Proceedings of 14th IOE Graduate Conference
Peer Reviewed
Year: 2023 Month: December Volume: 14
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Application of Glacio Hydrological Model for the Simulation of Stream Flow in Glacierized Tamakoshi River Basin, Nepal

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Abstract
The glaciers and snow-covered areas has been highly influential in the hydrology of the glacierized basin. Long-term water management will become more difficult as a result of climate change, which is anticipated to alter the water availability. Here we have set up Glacio hydrological Degree-day Model Version 2 (GDM V.2) as a hydrological model to simulate the discharge in Tamkoshi River basin (TRB) and quantified various runoff components. The model is first calibrated and validated for the period of 2004-2009 and 2011-2020 respectively where Nash-Sutcliffe Efficiency (NSE) is 0.77 and 0.80 for calibration and validation period. The monsoonal rain was anticipated to influence stream flow changes the most (46.86%), followed by base flow (37.57%), snow melt (12.17%), and glacier melt (3.18%) form the year 2004-2009 and rain (46.33%), followed by base flow (38.79%), glacier melt (3.27%), and snowmelt (10.77%) from 2011-2020 according to the model. We think the model can perform as an effective tool for research into the dynamics of hydrological systems and prospective effects of climate change on the Himalayan river basins.

Keywords
Climate change, Degree day factor, Hydrological modelling, Glacio hydrological degree-day model, Tamakoshi River Basin

1. Introduction

The shifting climate patterns are exerting a notable influence on the water balance and hydrological patterns in both the past and future, as indicated by [1]. This transformation is primarily driven by climate change and escalating temperatures, which are having a discernible impact on areas covered by snow and glaciers. Such alterations have direct consequences on the future availability of water downstream. Specifically, regions where snow and glaciers experience substantial melting play a crucial role in augmenting streamflow within river basins reliant on these sources [2]. Subsequently, the evolving climate is remoulding hydrological processes, thereby affecting the pattern of river flow and the total attainability of freshwater resources within the Himalayan River basin, as mentioned in [3]. In the past to explore the potential impact of climate change on water supplies, various methodologies and models have been applied. The effects of climate change on a river basin's hydrology and water resources should be simulated with the help of well-calibrated and validated models, in addition multifarious climate scenarios, to provide a credible and trustworthy estimate of uncertainty [4]. As a result, using a variety of climate and hydrological models is required to evaluate the response of hydrology to changing climate in a systematic manner, eventually estimating the future state of these water resources. To address the knowledge gaps in earlier studies concerning the Tamakoshi River Basin, the Glacio Hydrological Degree-Day Model has been utilized to simulate the contribution of each individual component to stream flow. The two melt-modeling methods now used to estimate the discharge of river basins that have undergone glacial are the energy balance model and the temperature index model. The GDM, Version 2.0, is a distributed and gridded glacio hydrological model that can simulate how hydrological factors affect river discharge. According to [5] GDM models the four major runoff components that make up total discharge: snowmelt, ice melt ,rainfall and base flow at daily time steps. The Glacio-hydrological Degree-day Model (GDM) simulates time ahead river discharge and the contribution of different water balance factors, together with snow and ice melt, rain, and base flow. Because it can operate with less data and few model parameters, GDM is beneficial for Himalayan catchments where data scarcity is common due to inaccessible terrain and a lack of meteorological station [6].

2. Study Area

One of the major tributaries of the Koshi river basin system, the Tamakoshi River, is a trans-boundary Himalayan river basin situated in eastern Nepal on the central Himalayas' southern slope. The basin is situated geographically on Dolakha and Ramechhap districts of Nepal form the country's political boundary. The basin is 2937.509 square kilometers having perimeter of 365.23 kilometers at the Busti gauging station, with 1,444.57 square kilometers on Chinese territory. Tamakoshi River basin is located at latitudes 27°20' N to 28°20' N and longitudes 85°40' E to 86°40' E, with heights ranging from 857 masl to 7323 masl nearby Mt. Cho Yu. Over 39% of the catchment (1163 km2) is over 5000 masl. This basin is predicted to have 85 glaciers covering a total area of 84.4 square kilometers in 2010 (ICIMOD, 2014). The study area including the hydro-meterological stations and the stream flow is in Figure 1.

