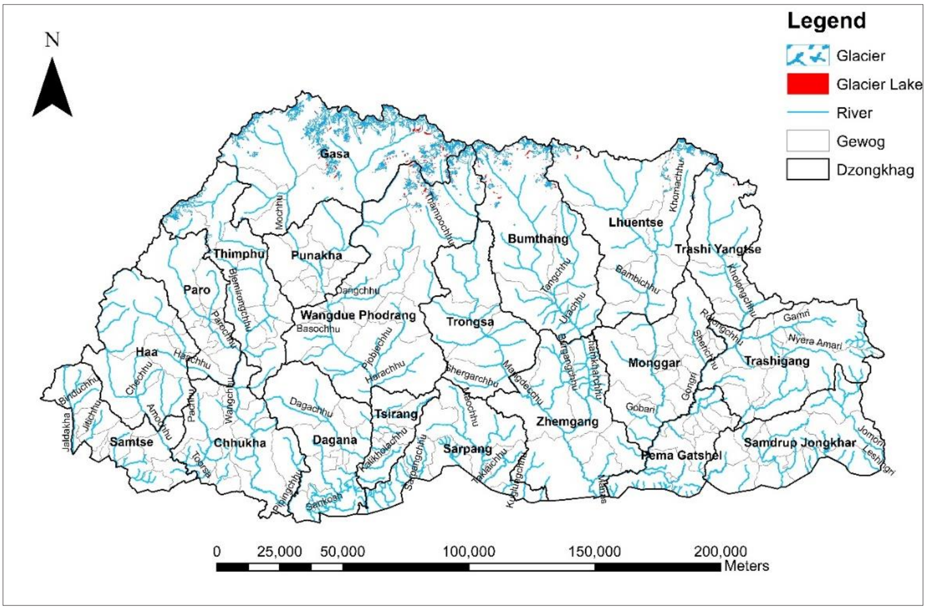

Figure 6 Location of Glacier and glacier lakes

Table 2 Total area of glacier lakes in the districts

S/No	District	Total surface area of glacier lakes (km^2)
1	Bumthang	10.02
2	Gasa	19.88
3	Lhuentse	3.10
4	Paro	0.20
5	Thimphu	0.49
6	Wangdue Phodrang	9.20
7	Trashi Yangtse	1.03

Table 2 shows the total surface area of glacier lakes in each district. Gasa district has maximum number of glacier lakes making a total surface area of 19.8 km^2. Only 7 districts out of 20 have glacier lakes at higher elevation.

2.4 Agriculture

The effect of temperature change is sensitive for plants as each plant variety has an optimum temperature range for both vegetative growth and production of seeds whereas too much or too little rainfall would also affect crop yield. Dry periods or an increase in temperature leads to increased incidences of pest and disease outbreaks whereas incessant rainfall leads to the risk of floods and landslides.

The most significant impact of climate change on agriculture in Bhutan is through the change in the timing of the monsoon (early/late) and the quantity of the rainfall as the production of paddy depends on the monsoon rain. The impact of climate change has resulted in the decline of crop yield, rise in loss of crops due to extreme events such as GLOFs, flash floods, and landslides triggered by antecedent moisture content and domestic animals to pests and diseases including wildlife predation in Bhutan. Some of the incidences of pest and disease outbreaks in past were rice blast disease from 1995 to 1997, corn blight from 2006 to 2007, and armyworm outbreaks from 2013 till date, GALS outbreak in Gyelposhing in 2006 to 2009 (NEC, 2020). There is also a record of an increase in fallow agricultural land due to lack of adequate irrigation water, rainfall, and extreme events such as river flooding and flash floods.

2.5 Hydropower

Hydropower is an economic backbone of the country, however; threats from climate change may impact the hydrological regime and hence on electricity generation from hydropower. Hydropower is a climate-sensitive sector as it is completely reliant on water levels and flows in the rivers, which is variable depending on good monsoon years.

