Flow Transfer through Spatially Distributed Hydrological (SPHY) Model in Tamakoshi River Basin of Nepal

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ABSTRACT

The availability of continuous hydrological records, both spatially and temporally, is often limited. This research employed a fully distributed Spatial Process in HYdrology (SPHY) model within the Tamakoshi River Basin to address this gap. The SPHY model was calibrated from 2004 to 2008 with NSE 0.62 at Busti station of Tamakoshi [2933.29 km^2] and validated from 2004 to 2008 with NSE 0.76 at Rasnalu station of Khimti [322.58 km^2]. Conversely, SPHY model was calibrated from 2004 to 2008 with NSE 0.79 at Rasnalu station of Khimti and validated from 2004 to 2008 with NSE 0.61 at Busti station of Tamakoshi. The observed annual average discharge at Busti station was 1632 m^3/s and Rasnalu station was 261 m^3/s during the simulation period. The annual average discharges at Benighat [862.09 km^2 downstream] transferred from Busti and Rasnalu models are 1963.1 m^3/s and 1961.32 m^3/s, respectively. Daily streamflow generated at Benighat from Busti and Rasnalu stations, closely aligns and perfectly matches and highly correlates, with the coefficient of determination 0.99. SPHY model is a good technique for prediction of flows in ungauged basins of Himalayan region. The SPHY model emerges as a robust technique for predicting discharge within the Himalayan River basin. This research holds the potential to serve as a valuable reference for generating streamflow data at ungauged locations, that are vital for planning, management and development of water resource projects.
Keywords: SPHY model, Ungauged River, Trans-boundary, Himalayan River Basins.

1. Introduction

Nepal has plentiful water resource coverage with three major perennial river systems (snow-fed), and several medium-sized (non-snow-fed) to small-size river basins along the country. However, several basins in Nepal are currently ungauged and do not match the World Meteorological Organization's (WMO) requirements for station network density (WMO, 2008). For hydrological and meteorological activities in terrains based on temperate Mediterranean and tropical zones, plains of comparable zones, and dry and polar regions, the WMO has established a baseline number of stations. Specifically, these regions should have one station for every 25-100 km^2, 600-900 km^2, and 1500-10,000 km^2 respectively (WMO, 2008). Notably, it is challenging to install and maintain instrumentation for real-time data retrieval from gauged or ungauged sites in data-scarce situations and inaccessible mountainous terrain regions due to the intricate interconnectedness of larger hydrological networks and smaller catchments. As a result, hydrological modeling may be used as a potential replacement strategy (Terink et al., 2015).

For continuous daily and monthly streamflow modeling in ungauged catchments, the combination of parameter transfer and drainage area ratio methods may be more effective than either approach alone in terms of efficiency (Li et al., 2019). Although several techniques have been used in the past to regionalize streamflow in ungauged basins, the physical characteristics of these catchments continue to make it difficult to obtain accurate streamflow data (Waseem et al., 2015). When comparing low flow estimates to high flow estimates in the central Himalayas, regionalization of flow duration curves that takes into account climate conditions and basin peculiarities produces lowered and ordinary persistent streamflow estimates (Panthi et al., 2021). The configuration and support of station networks are hampered by the political complexity of trans-frontier river areas in the scenery of the Nepalese river system, which is closely connected to the trans-Himalayan region. Successful water management downstream is hampered by these obstacles. Gaining knowledge of central basin factors such as annual precipitation, slope, channel

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length and elevations is necessary to account for increases in unmeasured streamflow. These factors have a significant impact on enhanced estimating techniques (DHM, 2004; Li et al., 2019; WECS/DHM, 1990).

The use of reliable hydrological models and suitable regionalization approaches is of the utmost importance when dealing with the complex issue of forecasting streamflow, particularly in cases when gauges are absent (Kim and Kaluarachchi, 2008). Despite the fact that a number of hydrological models are easily changeable both within and outside of their normal range (Bergstrom, 2006), inconsistencies may still happen due to the variety of calibration operations and distinguishing features (Van Liew and Mittelstet, 2018). A number of modeling techniques have been enhanced by utilising the regionalization process, which transfers data from gauged areas to those where gauges are absent, in order to improve regular estimates of streamflow in lacking-gauge basins (Razavi and Coulibaly, 2016). Evidently, rather than relying on empirical equations, these methods are predominantly included in hydrological models (Clark et al., 2017). Nevertheless, the SPHY model offers a thorough solution and incorporates dispersed features that are helpful for simulating endless unmeasured discharge states.

