Glacial Ice-melt Contribution to Streamflow in the Marshyangdi River Basin: Using Glacio-Hydrological Degree-Day Model

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Abstract

This study uses the Glacio-Hydrological Degree Day Model (GDM) to quantify the contribution of glacier ice-melt to streamflow in order to analyze the dynamics of the Marshyangdi River Basin (MRB) in central Nepal. GDM is useful in calculating the contribution of rainfall, ice-melt, snow-melt and base-flow of a river. Glacier melt modeling is essential for future water resource planning and disaster risk management because MRB, a glacier-fed basin in the Hindu Kush Himalaya (HKH) region, is extremely vulnerable to climatic changes. Air temperature, precipitation, digital elevation models, and land cover classification are the input data needed to accurately estimate daily discharge in the GDM model, which are calibrated and validated using data from 2004 to 2007 and validated from 2007 to 2010. 2007 is used in both period for ease in comparing four years for both period. Strong agreement is found between the model's performance and the measured discharge data (NSE ≈ 0.78, R2 ≈ 0.8). The findings show that glacial ice-melt contributes 1.5% – 4% of total discharge each year from Bimalnagar Station, snow-melt accounts for 7% - 10% of MRB's total yearly discharge, rain accounts for 52% - 58% and base-flow accounts for 32% - 36.5%. The peak contribution of glacial ice-melt is observed in August, with clean glacier ice-melt contribution and debris covered glacier ice-melt contribution of 6.82 m^3/s and 5.77 m^3/s respectively in the calibration period. Similarly, in the validation period the clean glacier and debris covered glacier ice-melt contribution are 7.56 m^3/s and 6.29 m^3/s respectively in August.

Keywords: clean glacier, debris covered glacier, discharge, Glacio-Hydrological Degree-Day Model, glacial ice-melt, Marshyangdi River Basin

Introduction

Glaciers in the mountain region act as a reservoir of freshwater for the people living downstream in the cities that are built in and around the river basins that have headwaters up in the mountains. These waters are not only used for drinking water, irrigation and hydroelectricity production but also influential in hydrological aspects like water resources management and disaster risk management. In addition to rainfall, base-flow and snow-melt, glacier ice-melt is one of the biggest contributors to downstream streamflow perennially especially in warm and dry summer months (Koboltschnig et al., 2008; Stahl & Moore, 2006; Verbunt et al., 2003; Zappa & Kan, 2007).

The 3500 km long Hindu Kush Himalayan (HKH) region, covering an area of more than 4.2 million km^2, is the largest store of ice outside the two polar regions and source for 12 river basins, including 10 major (transboundary) rivers – Tarim, Amu Darya, Indus, Ganges, Brahmaputra (Yarlung Tsangpo), Irrawaddy, Salween (Nu), Mekong (Lancang), Yangtse

(Jinsha) and Yellow (Huang He). These river networks flow through 16 countries, providing freshwater to 240 million people living in HKH region and 1.65 billion downstream (ICIMOD, 2023). The report further reveals the changes to the cryosphere in the region driven by global warming are "unprecedented and largely irreversible", predicting the loss of current glacier volume by up to 80% by the end of the century, on current emission paths. Mountainous regions are most vulnerable to the change in climate as temperature changes directly affects the rain versus snowfall ratio, and snow and glacier melt as well (Barnett et al., 2005). The pace of glacier response to climate change depends on their size with smaller sizes more rapid in response to change (Huss & Fischer, 2016). Snow and glacier melt contributes to about 30 – 50 % of total water discharge in some arid regions in the mountainous areas (Viviroli & Weingartner, 2004, Yin et al., 2014). Reduction of water resources in glacier-fed watersheds due to climate change affects the socio-economic development in the entire basin (Hagg et al., 2007, Luo et al., 2013) making the monitoring of glacier volume change and its resulting streamflow variation prediction of great importance.

The two main techniques for modeling melt currently used to estimate river discharge in glaciated basins are the energy balance model and the temperature index model. The energy balance method calculates melt as a residual component in the equation representing energy exchange processes at the glacier-atmosphere interface and incorporates all contributing energy fluxes (Kayastha & Kayastha, 2019). In contrast, the temperature index model relies on a statistical relationship between air temperature and melt rates to compute melting (Braithwaite, 1995; Hock, 2003). Although the energy balance method allows for comprehensive estimation of melt (Hock, 2003), its application in remote Himalayan glacier regions is often limited by the lack of necessary input data (Kayastha et al., 2020).

Given this challenge, temperature index models have seen wide application in the Himalayan river basins, where data availability is limited, to estimate discharge over differing time scales (Kayastha et al., 2000, 2006; Kayastha & Kayastha, 2019). The Glacio-hydrological Degree-day Model (GDM), Version 2.0, is a spatially distributed, grid-based model that is capable of simulating the influence of various hydrological components—namely snow-melt, glacier ice melt, rainfall, and base-flow—on river discharge (Kayastha et al., 2020). GDM is especially suitable for Himalayan catchments, where limited data, a few parameters, and minimal input are the rule, not the exception (Khadka et al., 2020).

Rainfall-runoff reactions to climate change unfold quite rapidly, while glacial melting proceeds in a much longer time component, from decades to centuries, spanning the life of the existing ice volume and the timeframe considered. Yet, with continued adequate ice reserves withdrawing under continued warming, and decrease in glacier area will gradually lead to melt generation in the long run (Khanal et al., 2021).