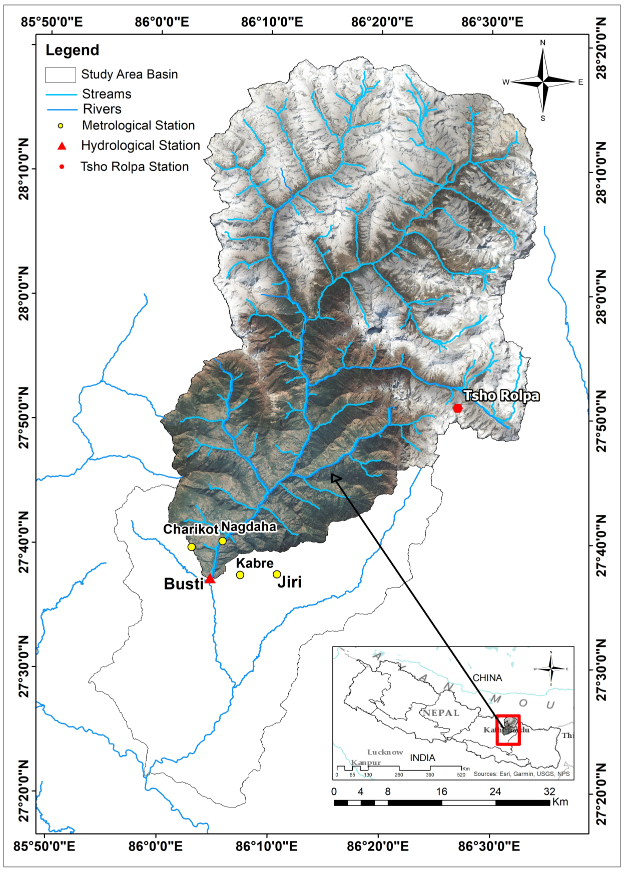

Figure 1: Study Area Map showing Hydro-Meteorological Station of Tamakoshi River Basin.

3. Materials and Methods

3.1 Input Data

From the Department of Hydrology and Meteorology (DHM), Hydro-Meteorological data were collected. The day-to-to observed Meteorological data from DHM range of the year 2004 to 2020. There are many flaws and gaps in the data provided by DHM. Therefore for better analysis and interpretation the baseline data from DHM was taken for 32 years. The IDW (Inverse Distance Weighted) was used to fill the missing rainfall data. Similarly, there are multifarious techniques to interpolate the missing temperature data but this case uses the temperature lapse rate method. The climatic and discharge station used in this model is in Table 1 GDM also requires static dataset i.e Digital Elevation Model and Landuse Land Cover. Grid elevation data in GDM is calculated with the help of Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), Global Digital Elevation Model (GDEM) v3, with a resolution of 30 meters, available from the United States Geological Survey (USGS). Extaction of the landuse data was done with a resolution of 10 meters from ESRI and introduced into QGIS software to be classified for clean and debris-covered glacier information [7]. The reclassification of the landuse and land cover using the LULC is in Figure 2 and Figure 3.

Table 1: Hydro-Meteorological stations used in the study

Station ID	Location	Type
1101	Nagdaha	Precipitation
1102	Charikot	Climatology
1103	Jiri	Agrometeorology
1124	Kabre	Agrometeorology
647	Busti	Discharge

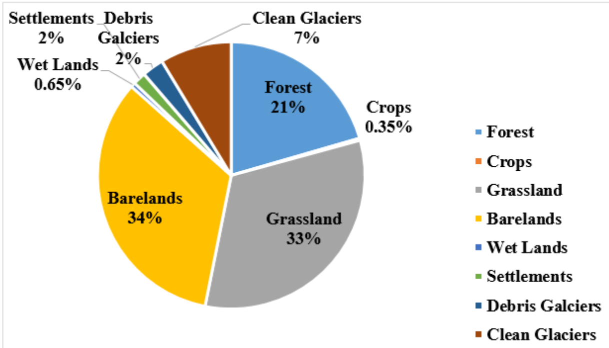

Figure 2: Pie Chart showing Land Cover classification of the Study Area in Percentage.

