

# IMPACTS OF CLIMATE CHANGE ON HYDROLOGICAL REGIMES IN BUDHI GANDAKI RIVER BASIN



नेपाल विकास अनुसन्धान प्रतिष्ठान  
Nepal Development Research Institute



ASIA-PACIFIC NETWORK FOR  
GLOBAL CHANGE RESEARCH

A Report Submitted to

**Nepal Development Research Institute**

Manbhawan, Lalitpur

By

**Nikita Khanal**

Central Department of Environmental Science

Tribhuvan University

Kirtipur, Nepal

August 2024

## ABSTRACT

This study assessed climate change impacts on hydrological regimes in the Budhi Gandaki River Basin (BRB) in central Nepal, covering 3881.16 km<sup>2</sup> with an altitudinal range of 315-8163 masl. The Glacio-Hydrological Degree-Day Model (GDM) was employed using historical data (2000-2023) and CMIP6 projections under SSP2-4.5 and SSP5-8.5 scenarios (2024-2100). Analysis of historical data revealed that BRB receives approximately 1530 mm annual precipitation, with 74% occurring during monsoon (June-September). Temperature data from Dhunibesi station showed a warming trend, with July and August being the hottest months (26°C) and January the coolest (13°C). Discharge at Arughat station exhibited an increasing trend, particularly after 2016. CMIP6 projections indicate little to no precipitation increase in the near-future (2024-2049), with gradual increases in mid- and far-future periods. Temperature projections show a gradual increase under SSP2-4.5 and an alarming rise under SSP5-8.5, reaching around 17°C annually by 2075-2100. The study utilized reclassified LULC maps from 2000 and 2024, incorporating eight classes including debris-covered glaciers. These maps were crucial for calibrating the GDM and simulating future discharge. GDM simulations project decreasing discharge trends compared to the baseline (157.60 m<sup>3</sup>/s), with reductions of approximately 25% under SSP2-4.5 and 20% under SSP5-8.5 for 2024-2100. Water balance analysis reveals baseflow as the largest contributor (~51%), followed by rainfall (~34%), snowmelt (~10%), and ice melt (~4%). Seasonal analysis shows increased discharge in winter, pre-monsoon, and post-monsoon seasons, but decreased monsoon discharge compared to baseline. The study highlights high spatiotemporal variability in climate change impacts and underscores the need for incorporating glaciers into large-scale hydrological models for improved climate change assessments. This research provides valuable insights for water resource management and adaptation strategies in glacierized Himalayan River basins under changing climatic conditions.

Keywords: Climate Change, Cryosphere, Hydrological Modelling, Shared Socioeconomic Pathways

# CHAPTER I: INTRODUCTION

## 1.1 Background

Snow and glaciers in the Himalayas modulate the water and energy fluxes along with the interchange of carbon between the land and atmosphere (Barry & Gan, 2021). They are abundant natural reservoirs releasing large amounts of freshwater year-round, which facilitate socioeconomic development and environmental needs in large areas of the High Mountain Asia (HMA) and surrounding regions (Shukla et al., 2017).

Elevation dependent warming, prominent in HMA, has resulted in increased temperature in the Himalayan regions, with Hindu Kush warming the most by 2.30C, due to climate change have had significant effects on the timing and long-term availability of snowmelt and glacier runoff. As a result, the spatial and temporal dynamics of downstream water availability have become increasingly concerning (Dimri et al., 2018). For the comprehensive hydrological simulation, the precise glacier extent and mass balance are essential components.

After the 1960s, with the launch of hydrological modelling processes, several models have been developed to simulate the hydrological processes. The models like the SPHY model, HBV model SWAT model, and GDM model aim to approximate water balance components via model parameterization (Arnold et al., 1998; Bergström, 1976; Bergstrom, 1992; Kayastha et al., 2020; Terink et al., 2015). These models classify streamflow components using robust statistical or empirical approach and simulate the streamflow components, including glacier-snow melt and cover, evaporation, precipitation, and baseflow over the basin (Wu et al., 2021). Runoff and its components are responsible for streamflow, and the fluctuations in runoff from year to year regulate streamflow (Adnan et al., 2022).

Many studies have investigated the changes in Nepal's hydrology, which includes a substantial upstream area of the Himalayas. However, comprehensive studies on the spatial and temporal evolution of glacio-hydrological dynamics are lacking.

## 1.2 Objectives

The general objective of the is to assess the impact of climate change on the hydrological regimes in Budhi Gandaki River Basin. The specific objectives of the study are:

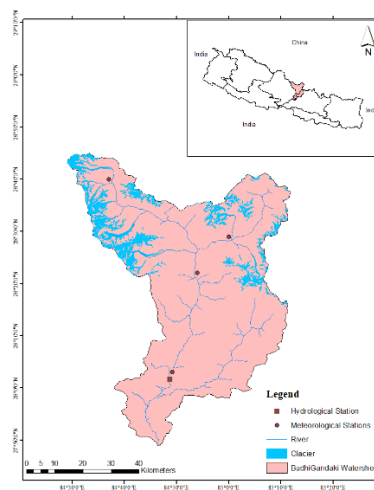
1. To simulate the future discharge change under different scenario
2. To understand the influence of different water balance components on hydrology.

## CHAPTER II: MATERIALS AND METHODS

### 2.1 Study Area

Budhigandaki River Basin (BRB), located in Central Nepal, originating from the Himalayan, covers an area of 3881.16 squares kilometers. It lies between latitudes 27°50' and 28°00' N and longitudes 84°30' and 85°10' E. The basin majorly covers Gorkha and Dhading District in Nepal and Kerong County in the Tibetan Autonomous Region of China. The physiographic region covered by the basin is Middle Mountains (Hill) and the Himalayan. The altitudinal gradient of the basin is 3723masl, ranging from 315masl at the confluence to 8163masl at the top of the basin with average slope of 4.77%. The river channel is nearly 113 km long and between 15 and 30 km wide. The river basin has a total of 173 glaciers in Nepal (RGI Consortium, 2023). There are three types of climatic zones found in the river basin, temperate climate with dry winter and warm summer (312m-3500m), polar tundra (3500m-6500m) and polar frost (6500m-8147m) (Karki et al., 2020).

The basin's hydrology has been determined based on gauging station No. 445 at Arughat, situated about 30 km upstream from its confluence with the Trisuli River. The mean annual precipitation of the basin is 1800mm with rainfall intensity being highest on the south-facing mountain slopes. Arughat station receives more than 2500 mm of annual precipitation, whereas the Tibetan part of the basin receives less than 700 mm. The mean annual flow of the basin is estimated at 240 m<sup>3</sup>/s (Betts & Jakob, 2002; Marahatta et al., 2021). Temperatures in the basin range from -2.0 °C in winter to 33.0 °C in summer.



**Figure 1: Map of Budhigandaki River Basin**

## 2.2 Data Collection

### 2.2.1 Hydrological-Meteorological Data

Meteorological data from four different stations, as shown in Table 1, are taken from the Department of Hydrology and Meteorology (DHM) based on the data availability. The daily temperature and precipitation data from 2000-2023 were taken for analysis due to relatively low missing value. Among them, data from 2000- 2012 was divided into train and test samples for the calibration and validation of the model. Similarly, streamflow data of period 2001- 2019 was taken from station at Arughat. The data was used for calibration and validation of the model. The data was visualized in MS Excel and the small gaps within the data were filled using multiple regression method in the python environment. The data of the stations has gap within 30% which makes it eligible for multiple regression interpolation method.

