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Application of Temperature Index Model for Estimating Daily Discharge of Sangda River Basin, Mustang, Nepal

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Abstract: With a paucity of glacio-hydrological data, the temperature index model often serves as a powerful tool in melt modeling on a basin scale. This study uses a positive degree-day factor to estimate snow and ice melt and then daily discharge of the Sangda River basin located in Mustang district, western Nepal. The basin encompasses 438 km^2 with ~12% glacierized area. The model, calibrated for 2012 and validated in 2013, simulates daily discharge efficiently when compared with the observed discharge. The Nash-Sutcliffe Efficiency (NSE) for calibration and validation years are 0.91 and 0.92 and volume difference are ~5% and ~7%, respectively. The relative contribution of snow and ice melt to the discharge in 2012 is ~19% and in 2013 is ~16%. The bias corrected temperature and precipitation data are forced in the model to generate future discharge of the basin for CMIP5 RCP4.5 and RCP8.5 scenarios. Between 2015 and 2050, the average discharge in the basin is 7.52 m^3/s and 7.57 m^3/s for RCP4.5 and RCP8.5 scenarios, respectively. The projected discharge is predicted to be highest during 2021-2030, whereas glacier melt is highest during 2041-2050 for both scenarios. The sensitivity tests reveal that a warm and dry climate generates more discharge than a wet and cool climate. These results from this study provide a general basis for water planners and policy makers to improve management of water resources in this region for present and future uses.

Keywords: Temperature-index model; Snow and ice melt; River discharge, RCP4.5 and RCP8.5.

Introduction

Glaciers are active reservoirs that play an important role in the hydrological dynamics of glacierized catchment as they release water in warm and dry periods, while store water during wet and cold periods (Fountain and Tangborn, 1985). Glaciers, ice, and snow cover 17% area of the Himalayan region (IPCC, 2007; Eriksson et al., 2009), and store about 12,000 km^3 of fresh water (Thompson and Gyawali, 2007), forming an integral part of the global hydrological and climate systems. They nourish major Asian watersheds through perennial rivers such as the Ganges, Indus and Brahmaputra (Messerli et al., 2004; Panday et al., 2013). Many studies have revealed that the mountain regions are particularly in danger, both because warming trends are higher and because the impacts are enlarged by altitudinal variability over small distances (Immerzeel et al., 2010; Immerzeel et al., 2012). Regional climate investigations by the IPCC (2007) indicate that the median temperature will rise up to 3.7 °C in central Asia by the end of the 21st century. It has also predicted that the temperature increase in the Himalayan region has been greater than the global average of 0.74 °C over the last 100 years. Likewise, snow cover and glacier area, whose spatial variability is more pronounced in

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the huge mountain systems of the Himalayas (Vivroli et al., 2011), respond to changes in both temperature and precipitation and they exhibit a strong negative correlation with air temperature in most areas.

Studies conducted by ICIMOD (2007, 2011) show clear evidence that Himalayan snow and glaciers have been melting at an unprecedented rate in recent decades. The reduction in both glacier volume and area is influenced by the intensity of the seasons and affects the inter-annual variation of runoff (Imgard et al., 2007). Analytical studies representing temperature increases of 1-3 °C in the western Himalayan region for the period of 1987-1990 suggest an increase in glacial melt runoff by 16-50% (Singh and Kumar, 1997). Linear regression analysis by Archer (2003) indicates that a 1 °C rise in mean summer temperature could result in a 16% increase in summer runoff into the Hunza and Shyok River due to accelerated glacier melt. The future climate variables simulated by Akhtar et al. (2008) using a regional climate model indicate that the annual mean temperature will rise up to 4.8 °C and an annual mean precipitation up to 16% by the end of the 21st century (2071-2100). And the Nepal Himalayas are no exception. Few studies have considered them as highly sensitive to the changing climate, even though the glaciers in this region have retreated remarkably in the past two decades (Fujita et al., 2001).

A recent glacier modelling study conducted by Shea et al. (2015) in the Everest Region shows that modelled glacier sensitivity to temperature change is high, with large decreases in ice thickness and extent for even the most conservative climate change scenarios, with increased precipitation and reduced warming in the region. As such, understanding the temporal changes in the length, width, area, volume and mass balance of the glaciers is pivotal in evaluating the sensitivity and dynamic responses of the glaciers to the changes in temperature and precipitation (Haeberli et al., 2007). In the light of existing uncertainty about future climate scenarios, data gaps and glacier mass losses (Hewitt, 2005), the Himalayan region presents a huge challenge in terms of future water availability and management (Akthar et al., 2008; Scherler et al., 2011; Bolch et al., 2012). Though understanding glacier dynamics in the Himalayan region is extremely difficult because of remoteness, hostile terrain, large variations in climates over short horizontal distances, and irregular monitoring (Immerzeel et al., 2010; Pellicciotti et al., 2012), a sound and comprehensive assessment of individual glaciers is required for understanding future water security and better management of these resources, as Himalayan glaciers are water towers supporting millions of lives downstream (Immerzeel et al., 2010; Brown et al., 2014).

