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Flow Characteristics in Climate Change Scenario: a case study of Tamakoshi sub-basin of Koshi River

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Abstract

The Himalayan catchments in Nepal are of great significance in terms of its water resources available for domestic use or for development sectors like hydropower or irrigation. With the evolving issue of climate change, the hydrological system of these catchments is predicted to alter, thus making the future development of water resources more challenging. Therefore, this research focuses in estimating the future changes in the flow in Tamakoshi basin of Nepal. The projections are based on one regional climate data of PRECIS: ECHAM05 using a degree-day based Snowmelt Runoff Model (SRM) for the period of 2021-2060. The model simulates runoff integrating daily series of temperature, precipitation and remotely sensed snow cover data. Runoff for the year 2000-2008 was set as baseline period to assess the changes in flow in future condition. With an average Nash-Sutcliffe Efficiency of 0.832 and a volume difference of 1.47%, the result for the baseline period shows an annual contribution of 26.5% of snowmelt to the total flow. Seasonally, the largest contribution was found during post-monsoon season which accounts to 68% of the total flow. Also total runoff in the Tamakoshi basin is projected to increase at the rate of $1.72 m^3/s$ per year in response to increase in projected precipitation (12.21mm/year) and temperature data (0.057°C/year) in the basin. The annual runoff is anticipated to increase after 2050 while flow during pre-monsoon season is expected to increase significantly. Based on model simulation, a significant shift in monthly peak flows of August to July is expected after 2050 in the basin.

Keywords: Climate change, degree day, runoff, snow cover, snowmelt

Introduction

Himalayan catchments of Nepal are regarded as important source of water for people residing in upstream and downstream region, as they are the repositories of snow, ice, permafrost, glacier and glacier lakes.All these contribute to the total runoff including contribution from rainfall and ground water.The magnitude of the contribution of each of these runoff components to the total runoff determines the basin's runoff composition and to a large extent also its response to climate variability and change(Lutz et al., 2014).Numerous research have indicated a widespread impact of climate change in Himalayan catchment with the evidences of rapid retreat of glaciers (Fujita et al., 2000), formation of new glacier lakes and expansion of existing one (Mool et al., 2001), increase in snowline(Jones, 1999), changes in solid to liquid precipitation ratio(Agrawala et al., 2003; Chaulagain, 2006) and rapid melting of snow in lower latitudes (Singh and Bengtson, 2004). The research conducted by Lutz et al. (2014) indicates an increase in runoff in Asia based on an ensemble of climate model data. This also indicated an increase in annual runoff by 10% for RCP4.5 and 27% for RCP8.5 scenarios in upper Ganges Basin. Geographic areas of Himalayan catchments, which are highly susceptible to changing climate, are thus, of major concern because changes in the hydrology of these catchments is expected to affect the seasonality of runoff (Adam et al., 2009). Moreover, development sectors like irrigation and hydropower, which are already under stress during non-monsoon months in the country, would further be exaggerated under climate change condition (Chaulagain, N. P., 2015).

Tamakoshi basin, a glaicerized basin in Nepal, is one of the potential sites for hydropower generation with an estimated potential of 1107MW. Several hydropower projects are underway; like 456MW of Upper Tamakoshi Hydroelectric Project (UTKHEP) are under execution, along with a planned one with a potential of 370MW (Shilpakar et al., 2009). To assess the changes/variations that the climate change will induce in near future, suitable hydrological model in the basin seems imperative. Since the Himalayan catchments are highly heterogeneous and also with very sparse meteorological station network, a simple robust model, appropriate to these conditions is required in this study. Thus, this study uses SRM model to quantify the variability in the stream flow using daily projected climate data to evaluate changes in future hydrology of the Tamakoshi basin.