There will be temporal and spatial variation in flow with high flows during monsoon and very low flows during the lean season making the management of the hydropower system complex (NEC, 2020). This will notably affect electricity production, domestic supply as well as exports due to disruption of average flows for optimum hydropower generation. The other major issue is the formation of supra-glacial lakes due to increasing temperatures and the existence of numbers of potentially dangerous glacier lakes upstream which impose risk from GLOFs and bursting of hydropower dams. Based on the HEC-HMS hydrological modeling, it was determined that the total annual flow in all the basins would increase in future times both for RCP 4.5 and RCP 8.5 as shown in Figure 7. Therefore, for the development of hydropower plants, it is evident that more flow would be available up-to the end of the century under climate change scenarios. However, the squeezing of the bell-shaped flow regime (more increase when there is enough flow and decrease or nominal increase when the rivers are dry), is bad for hydropower development as the higher flow in the monsoon would only spill over and the lean season flow generation would not be positive or become worse (NEC, 2020).

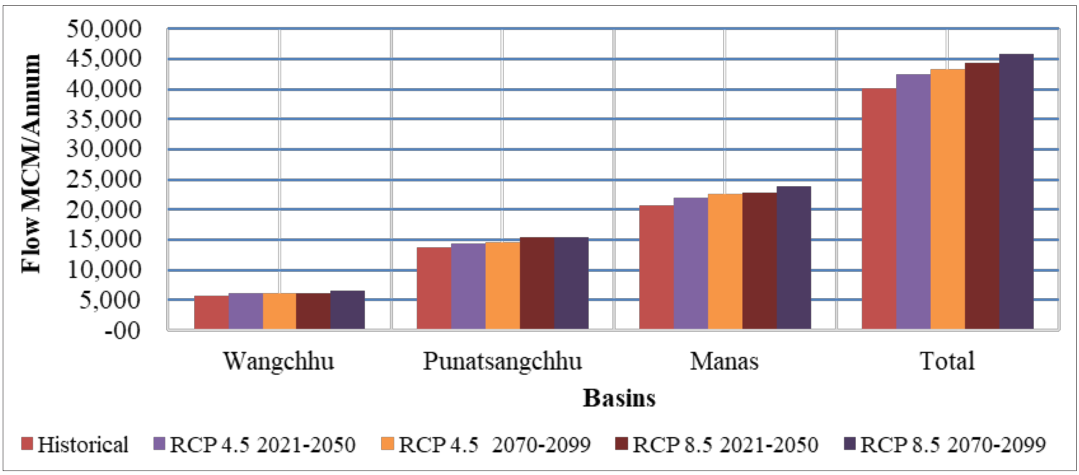

Figure 7 Total annual flows in the basins of Bhutan under different climate scenarios (NEC, 2020)

3. Bhutan's way forward to a Climate Resilient society

Bhutan accomplished its First National Communication to the United Nations Framework Convention on Climate Change (UNFCCC) in 2000, Second National Communication in 2011, and Third National Communication in 2020. It identifies the key climate change concerns for the country in various sectors that are sensitive to climate. Bhutan's vulnerability to climate change and adaptation plans are also clarified in National Adaptation Plan (NAPs) and Bhutan National Adaptation Programme of Action (NAPA) projects. The objectives of NAPA is to identify immediate projects and activities that can help communities adapt and to integrate climate change risks into the national planning process.

The NAPA I project is on reducing climate change-induced risks and vulnerabilities from GLOF covering 3 NAPA (2006) priority areas, implemented in 2008-2013, NAPA II project on addressing the risk of climate-induced disasters through enhanced national and local capacity in Bhutan, addressing 6 NAPA (2012) priority areas, and NAPA III on enhancing sustainability and climate resilience of forest and agricultural landscape and community livelihoods in Bhutan which started on October 2017.