Taking into account these limitations, many studies are carried out in the region using simple to complex glacio-hydrological modelling approaches to fill the large data gaps prevalent in the Himalayan basins. Glacio-hydrological models are used because they can be tailored to fit the characteristics of available data. Also the concept of using regional hydrologic models for assessing the impacts of climatic change has several attractive characteristics (Gleick, 1986). Detailed studies using a deterministic model in mountain basins have also been carried out. Rango (1992) used the Snowmelt Runoff Model (SRM) for the Rio Grande and Kings River basins in North America to study the changes in snowmelt runoff under warmer climate scenarios. HBV Light model, developed by Uppasala University, has long been used in many parts of the world for river runoff simulation since its development. The degree-day methods have been in use in many variants for more than a century. They are found to perform well in the Alps (Braun and Renner, 1992), Greenland (Braithwaite, 1995), Scandinavia (Hock, 1999), the Himalayas (Sing and Kumar, 1997; Kayastha, 2005; Pradhananga et al., 2014), and New-Zealand (Woo and Fitzharris, 2010). They have been used to investigate the sensitivity of glaciers to climate change (Laumann and Reeh, 1993; Johanneson et al., 1995; Brathwaite and Zhang, 1999; De Woul and Hock, 2005; Pradhananga et al., 2014). Few studies have investigated the physical causes of the good correlation between air temperature and ice melt, though net radiation generally is the greater incoming energy flux yet is poorly correlated to air temperature (Pellicciotti et al., 2005; Sicart et al., 2008).

This study uses the elevation-dependent temperature index model to estimate daily discharge of one of the least studied basins, the Sangda River basin in Mustang district, Nepal where data availability is limited. The model is also used for calculating relative contribution of runoff components, mainly snow and ice melt in the river, and future discharge projections using CMIP5 ensemble temperature and precipitation data for RCP4.5 and RCP8.5 emission scenarios.

Study Area

The Sangda River basin lies in the Trans-Himalayan zone of Mustang district, western Nepal (Figure 1). Part of the Sangda River originates from Mukut Himal and the southern edge of the Tibetan Plateau. The basin

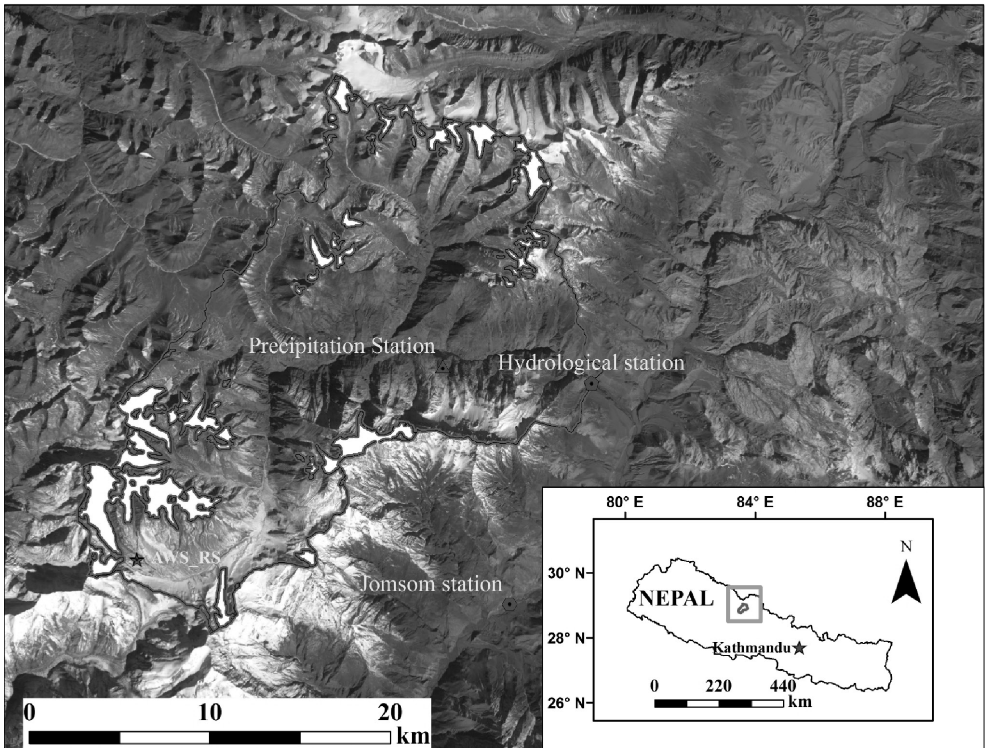

Figure 1: Study area map including the location of hydro-meteorological stations with inset map of Nepal showing the location of the Sangda River basin.

encompasses 437.86 km^2, geographically extending from 83.5° to 83.83 °E and 28.73° to 29.67 °N. Of the total basin area, 51.7 km^2 (11.82%) is glacerized, which is calculated from Global ASTER DEM (2011) of resolution 30 m, LandSat 4,5 TM imagery (2011), and glacier outlines from the ICIMOD inventory (2010). The total length of Sangda River is ~39 km. The region is part of the Southern Tibetan Detachment System, and its geology consists of fossiliferous sedimentary rocks. The topography of this region varies from mid-altitude Himalayas to trans-Himalayas with elevations ranging from 2960 to 6460 m a.s.l and a mean slope of 30.5°. The basin has a diverse climate, ranging from arid tundra at the highest altitudes, through alpine, and becomes windy cold temperate with decreasing altitude. The region receives the lowest annual rainfall in the entire country ranging from 285 mm at lower elevations (Jomsom at elevation 2744 m a.s.l.) to 253 mm (Sangda at elevation 3570 m a.s.l.) at higher elevations, with much less precipitation variability in space and time relative to other areas of Nepal as the region is characterized as a rain shadow zone.