**Table 1: List of meteorological stations used in the study**

S.N.	Station Name	Type of Data	Latitude	Longitude	Elevation (m)
1.	Larke Samdo	Precipitation	28.66667	84.61667	3650
2.	Jagat	Precipitation	28.36667	84.9	1334
3.	Arughat	Precipitation	28.0435	84.81293	518
4.	Dhunibesi	Temperature	27.72288	85.16431	991
5.	Arughat	Hydrology	28.04	84.82	485

### 2.2.2 Global Climate Data

The monthly gridded historical and future temperature and precipitation data of Institut Pierre Simon Laplace Climate Modelling Centre (IPSL-CM6A-LR) from Coupled Model Intercomparison Project Phase 6 (CMIP6) under the SSP2-4.5 and SSP5-8.5 was provided to Glacio-Hydrological Degree Day Model (GDM). The historical CMIP6 data and temperature and precipitation of APHRODITE from 2000-2014 A.D was used to bias correct the future CMIP6 data, to simulate the discharge under SSP2-4.5 and SSP5-8.5 from 2024 to 2100 A.D. The IPSL-CM6A-LR model

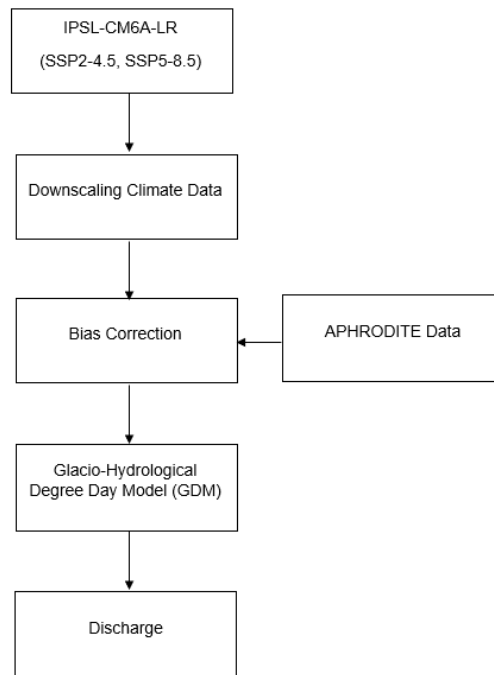
was chosen as warm-dry is an extreme scenario for glacierized Himalayan River basin. The data obtained from the GCM was downscaled using Climate Data Operator (CDO) tool and bias corrected using quantile mapping.

### 2.2.3 Spatial Data

The Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) of 90m resolution was used for elevation related data in GDM. The land use and land cover (LULC) map of 2000 A.D of HKH region was obtained from International Centre for Mountain Development (ICIMOD) to calibrate and validate the model and the LULC map of 2024 A.D of 10m resolution was obtained from Environmental Systems Research Institute (ESRI) to simulate the discharge. The debris covered glacier map was taken from the study conducted by Herreid & Pellicciotti, (2020) to prepare a LULC map. The map was reclassified to create eight classes. These classes are significant in GDM to calculate the flow coefficient separately for each land type.

### 2.3 Methods

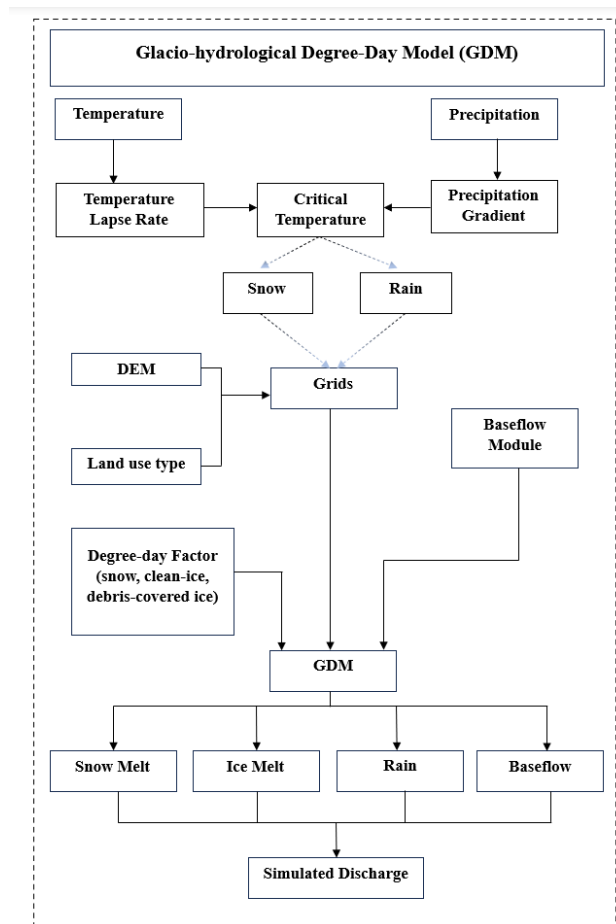
The study utilizes hydrological modelling technique and primarily requires secondary data. The data is then fed into the model to generate the discharge simulation results. The detailed flowchart is shown in figure 2.



**Figure 2: The flowchart of the study**

### 2.3.1 Glacio-hydrological Degree-day Model (GDM)

The GDM version 2.0 is a glacio-hydrological model, with a distributed and gridded function, that simulates daily discharge estimates along with the contribution from different water balance components such as snow and ice melt, rain, and baseflow. The workflow of the GDM is presented in figure 2.



**Figure 3: The flowchart showing the workflow of GDM**

The GDM model is based on a simplified version of Braithwaite & Olesen, (1989) called degree-day approach, based on which glacier ice and snow melts are estimated even with the minimal data availability as shown in equation 1

$$M = (k_s \text{ or } k_b \text{ or } k_d) \times T \text{ if, } T > 0, \quad (1)$$

$$0 \text{ if, } T \leq 0$$

Where  $M$  is snow or ice melt (mm d<sup>-1</sup>) in each grid,  $T$  is daily air temperature (°C).  $k_s$ ,  $k_b$  and  $k_d$  are degree-day factors (mm °C<sup>-1</sup> d<sup>-1</sup>) for snow, clean ice and debris-covered ice, respectively. The hydrological response of baseflow and rainfall runoff influence in the discharge is simulated based on the concept of two reservoir, shallow and deep aquifers, modeling concept of SWAT. The basin is divided into grids and the classified ESRI LULC map is extracted to individual grid. The daily temperature and precipitation data of DHM are extrapolated into each grid from the reference stations to force the model for simulation. The temperature thresholding determines whether the precipitation in each grid is in the form of rain or snow.