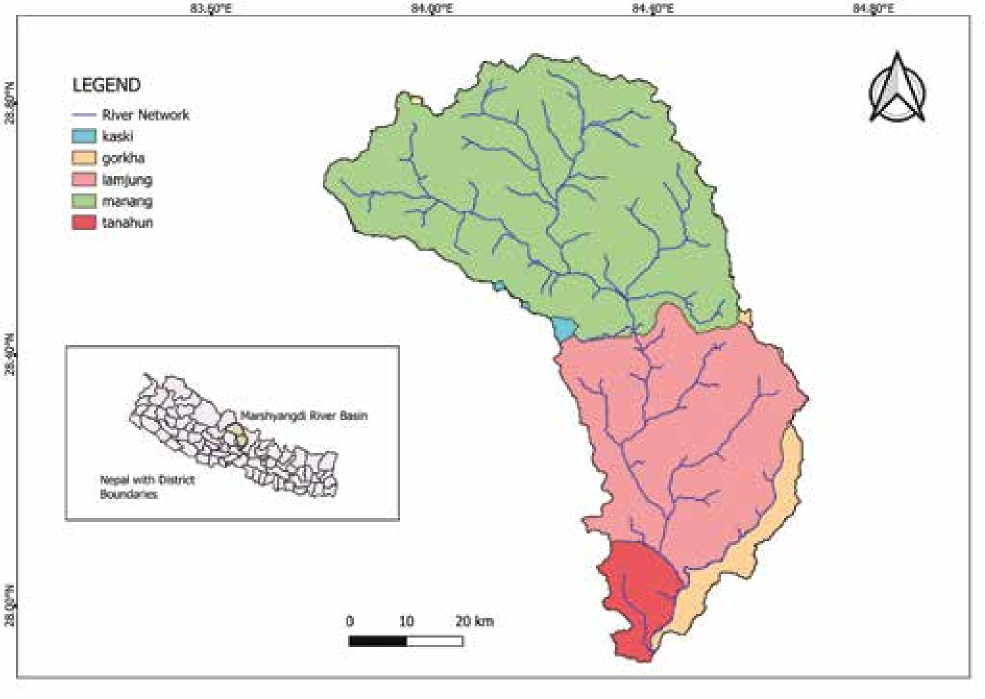
Study Area

Marshyangdi River Basin (MRB) is one of the most important river systems of Nepal and acts as a sub-basin of the Gandaki River Basin (GRB). Located between 27.8 to 28.9 degrees North latitudes and 83.7 to 84.8 degrees East longitude, the watershed area of 4048 km^2 drains through Bimalnagar, situated at 373 m above sea level (asl) (Department of Hydrology and Meteorology, DHM) in Tanahun district of Gandaki Province. 150 km long Marshyangdi river has its headwaters north of Annapurna Range, originating from the Tethyan Sedimentary Series (TSS), and passes through Greater Himalayan Sequence (GHS) while flowing southeast and ultimately cuts through Lesser Himalayan Sequence (LHS) while turning southwards until it meets Trishuli River in Mugling (Evans et al., 2001). The altitude of MRB varies between 356 and 7777 m asl resulting in the presence of subtropical to alpine climatic zones. 543 km^2 of glaciated area is present in the watershed between 4000 m and 6500 m asl constituting about 13.41% of total watershed area, within which 5.15% of glacier is covered by debris (28 km^2).

The basin with a mean slope of 29.4 degrees have a population of approximately 770,000 people (CBS, 2019) and the most common patterns of land use are grassland, barren land and agricultural land (ICIMOD, 2010). MRB covers most of the Annapurna Circuit Trail (ACT) area, one of the most popular trekking routes of Nepal, a key economic and livelihood provider with agriculture and crop production, adventure and water activities, a cultural hub with numerous temples and monasteries, in addition to different irrigation projects and hydroelectric power stations that lie on the river. Marshyangdi river is a dendritic perennial river originating at the confluence of Khangsar and Jharsang rivers in Manang district before politically crossing the boundaries of Lamjung, Tanahun and Gorkha in the south-east direction.

Figure 1

Location map of MRB with political boundaries and river network.



Input Data

Meteorological and Hydrological Data

Daily air temperature and precipitation, which are the main input data of respective river basins to the model, are obtained from Department of Hydrology and Meteorology (DHM), Government of Nepal. Considering the location of the stations within the MRB and the availability of data from 2004 to 2010, seven stations are selected as shown in Table 1. The temperature lapse rate and precipitation gradient in the basin are calculated using data of air temperature and precipitation collected at the climatological stations of Khudi Bazar situated at 838m asl and Chame situated at 2680m asl.

Table 1

List of Meteorological stations used in the study.

S. N.	Station ID	Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)	District
1	802	Khudi Bazar	28.28	84.35	838	Lamjung
2	807	Kunchha	28.12	84.34	820	Lamjung
3	816	Chame	28.55	84.23	2680	Manang
4	820	Manang Bhot	28.66	84.02	3556	Manang
5	823	Gharedhunga	28.14	84.58	1088	Lamjung
6	847	Besishahar	28.23	84.38	686	Lamjung
7	856	Rainastar	28.07	84.47	588	Lamjung

Three hydrological stations are situated in the basin, namely Khudi Bazar (439.3), Bhakundebesi (439.35) and Bimalnagar (439.7) out of which Bimalnagar was selected as the outlet point for the study. Daily discharge data from 2004 to 2010 were obtained from DHM and were used in the study. The gauged flow data were included to the model for two main reasons: first, to create inlet discharge points that would replicate the basin's current circumstances; and second, to do sensitivity analysis, model calibration, and validation at the outlet. Daily observed data from 2004 to 2007 AD were used for the calibration procedure, while data from 2007 to 2010 AD were used for the validation phase.

Table 2

List of hydrological stations used in the study.

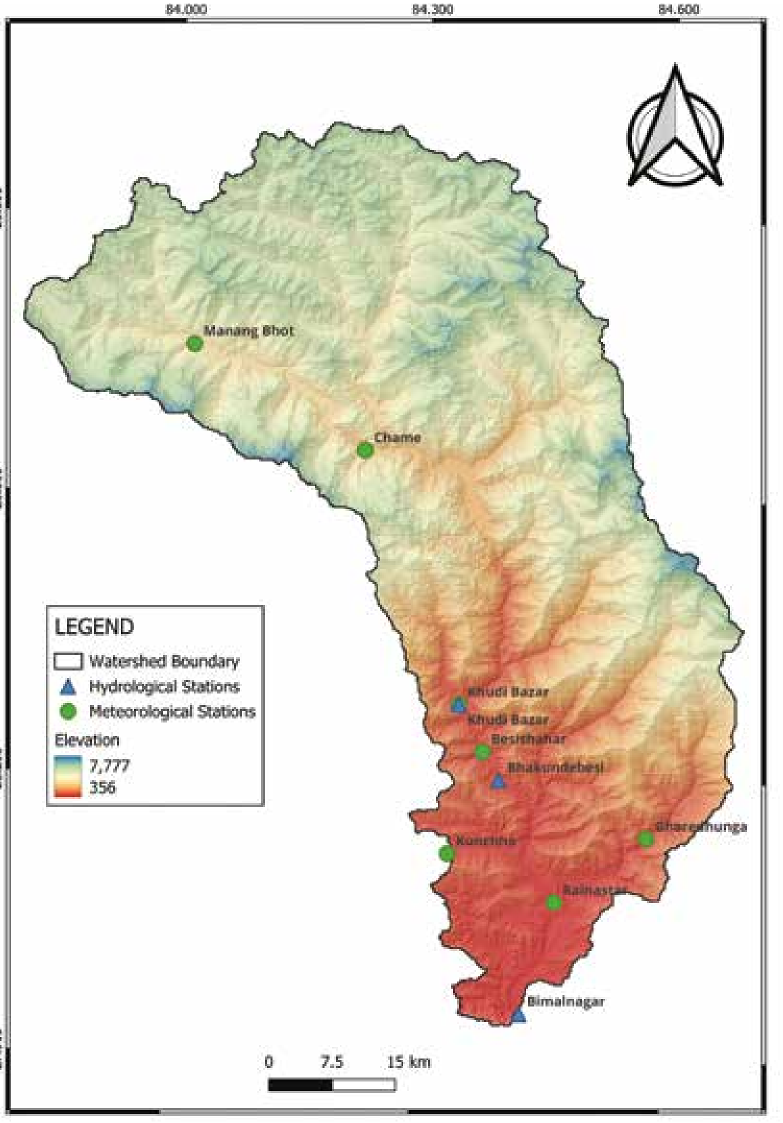
S. N.	Station ID	Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)	District
1	439.3	Khudi Bazar	28.28	84.35	789	Lamjung
2	439.35	Bhakundebesi	28.20	84.40	650	Lamjung
3	439.7	Bimalnagar	27.95	84.43	373	Lamjung