The description of hydro-meteorological stations with their location is given in Table 1. Daily temperature of Jomsom Meteorological Station and Rikha Samba Station and daily precipitation of Sangda Station (2012-2013) are used for modelling approach.

Table 1: Stations whose data have been used in this study for simulating daily discharge

S.N	*Name*	*Type*	*Location*	*Elevation (m)*	*Type of measurement*
1	Hydrological station	Radar Sensor Level (RLS)	28.89ºN, 83.77ºE	2930	Water level
2	Jomsom DHM station	Meteorological Station	28.47ºN, 83.43ºE	2744	Air temperature and precipitation
3	Sangda station	Precipitation Station	28.54ºN, 83.41ºE	3570	Daily precipitation
4	AWS RS	Automatic Weather Station	28.79ºN, 83.52ºE	5392	Air temperature, precipitation, incoming short wave radiation, relative humidity, wind speed and direction

Methods

Hydro-meteorological Dataset

A rating curve is developed from measured discharge and water level data (Figure 2) recorded by a Radar Sensor Level (RLS) installed at the gauging site of Sangda River at Tiri, Mustang by the Cryosphere Monitoring Project (CMP) in January 2012. A series of discharge measurements using the area velocity method has been carried out at different times of the year, mainly in low flow season (8th January 2013 and 28th-31st December 2014), high flow season (14th- 23rd September 2014), and mid-flow season (22nd May 2014) to include the temporal variability of river runoff. Water level data is recorded by the RLS every five minutes and a daily average is used to draw a relationship between the water level and measured discharge data. The peak discharge is derived by using the slope-area method based on a field survey carried out by the CMP. The HQ rating package extensively used by the Department of Hydrology and Meteorology (DHM), Government of Nepal is used to develop a discharge rating. This package is based on the widely accepted stage-discharge relation given in Equation 1.

$$Q = a(H - H_0)^b \tag{1}$$

where Q is discharge in m^3/s, a is a constant that is numerically equal to the discharge when the head (H–H_0) equals unity; (H–H_0) is head or depth of water of the control; H is the gauge height of the water surface; H_0 is the gauge height of zero flow; and b is the slope of the rating curve.

Temperature data of Jomsom and Rikha Samba Automatic Weather Stations (AWS) and precipitation data of Sangda station are used in this study for melt calculations. Daily temperature, precipitation and discharge data of those stations are shown in Figure 3.

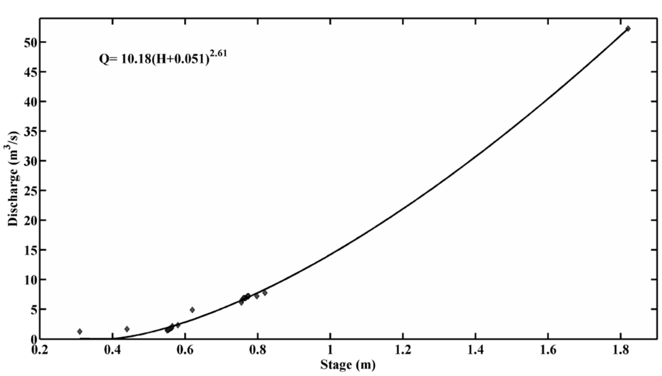

Figure 2: Rating curve of Sangda River developed between stage height and discharge.

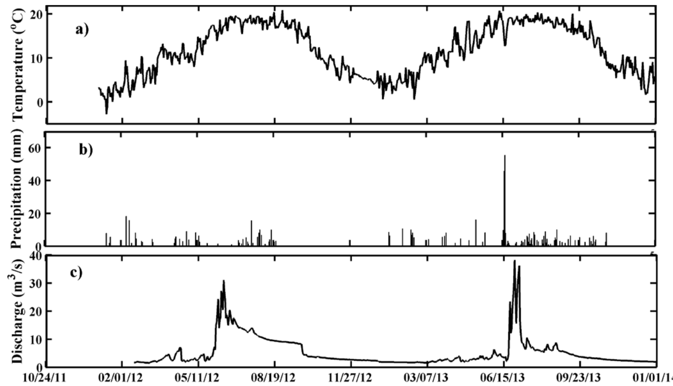

Figure 3: Daily hydro-meteorological observation during 2012-2013: (a) Daily air temperature recorded at Jomsom Station, (b) Daily precipitation recorded at Sangda Station and (c) Daily discharge calculated from the rating curve.

Spatial Extrapolation of Meteorological Data

The 30 m resolution DEM acquired through the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) from USGS GloVis site is used for constructing a hypsograph of the basin. The DEM of Sangda River basin is reclassified into 19 elevation bands of 200 m each (Figure 4), which is assumed to exhibit different homogenous hydrological characteristics. Mean hypsometric elevation for each elevation zone is then calculated to interpolate the temperature and precipitation data for each elevation band. The interpolation is based upon an altitude-dependent regression of the observations at stations located in or near the basin.