The surface runoff encompassing the water balance component is calculated grid wise as shown in equation 2.

$$Q_G = Q_r \times C_r + Q_s \times C_s + Q_i \quad (2)$$

Where  $Q_G$  is the surface runoff in m<sup>3</sup> s<sup>-1</sup>,  $Q_r$ ,  $Q_s$  and  $Q_i$  is the discharge from rain, snow melt and ice melt respectively in m<sup>3</sup> s<sup>-1</sup> and  $C_r$  and  $C_s$  are rain and snow coefficients respectively. Here  $Q_G$  is surface runoff from each grid. The contribution of total surface runoff and the total baseflow from all grids are calculated as shown in equation 3 and 4.

$$Q_R = \sum_{G=1}^n Q_G \quad (4)$$

$$Q_B = \sum_{G=1}^n Q_b \quad (4)$$

Where  $Q_R$  and  $Q_B$  are the total surface runoff and total baseflow contribution from all the grids.  $Q_b$  is the baseflow from each grid and  $n$  is the number of grids. By routing the baseflow and surface discharge to the outlet of the basin, the total discharge is then computed through equation 5.

$$Q_d = Q_R \times (1 - k) + Q_{R(d-1)} \times k + Q_B \quad (5)$$

Where  $Q_d$  is the total discharge (m<sup>3</sup> s<sup>-1</sup>),  $k$  is the recession coefficient and  $d$  are the  $d$ th day. The value of recession coefficient ( $k$ ) is derived from the equation 6, given by Martinec & Rango (1986).

$$K_{d+1} = x Q^{-y}_d \quad (6)$$

Where,  $x$  and  $y$  are constants calculated from this equation.

The calibration constants used for GDM are presented in table 2. The recession constants, positive degree day factors, and snow and rain coefficients are the main parameters among

others. The model is calibrated using various positive degree-day factors, and a set of degree-day factors that fall within the range of derived degree-day factors based on past studies in the Nepalese Himalayan glaciers are used for various months with lower values allocated during monsoon season. Alternately, higher values are allocated during monsoon season for land use runoff coefficients.

**Table 2: Calibration parameters with their respective values used in GDM**

	Parameters	Symbol	Value
	Critical temperature	$T_{crit}$	2°C
	Temperature lapse rate	$\Gamma$	0.6°C 100 m <sup>-1</sup>
	Recession coefficients	x and y	0.6 and 0.7
Runoff coefficient	Land use type 1	$C_1$	0.4–0.50
	Land use type 2	$C_2$	0.25–0.3
	Land use type 3	$C_3$	0.2–0.3
	Land use type 4	$C_4$	0.8–0.95
	Land use type 5	$C_5$	0.5-0.95
	Land use type 6	$C_6$	0.1-0.5
	Land use type 7	$C_7$	1
	Land use type 8	$C_8$	1
Degree-day factor (mm°C <sup>-1</sup> d <sup>-1</sup> )	Snow	$k_s$	6–10
	Clean ice	$k_b$	5–8
	Ice under debris	$k_d$	3
Baseflow (Luo et al., 2012)	Delay time for overlying geological formation for shallow aquifer percolation	$\Delta_{gw,sh}$	50 d
	Recession constant for shallow aquifer	$\alpha_{gw,sh}$	0.6
	Delay time for deep aquifer percolation	$\Delta_{gw,dp}$	150 d
	Recession constant for deep aquifer	$\alpha_{gw,dp}$	0.7
	Seepage constant for deep water percolation	$\beta_{dp}$	0.4

### 3.3.2 Performance Indices

The evaluation of the model efficiency was carried out by comparing the observed discharge of the study area with the daily time series simulated discharge. The Nash-Sutcliffe Efficiency (NSE) index derived from Nash & Sutcliffe, (1970) was used to evaluate the result using the equation 7.

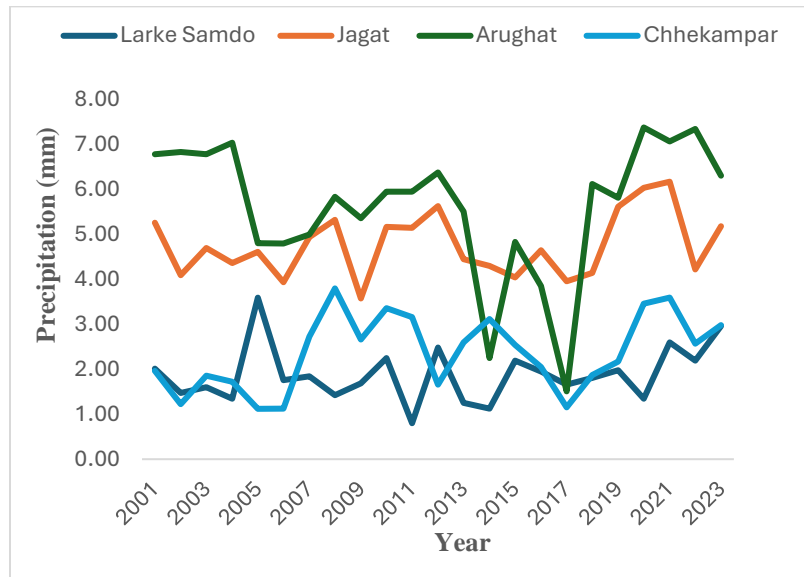
$$NSE = 1 - \frac{\sum_{i=1}^d (Q_{obs} - Q_{sim})^2}{\sum_{i=1}^d (Q_{obs} - Q_{avg})^2} \quad (7)$$

Where,  $Q_{obs}$  is the daily observed discharge,  $Q_{avg}$  is the average observed discharge and  $Q_{sim}$  is the daily simulated discharge.

## CHAPTER III: RESULTS

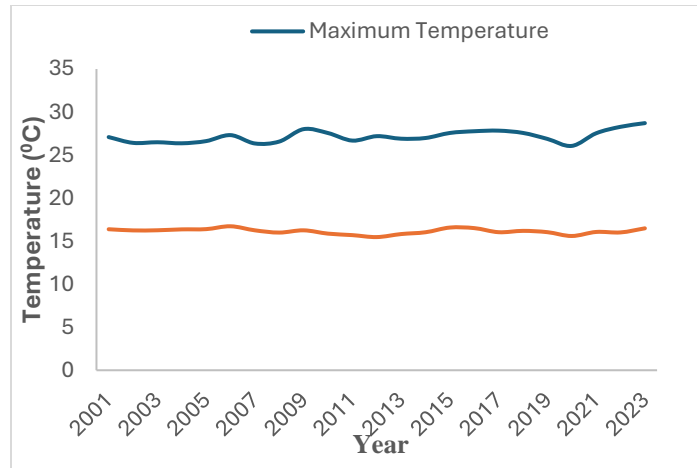
### 3.1 Temperature, Precipitation and Discharge trend of the basin

The daily temperature, precipitation and discharge data obtained from DHM was analyzed using MS Excel. The BRB received approximately 1530 mm of annual precipitation with 74% of rainfall in monsoon (June-September). The highest rainfall was in July with approximately 23% and November is the dry month receives less than 1% of total annual precipitation. The average annual temperature and precipitation was generated using pivot table and was plotted. Figure 4 shows the average annual precipitation of four different stations. The trend shows that the most precipitation occurs in Arughat of BRB. The second highest precipitation occurs in Jagat station. From this data we can say that the lowest lying station receives most precipitation and it decreases with increasing elevation with Larke Samdo receiving lowest amount of precipitation. The average annual precipitation is increasing since 2017 which might be attributed to erratic rainfall during monsoon season.