Study Area

The research is carried out in Tamakoshi basin of Nepal. Tamakoshi River is one of the tributaries of Saptakoshi River that extends from 27˚37´32"- 28˚ 19´06" to 85˚59´56"- 89˚ 34´32"and lies about 90km North Eastof Kathmandu valley. It is a trans-boundary river, with drainage area of 3132 km2atBusti gauging station and with an average areal length of 86 km. The river runs through RongharChhu and Lapcha that is originated in Tibet and flows down to Nepalese boundary. Nearly 52% of the basin lies in China and the rest in Nepal. The river ultimately joins the Sunkoshi confluence, farther at the downstream. The basin ranges at an elevation of 797 to 7311 m.a.s.l. with a mean elevation of 5080 m. It is located in Dolakha district of Nepal and is adjoined by Sindhupalchowk (west), Ramechap (east-south) and Solukhumbu (east) districts in its surroundings (Figure 1). There are seven high peaks with elevation greater than 6000m (Shilpakar et al., 2009). About 56% of the basin lies at an elevation above 5000 m while 39% lies at an elevation range of 3000-5000 m. Based on MODIS data of 2000 to 2011, the mean snow cover area (SCA)of the basin is 742 km2 i.e. 24% of the basin is covered with snow. As the permanent snowline in the country ranges from 4500-5000 m, 14 % of SCA lies at an elevation range of 3000-5000 m. The basin is reported to consist of 27 glaciers (ICIMOD, 2011) and 24 glacial lakes (Bajracharya et al., 2014) within Nepal. Altogether, four meteorological stations were used in this study, which consists of two precipitation stations and two temperature stations (Figure 1).

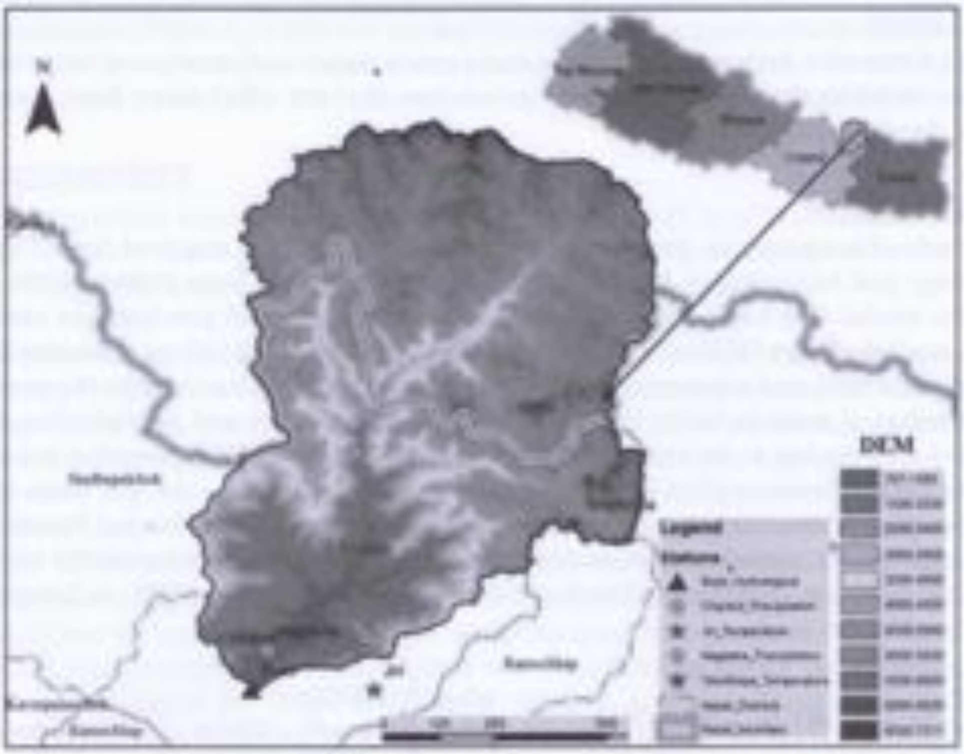

Figure 1. Study area - Tamakoshi sub-basin

Methodology

Model Structure and Evaluation Criteria

Snowmelt runoff model (SRM) is a conceptual, degree-day based hydrological model, which has been extensively used over the globe. The model simulates the daily runoff from a precipitation event as rain and snow and also from the daily snow cover area. It is also capable of assessing impact of climate change impact on runoff and snow cover area. The daily stream flow is simulated by the equation 1 given by Martince (2008) as follows:

$$Q_{n+1} = \sum [C_{Sn} a_n (T_n + \Delta T_n) S_n + C_{Rn} P_n] A_n \left({}^{1000}/_{86400} \right) (1 - k_{n+1}) + Q_n K_{n+1}$$