Geo-Spatial Data

The Digital Elevation Model (DEM) of 30m resolution was downloaded from Earthdata (https://www.earthdata.nasa.gov/) from Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 3 in GeoTIFF file format and was used for the grid elevation information.

Figure 2

Digital elevation model of Marshyangdi River Basin.

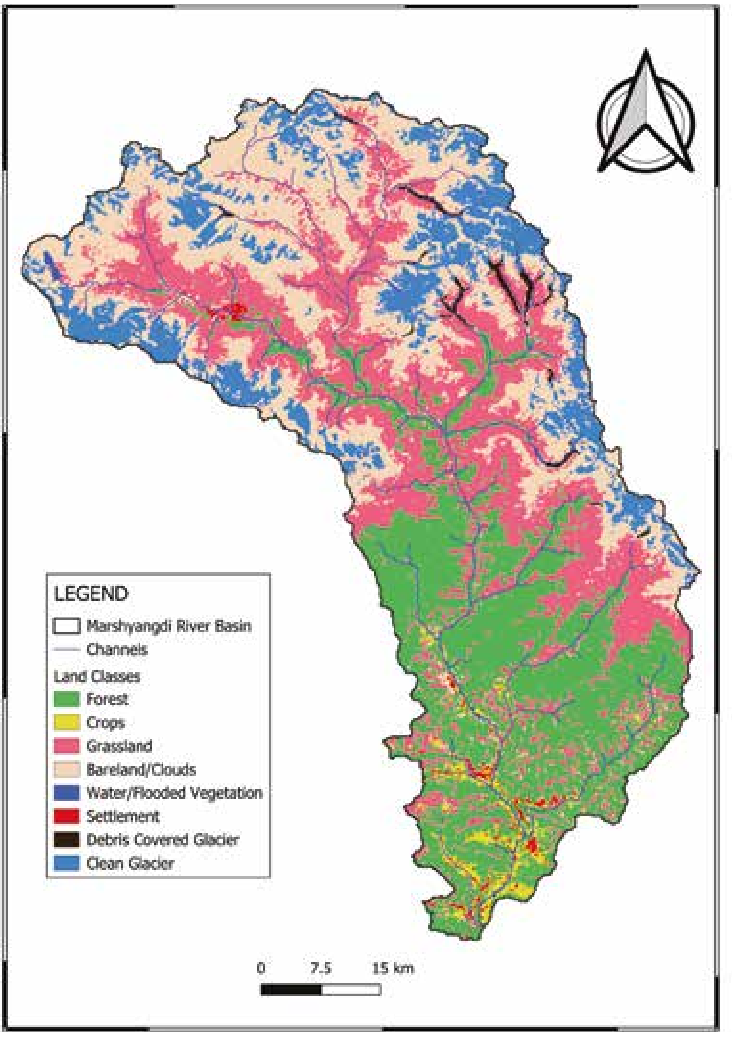


Land Use Land Cover Map

Global Land Use Land Cover Data was downloaded from ESRI Sentinel – 2 Land Cover Explorer (https://livingatlas.arcgis.com/landcoverexplorer) having a resolution of 10m. The LULC data contains land classification of snow and ice as a single class. To use more details, Glacier Data of HKH region containing, among other features, the clean and debris covered ice classifications was downloaded from International Center for Integrated Mountain Development (ICIMOD)'s Glacier Inventory. The shape files containing these data were divided into clean ice and debris covered glacier and converted to raster format and then overlapped into the LULC map.

Figure 3

Land use land cover classification map of Marshyangdi River Basin.



Methodology

Glacio-hydrological Degree-day Model (GDM)

GDM v2.0 is a distributed and gridded model having the capacity to simulate four runoff components - rainfall, base-flow, snow-melt and glacier ice melt – and its impact on river discharge (Kayastha & Kayastha, 2019; Kayastha et al; 2020). Glacio-hydrological phenomena is simulated by the melt module in GDM using a temperature-index model. GDM is calibrated by adjustment of key parameters like degree-day factors, snow and rain runoff coefficients and recession coefficients. The degree-day factors and critical temperatures are calculated as done in studies by Kayastha et al. (2006) and Khadka et al. (2015). In addition to these factors, monthly sunshine hours are required to calculate potential evapotranspiration using the Thornthwaite equation (Gupta et al; 2019). The monthly sunshine hours are based on estimates from an earlier research (Niroula et al., 2015). Using degree-day method, the model calculates melt for snow, clean ice and ice beneath debris (Khadka et al., 2020) independently as shown:

$M = \{(Kd \text{ or } K_s \text{ or } Kb) \times T \text{ if, } T > 0\} \{0 \text{ if, } T \leq 0\}$ Eq. 1

The amount of snow or ice melt, in mm/day (M) in each grid depends on the air temperature in degrees Celsius (T) as well as the degree day factors for snow clean ice and debris covered ice (k_s, kb and kd respectively) which represent how much melt occurs per degree Celsius, per day (Khadka et al., 2020), respectively as in Equation.