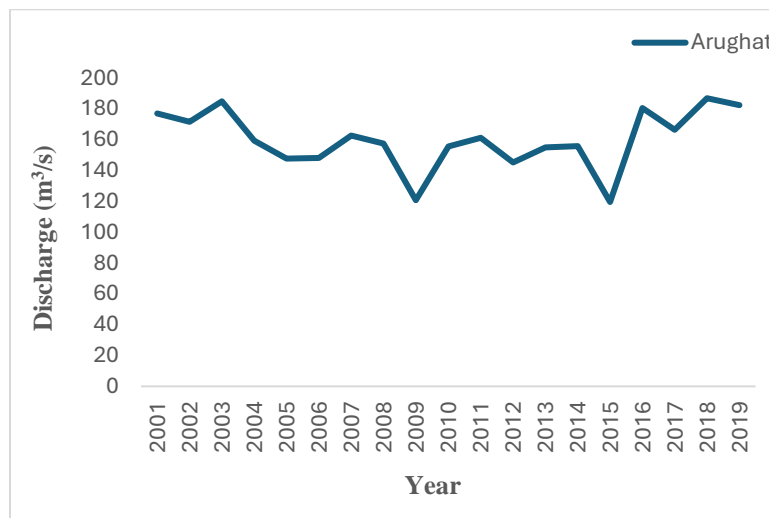
**Figure 4: Average annual precipitation of four stations in BRB**

As per the station data, July and August are the hottest month of the year with average temperature of approximately 26°C. Similarly, January is the coolest month with average temperature of approximately 13°C. The station being at lower elevation shows data accordingly. The maximum and minimum temperature of Dhunibesi station in figure 5 shows stable trend compared to precipitation. The temperature is increasing in the region with a slight drop in 2020 and again increasing till date.



**Figure 5: Average annual temperature of Dhunibesi station**

Similarly, the discharge recorded at Arughat Station as shown in figure 6 illustrates that the discharge is also in increasing trend mostly after 2016. The increase in temperature and precipitation can both facilitate increased streamflow in the river.



**Figure 6: Average annual discharge of Arughat station in BRB**

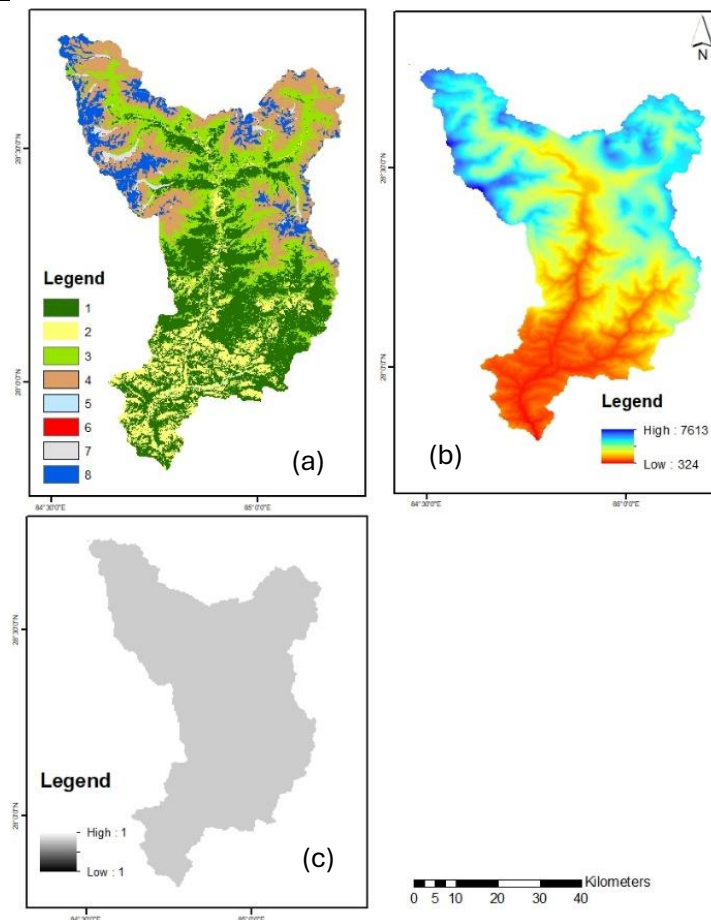
### 3.2 Land Use and Land Cover

The LULC map of HKH region during 2000A.D taken from ICIMOD and the LULC map of 2024 A.D taken from ESRI was reanalyzed as per the requirement of GDM. The maps were re-gridded, and the cell size was made 180\*180m. The debris cover glacier maps were also mosaiced into the LULC map and the previously covered areas were converted into bare lands. The maps were divided into eight different classes as shown in table 3. The map for 2000A.D was generated for

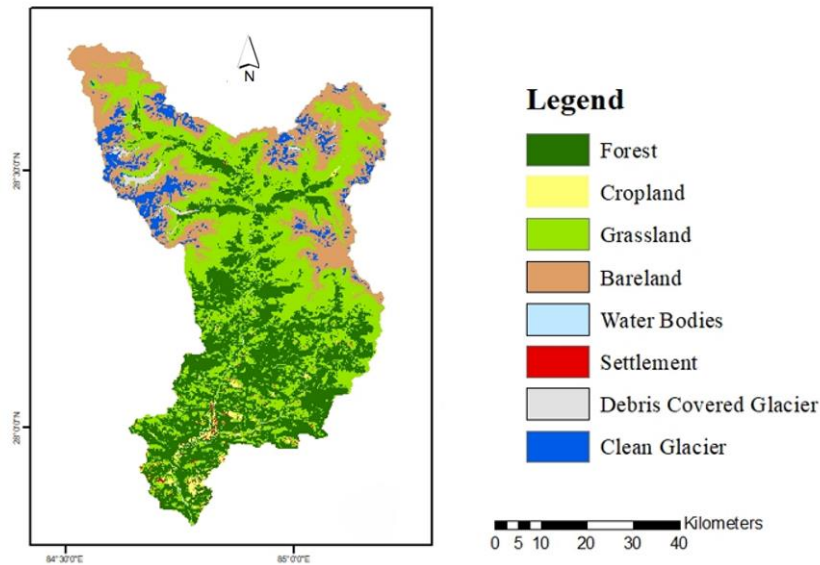
calibration and validation of the model and maps for 2024A.D were generated to simulate the discharge of the basin as shown in figure 7 and 8 respectively. Additionally, the mask map was also created using the DEM data of the basin in ArcMap as shown in figure 7.