In this study, the spatially distributed hydrological model (SPHY), which could transfer continuous streamflow to an ungauged basin, is used to examine the applicability of in-situ data to estimate ungauged discharge from the donor to the target site. The main aim of this study is to use a hydrological modeling system to determine the suitability of ungauged streamflow data.

2. Data and Methods

2.1. Study Area

Tamakoshi River is a transboundary Himalayan river basin, which is one of the main tributaries of the Koshi River basin system of Nepal (Figure 1). Tamakoshi River basin has an elevation range from 455 masl to 6945 masl. Tamakoshi River Basin originated from the Tibetan plateau and merges with Sunkoshi River at Benighat. Tamakoshi River Basin lies in Dolakha and Ramechhap districts of Nepal. The total basin occupies 4117.96 km^2 up to Benighat before merging with Sunkoshi River. There are two discharge gauging stations upstream of Benighat: one in Tamakoshi at Busti having a basin area of 2933.29 km^2 and another in Khimti at Rasnalu having a basin area of 322.58 km^2. The remaining area of 862.09 km^2 downstream of the Tamakoshi River Basin is ungauged up to Benighat before it merged with Sunkoshi River. The Tamakoshi River Basin extends from the high Himalayas to the Silwalik range (Khadka et al., 2014). The climate of the basin typically varies from tundra to tropical (Karki et al., 2016).

2.2. Data Used

SPHY model uses mainly two kinds of data sets: static and dynamic datasets. These are land use/land cover (LULC) map, soil map, digital elevation model and hydro-meteorological parameters precipitation, temperature (average, minimum and maximum) and discharge. The Globecover (2009) dataset is open source. Digital Elevation Model (DEM) of Shuttle Rader Topographic Mission (SRTM) 3 arc seconds is hydrologically conditioned. The glaciers inventory outlines RGI 6.0 South Asia East is used (Consortium, 2017).

The dynamic datasets like precipitation, minimum and maximum temperatures and discharges are collected from the Department of Hydrology and Meteorology (DHM). The missing rainfall data are filled using Normal Ratio Method and temperatures using lapse rate of 0.0065 °C/m. The dynamic datasets of discharge and climatic stations used in this research are quantified in Table 1 and their geographical locations are presented in Figure 1.

2.3. Model Description

SPHY model is a spatially distributed cell-by-cell basis leaky bucket type of model. SPHY model simulates large-scale basin-to-catchment scale hydrology. SPHY model is glacier module concept (Terink et al., 2015). For snow processes three steps were involved: snow and rainfall depending on the threshold of temperature, snowmelt, refreezing and storage using the degree day approached and snowmelt runoff when air temperature above the melting point for each grid cell. The glacier processes involved glacier melt used degree day approaches, glacier percolation was ground water and glacier runoff from glacier melting processes from both debris-covered and free zone. Soil water process involved three steps root zone layer, subzone and groundwater layer. During the soil water process involved surface runoff, actual evapotranspiration, lateral flow, percolation, groundwater recharge and baseflow occurred. The total runoff routing is the summation of the flow of these processes. SPHY model simulates the total runoff from each setup from the desired outlet of the basin. Each and every runoff is routed downstream using a simple recession coefficient. The meteorological stations and outlets create in respective locations in delineated watersheds of cloned DEM. The locations of meteorological stations require bilinear interpolation for the interpolation method. Outlets of each subbasin are mandatory to place and must located on the river network. The Accuflux function of SPHY model the determines flow accumulation for total discharge in locations of outlets in the river network.

2.4. Runoff Routing

In streamflow routing is referred to transport of water through an open-channel system network. Since unsteady