The surface runoff (QG) includes the runoff resulting from rainfall melting snow and ice melt, from each grid as indicated in the equation provided below:

$QG = Q_r \times C_r + Q_s \times C_s + Q$ Eq. 2

Where, Q_r = amount of runoff from rain (m^3/s)

Q_s = amount of runoff from snow-melt (m^3/s) Qi = amount of runoff from ice-melt (m^3/s)

C_r and C_s are coefficient of impact of rain and snow respectively whereas QG indicates surface runoff from each grid in m^3/s.

Contribution of surface runoff (QR) and total contribution of base-flow (QB) from all grids are calculated and then are directed towards the sub basin outlet using routing equation as shown below:

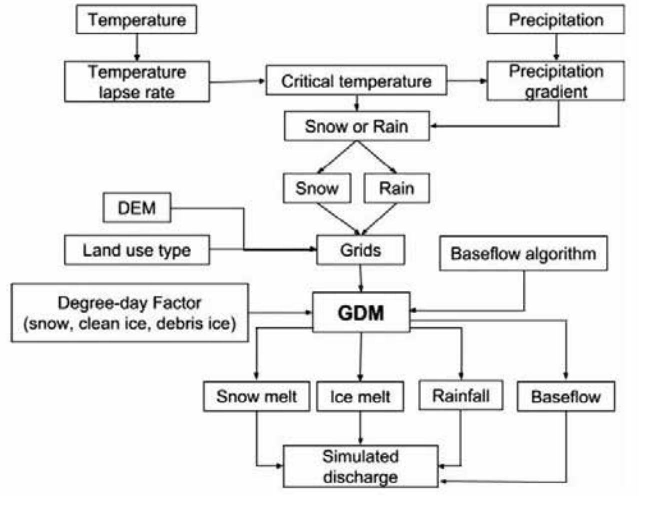
$Qd = QR \times (1 - k) + QR(d\text{-}1) \times k + QB$ Eq. 3

The recession coefficient (k) is used to calculate total discharge (Qd) in m^3/s for any given day (d). We determine the value of "k" by solving Eq. 4. The constants "x" and "y" obtained from this equation are computed as 0.93 and 0.009 for the basin (Khadka et al., 2020)

Kd+1 = x Q-yd Eq. 4

Figure 4

Flow chart of the glacio-hydrological degree-day model (GDM).



As shown in Figure 4, the flowchart representing the framework of the research clearly indicates the process followed for the smooth execution of GDM model to generate the streamflow components of a river basin.

Hydrological Simulation

Simulation Experiment Design

GDM's performance is first calibrated over a four-year period (2004–2007) and then assessed over an additional four years (2007–2010) by contrasting the observed and simulated discharges at the outlet point of Bimalnagar hydrological station in MRB with each other. The degree-day factors for snow and ice melt, among other melt module parameters, are derived from field observations conducted by Kayastha et al. (2000) in the Nepal Himalayas. Based on field observations of the Khumbu and Lirung Glaciers in the Nepal Himalayas, it is estimated that the degree-day factor for ice-melt of a debris-covered glacier is approximately half of the ice-melt from clean glacier.

Performance Indices

By contrasting the daily time series of observed and simulated discharges, the effectiveness of the model's performance is evaluated. The model result between the simulated and observed discharge is evaluated using the Nash-Sutcliffe Efficiency (NSE) index (Nash and Sutcliffe 1970), as indicated below:

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

Where, Qobs = daily observed discharge

Qsim = daily simulated discharge

Qavg = average observed discharge

The volume difference can also be used to determine model accuracy using the following equation:

$$VD = \frac{V_R - V'_R}{V_R} \times 100$$

where VR and V'R is the measured and the simulated discharge, respectively.

Results and Discussions

Model Calibration and Validation

Recession coefficients, snow and rain coefficients, and positive degree-day factors are the primary GDM parameters that need to be adjusted. Several positive degree-day factors, each unique to a distinct month and lying within the expected range of degree-day factors recorded on different glaciers in the Nepal Himalayas, are introduced to the model in order to improve it. Likewise, the model is calibrated for recession coefficients as well as snow and ice coefficients. Table 3 contains a list of all the calibrated parameters and coefficients used in the model calibration.

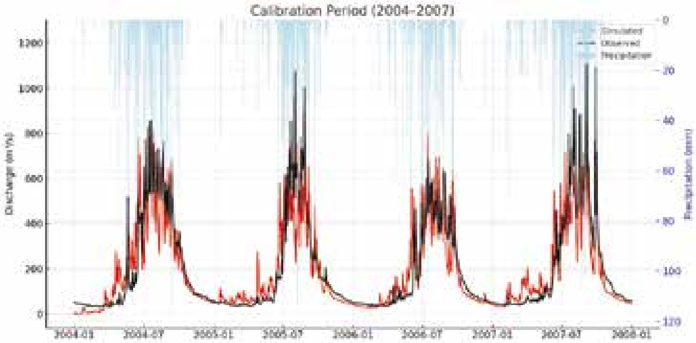
Table 3

Calibrated parameters for GDM in MRB.

Parameters		MRB
Critical temperature		2 °C
Temperature lapse rate		0.006 °C/m
Recession coefficient		0.7
Latitude : Geographical coordinate system at the centroid of study area		28.5
Runoff coefficient	Land use type 1	0.3-0.7
	Land use type 2	0.5-0.8
	Land use type 3	0.5-0.7
	Land use type 4	0.3-0.7
	Land use type 5	0.95
	Land use type 6	0.95
	Land use type 7	1
	Land use type 8	1
Degree day factor	Snow melt	7–8.5 mm °C-1 day-1
Degree day factor delay time of the overlying geologic formations (days).	Ice melt	6–10.5 mm °C-1 day
	Ice under debris	3 mm °C-1 day-1
	dgw,sh	20 days
Recession constant for shallow Aquifer	agw,sh	0.5
Delay time or drainage time of the deep aquifer geologic formation (days)	dgw,dp	100 days
Recession constant for deep quifer	agw,dp	0.5
Coefficient of shallow aquifer percolation to deep aquifer	ßdp	0.7

Figure 5

Precipitation distribution and observed vs. simulated discharge for the calibration period (2004 – 2007) (above) and validation period (2007 – 2010) in MRB.