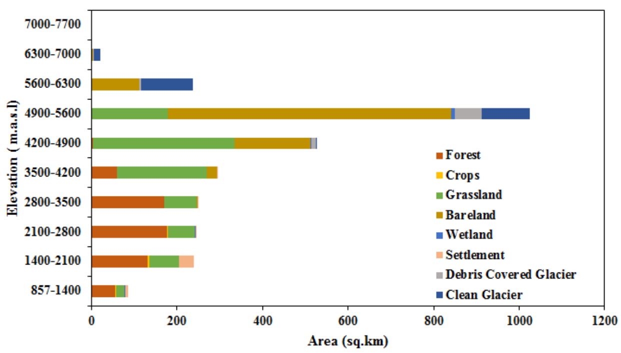

Figure 3: Classification of LULC according to the elevation.

3.2 Model Setup

The GDM, Version 2.0 is a gridded and distributed glacio hydrological model able of simulating the contribution of hydrological components in the discharge of river. In total discharge GDM simulates four different runoff components: snowmelt, icemelt, rainfall and baseflow at daily time steps [5]. The GDM models contribution and the future discharge from water balance components (snow melt rain, ice-melt and base flow) to the river discharge in the river basin. GDM is effective for Himalayan catchments where data scarcity is widespread due to impassable terrain and a dearth of weather stations because it can function with little data and few model parameters [6]. The model for the discharge simulation is forced using daily precipitation and temperature extrapolations to each grid from the reference station. Whether precipitation occurs in each grid in the form of rain or snow at each time step depends on the threshold temperature (T_T), which is as follows:

$$\text{Precipitation} = \begin{cases} \text{rain}, & \text{if} \quad T \geq T_t \\ \text{snow}, & \text{if} \quad T < T_t \end{cases}$$

Here, T is extrapolated daily air temperature for grids and T_T is threshold temperature, both in degree celcius. In each grid, daily icemelt from debris free and debris-covered ice and snowmelt from glacierized and glacier free areas is measured as:

$$M = \begin{cases} K_d \text{ or } K_s \text{ or } K_b \times T, & \text{if} \quad T \geq T_t \\ 0, & \text{if} \quad T < T_t \end{cases}$$

where, M is the ice or snow melt in mm day^{-1} in each grid, T is daily air temperature in °C, Kd, Ks, and Kb are the degree-day factors for debris-covered ice, snow and clean glacier ice in mm $°C^{-1}$ day^{-1}. The model looks for the multilayer melting of the snow above clean ice and debris-covered ice. Base flow is calculated applying a base flow simulation approach as in SWAT. Two aquifer system: deep and shallow aquifer system concept is applied to simulate the base flow in glacier and snow melt dominated basin [4, 8] . When compared to a single reservoir system, a two reservoir system releases discharge during a recession and ensures that the level of discharge is far closer to what is observed during that time. Figure 4 shows the overall framework that were carried out to analyze and evaluate the Impacts of climate change on the study area using GDM V.2.