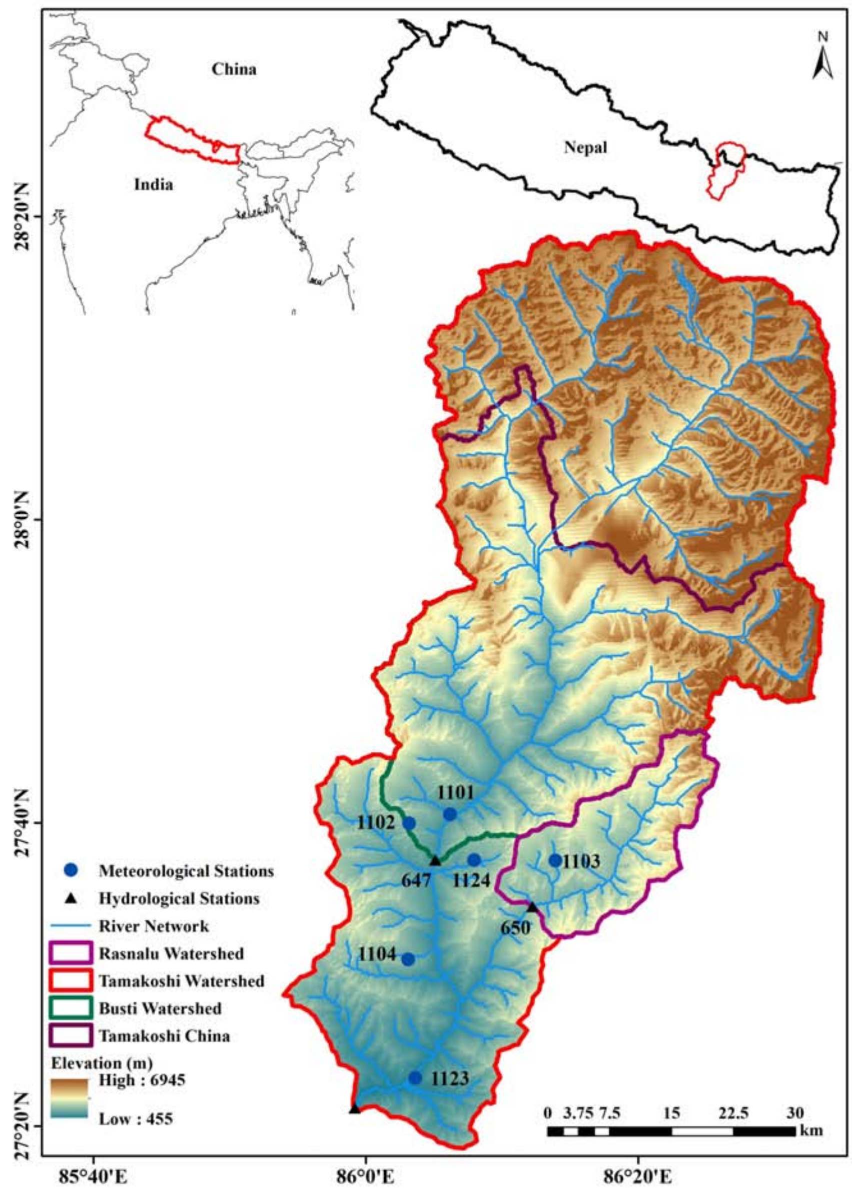

FIG. 1. Hydrological and Meteorological stations of Tamakoshi River Basin.

flow from open channel, streamflow routing often involves complex partial differential equations. SPHY model calculates the accumulated amount of water for each cell that flows out of the cell by cell into downstream cell. The accuflux PCRaster built-in function in SPHY model, which calculates the accumulated runoff from its upstream cells for each cell, including the specific runoff generated within the cell itself. SPHY model implements a flow recession coefficient (kx (–)) that accounts for flow travel time, which can be a result of the channel friction. Using this coefficient Kx, the river flow in SPHY is calculated using the following three equations below.

$$Q_{tot*} = \frac{Q_{Tot}.0.001.A}{24.3600} \tag{1}$$

$$Qaccu,t = accuflux(Fdir,\ Qtot*) \tag{2}$$

$$Qrout,t = (1 - Kx)\,.Qaccu,t + kx.Qrout,t-1 \tag{3}$$

where, Q_tot* (m^3/s) the specific runoff on day t, QTot the specific runoff in mm on day t, A (m^2) the grid-cell area, Qaccu,t (m^3/s) the accumulated streamflow on day t

Table 1. Hydrological and Meteorological stations.