The adjustment value of number of degree days for each elevation zone is computed using equation 2.

$$\Delta T = \gamma \cdot (h_{st} - h)\frac{1}{100} \tag{2}$$

where γ is average vertical temperature lapse rate which is calculated using daily temperature data (2011-2013) of Jomsom Meteorological Station and Rikha Samba Automatic Weather Station; T_{st} is the air

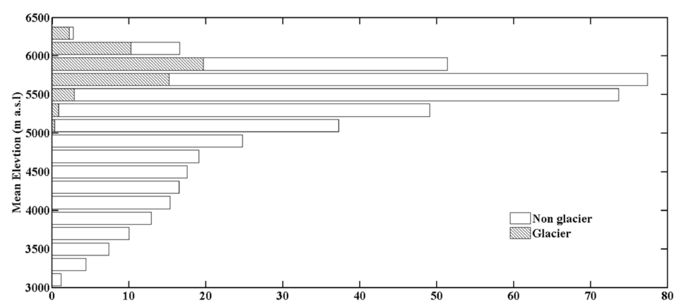

Figure 4: Hypsograph of Sangda River basin.

temperature of the base station; T is air temperature of the station located at higher elevation; h_{st} is altitude of the temperature base station and his mean hypsometric elevation for a given zone. The value of the precipitation gradient is difficult to estimate in this basin because precipitation data are scarce. Precipitation data of Sangda station are used and the assumption is made that there is no spatial variability in precipitation in the basin.

Modelling Approach

A simple water balance equation is used for estimating the discharge of the Sangda River basin. Precipitation, snow and ice melt, and base-flow account for runoff whereas the coefficient which is a ratio of rainfall and snowmelt accounts for loss of water in the basin as shown in equation 3.

$$Q = M_t + C_s + R_t \times C_r + Q_{bf} \qquad (3)$$

where Q is the total discharge (m^3/s); M_t is the total snow and ice melt (m^3/s); R_t is total rainfall in m^3/s; C_s and C_r are coefficients of snowmelt and rainfall, respectively, and Q_{bf} is the base flow in m^3/s.

Baseflow Separation

Base-flow separation is carried out in R-studio with the help of an in built package 'EcoHydRology' developed by Archibald (2015) based on the study of Chapman (1999). This base-flow separation tool in 'EcoHydRology version 0.4.12' is an automated method which uses a digital filter technique that associates high frequency waves with direct runoff, and low frequency waves with the base flow (Nathan and McMahon, 1990; Eckhardt, 2005).

Temperature-index Melt Model

Temperature-index models are widely favoured as a pragmatic means of simulating glacier and snow melt because of their simplicity and limited demands for in-situ data (Braithwaite, 1995; Hock, 2003). Temperature-index methods imply a strong simplification of complex physical processes. Differences between the snow and ice are often taken into account by specifying two different values of degree day factor for two types of surfaces in a simple temperature-index model. The general melt equation used in this study is given by:

$$M_i = \begin{cases} DDF_s / DDF_t \times T & \text{if } T > T_o \\ 0, & \text{if } T \le T_o \end{cases} \qquad (4)$$

where M is the total snow and ice melt, i is the index of a given elevation band, T is the air temperature (°C), T_o is the threshold temperature and DDF (mm/d/°C) is the positive degree day factor used in the model. The degree day factor plays a very crucial role in temperature index modelling. Considering the fact that DDFs are subject to significant small scale variability (Hock, 2003), in this model the spatial discretization of DDF for snow and ice is done by reclassifying the entire basin into different elevation bands so that melt rates vary as a function of elevation and to obtain satisfying simulations of daily discharge.

Snow-rain Partitioning

A transition scheme is used to separate snow and rain in this study. Correct estimation of the aggregation state of precipitation is important for the modelling of hydrological processes in high mountain catchments. Although this modelling approach is based on a simple threshold function (Equation 5) and does not reflect the observed phenomenon, the results from previous studies have shown that use of a simple temperature threshold is acceptable for modelling hydrological processes in glacerized regions (Kayastha et al., 2005; Hagg et al., 2007).

$$\begin{cases} \text{Precipitation} = \text{Snow} \quad \text{if } T \le 0 & \text{(All Snow)} \\ \text{Precipitation} = \text{Snow} + \text{Rain} \quad \text{if } 0 \le T \le 2 & \text{(Snow and rain)} \\ \text{Precipitation} = \text{Rain} \quad \text{if } T > 2 & \text{(All Rain)} \end{cases} \qquad (5)$$

The recession coefficient as calculated by Martinec et al. (1983), as shown in Equation 6, is used for modifying recession flow in this basin.

$$Q_n = Q_o \times K^n \qquad (6)$$

where K^n is the recession coefficient for the n^{th} day, Q_o is the initial discharge (m^3/s), and Q_n is discharge after recession (m^3/s). The value of K is obtained by solving Equation 7, where the constants x and y are obtained by recession flow plot (Martinec and Rango, 1986).

$$\begin{cases} K_1 = x \times Q_1^{-y} \\ K_2 = x \times Q_2^{-y} \end{cases} \qquad (7)$$

A list of calibrated parameters used in this study is shown in Table 2. Some parameters were measured in the field and calculated with the help of empirical equations whereas a few are taken from literature.