**Table 3: The land use and land cover classes and types used in GDM**

S.N.	LULC Class	LULC Type
1	1	Forest
2	2	Croplands
3	3	Grasslands
4	4	Bare land/ Clouds
5	5	Water/ Flooded Vegetation
6	6	Settlement
7	7	Debris Covered Glacier
8	8	Clean Glacier



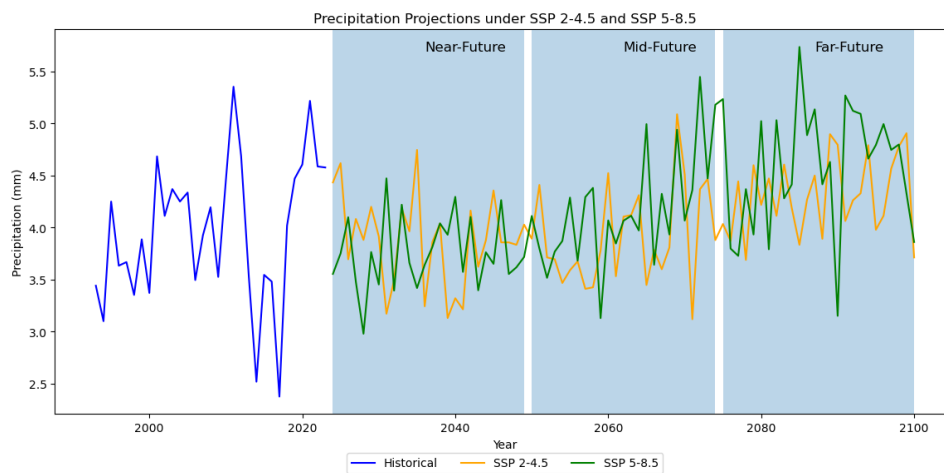
**Figure 7: The (a) reclassified LULC map of 2000 A.D, (b) DEM map and (c) Mask map used in calibration of GDM**



**Figure 8: The LULC map of 2024 A.D**

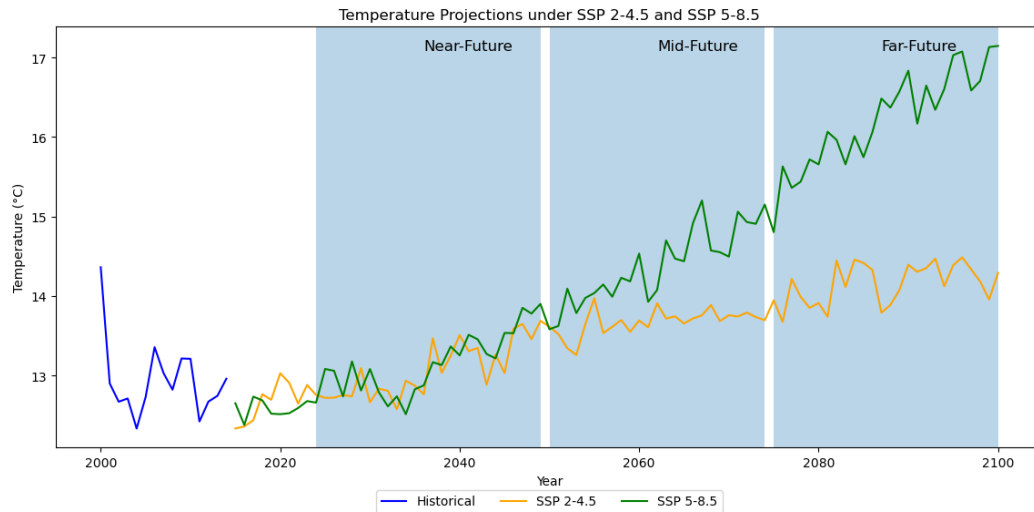
### 3.3 Global Climate Data

The temperature and precipitation data of SSP 2-4.5 and SSP 5-8.5 obtained from IPSL-CM6A-LR was bias corrected using quantile mapping method. The precipitation trend as shown in figure 9 shows little to no increase in precipitation in near-future (2024-2049) with slight increase latter year in mid-future (2050-2074) which continues to increase in far-future (2075-2100). The SSP 5-8.5 shows prominent increase and decrease spikes with far-future showing more unstable precipitation among all.



**Figure 9: Average annual time series of historical and GCM precipitation data**

Similarly, the temperature trend illustrated in figure 10 shows the gradual increase in temperature compared to historical data. The SSP 2-4.5 shows slight increase throughout the 21st century while the SSP 5-8.5 shows alarming increase in temperature reaching around 17°C in average annually during the far-future (2075-2100) period.

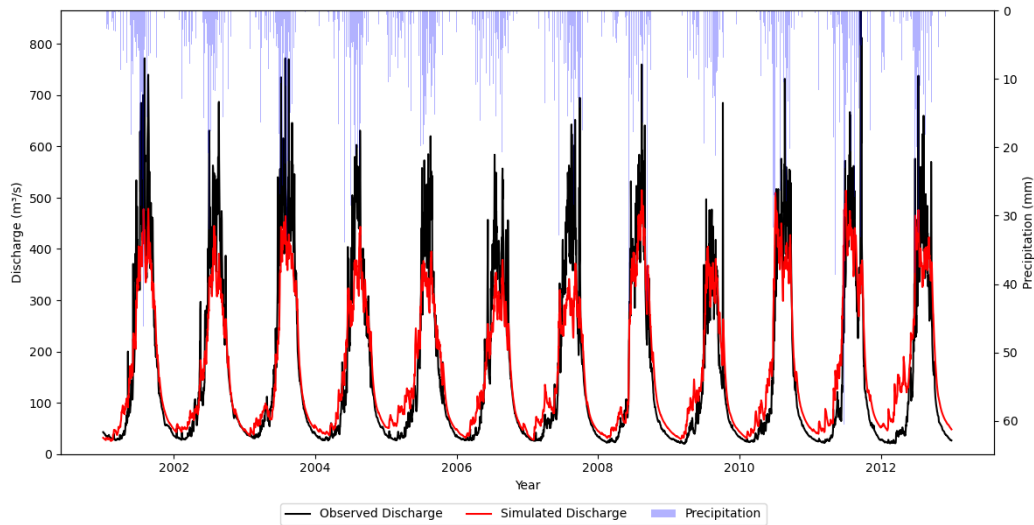


**Figure 10: Annual average time series of historical and GCM temperature data**

### 3.4 Hydrological Modeling

#### 3.4.1 Model Calibration

The performance of model was calibrated using different positive degree-day factors and a set of degree day factors implemented for various month. The model was calibrated over a period of six years (2001- 2006) and validated over a period of another six years (2007-2012) with a year of warm-up period as shown in figure 11. The model is unable to replicate the observed discharge pattern from March to May, which is the pre-monsoon season. As GDM does not employ a soil map, it underestimates infiltration and overestimates surface runoff, which causes the model to overestimate discharge during this time. We can state, in general, that GDM is able to capture the BRB's overall hydrological dynamics.