Meteorological Stations						
Station ID	Location	Type	Long	Lat	Elevation	Frequency
1115	Nepalthok	Precipitation	85.85	27.42	690	Daily
1123	Manthali	Climatology	86.06	27.39	497	Daily
1027	Bahrabise	Climatology	85.90	27.79	884	Daily
1101	Nagdaha	Precipitation	86.10	27.68	909	Daily
1102	Charikot	Climatology	86.05	27.67	1940	Daily
1103	Jiri	Agrometeorology	86.23	27.63	1877	Daily
1104	Melung	Precipitation	86.05	27.52	1536	Daily
1124	Kavre	Agrometeorology	86.13	27.63	1755	Daily
Hydrological Stations						
Station ID	Locations	Types	Long	Lat	Elevation	Frequency
647	Busti	Cable Way	86.08	27.63	849	Daily
650	Rasnalu	Cable Way	86.20	27.58	1520	Daily

without flow delay taken into account, Qrout,t (m^3/s) the routed streamflow on day t, Qrout,t-1 (m^3/s) the routed streamflow on day t-1, F the flow direction network, and kx (–) the flow recession coefficient. kx has values ranging between 0 and 1, where values close to 0 correspond to a fast-responding catchment, and values approaching 1 correspond to a slow-responding catchment.

2.5. Model Simulation

The SPHY model was calibrated on a manual and trial basis. SPHY model calibrated with observed discharge at Busti station of Tamakoshi river basin and validated at Rasnalu station of Khimti Khola watershed from 2004 to 2008. Similarly, the model was calibrated at Rasnalu station of Khimti Khola watershed and validated at Busti station of Tamakoshi river basin from 2004 to 2008. The same model was calibrated and validated in the same basin with same parameters (Terink et al., 2017).

The continuous flows were transposed by calibrated and validated SPHY model in upstream station Busti and Rasnalu downstream of these stations to Benighat. Busti and Rasnalu is donor basin to Benighat where Benighat is the total stream flow receiver of Tamakoshi river basin.

This study has two approaches to ungauged flow estimation that is the flow simulated from Busti station and another flow simulated from Rasnalu station due to spatial distributed features of SPHY modeling system. On the basis of calibrated gauged stations, streamflow were transposed from both stations model simulated flows at Benighat. SPHY model parameters were calibrated at station for better performance but total runoff at Benighat was estimated without calibration on the basis of calibrated parameters of gauged stations.

The model performance was evaluated by Nash Sutcliffe Efficiency (NSE), simulated discharge was evaluated with observed discharge by statistical parameter through coefficient of determination (R^2) and the volume difference between observed and simulated was evaluated by Pbias.

2.6. Performance of Model Evaluation Methods

The SPHY model is evaluated by the Nash Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970). NSE is ranging from -∞ to 1, the better performance if the model is closer to 1 is an excellent fit.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{4}$$

The variation of simulated and observed discharge by SPHY model was evaluated by the coefficient of determination (R^2). The range of coefficient of determination (R^2) is 0 to 1, closer to 1 is the best fit.

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \overline{O})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}\sqrt{\sum_{i=1}^{n}\left(S_i - \overline{S}\right)^2}} \right)^2 \tag{5}$$

The goodness of fit between simulated discharge by SPHY model and observed discharge was calculated using the percent of bias (Pbias).

$$Pbias = 100 \times \left[\frac{O_i - S_i}{O_i} \right] \tag{6}$$

where, Oi is measured observed discharge, Si is simulated discharge, O is observed average discharge and S is simulated average discharge.

3. Results and Discussion

3.1. Gauged Simulation

The SPHY model performed at Busti gauging station efficiency with Nash Sutcliffe Efficiency (NSE) equal to

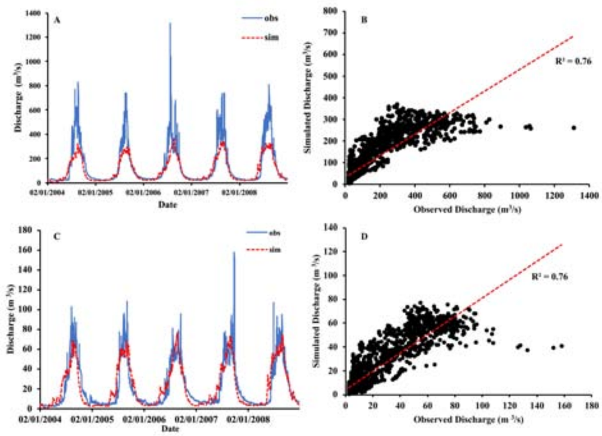

Fig. 2. Hydrograph of calibrated model with observed discharge (A) and Scatter plot (B) at Busti, hydrograph of validated model (C) and Scatter plot (D) at Rasnalu.