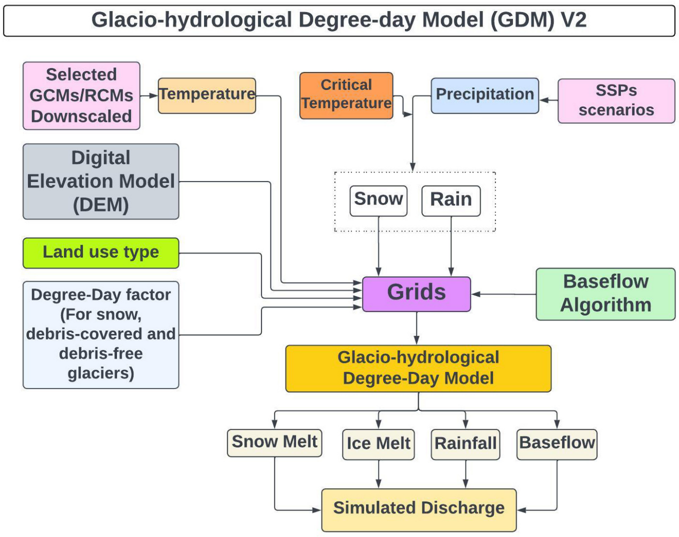

Figure 4: Flow Chart showing the methodology of the GDM v.2

3.3 Hydrological simulation

3.3.1 Simulation Experiment and Design

The GDM's performance undergoes an initial calibration phase spanning six years (2004–2009), followed by validation period of another ten years (2011–2020). This evaluation involves a comparison between the simulated and observed discharge data obtained from the Busti hydrological station in Tamakoshi River basin regions. Notably, critical parameters in the melt module like the degree-day factors for snow and ice melt, are established based on conduction of the Nepal Himalayas field observations [9].

3.3.2 Perfomance Index

The model accuracy can be assessed thorough two accuracy criteria: Nash–Sutcliffe Coefficient [10] Eqn. (1) and Volume Differences Eqn. (2) that is applied to evaluate the model outcome between the the observed discharge and simulated discharge.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2}{\sum_{i=1}^{n}(Q_i - \overline{Q})^2} \tag{1}$$

Where,
n: Number of days
Q_i: Daily measured discharge
Q_i': Simulated measured discharge
$\tilde{Q}$: Average discharge of the given year in m^3/s.
ii. Volume Difference:

$$VD(\%) = \frac{(VR - V'R)}{VR}\text{Ö}100 \tag{2}$$

Where,
V_R: Measured runoff volume
V_R': Simulated runoff volume in m^3.

4. Results and Discussion

4.1 Model Calibration and validation

The model is calibrated using a variety of positive degree-day factors as well as a set of degree-day factors, for each month is

Table 2: Calibration parameters used in GDM and their respective values in Tamakoshi River basin

Parameters	Symbol	Units	Values
Critical Temperature		°C	2
Temperature Lapse Rate		°C/m	0.058
Runoff coefficient (Land Use Land Cover Type)			
Land Cover Type 1. Forest			0.3 to 0.6
Land Cover Type 2. Crops			0.5 to 0.7
Land Cover Type 3. Grassland			0.5 to 0.6
Land Cover Type 4. bare land			0.3 to 0.6
Land Cover Type 5. Flooded Vegetation			0.95
Land Cover Type 6. Settlement			0.95
Land Cover Type 7. debris covered glacier			1
Land Cover Type 8. clean glacier			1
Degree Day Factor			
Snow (Ks)t		mm/(°C*d)	8 to 9.5
Bare ice (Kb)		mm/(°C*d)	8 to 10.5
Debris covered ice (Kd)		mm/(°C*d)	3
Time delay (shallow aquifer geologic formations)	δ gw,sh		10 days
Recession constant (shallow aquifer)	α gw,sh		0.5
Time delay (deep aquifer geologic formations)	δ gw,dp		230 days
Recession constant (deep aquifer.)	α gw,dp		0.5
coefficient of shallow aquifer percolation to deep aquifer	β dp		0.80