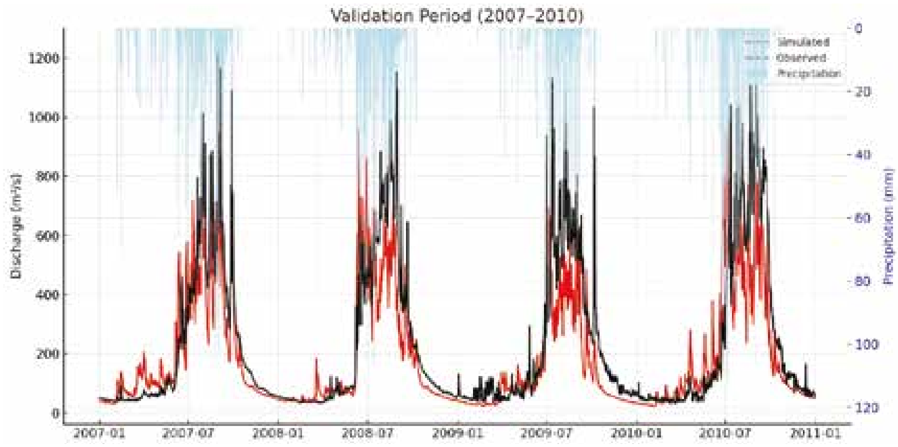
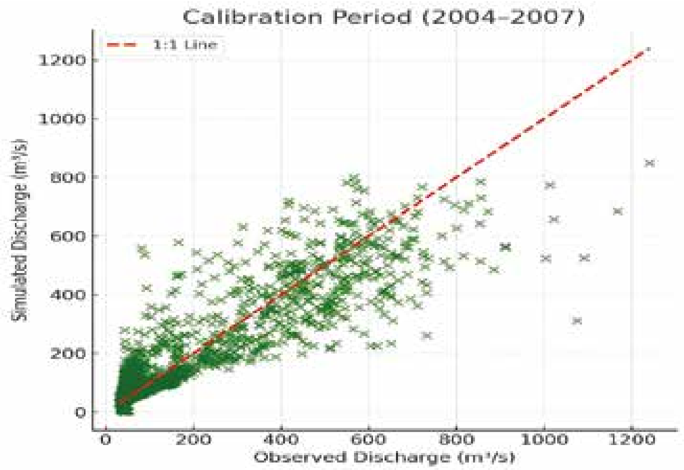
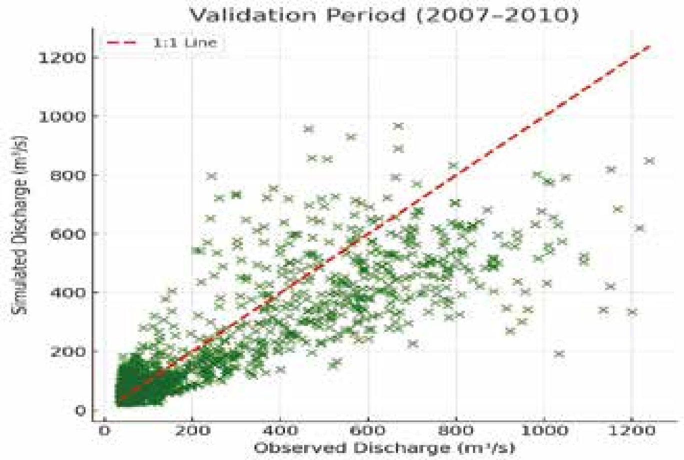


Figure 6

Scatter plot between the observed and simulated values for the calibration period (2004-2007) (above) and validation period (2007-2010).





For both the calibration and validation periods, the daily simulated discharge is contrasted with the discharge hydrograph of the MRB at Bimalnagar (Figure 2). Both the high and low observed discharges at Bimalnagar Station are consistent with the model's simulated discharge. The model's slight overestimation of the pre- monsoon or low-flow period may be related to the distribution of precipitation. Precipitation at glacier altitude may be two to ten times higher than the valley bottoms, therefore the distribution of precipitation to higher elevations from the reference station at lower elevation may not be very representative (Immerzeel et al., 2015). Barry (2012) also discussed that the precipitation gradient in the mountains can vary vertically and horizontally. Representing precipitation patterns can be difficult due to the Himalayan region's complicated geography, which can affect how and when precipitation is distributed in terms of space and time at higher elevations (Kayastha & Kayastha, 2019). Nevertheless, even with minimal input data, the model effectively replicates daily discharge, obtaining favorable Nash-Sutcliffe Efficiency (NSE) values and R2 values and keeping the volume difference within ±5%.

The best-performing parameter for MRB is used to assess the model's performance. While the volume difference is between ±5%, the calibration and validation periods' Nash-Sutcliffe Efficiency (NSE) values for MRB is >0.75, the coefficient of determination (R2) value is ~0.8 as well. As shown in Table 4, the model performs satisfactorily in MRB during the calibration and validation phases.

Table 4

NSE and volume difference for the calibration and validation periods.

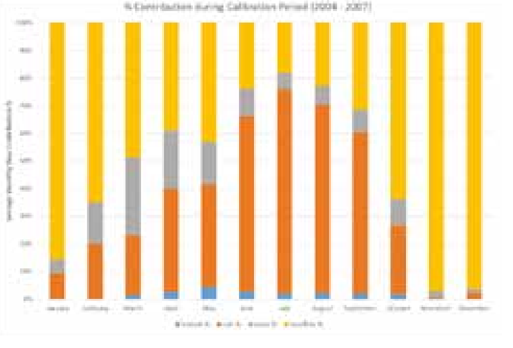
	Calibration	Validation
NSE	0.7864	0.7648
Volume Difference	-3.39 %	1.08 %
R^2	0.796	

Contribution of Glacial Ice-melt to Total Discharge

The GDM model's output is the daily discharge data of four different streamflow components including glacial ice melt. The mean monthly contributions of snow-melt, rainfall, base-flow, and ice-melt (clean and debris) in MRB during the calibration and validation periods are displayed in Figure 10. Observing the output in MRB, the primary source of discharge is rain during the monsoon season (June to September), whereas base-flow contributes all year long, reaching its peak during the late monsoon.

Figure 7

Contribution of base-flow, rain, snow melt and ice melt for the calibration (above) and validation periods in MRB.