Equation 1

Where Q (m^3/s) is discharge at day n+1, C_{Sn} and C_{Rn} is the runoff coefficient due to snow and rain for each zone (n), a is degree day factor (cm/°C/day), $(T_n + \Delta T_n)$ is the degree days (°C), S is the ratio of the snow covered area to the zonal area, P is precipitation (cm) per day, A is the basin area (km^2) and k is the recession coefficient, 10000/86400 is a conversion factor from runoff depth to discharge. The relationship between the observed and simulated discharge is evaluated using Nash Sutcliffe Efficiency (NSE),Pearson correlation coefficient (r) and through visual inspection of hydrograph. A NSE and Pearson correlation coefficient value close to 1 signifies better representation of simulated data to the reality, while a D_v value near to zero indicates less bias in simulated volume of flow data compared to the observed one. Thus, this criterion is used in this study to assess the precision of the model simulation.

Model input

The model demands a daily series of temperature, precipitation and snow cover area. Along with these three variables there are other seven parameters that are either taken from literatures or estimated through calibration process.

Input variables

Daily records of temperature, precipitation and discharge data are acquired from Department of Hydrology and Meteorology (DHM) of Nepal, where the data from 2000 to 2008 was only used in the model. The basin consists of only two temperature and precipitation stations viz., Jiri (2002 m), TshoRolpa (4580m) and Nagdaha (850 m), Charikot (1940 m) respectively. A daily average of maximum and minimum temperature data wereused as an input in the model. Since the meteorological stations in the basin is scarce, the temperature and precipitation data from this limited stations has to be extrapolated with respect to the defined elevation zones (Figure 1), for the better representation of precipitation-runoff relationship. As the basin is divided into 11 elevation zones, the temperature for each elevation zone was estimated by using a lapse rate and hypsometric elevation relationship. Moreover, precipitation extrapolation to the mean hypsometric elevation zone by an altitude gradient, suggested by Seko(1987) in Langtang basin has been used in this study.

$P_{j,n} = P_{BH}$ when $h_j < 4000$m

$P_{j,n} = P_{BH}\{1 + 0.003\,(h_j - 4000)\}$ when $4000\text{m} < h_j < 5000$m .... Equation 2

$P_{j,n} = 1.3\,P_{BH}$ when $h_j > 5000$m

To evaluate the changes in future, a Regional Climate Model of PRECIS-ECHM05 data was used. The data was also acquired from DHM Data Portal and the climate recoed ranges from 2020-2060 years. A power transformation technique (Terink et al., 2010; NDRI, 2013), which is based on a method of rectifying the mean and coefficient of variation between the observed and model data, was used for correcting the precipitation data in this study. While a method developed by Leadner and Buishand (2007) i.e. a delta change approach was used for temperature data.

The geo-spatial data in the study area includes digital elevation model (DEM) and satellite derived snow cover data. For a topographical data, the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) DEM with 30x30 m spatial resolution was used. The area elevation and hypsometric data (Figure 2), extracted from DEM is used for extrapolating temperature and precipitation from the base station to its respective hypsometric elevation.

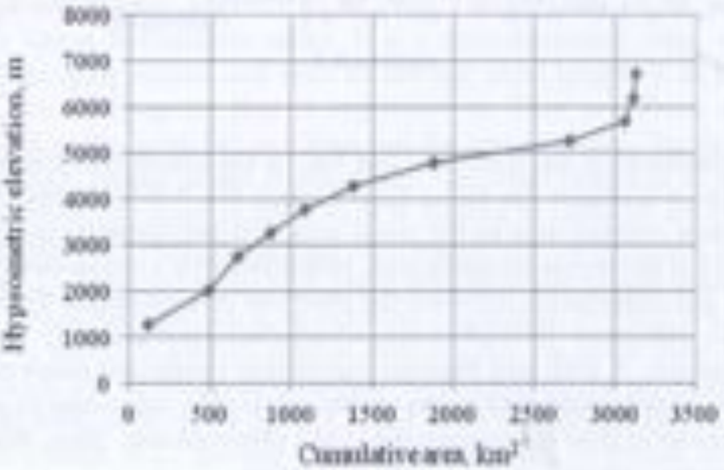

Figure 2. Area-elevation curve derived from DEM of Tamakoshi basin

Snow cover area (SCA) is a major input of the model. A daily product of MODIS satellite data with a spatial resolution of 500m by 500m was used in this study. As the basin is divided into 11 elevation bands, the SCA for each elevation bands is extracted using ArcGIS9.3 tools. The SCA in this study includes snow, lake ice and lake. SCA was assumed to be zero for elevation below 3000 m.