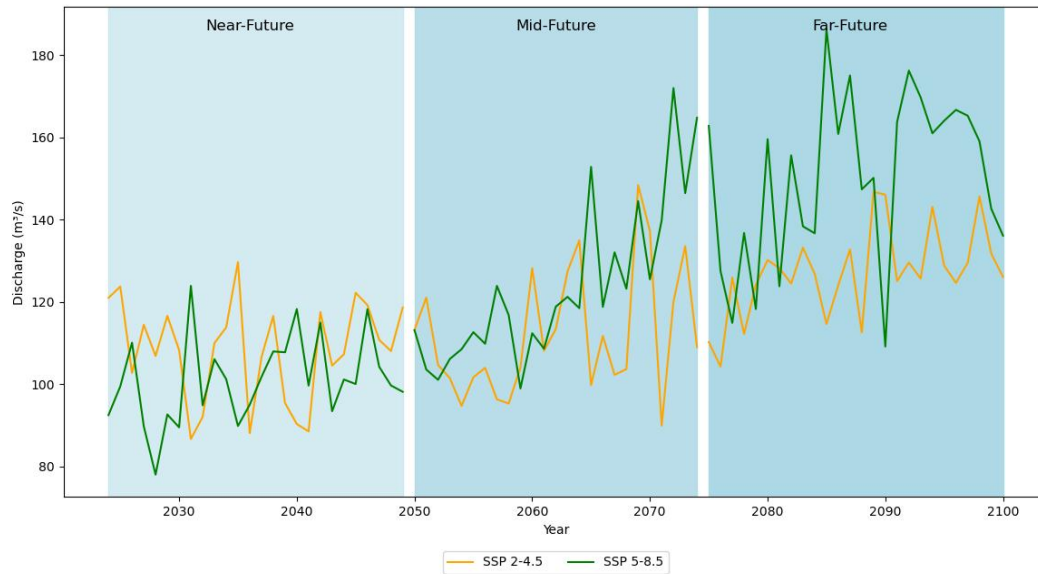


**Figure 11: The observed and simulated discharge with precipitation during period 2001-2012 A.D.**

Nash-Sutcliffe Efficiency was used to analyse the model accuracy for the calibration and validation period. Due to errors in parameter calibration, model design, and input data measurement, predictions made by models like GDM are subject to some degree of uncertainty. If the NSE index is more than 0.7, we in this study consider that the model has a better degree of confidence and accuracy. The NSE is calculated to be  $\geq 80$  in BRB during both the calibration and validation periods, with 0.85 for the former and 0.83 during the latter, considering that the model performed well during calibration and validation.

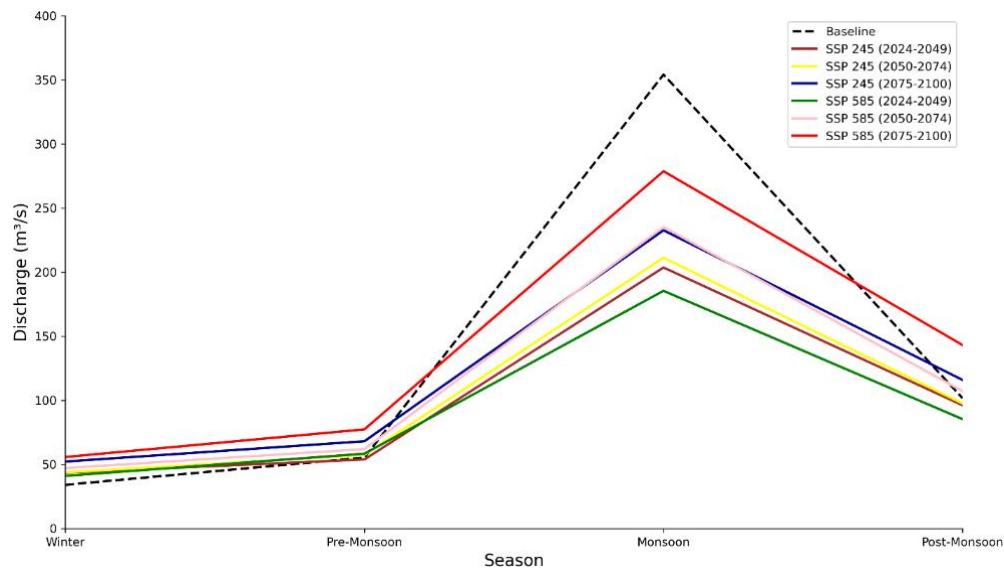
#### 4.5.2 Discharge Simulation

The simulation of future discharge using IPSL-CM6A-LR from 2024 to 2100 A.D under SSP 2-4.5 and SSP 5-8.5 scenario was performed using GDM. The simulated discharge was separated into three reference period i.e. Near-Future (2024- 2049A.D), Mid-Future (2050-2074 A.D) and Far-Future (2075- 2100 A.D). Figure 12 shows the simulated discharge under SSP 2-4.5 and SSP 5-45 separated into the respective periods. In near-future period, the discharge is consistent with some fluctuations while the discharge starts to increase in mid-future and the finally far-future shown higher discharge under both the scenarios. The baseline discharge obtained from DHM during period 2000-2012 was 157.60 m<sup>3</sup>/s. The discharge seems to decrease for both the scenarios with SSP5-8.5 showing relatively more discharge. The discharge has decreased by approximately 25% under SSP2-4.5 for period 2024- 2100. Similarly, the discharge has decreased by approximately 20% under SSP5-8.5.



**Figure 12: The annual average simulated discharge for period 2024-2100 under SSP 2-4.5 and 5-8.5**

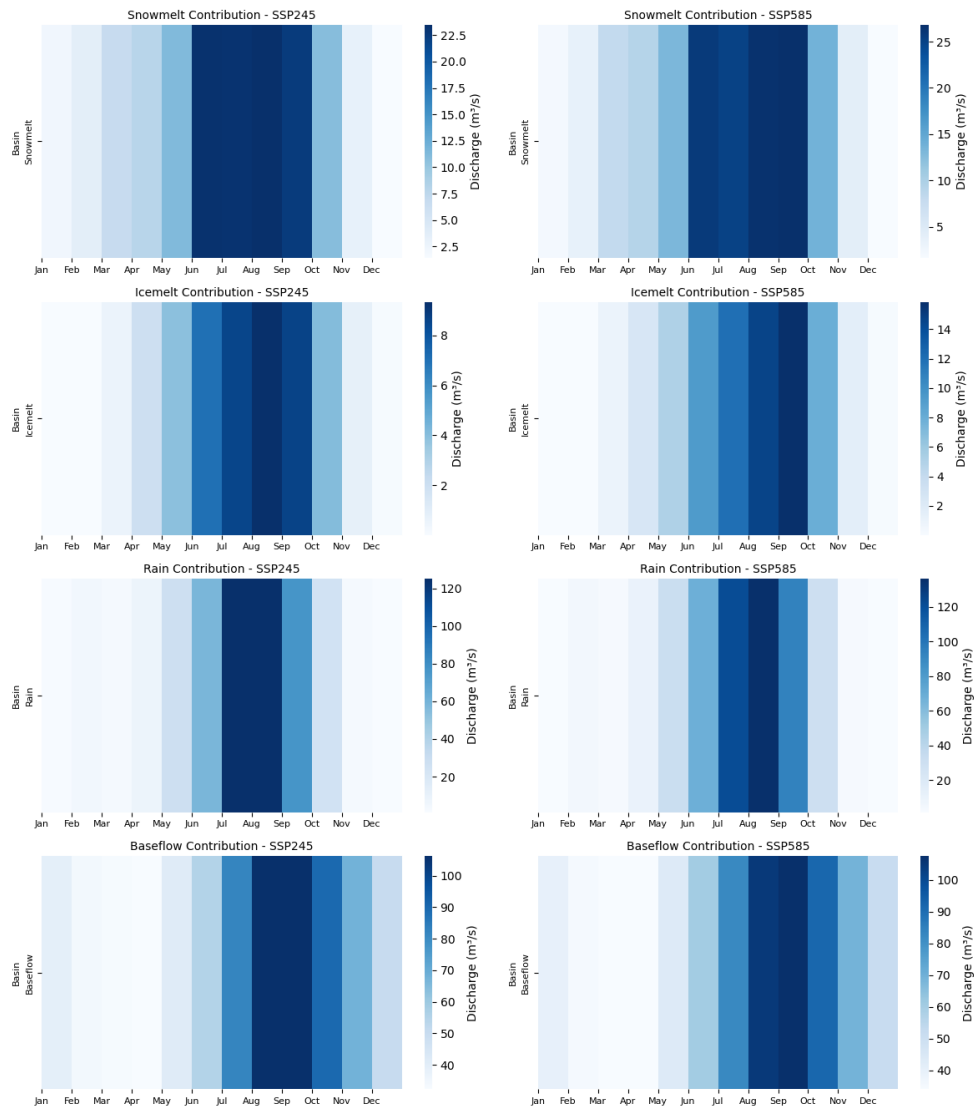
Similarly, figure 13 shows the seasonal discharge under different scenario plotted with the baseline discharge. The figure shows the increase in discharge in winter, pre-monsoon season and post-monsoon season in future in all reference period but during the monsoon season, the discharge seems to decrease compared to the baseline discharge. This could be due to lack of soil dynamics information as GDM does not use soil maps. Despite, the discharge is significantly higher in SSP 5-8.5 compared to SSP 2-4.5.