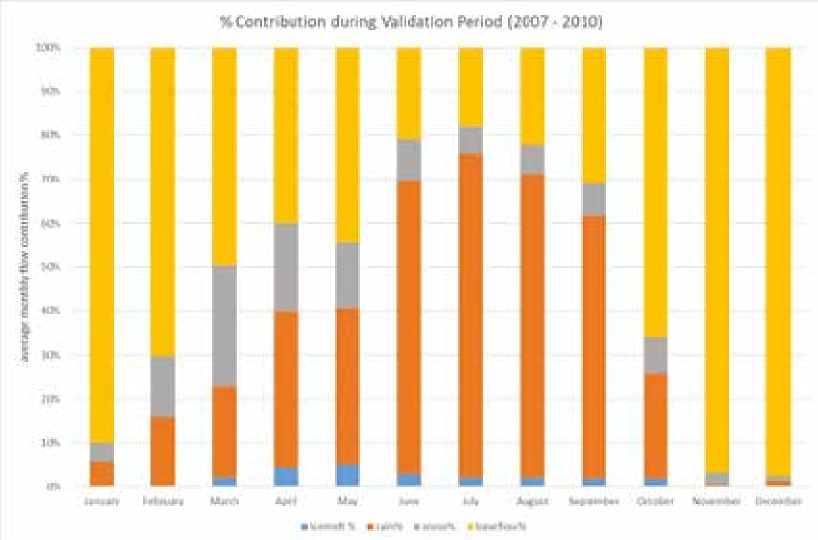
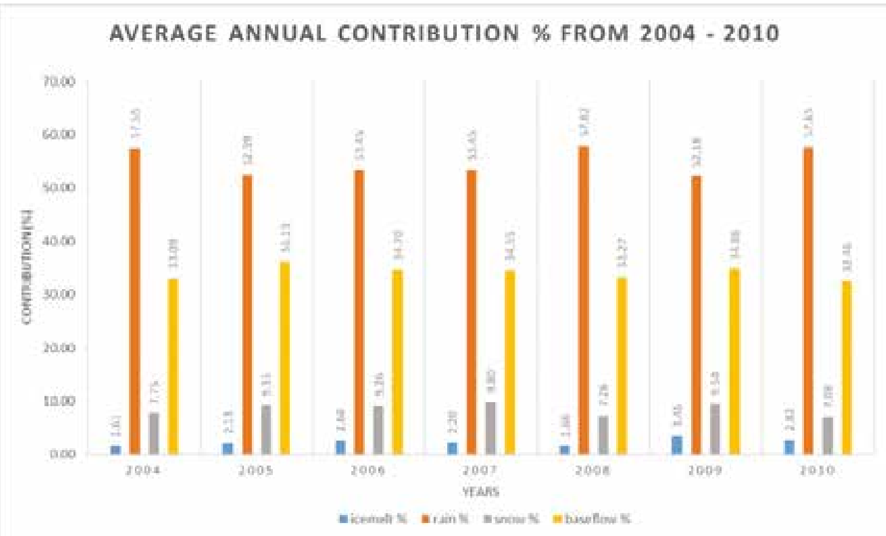


Figure 7 shows the annual contribution percentage of all four components during both the calibration and validation periods. Snow-melt accounts for 7% - 10% of MRB's total yearly discharge, whereas ice-melt accounts for only 1.5% - 4% of total discharge, rainfall accounts for 52% - 58% and base-flow accounts for 32% - 36.5%.

Figure 8

Annual percentage contribution of Glacier Ice-melt along with other components in the MRB.



Glacial Ice-melt is an important component for perennial streamflow due to its drip irrigation like discharge of meltwater. But due to the freezing temperature of the winter months ice-melt contribution is very small during November to February in both the calibration as well as validation period as shown in figure 8. Due to temperature and precipitation, the ice melt contribution to discharge starts in the pre- monsoon season and peaks between June and October.

The peak contribution of glacial ice-melt is observed in August, with clean glacier ice-melt contribution and debris covered glacier ice-melt contribution of 6.82 and 5.77 m^3/s respectively in the calibration period. Similarly, in the validation period the clean glacier and debris covered glacier ice-melt contribution are 7.56 and 6.29 m^3/s respectively in August. The contribution of ice-melt from clean glacier and debris covered glacier does not show a high difference in contribution visually even though the land cover land use classification showed a distribution of 12% clean glacier area while debris covered glacier area constituted only 1% of the basin. The debris covered glaciers lie at lower elevations while majority of the clean glaciers lie in higher elevation. The ice-melt is higher in lower elevation due to higher temperature than in the higher elevation.

Figure 9

Contribution of Glacier Ice-melt during calibration (above) and validation period in the MRB.