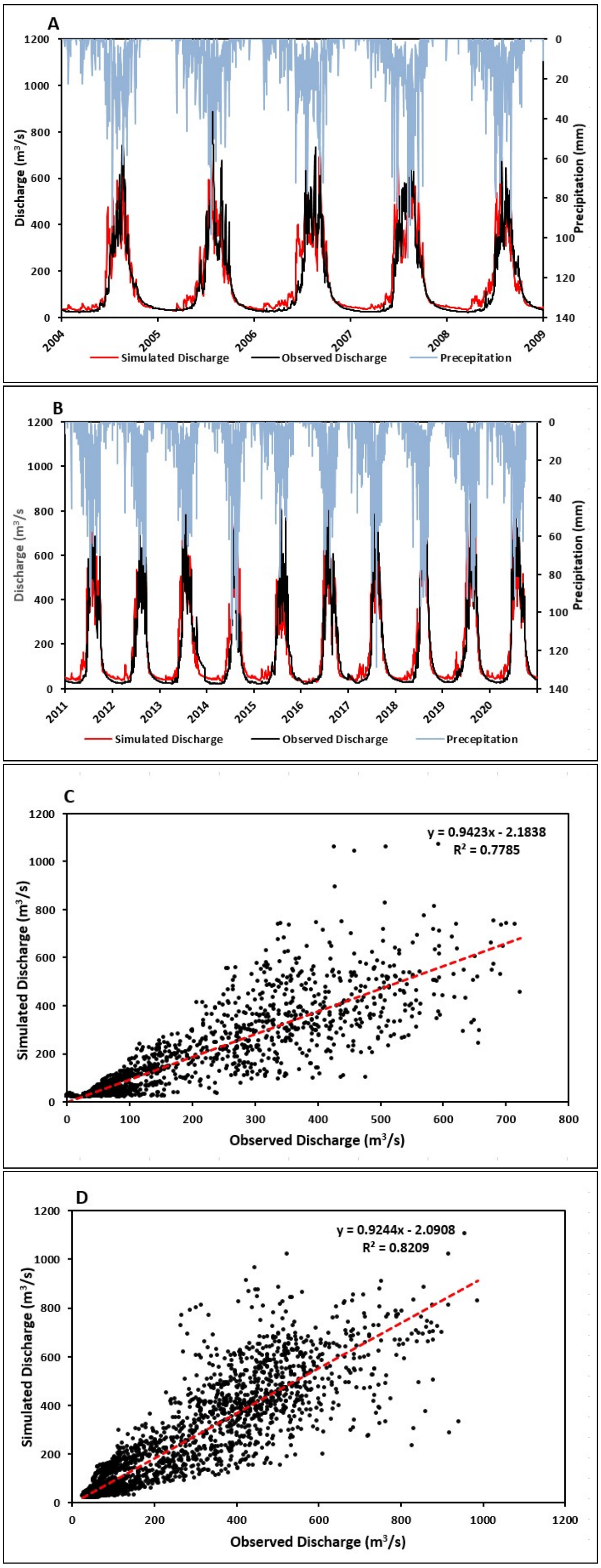

Figure 5: (A) Precipitation distribution and observed vs Simulated discharge for calibration (2004-2009),
(B) Precipitation distribution and observed vs Simulated discharge for validation (2011-2020), Scatter plots show the fit between the observed and simulated values for the calibration (C) and validation (D) periods.

chosen that falls within the extend of the approximated degree-day factors on various glaciers in the Nepal Himalayas. Additionally the model is calibrated with the help of ice and snow coefficients. Table 2 provides a list of all the calibrated variables and coefficients utilized in the investigations using GDM. The model is setup for Busti river basin station (ID 647) including the support of observed day-to-day discharge from the station and simulated discharge from the model the calibration for the year 2004-2009 and validation from the year 2011-2020 was done. The best performing parameter for the basin is used to assess the model's performance. The calibration and validation (Figure 5) Nash-Sutcliffe Efficiency (NSE) values are 0.77 and 0.80, whereas the volume difference is 7.8% and 9.5% simultaneously and the R2 values for calibration is 0.77 and for validation is 0.82. Hence , During the basin's calibration and validation periods ,the model's performance is very good [11].