The objective of the NAP is to reduce vulnerability to the impacts of climate change and to integrate adaptation into all levels of development planning. This document was prepared under the direction of the National Environment Commission, supported by the working groups from five key areas: agriculture and livestock; forestry and biodiversity; health; water resources and energy; and natural disasters and infrastructure. The Bhutan NAPA is conceived as a living document, which may be from time to time be updated once the prioritized projects are implemented.

Bhutan has also developed a Climate Change Policy last year. The goal is to provide strategic guidance to ensure that Bhutan remains carbon neutral and protects the wellbeing of the people of Bhutan by adapting to climate change in an efficient and effective manner, to ensure meaningful participation of all relevant stakeholders in climate change action in a coordinated and coherent manner with clear roles and responsibilities; and to ensure that the challenges and opportunities of climate change are addressed at all appropriate levels, through adequate means of implementation (finance, technology, capacity building, and awareness) and integration into relevant plans and policies (NEC, 2020, a).

There is an existing GLOF Early Warning System (EWS) in the Punatshangchhu basin along the Punakha-Wangdue valley, Mangdechhu sub-basin, and Chamkharchhu sub-basin set up and monitored by the Department of Hydro-Met Services (DHMS) under the Ministry of Economic Affairs (MOEA). There are two GLOF EWS installed in the Mangdechhu sub-basin, one at Jongthang and another at Bjizam, and three GLOF EWS installed in Chamkharchhu sub-basin, located at Tshampa, Kurjey, and Khangtang on Chamkharchhu.

The Flood Engineering and Management Division (FEMD) under the Department of Engineering Services (DES), MoWHS conducts the preliminary flood hazard assessment for all the 20 Dzongkhags in Bhutan and identify flood-prone areas. The assessments are usually conducted through field trips and consultation with the locals who have seen flooding in their communities. After the assessment, necessary mitigation works are planned and implemented in the flood-prone areas. The Dzongkhag administration is recommended to carry out the flood protection works with technical support from the FEMD, DES, MoWHS.

4. Conclusion and recommendations

Since floods can occur at any time of the year and any place affecting lives and properties downstream, it is important to prioritize efforts that aim to improve the detection, protection, and even forecasting of floods threat. Preventive measures to reduce vulnerability to floods include controlling built-up areas along river courses, ensuring adequate space for rivers to move naturally, and implementing river training works in priority areas to prevent flooding of existing settlements and agricultural land. Flood level monitoring and public warning systems, including the provision of an adequate number of river gauging stations should be at place as they are vital components of flood management. A GLOF early warning system has to be set up in the Kurichhu sub-basin because Terjatse Tsho with a surface area of 167,540 m^2 located at north eastern side of Lhuntse Dzongkhag is identified as a potentially dangerous glacial lake.

The hydropower sector is at stake due to the impact of climate change on water resources, therefore other natural sources of energy such as renewable energy should be explored. This might help us avoid importing energy from India during lean seasons and cold winters.

There is a need to mainstream climate change in agriculture in order to perceive and understand climate science. Agriculture sector should use climate data into their agriculture field and research. There is a need to have pests and diseases forecasting system in place to carry out timely intervention to prevent, mitigate or adapt to the new emerging pests and diseases in crops and livestock.

The watersheds that are degrading in some parts of the country should be protected and restored to avoid increased incidences of water sources drying up. Groundwater should be explored in Bhutan before climate change impacts our drinking and irrigation water severely. The extent of groundwater available in Bhutan and its future potential in the wake of changing climate should be studied properly. A database on groundwater should be built and maintained because the critical water stresses areas can explore groundwater accordingly.

The NEC has developed a Climate Change Policy for the country after finding a lot of duplication of efforts in the institutions due to a lack of clarity in roles and mandates. It is also to coordinate a similar approach in all institutions in determining national priorities in addressing climate change. The capacity of all relevant stakeholders should also be enhanced to tackle climate change.

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