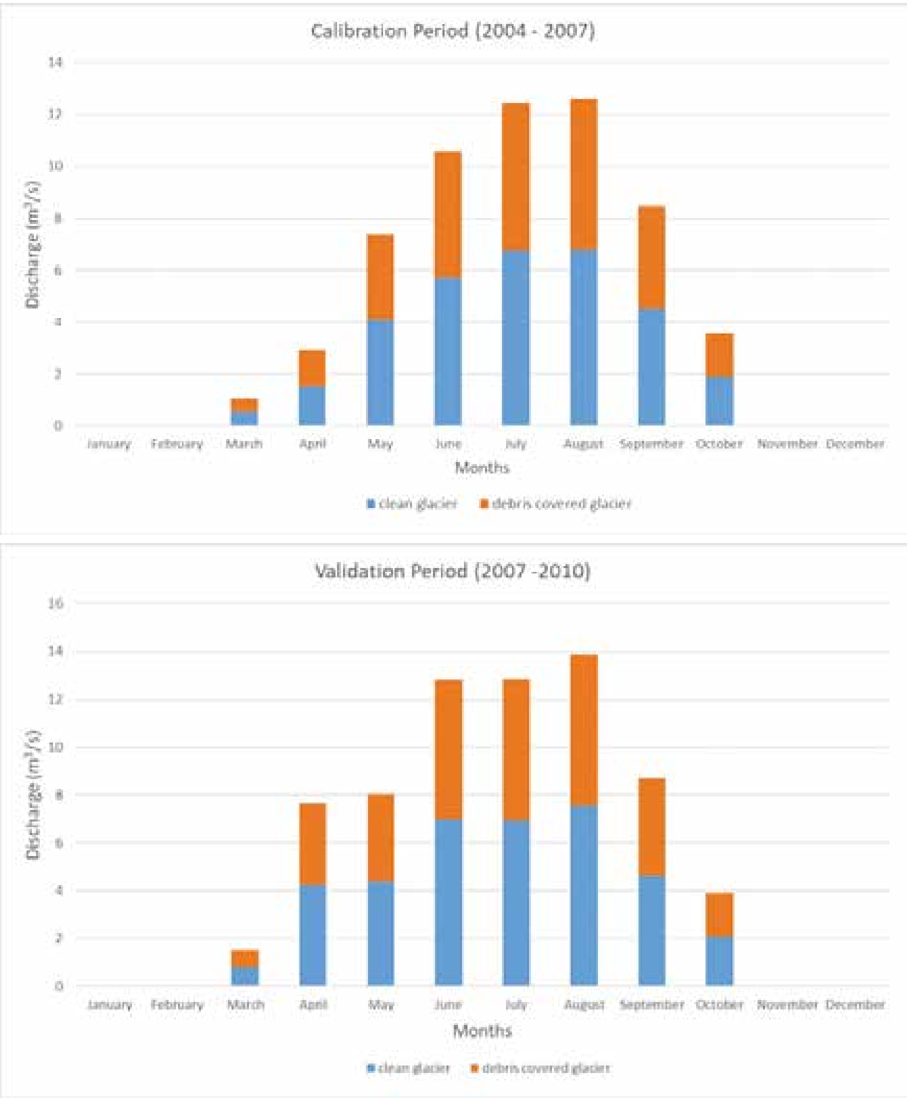
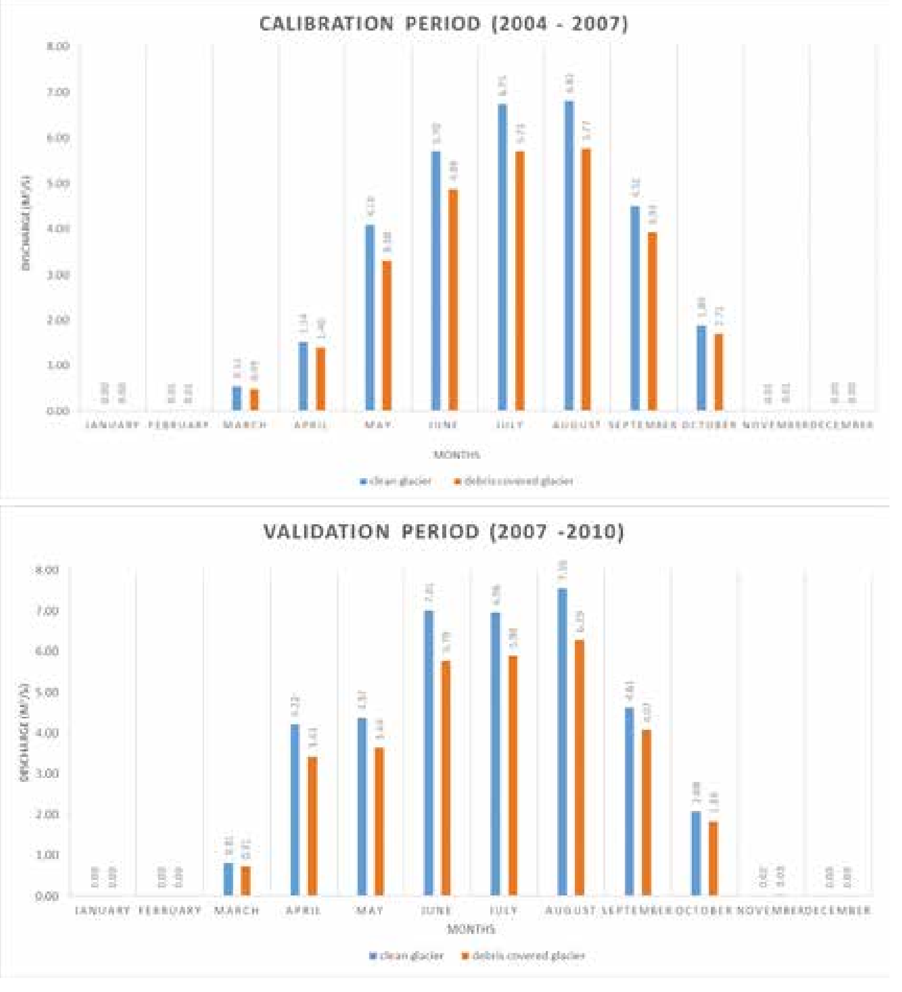


Figure 10

Average monthly discharge of clean and debris-covered glaciers.