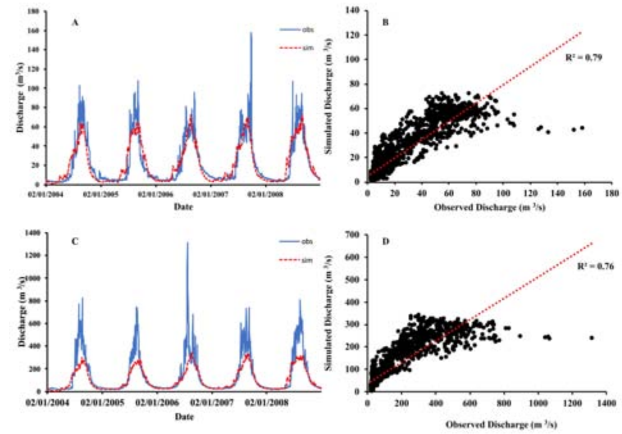

Fig. 3. Hydrograph of calibrated model with observed discharge (A) and Scatter plot (B) at Rasnalu, hydrograph of validated model (C) and Scatter plot (D) at Busti.

0.62, coefficient of determination (R^2) of the observed discharge and simulated discharge equal to 0.76 and simulated volume biases with observed discharge (Pbias) equal to 26%. The validation at Rasnalu station achieved model efficiency of NSE equals to 0.76, R^2 equals to 0.76 and Pbias equals to 4%. The model performance NSE and volume differences Pbias was better results in validated period than calibrated period but R^2 is similar between validated period and calibrated period. The hydrographs of calibrated and validated discharge at both stations underestimated the peak discharge during rainy months. This perhaps be due to the input data quality, model assumptions, local conditions, uncertain input data and insufficient data during extreme events (Tigabu et al., 2023). The calibrated and validated hydrograph with their respective scatter plots of Busti station are presented in Figure 2.

Similarly, SPHY model calibrated at Rasnalu station achieved model performance with NSE equals to 0.79, R^2 equals to 0.79 and Pbias equals to 4%. The validation at Busti station was performed with NSE equals to 0.61, R^2 equals to 0.76 and Pbias equals to 26%. The hydrograph of calibrated and validated discharge at both stations shows the underestimated discharge during rainy months. This might be due to the input data quality, model assumptions, and local conditions (Tigabu et al., 2023; Nguyen et al., 2022; Abbaspour et al., 2019). SPHY model shows better simulation to low flow than high flow. The model efficiency NSE, R^2 and Pbias were better simulated in calibrated period than validated period. The calibrated and validated hydrographs with their respective scatter plots of Rasnalu station are presented in Figure 3. SPHY model was better performed in the Rasnalu gauging station than in the Busti station.

SPHY model underestimated the peak discharge at Busti station. This discrepancy could potentially be attributed to both discharge stations' statistics falling within the 'fair' category based on DHM's assessment of discharge data, categorized as poor, fair, or good. Additionally, the meteorological stations observed in the Busti watershed may not be sufficiently representative of the entire watershed's actual conditions.Furthermore, in the Himalayas basin, the cascading type of hazard has recurrently manifested (Adhikari et al., 2023; Talchabhadel et al., 2023) due to extreme events leading to the obstruction of river network runoff. The parameters were calibrated and validated with values quantified in Table 2. The routing parameter recession coefficient (Kx) and groundwater parameters delta GW and alpha GW were more sensible parameters in the basin during calibration process.

3.2. Ungauged Simulation

The presence of discharge gauging stations is crucial for improving the calibration and validation of hydrological models for ungauged basins. Accurate calibration is difficult to achieve without these stations and because data records have gaps. Even in situations when calibration is not used, hydrological models discover their calibration efficacy within a range of conditions, both inside and outside of that range (Bergstrom, 2006). Here in this study, SPHY model parameters of calibration are independent within range at gauged stations (Table 2). The comparison of streamflow transposed at Benighat from two calibrated gauged stations Busti and Rasnalu showed the highly correlated streamflow records.

Figure 4 showed that daily streamflow generated at Benighat from Busti and Rasnalu SPHY models are closely aligned and perfectly matched. The scatter plot between flow simulation from Busti and Rasnalu highly correlated flow and coefficient of determination by 0.99.

TABLE 2. Calibrated parameters.