Table 2: A list of calibrated parameters used in this study

Parameters	*Values*
Threshold temperature (T)	2 °C
Lapse rate (γ)	6.2 °C
Degree day factor for snow (*DDFs*)	4.5-5 mm/°C/d (upto 5000 m; Kayastha et al., 2005) 7.5-9.5 mm/°C/d (above 5000 m; Kayastha et al., 2005)
Degree day factor for ice (*DDFi*)	7.5-10.5 mm/°C/d (upto 5400 m; Kayastha et al., 2005) 16.2 mm/°C/d (5400-5500 m; from field) 12.2 mm/°C/d (above 5500 m; from field) Sept 2013
Coefficient of snowmelt and rainfall (*Cs* and *Cr*)	0.6, 0.4 (Jan-May) 0.4, 0.6 (Jun-Sep) 0.6, 0.4 (Oct-Dec)
X and Y	0.85, 0.016 (Pre-monsoon and Post monsoon) 0.72, 0.012 (Monsoon)

Assessment of the Model Accuracy

Using accuracy tests to determine whether the simulation matches measured discharge, the non-dimensional Nash-Sutcliffe coefficient (NSE), the volume difference (VD), log NSE, Root mean square error (RMSE) and combined measure (ME) are performed.

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i)^2}{\sum_{i=1}^{n}(Q_i - Q_1)^2} \tag{8}$$

where Q_i is measured daily discharge, Q'_i is computed daily discharge, Q'' is average daily discharge for the simulation period, and n is number of daily discharge values. The *NSE* values vary from 0 to 1, with 1 indicating a perfect fit. The volume difference, *VD*, is computed using Equation 9.

$$\text{VD}[\%] = \frac{V_K - V_R}{V_K} \times 100 \tag{9}$$

where V_R is measured runoff volume and $V_{R'}$ is simulated runoff volume. *VD* can take any value, the smaller the value is, the better the model results are.

$$\log \text{NSE} = 1 - \sum_{i=1}^{n}(\log Q_i - \log Q_i)^2 \, / \sum_{i=1}^{n}(\log Q - \log Q_i)^2 \tag{10}$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_1 - Q_i)^2} \tag{11}$$

$$\text{ME} = \text{NSE} + \log \text{NSE} + \text{VD} \tag{12}$$

Sensitivity Analysis

The effect of temperature on the hydrological response of the basin is studied independently and in combination with precipitation by altering the annual air temperature and precipitation by ±1, and ±2 °C, and annual precipitation by ±10% and ±20% separately from the simulation condition.

Future Dataset

For future climate projections, Regional Climate Model (RCM) data are used. Daily precipitation and temperature data from the Weather Research and Forecasting (WRF) model are acquired from the Bjerkens Centre for Climate Research (BCCR), University of Bergen, Norway. Representative Concentration Pathways (RCPs) are four greenhouse gas concentration trajectories adopted by the IPCC for its fifth assessment report in 2014. The RCP4.5 and RCP8.5 are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values, +4.5 and +8.5 W/m^2, respectively. Two climate scenarios, Coupled Model Intercomparison Project 5 (CMIP5) RCP4.5 and RCP8.5, are used in this study. Temperature and precipitation data generated for Sangda station are bias corrected with a statistical approach using the method proposed by Cheng et al., 2007 (Equation 13) for temperature and Weiland et al., 2010 (Equation 14) (Cheng et al., 2007) for precipitation.

$$T_{corrected} = (T_{\text{mod}} - T_{\text{mod}}) \times \frac{\sigma T_{obs}}{\sigma T_{\text{mod}}} + T_{obs} \tag{13}$$

where $T_{corrected}$ is the value obtained after calibration. T_{obs} and T_{mod} are the observed and modelled daily temperature, respectively. T_{mod} is the mean daily value of modelled temperature (Weiland et al., 2010).

$$P_{corrected} = P_{\text{mod}} \frac{P_{obs}}{P_{\text{mod}}} \tag{14}$$

where P_{mod} is the daily modelled precipitation, and P_{obs} and P_{mod} are the average observed and modelled precipitation for 2007-2014.

Results and Discussion

Discharge Simulation and Model Performance Assessment

The observed and simulated daily discharges are shown in Figure 5. The year 2012 is taken as a calibration year and 2013 as a validation year. With a high coefficient of determination, above 0.90, NSE ~0.91 and VD ~5-7%, this model seems to perform well for both calibration and validation years. This simple yet efficient model has captured both base flow and seasonal flow taking well into account temperature and precipitation forcings on the ablation processes of snow and ice for both years. From Figure 5, it is also evident that the Sangda River basin has a classic snow-melt hydrograph, with greater contribution of snow melt in summer monsoon period than rainfall. The success of air temperature as the sole variable driving the temperature index model is attributed to the high correlation of temperature with several energy balance components (Ambach, 1988; Braithwaite and Olesen, 1990; Lang and Braun, 1990; Hock, 2003).

Table 3 shows the model performance assessment carried out using different tools. The model performance assessment carried out by using different assessment tools like N.S.E., V.D., RMSE and M.E. shows a very good result for this temperature index model that is modified and parameterized with elevation bands, yet the melt affected by slope, aspect and shading yielding high spatial variability in melt rates is not addressed properly in this study.