Input parameters

The seven parameters required by the model area lapse rate (γ), critical temperature (T_{CRIT}), degree day-factor (a), time lag (L), rainfall contributing area (RCA), recession coefficient (k), runoff coefficient due to rain and snow (CR and Cs).

Table 1 displays the summarized range of values used for the parameters. As an important aspect of distributing temperature with respect to elevation zone, the lapse rate for the basin is derived using temperature data from Jiri (2002 m) and TshoRolpa (4580 m) stations, which is about 5.32°C/Km. Precipitation in the Himalayan region falls in two form; rain and snow. This form of precipitation is governed by temperature that is below freezing point. Critical temperature is a threshold temperature that separates these two forms. A 0°C of this temperature was assumed for all elevation zones in this study. With the defined threshold temperature and the index temperature, degree day factors estimates the melt from the snow. The value of degree day factor is different for ice and snow and varies with changing snow properties. Elevation <4000 m and >6000 m was considered as snow, while it was considered as ice for the elevation range of 4000-6000 m. The degree day factor in this study depends on the elevation and is derived from the research conducted by Kayastha et al. (2003). Time lag is the difference between the start of increasing temperatures and the corresponding increase in runoff from the basin. A value of 12.11 hours was used as time lag in the study area. Usually a "0" and "1" value is used for RCA parameter. A "1" value indicates that, all the precipitation fall during the simulation period will be immediately transformed into runoff with no storage in the snowpack. While a zero value signifies the dry condition of the snowpack and that all fall be stored into snow pack. RCA values are used with respect to elevation and season (May to Sept =1, Oct to Apr = 0). A zero value was used at elevation >5500m in this study.

Table 1. Parameters value of Tamakoshi basin

Parameters	**Values**	**Parameters**	**Values**
γ	5.32°C/Km	RCA	1 (May-Sept) 0 (Oct-Apr)
T_{CRIT}	0°C	k	x = 1.007-1.253
A	0.7-1.05cm/°C/day		y =0.029-0.064
L	12.11hrs	$C_s=C_s$	0.432

Recession coefficient and runoff coefficient are the most sensitive parameters which are highly experienced by SRM model users. These parameters require adjustment until the results are fine tuned with the observed data. These two parameters were estimated during calibration of the model, while other parameters were extracted from past studies. The time series of discharge data at Busti station for the year 2001 was used for calibration in this study and rest of the years for validation. The period of 2000-2008 in this study was set as baseline period to evaluate changes in future with respect to projected climate data. Recession coefficients indicates the proportion of daily melt water of snow contribution to the daily runoff (Hong, et al., 2003) and is determined through historical discharge data (Equation 3). The model used x and y coefficients that balances the base and peak flows of the hydrograph. A monthly values of x and y was generated based on Equation 3 and ranges from 1.007-1.253 for x and 0.029-0.064 for y parameters.

$$k_{n+1} = xQ_n^{-y} \text{ .... Equation 3}$$

Runoff coefficients determine the losses where the model demands the data in two forms of precipitation viz. runoff coefficient due to snow and rain. Annual runoff coefficient is calculated in this study through historical precipitation and discharge data. Though the coefficient differs for snow and rain, a similar value of C_s=C_r was used in this study. However, for elevation below 3000, C_s was assumed to be zero.

Results and Discussion

Climate data analysis

The study uses regional climate model of PRECIS-ECHAM 05 precipitation and temperature data for the period of 2020-2060. A thiessen average of precipitation data was used for its analysis. A linear regression analysis of average annual rainfall data in Figure 3 depicts an increase at a rate of 12.21 mm/year. Similarly, annual trend of temperature data for Jiri and Tsho Rolpa stations indicates more warming in future with a more increase at a rate of 0.0561° C/year and 0.0597° C/year for respective stations. Khadka et al. (2014) has also observed an increasing pattern in both temperature and precipitation in future using two GCM data i.e. for HadCM3 for SRES A2 and B2 and CGCM3 for SRES A2 and A1B scenarios.