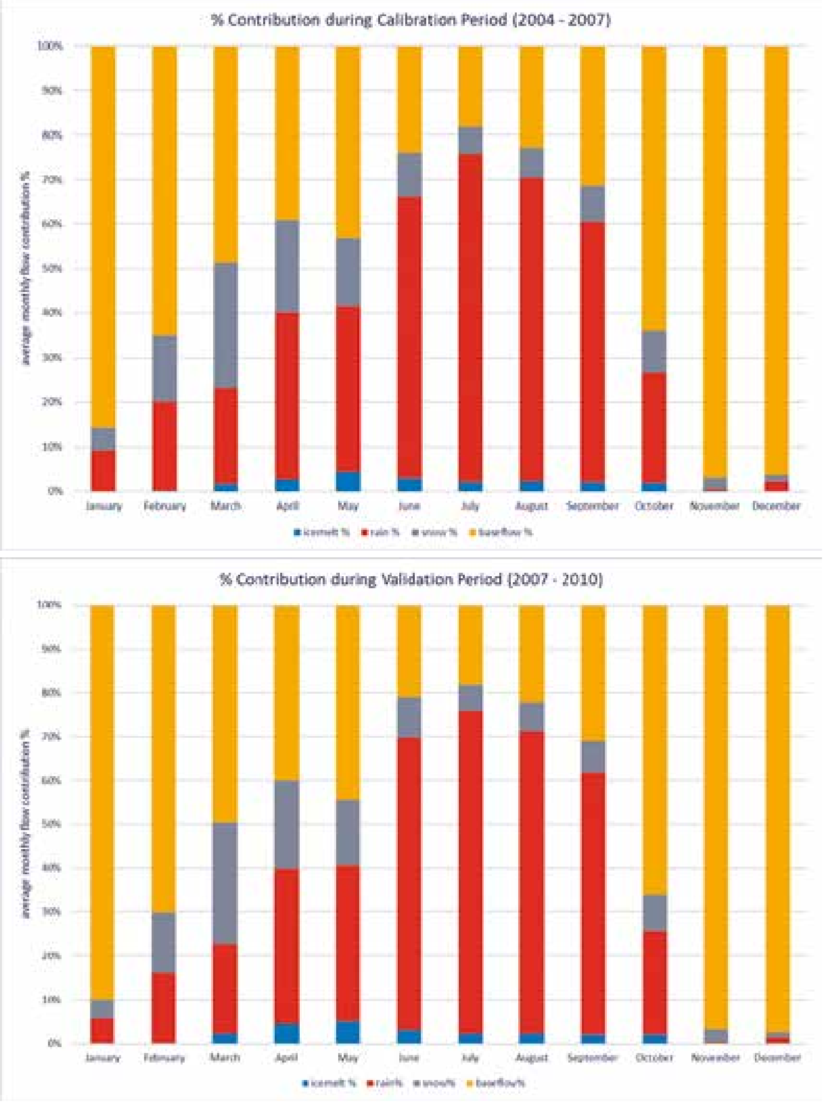


Seasonal Analysis of the MRB

The discharge output from the GDM reveals distinct seasonal hydrological patterns in the Marshyangdi River Basin, with base-flow dominating during the dry winter months (January to March), providing a steady stream when other sources are minimal. As temperatures rise from April to June, ice-melt becomes increasingly significant, peaking in June, while snow-melt declines and rainfall begins contributing more. During the monsoon season (July to September), rainfall becomes the primary contributor, especially in July and August, overshadowing base-flow and snow-melt, though ice-melt still plays a role before tapering off. From October to December, base-flow regains prominence, with minor snow-melt resuming as new snowfall begins. This cycle highlights the critical roles of base-flow in dry periods, ice-melt in pre- monsoon months, and rainfall during the monsoon in sustaining the river's seasonal flow.

Figure 11

Monthly contribution percentage of streamflow components.



Conclusion

Glacio-hydrological Degree-day Model (GDM) is a very capable and geographically suitable model for the estimation of glacial ice-melt along with rain, snow and base-flow component in the glaciered basins of mountainous terrain like Nepal. To estimate discharge and its components, the Marshyangdi River Basin (MRB) has been expertly subjected to the GDM. This model offers important insights into the complex hydrological dynamics of the basin, taking into account base-flow contributions, rainfall, snow-melt, and ice-melt. The model repeatedly shows that it can accurately reproduce discharge patterns during both the calibration and validation phases, despite its simplicity. Notably, the R^2 value stays strong at roughly 0.79, highlighting its outstanding performance, with the volume difference being around -5 to 2%. Selection of watershed in higher altitudes would have increased the contribution of glacier ice-melt in the model. The model presents itself as a suitable instrument for investigating the dynamics of hydrological systems and the possible effects of climate change on the river basins of the Himalayas.

The output of discharge data in daily discharge of every component is very useful in further analysis and required graphical and tabular representations. The variability of temporal scale is possible in daily, monthly, annual classification assisting in seasonal analysis and study of seasonal variation as well. The model is also very capable in simulation of hydrological dynamics with future climate change scenarios. Although this paper does not delve into the future projection according to climate change scenarios, other studies by Kayastha & Kayastha (2019) in Trishuli and Marshyangdi, Yang et al. (2022) in Urumqi River and Khadka et al. (2020) in Koshi, using GDM model successfully simulated the future scenarios highlighting the competence and versatility of the model and its data output.

The main advantages of the model are its simplicity and applicability, especially in areas with little data, such as the Himalayas. By using the degree-day factor (DDF), which creates a clear correlation between air temperature and melt rates, it is possible to simulate glaciers and snow-melt effectively without the need for complex meteorological inputs. For remote high-altitude basins where in-situ data on wind, humidity, and radiation are frequently unavailable, this makes it extremely useful. Because temperature data is easier to obtain from local weather stations or reanalysis datasets, the degree-day approach offers a trustworthy estimate of meltwater contributions. Hydrologists and planners working in difficult alpine areas with little observational infrastructure might thus benefit greatly from this model.

The model's dependence on temperature to drive melt processes, which ignores other significant energy fluxes including humidity, wind, and solar radiation, is one of its main drawbacks. These elements can have a big impact on melt rates, particularly in high mountain regions with erratic weather patterns. Furthermore, the model makes the assumption that glacier properties are homogeneous, ignoring changes in albedo, slope orientation, and debris cover—all of which can cause melt to vary spatially. Also, the model is devoid of a routing component and does not account for subsurface or groundwater flow processes, which might affect the timing and amount of streamflow, especially in catchments with substantial base-flow contributions or during the dry season.

In MRB, glacier melt is essential for maintaining streamflow, especially in the pre-monsoon and late-monsoon seasons when precipitation and snow-melt input are scarce. The use of the GDM model showed that, particularly in high-altitude sub- basins with substantial glacier cover, glacier melt plays a significant role in total runoff. During the calibration and validation stages, the model closely matched observed hydrographs and accurately represented the temporal variation of meltwater discharge emphasizing the usefulness of temperature-based models for estimating melt contributions in Himalayan River systems, where glaciological and meteorological data are frequently lacking or unavailable.

The glacier-fed flows are crucial for mitigating inter-annual and seasonal fluctuations in water availability in the face of shifting climate conditions. The GDM model predict a higher melt rate in the near future as air temperatures rise, which could improve river discharge prior to a long-term drop brought on by glacier retreat.

Recommendations

These results highlight the necessity of incorporating glacier melt dynamics into the region's long-term planning for water resources and climate adaption plans. For hydrological forecasts to be resilient in the face of ongoing climate change, the glacier component needs to be regularly checked and enhanced using new data, such as temperature lapse rates and glacier mass balance.

Consider incorporating glacier retreat modeling using OGGM to increase the accuracy of the GDM in glacierized river basins. The precision of GDM is significantly enhanced by this data, which includes annual retreat rates and variations in ice area. Modeling changes in wetlands, agricultural land, forest cover, bare land, and settlement areas is advised. More accurate and trustworthy results can be obtained by integrating data about these changes in land cover and use into the GDM. The contributions of rain, snow-melt, ice-melt, and base-flow to the basin's stream flow can be thoroughly examined by doing an isotope test.

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