Descriptions	Calibrated Parameters	Busti	Rasnalu	Units
Routing	Recession Coefficient	0.94	0.96	
Ground water	deltaGW	180	180	
	alphaGW	0.01	0.01	
Glacier	GlacF	0.9	0.9	mm /°C/day
	DDFDG	2	2	mm /°C/day
	DDFG	4	4	mm /°C/day
Snow	SnowSC	0.5	0.5	mm /°C/day
	DDFS	5.5	5.5	mm /°C/day
	Tcrit	0	0	mm /°C/day
Soil	Root Layer	10	1600	mm/day
	Sub Layer	10	1600	mm/day
	Capillary Rise	1	2	mm/day

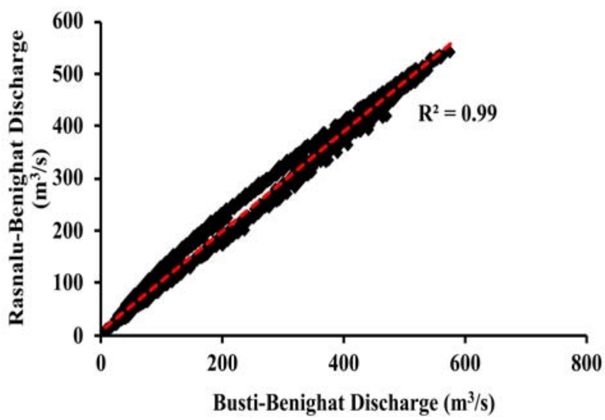

FIG. 4. Scatter diagram of transposed discharge from Busti station and Rasnalu station.

The daily average observed discharges of donor catchments at Busti and Rasnalu stations were 138.72 m^3/s and 21.88 m^3/s respectively. The daily average discharges at receiver Benighat basin transferred by SPHY models of Busti and Rasnalu are 164.35 m^3/s and 164.18 m^3/s respectively. The daily estimated discharges from 2004 to 2008 are plotted in Figure 5a. This figure showed that the daily flow transposed from two calibrated sites to an ungauged site perfectly matched. The flow pattern of the ungauged flow is completely aligned as aforementioned. The continuous daily flow simulation at the ungauged site is complicated due to erratic behavior of rainfall although distributed feature of model is a good approach for ungauged continuous data generation.

Figure 5b showed that the lowest flow was estimated in February and maximum discharge was simulated in August at Benighat for both transposed from both gauging stations. Table 3 showed that rising discharge in May and recession discharge in November transposed from both gauged stations at Benighat. Busti-Benighat transposed streamflow leads discharge in May to August and then Rasnalu-Benighat transposed streamflow data leads September to December. The detail of monthly flow transposed from Busti and Rasnalu gauge station with averaging value at Benighat is presented in Table 3. The observed annual average discharge at Busti station is 138.72 m^3/s and Rasnalu station is 21.88 m^3/s during simulation period. The annual average discharges at Benighat transferred from Busti and Rasnalu models are 163 m^3/s and 164 m^3/s respectively which are very similar shown in Figure 5c and Table 3. SPHY model has simulated a greater amount of discharge at Benighat than a summation of discharges at Busti and Rasnalu gauging stations, which seems logical because discharge downstream is always greater than upstream due to stream network system in large river basins. The streamflow data simulated by SPHY model at the ungauged site from calibrated gauged stations is almost similar in volume due to the spatially based distributed feature of models. The ungauged discharge comparison at Benighat transposed from two different upstream gauged stations shows almost similar discharge on a daily, monthly and annual basis. Model simulation and parameter calibration with gauged to ungauged same basin same input climatic datasets in SPHY model is a good approach for ungauged streamflow estimation. There are numerous methods for ungauged streamflow data generation among them fully distributed model is a very good alternative method for ungauged streamflow information as it requires large numbers of parameters (Patil and Stieglitz, 2014). The comparative discharge transposed from different calibrated stations is a better improvement technique using a fully distributed hydrological model for ungauged flow estimation. The water resource project developers will be beneficial from continuous ungauged streamflow records simulation techniques using this model.