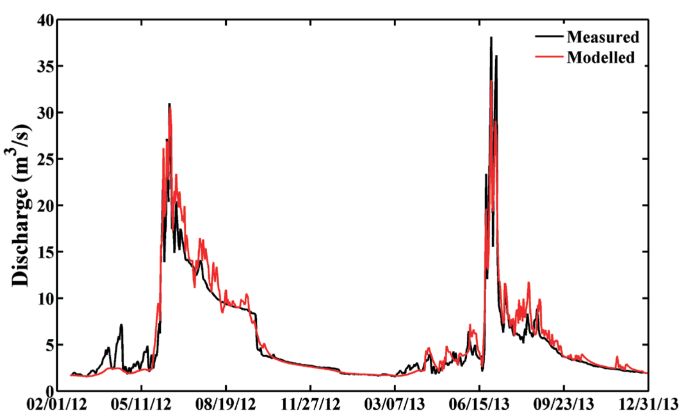

Figure 5: Simulated and measured daily discharge (2012 -2013).

Table 3: The temperature index model performance in calibration and validation year

Assessment tools	*Calibration year*	*Validation year*
R^2	0.95	0.93
N.S.E.	0.91	0.92
V.D.	5.32%	7.1%
R.M.S.E.	1.62	1.31
Log N.S.E.	0.9	0.91
Combined measure (ME)	1.86	1.91

Contribution of Snow and Ice Melt in River Discharge

This model output is also used for estimating the relative contribution of snow and ice melt to river discharge. Contributions of base flow and rain are higher in Sangda River basin in both calibration and validation years. Figure 6 portrays the relative contribution of snow and ice melt and rain plus base flow in the basin for 2012 and 2013.

Contribution of snow and ice melt is higher during the monsoon months (June-September) in the calibration year, as is the contribution of base flow and rain. However, in the winter months (November-March) river discharge is only attributed to base flow in the basin since in winter no precipitation events take place and even if there is a precipitation event, the melting of snow and ice is hindered by negative air temperatures. Thus April is the onset of the melting period in the basin with rising air temperatures that melts down some of the accumulated snow and ice from winter. Contribution of snow and ice melt in the total river runoff in the year 2012 is ~19% and the contribution of rain and base flow is ~81%. Similarly, in the year 2013, the contribution of snow and ice melt is ~16% and of rain and base flow

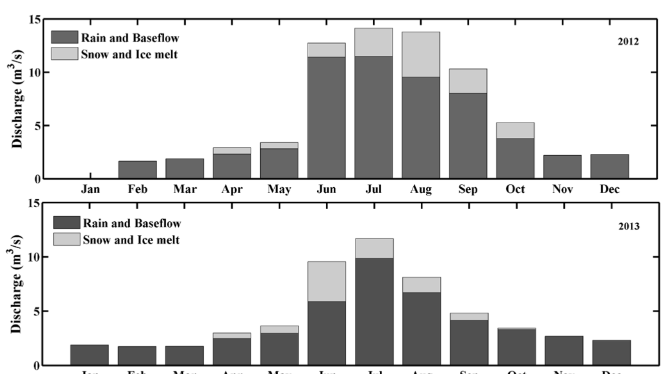

Figure 6: Contribution of snow and ice melt and rain and base flow in Sangda River basin for 2012 (upper panel) and 2013 (lower panel).

is ~84%. This result suggests that the contribution of snow and ice melt varies year to year and month to month depending upon the amount of precipitation the basin receives.

Future Climate Data Analysis

The projected period of future climate is from 2015 to 2050 in this study. The Mann Kendall trend analysis is performed for both temperature and precipitation data downscaled for RCP4.5 and RCP8.5 emission scenarios. No significant trend in the temperature data is found with p-value 0.106 and 0.309, and Sen's slope 0.017 and 0.012 for RCP4.5 and RCP8.5, respectively. Likewise, the projected precipitation (2015-2050) for both emission scenarios RCP4.5 and RCP8.5 also show no significant trend with p-value 0.213 and 0.296 and Sen's slope 3.004 and -2.37, respectively. Figure 7 shows temperature and precipitation trends for RCP4.5 and RCP8.5. Though both emission scenarios are not showing significant trends in precipitation and temperature data over the years, the occurrence of a number of extreme events like extreme hot and cold days, and higher precipitation is increasing in the RCP8.5 emission scenario as can be seen in Figure 7 (lower panel).

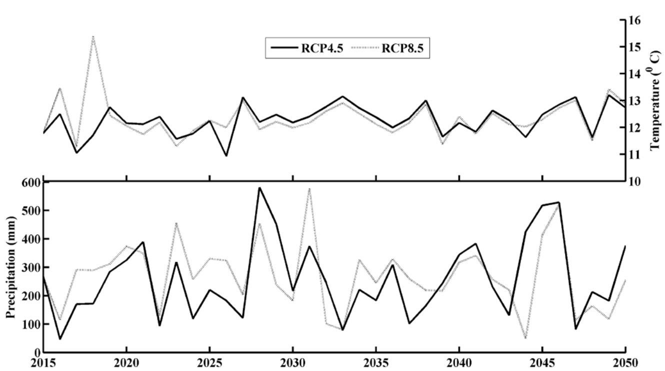

Figure 7: Projected annual temperature and precipitation of Sangda Meteorological Station (2015-2050) for RCP4.5 (upper panel) and RCP8.5 (lower panel).