**Figure 13: The seasonal discharge under different SSP scenarios**

### 4.5.3 Contribution from Water Balance Components

The contribution of different water balance components in the simulated discharge under different scenarios is shown in figure 14 and table 4 where Figure 14 shows the monthly contribution and table 4 shows the contribution in different reference period. A significant contribution of Snowmelt and Ice melt can be seen during the monsoon season under both scenarios. The contribution of Rain is also significant during monsoon, mostly in July and August period, while the contribution of Baseflow is higher in August, September, December and January.



**Figure14: The monthly contribution of Snowmelt, Ice melt, Rain and Baseflow to the simulated discharge.**

The contribution of baseflow is high among all other components followed by rain as shown in table 4. The contribution increases with the time and SSP5-8.5 shows relatively more contribution than SSP2-4.5. The contribution of Snowmelt is approximately 10% in both scenarios, ice melt is approximately 4%, rain is approximately 34% and baseflow is approximately 51% of the total discharge which increases with reference periods.

**Table 4: Contribution of water balance components in different reference period.**

<b>S.N.</b>	<b>Scenario</b>	<b>Snowmelt (mm)</b>	<b>Ice melt (mm)</b>	<b>Rain (mm)</b>	<b>Baseflow (mm)</b>
1	SSP2-4.5 (2024-2049)	10.57	3.54	35.18	58.69
2	SSP2-4.5 (2050-2074)	11.50	4.14	37.04	58.98
3	SSP2-4.5 (2075-2100)	12.90	3.64	43.22	66.92
4	SSP5-8.5 (2024-2049)	10.86	4.01	31.61	54.19
5	SSP5-8.5 (2050-2074)	13.53	5.99	41.43	62.32
6	SSP5-8.5 (2075-2100)	15.72	7.57	54.04	72.43

## CHAPTER IV: CONCLUSION AND DISCUSSIONS

### 4.1 Conclusion

This study assessed the impact of climate change on glaciers and river basin under different climatic scenarios using hydro-meteorological data and bias corrected GCM data from 2001 to 2023. Historical hydro-meteorological data shows high daily, monthly and annual variation in the basin. In recent years, both temperature and precipitation stations show significant positive trend. This study assesses the discharge of BRB under different climatic scenarios for the period of 2024- 2100. The result shows the decreasing discharge trend compared to the baseline discharge, with significant increase from 2024 to 2100 A.D.

### 4.2 Discussions

The temperature and precipitation pattern of the BRB shows the increasing trend in recent years and is supposed to increase continuously under SSP2-4.5 and SSP5-8.5. High spatiotemporal variability in the impact of climate change is demonstrated by the rise in seasonal hydro-climatic extremes in South Asia and the increasing severity of hydro-climatic extremes during only one season in Southeast Asia, showing further studies of climate projection in local and larger level is necessary. For SSP119, SSP245, and SSP585, roughly 16%, 20%, and 24% of minor glaciers, respectively, are expected to vanish before the middle of the twenty-first century in the High Mountain Asia (Zhao et al., 2023). Similarly, Jia et al., (2020) also suggested that the temperature and precipitation data correlates well with the runoff of the catchment area in the study of runoff changes from Urumqi glacier number 1. The runoff during the period of 1993–2018 increased by  $114.39 \times 10^4 \text{ m}^3$ , which was 1.7 times the average runoff during the period 1959–1992.

The increase in glacier melt can significantly affect the discharge of the BRB. A comparative study between the glacier model and hydrological conducted by Hanus et al., (2024) found that with incorporation of glaciers in the modeling study, the increase in future discharge is attenuated while the decreases are exacerbated when glaciers are represented explicitly in the study. This study highlights the need of incorporating glaciers into large scale hydrological models for improved climate change studies, specifically while aiming on summer months or extreme years.

The contribution of Snowmelt is approximately 10% in both scenarios, ice melt is approximately 4%, rain is approximately 34% and baseflow is approximately 51% of the total discharge which increases with reference periods. Budhathoki et al., (2023) employed an HBV light model in glacierized Tamakoshi River Basin to quantify the water balance components and predicted that

the 13% and 5% of the streamflow was governed mostly by glacier melt and snow melt respectively. The contribution of runoff components to streamflow has been on the rise, while the changes in water storage have been declining over the recent decade.

In this study, discharge seems to decrease for both the scenarios with SSP5-8.5 showing relatively more discharge. The discharge has decreased by approximately 25% under SSP2-4.5 for period 2024- 2100. Similarly, the discharge has decreased by approximately 20% under SSP5-8.5. The study The Marshyangdi River's discharge trend under SSP2-4.5 and 8.5 is increasing for the near, mid, and far futures; however, under SSP2-4.5, the discharge trend is decreasing for the far future, in the time of 2025-2100 (Sangroula et al., 2022).

Assessing the proportional contribution of glacier-derived meltwater to river discharge is essential for understanding the role of glaciers in water availability across extensive river basins. However, this proportion is highly sensitive to the accurate representation of the discharge regime. Overestimating or underestimating basin discharge directly impacts the perceived contribution of glacier melt, potentially leading to inflated or deflated estimates. Additionally, since water abstractions reduce overall discharge, calculating the glacier contribution as the ratio of runoff to discharge likely represents an upper bound on the glacier's actual impact (Gascoin, 2024). Consequently, further advancements in the precision of large-scale hydrological models will be crucial in reducing the uncertainty surrounding the true contribution of glacier melt.