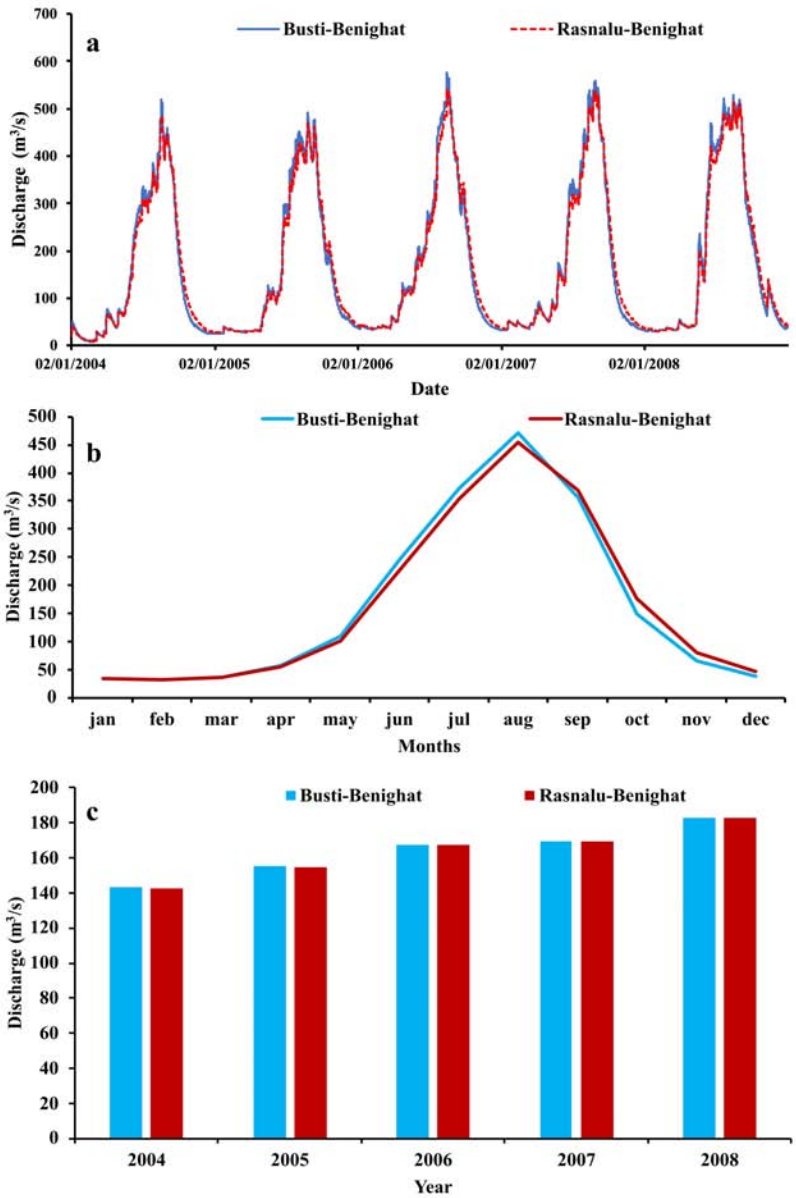

FIG. 5. Ungauged simulation at Benighat (A) Daily discharge, (B) Monthly discharge and (C) Scatter plot of Busti and Rasnalu transpose discharge at Benighat.

TABLE 3. Monthly and annual discharge (m^3/s) of Benighat transposed from Busti and Rasnalu.

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Busti-Benighat	33	31	37	56	109	245	373	471	356	149	64	38	163
Rasnalu-Benighat	34	31	36	54	101	225	354	455	369	176	81	46	164
Average	34	31	36	55	105	235	363	463	363	162	72	42	163.5

4. Conclusion and Recommendation

Hydrological estimates at ungauged basins are an important task for the planning and design of water resources projects. SPHY model has simulated the highly matched and correlated discharge at ungauged sites transferred from two different gauging stations. The model performance at

Rasnalu station is better than at Busti station. The ungauged discharges of daily, monthly and annual are estimated from upstream gauged stations to downstream ungauged locations. The low flows are better matched than the high flows in the prediction of stream flows. However hydrological models are independently streamflow simulated. In the upstream catchment of Busti gauge station, spatial and temporal coverage of climatological station data are limited, which cover 71% of the total basin area. Discharge gauging stations and observations are limited at transboundary Himalayan river basins, mainly in least developing countries like Nepal due to difficulties in continuous monitoring, maintenance and high cost. However, the lacking of proper data upstream of Busti gauging station reveals that further studies in ungauged basins may enhance hydrological simulation capability using satellite data.

This study claims that the SPHY model is appropriate for mountain catchments in Nepal. Hence it is recommended for further use in other mountain basins having the presence of snow and glaciers. Similarly, the model should be applied in small basins of hills and plains to verify the results and its applicability.

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