4.2 Contribution of Snow Melt, Ice melt, Rain and Base flow

The model gives the contribution of different components like Ice Melt, Base flow, Rain runoff and Snow melt that are the components of the discharge. Figure 6 shows the average annual monthly contributions of the discharge components for the calibration and validation period of total average annual monthly discharge. Here, snowmelt contributes 12.17% of the total annual discharge, icemelt contributes 3.18% (from clean ice and ice under debris), rain contributes 46.86%, and base flow contributes 37.57% during the calibration period (2004-2009). Likewise, snowmelt contributes 10.77% of the total annual discharge, icemelt contributes 3.27% (from clean ice and ice under debris), rain contributes 46.33%, and base flow contributes 38.79% during the Validation period (2011-2020). Our study shows that the rain dominates the contribution in monsoon period which is followed by base flow contribution and the base flow contribution is throughout the whole year. By [12, 13] in Narayani river basin by SPHY model the contribution of rain runoff is 63%-65%, snow melt 9%-12% , ice melt is 3%-4% , and base flow is 21%. This research intently matches the contribution of snow melt and ice melt, besides the contribution of rain and baseflow is varied this may be due to the area coverage of the basin i.e the Narayani basin is about 37 times bigger than our study area river basin. Hence the runoff contributions by different component is varied.

5. Conclusion and Recommendation

Glacio-hydrological Degree-day Model (GDM) has accurately predicted discharge in river basins in the glaciated Himalayas. This model accounts for snowmelt, ice melt, rainfall, and base flow to give important cognizance into hydrological dynamics of basin. Despite being straightforward, mentioned model successfully simulates discharge and exhibits respectable accuracy throughout both the calibration and validation phases. In these stages, the coefficient of determination (R^2) maintains a stable value of 0.77 and 0.82, Volume differences 7.8% and 9.5% and the Nash-Sutcliffe Efficiency (NSE) values for the river basins consistently range from 0.77 to 0.80 for calibration and validation period respectively which shows

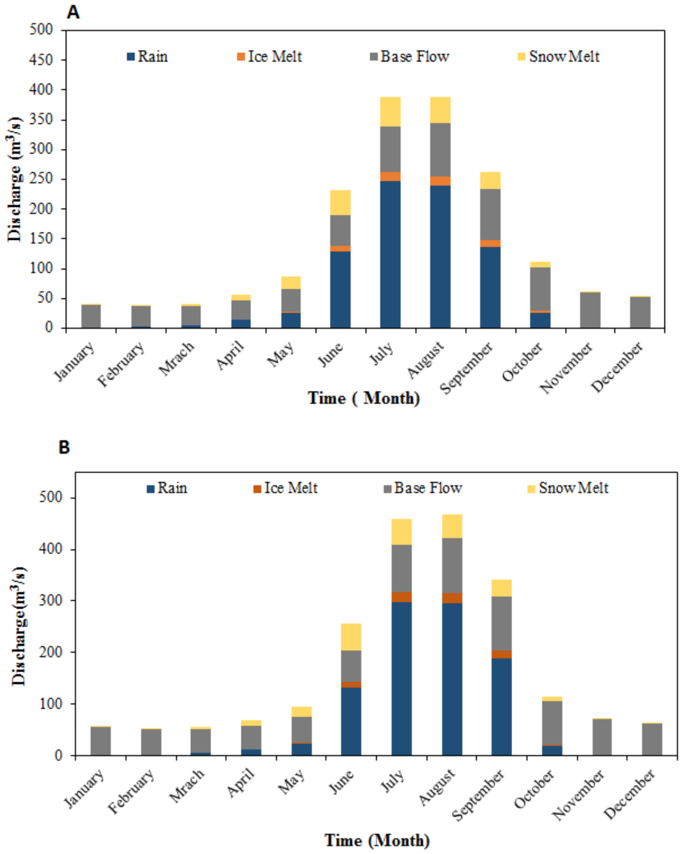

Figure 6: (A) Baseflow, Rain, Snowmelt, and Icemelt contributions for the calibration period (2004-2009) (B) Baseflow, Rain, Snowmelt and Icemelt contributions for the validation period (2011-2020)

GDM a promosing instrument for researching the dynamics of hydrological systems and possible climatic effects on river basins of Himalayas. According to our research, the contribution of snow and glacier melting to overall stream flow height in the monsoon season, while winter has negligible flow. Similarly the rain dominates the contribution in monsoon period which is followed by base flow contribution and the base flow contribution is throughout the whole year.

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