Future Discharge Projection

Many studies have suggested that the response of river discharge to climate warming is immediate in the initial phase (Braun et al., 2000, Jansson et al., 2003). With the rapid warming, additional water is released from glacier storage due to intensified melting, resulting in a significant increase in glacier runoff. But this is not the case in this basin; in both emission scenarios the climate has responded very insignificantly to what is predicted by AR5 (IPCC, 2014), i.e. an increase in temperature by 1.4 ºC and 2.0 ºC in the mid 21st century (2046-2065) for RCP4.5 and RCP8.5, respectively. No drastic changes in the future discharge in the basin is predicted for the Sangda River basin.

The projected river discharge shows an insignificant increasing trend for RCP4.5 with a p-value of 0.002 and Sen's slope of 4.12×10^{-4}. The average discharge for the entire period (2015-2050) in the RCP4.5 scenario is ~7.52 m^3/s, which is slightly greater than the present discharge value (6.48 m^3/s). However, no significant trend is observed in future discharge in the RCP8.5 scenario, with a p-value of 0.179 and Sen's slope of 1.55×10^{-4}. The average discharge recorded for the period is ~7.57 m^3/s, which is also slightly greater than present discharge in the basin. Some higher discharges recorded for RCP4.5 scenario are 8.27 m^3/s, 8.11 m^3/s, 8.02 m^3/s, 8.18 m^3/s, 8.07 m^3/s and 9.13 m^3/s in the years 2021, 2024, 2025, 2031, 2042 and 2046, respectively. Likewise, in RCP8.5 some higher discharges are recorded in the year 2026 (8.1 m^3/s), 2031 (8.14 m^3/s), 2042 (8.04 m^3/s) and 2046 (9.04 m^3/s).

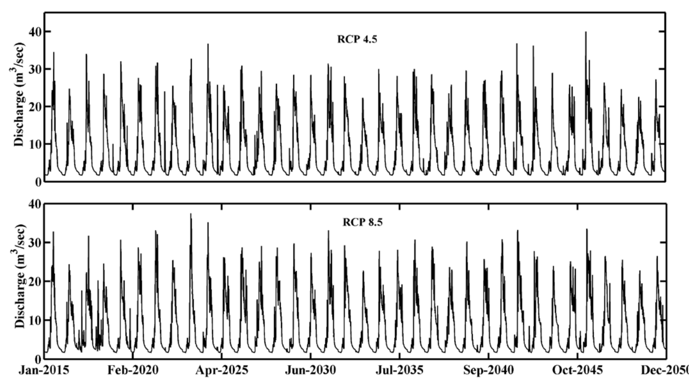

Figure 8: Projected discharge for the period (2015-2050) in RCP4.5 (upper panel) and RCP8.5 (lower panel).

Snow and Ice Melt Contribution in Future

The contribution of snow and ice melt in RCP4.5 scenario for 2015-2050 is ~17% and rain and base flow is ~82%, whereas the contribution of snow and ice melt in RCP8.5 scenario for the same period is ~15% and of rain and base flow is ~85%. From Figure 9, it is also apparent that the contribution of snow and ice melt extends to greater portions of the year for both scenarios; however, the higher contribution of snow and ice melt is in the months of May to September. The snow and ice melt in the basin outside these months can be attributed to higher radiation resulting in melt.

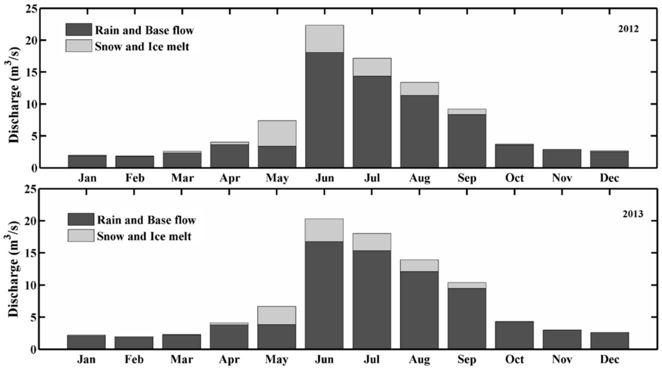

Figure 9: Projected contribution of snow and ice melt in future river runoff in RCP4.5 (upper panel) and RCP8.5 (lower panel).

Decadal Changes in the Contribution of Snow and Ice Melt

Table 4 shows average discharge, average snow melt, and average ice melt in the Sangda River basin in two different scenarios for different time periods. The contribution of snow and ice melt in each period is greater in the RCP8.5 scenario than in the RCP4.5 scenario. The maximum average discharge occurs during 2021-2030 in both scenarios, and in the later two decades relatively less discharge is observed. However, in both scenarios the ice melt has an increasing trend, which signifies a somewhat decadal anomaly in future projected discharge. Similar results are found in previous studies too. In the Yangtze River source region, China, Lui et al. (2009) found as an indication of decadal anomalies decreased runoff but increased glacier melt runoff, mainly during the 1990s, and plentiful river runoff, though glacier runoff indicated a negative trend in 1961-70.