## REFERENCES

- Adnan, M., Liu, S., Saifullah, M., Iqbal, M., Ali, A. F., & Mukhtar, M. A. (2022). Spatiotemporal variations in runoff and runoff components in response to climate change in a glacierized subbasin of the Upper Indus Basin, Pakistan. *Frontiers in Earth Science*, *10*, 970349. <https://doi.org/10.3389/feart.2022.970349>
- Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). LARGE AREA HYDROLOGIC MODELING AND ASSESSMENT PART I: MODEL DEVELOPMENT <sup>1</sup>. *JAWRA Journal of the American Water Resources Association*, *34*(1), 73–89. <https://doi.org/10.1111/j.1752-1688.1998.tb05961.x>
- Barry, R. G., & Gan, T. Y. (2021). *The global cryosphere: Past, present and future* (2nd ed). Cambridge university press.
- Betts, A. K., & Jakob, C. (2002). Evaluation of the diurnal cycle of precipitation, surface thermodynamics, and surface fluxes in the ECMWF model using LBA data. *Journal of Geophysical Research: Atmospheres*, *107*(D20). <https://doi.org/10.1029/2001JD000427>
- Braithwaite, R. J., & Olesen, O. B. (1989). Calculation of Glacier Ablation from Air Temperature, West Greenland. In J. Oerlemans (Ed.), *Glacier Fluctuations and Climatic Change* (Vol. 6, pp. 219–233). Springer Netherlands. [https://doi.org/10.1007/978-94-015-7823-3\\_15](https://doi.org/10.1007/978-94-015-7823-3_15)
- Budhathoki, B. R., Adhikari, T. R., Shrestha, S., & Awasthi, R. P. (2023). Application of hydrological model to simulate streamflow contribution on water balance in Himalaya river basin, Nepal. *Frontiers in Earth Science*, *11*, 1128959. <https://doi.org/10.3389/feart.2023.1128959>
- Dimri, A. P., Kumar, D., Choudhary, A., & Maharana, P. (2018). Future changes over the Himalayas: Maximum and minimum temperature. *Global and Planetary Change*, *162*, 212–234. <https://doi.org/10.1016/j.gloplacha.2018.01.015>
- Hanus, S., Schuster, L., Burek, P., Maussion, F., Wada, Y., & Viviroli, D. (2024). *Coupling a large-scale glacier and hydrological model (OGGM v1.5.3 and CWatM V1.08) – Towards an improved representation of mountain water resources in global assessments*. <https://doi.org/10.5194/egusphere-2023-2562>
- Jia, Y., Li, Z., Jin, S., Xu, C., Deng, H., & Zhang, M. (2020). Runoff Changes from Urumqi Glacier No. 1 over the Past 60 Years, Eastern Tianshan, Central Asia. *Water*, *12*(5), 1286. <https://doi.org/10.3390/w12051286>

- Karki, R., Ul Hasson, S., Gerlitz, L., Talchabhadel, R., Schickhoff, U., Scholten, T., & Böhner, J. (2020). Rising mean and extreme near-surface air temperature across Nepal. *International Journal of Climatology*, 40(4), 2445–2463. <https://doi.org/10.1002/joc.6344>
- Kayastha, R. B., Steiner, N., Kayastha, R., Mishra, S. K., & McDonald, K. (2020). Comparative Study of Hydrology and Icemelt in Three Nepal River Basins Using the Glacio-Hydrological Degree-Day Model (GDM) and Observations From the Advanced Scatterometer (ASCAT). *Frontiers in Earth Science*, 7, 354. <https://doi.org/10.3389/feart.2019.00354>
- Marahatta, S., Devkota, L. P., & Aryal, D. (2021). Application of SWAT in Hydrological Simulation of Complex Mountainous River Basin (Part I: Model Development). *Water*, 13(11), 1546. <https://doi.org/10.3390/w13111546>
- Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology*, 10(3), 282–290. [https://doi.org/10.1016/0022-1694\(70\)90255-6](https://doi.org/10.1016/0022-1694(70)90255-6)
- RGI Consortium. (2023). *Randolph Glacier Inventory—A Dataset of Global Glacier Outlines, Version 7* [Dataset]. [object Object]. <https://doi.org/10.5067/F6JMOVY5NAVZ>
- Shukla, S., Kansal, M. L., & Jain, S. K. (2017). Snow cover area variability assessment in the upper part of the Satluj river basin in India. *Geocarto International*, 32(11), 1285–1306. <https://doi.org/10.1080/10106049.2016.1206975>
- Terink, W., Lutz, A. F., Simons, G. W. H., Immerzeel, W. W., & Droogers, P. (2015). SPHY v2.0: Spatial Processes in HYdrology. *Geoscientific Model Development*, 8(7), 2009–2034. <https://doi.org/10.5194/gmd-8-2009-2015>
- Wu, J., Li, H., Zhou, J., Tai, S., & Wang, X. (2021). Variation of Runoff and Runoff Components of the Upper Shule River in the Northeastern Qinghai–Tibet Plateau under Climate Change. *Water*, 13(23), 3357. <https://doi.org/10.3390/w13233357>
- Zhao, H., Su, B., Lei, H., Zhang, T., & Xiao, C. (2023). A new projection for glacier mass and runoff changes over High Mountain Asia. *Science Bulletin*, 68(1), 43–47. <https://doi.org/10.1016/j.scib.2022.12.004>

## **Personal Opinion of the use of WECCS-Gen Tool and recommendations on it**

The WECCS-Gen tool is an essential resource in climate change studies, particularly in modeling and predicting discharge under various weather scenarios. Its user-friendly interface and easy design make it accessible even to those with limited technical expertise, while the clarity of its outputs ensures that the results can be easily interpreted and applied in research. The recommendations on the tool are as follows:

1. The system requirements can be decreased if the tool can be developed to run in windows as well.
2. The required modules should be properly defined within the code.
3. The bugs in the code have hindered the run so code needs to be debugged if not already.

## **Brief-Bio**

I am an Environmental Science graduate pursuing a master's degree, from Central Department of Environmental Science, Tribhuvan University, with a strong passion for advancing climate change knowledge and community-level impact. With a strong focus on disaster risk reduction and climate change, I am driven by a commitment to environmental conservation. My positive attitude and dedication empower me to apply my knowledge and skills to create meaningful impacts in this critical field. My field of interests are glaciers, climate induced disaster risk reduction and management and environmental resilience. I am a Motivated learner with the ability to absorb effectively and committed to upskilling and expanding knowledge in climate change. I am dedicated and have unyielding spirit despite numerous hurdles and possess the ability to work collaboratively in fast-paced environments, demonstrating adaptability and a commitment to continuous learning and improvement. I possess intellectual curiosity, perseverance, and a passion for understanding the challenges posed by climate change, particularly in the context of cryosphere science. I have a creditable skill in Windows and Linux (WSL) and is equipped with basic python and intermediate level of R programming language. Similarly, I am knowledgeable in geographical information systems, both ArcGIS and QGIS. I also have intermediate knowledge on different glacio-hydrological models like SPHY, OGGM and GDM.