Sensitivity Analysis

The parameters chosen to test sensitivity of river runoff to changing climates are temperature (±1 ºC and ±2 ºC) and precipitation (±10% and ±20%), without considering the change in glacier area. Though much greater uncertainty surrounds the estimates of changes in regional precipitation, both increases and decreases in average annual precipitation and temperature are modelled in this study to check how changing (warming and cooling, dry and wet) climate impacts the river discharge of this basin.

Some studies have revealed that glaciers in the Nepalese Himalaya appear to be highly sensitive to changes in temperature, and projected increases in precipitation are insufficient to offset the increased glacier melt (Shea et al., 2015). In this study we also find that a warmer but drier climate will have more impact on river runoff than a cooler and wetter climate in the basin, relative to current conditions. And from this result, we can anticipate that a warming climate will result in more discharge than a wetter climate because with warmer temperatures, even with or without any changes in the total annual precipitation, more of it will occur in a liquid form (i.e., rainfall) instead of a solid form (i.e., snowfall). Rainfall, unlike snowfall, will not be stored; instead it will immediately drain out from the basin. This may result in more floods downstream during the monsoon. Table 5 shows sensitivity tests in terms of volume differences for different climatic scenarios in the Sangda River basin. When temperature is increased by 2 ºC and precipitation by 20%, the river runoff is increased by +52.3%, whereas when temperature is decreased by 2 ºC and precipitation by

Table 4: Contribution of snow and ice melt in different periods for RCP4.5 and RCP8.5

Date	*Average discharge (m^3/s)*	*Average snow melt (m^3/s)*	*Average ice melt (m^3/s)*	*Ice melt %*	*Snow melt %*
			RCP4.5		
*2015-2020	7.45	1.19	0.072	0.97	15.97
2021-2030	7.65	1.38	0.080	1.07	18.04
2031-2040	7.47	1.21	0.087	1.17	16.2
2041-2050	7.46	1.204	0.094	1.27	16.14
			RCP8.5		
*2015-2020	7.54	1.11	0.086	1.14	14.72
2021-2030	7.68	1.35	0.087	1.14	17.57
2031-2040	7.53	1.22	0.097	1.29	16.21
2041-2050	7.50	1.204	0.103	1.37	16.05

*Note that period 2015-2020 is not considered in decadal analysis because it includes only a five-year period.

Table 5: Change in discharge in percentage for different sensitivity tests

Parameters	*Test*	*Volume difference (%)*
Temperature	T+1 ºC	+27.4
	T–1ºC	–6.8
	T+2 ºC	+39.7
	T–2 ºC	–8.9
Precipitation	P+10%	+13.7
	P–10%	–3.9
	P+20%	+17.4
	P–20%	–26.7
Combination of temperature and precipitation	T+1 ºC & P+10%	+32.0
	T–1 ºC & P–10%	–9.0
	T+1ºC &P–10%	17.9
	T–1ºC & P+10%	-5.01
	T+2 ºC & P+20%	+52.3
	T–2ºC & P–20%	–17.2
	T+2ºC & P–20%	+21.17
	T–2ºC & P+20 %	–15.5

20%, the river discharge decreases by 17.2%. Likewise, an increase in temperature by 2 ºC and a decrease in precipitation by 20%, results in a +21.17% volume increase in discharge and a decrease in temperature by 2 ºC and increase in precipitation by 20% results in a –15.5% volume difference in discharge. These figures signify that temperature is the most influential parameter for temperature index modelling. Precipitation too has an influential role in the model but its role is overshadowed by the role of temperature. Beside these two controlling parameters, DDF of ice and snow and glacier area too play a crucial role in the temperature index model.

Conclusion

The elevation-dependent temperature index modelling approach applied in Sangda River basin simulated daily discharge pretty well in both calibration and validation years with Nash-Sutcliffe Efficiency (NSE) 0.91 and 0.92, and volume difference (VD) 5.23% and 7.1%, respectively. This model also gave us insight into the hydrological dynamics of the Sangda River basin by quantifying the contribution of snow and ice melt to total discharge in the basin. The snow and ice melt contribution in the calibration year is 19% and in the validation year is 16%, which suggests that snow and ice melt vary year to year in the basin. In the same study we also explored the sensitivity of basin discharge to warm, cool, dry, and wet climatic conditions. Modelled basin discharge sensitivity to temperature change is higher compared to changes in precipitation.

Two emission scenarios, RCP4.5 and RCP8.5, used to predict future discharge of the basin (2015-2050) show an insignificant trend. However, from decadal discharge and melt analyses, ice melt is found to increase for the periods 2021-2030, 2031-2040 and 2041-2050 significantly. Thus temperature index model parameterized with elevation characteristics to account spatial heterogeneity in snow and ice melting is a good melt modelling approach in places where data availability is limited. This model estimates daily melt and discharge with sufficient accuracy and can also be used to assess the sensitivity of melt processes to climate change for most practical purposes (Ohmura, 2001). The higher efficiency of this temperature index model, however, does not provide the detailed internal physical processes involved in real situations. For better understanding of real situations, a distributed modelling approach which incorporates the ground water and soil properties is a must. A long-term monitoring programme and installation of permanent weather stations can provide invaluable data for future research and proper management of natural resources of the region.

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