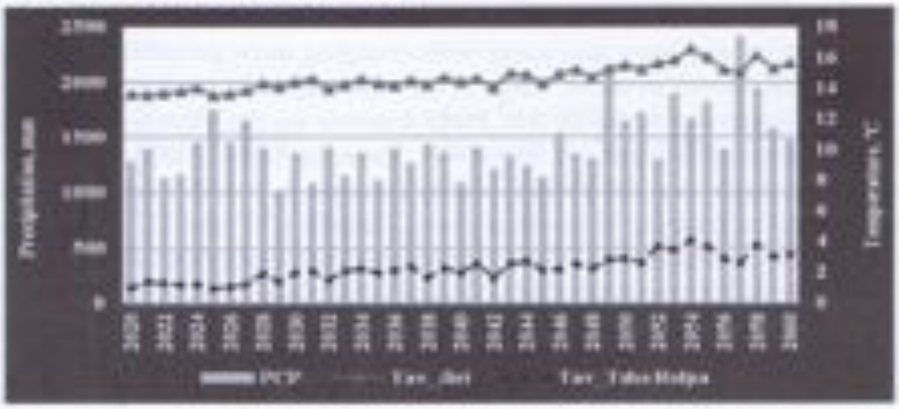

Figure 3. Annual average precipitation and temperature trend in Tamakoshi basin *Runoff Simulation and snowmelt contribution in the baseline period*

The year 2000-2008 was used for runoff simulation in this study, where the year 2001 was used for calibrating parameters. Due to missing hydrological data in the year 2002, validation was not performed for this year. Thus an eight year period was set as baseline period to evaluate the changes in flow in future using projected climate data of ECHAM 05. Flows in the year 2001 were simulated with a high degree of efficiency i.e. a NSE of 0.927, r of 0.963 and a slightly overestimated volume of -2% (Figure 4).

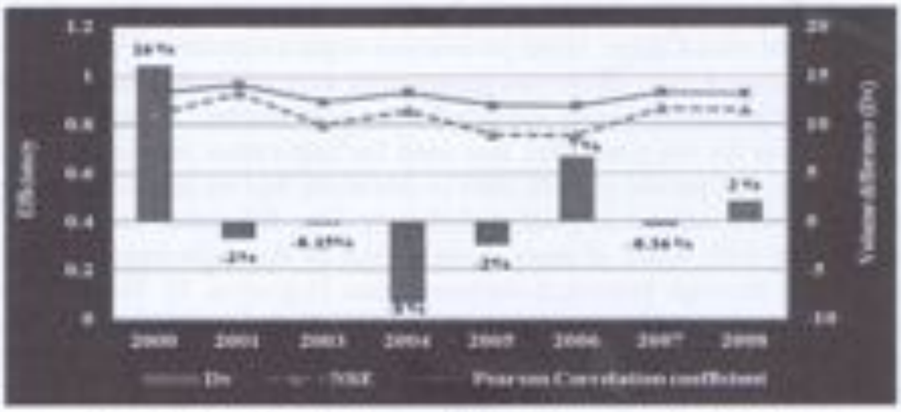

Figure 4. SRM model evaluation results for the period of 2000-2008

The maximum high flow recorded during the baseline period was 1310 m^3/s. But the model was only able to simulate this flow to 839.4m^3/s.Figure 5a clearly shows the model inability to capture extreme events especially during monsooh season as shown in monthly hydrograph of Figure 5b. This could be because of less spatial coverage of precipitation stations in the basin that otherwise could have correlated with the extreme runoff events during the baseline period. Also this high flows could be because of breaching of some natural lake impoundments located in the upstream region, where the model fails to capture such events. Similarly, the low flow recorded during the baseline period was 13.2 m^3/s, while such flow was simulated to be 14.4m3/s. Though the low flows are very slightly overestimated, such flows simulated by the model highly corresponds to the observed low flow records. Moreover, with the range of parameters optimized in the calibration period, flows were found to be well simulated during the validation year. On average the flows were well simulated with a NSE of 0.832 and a volume difference of 1.47%.

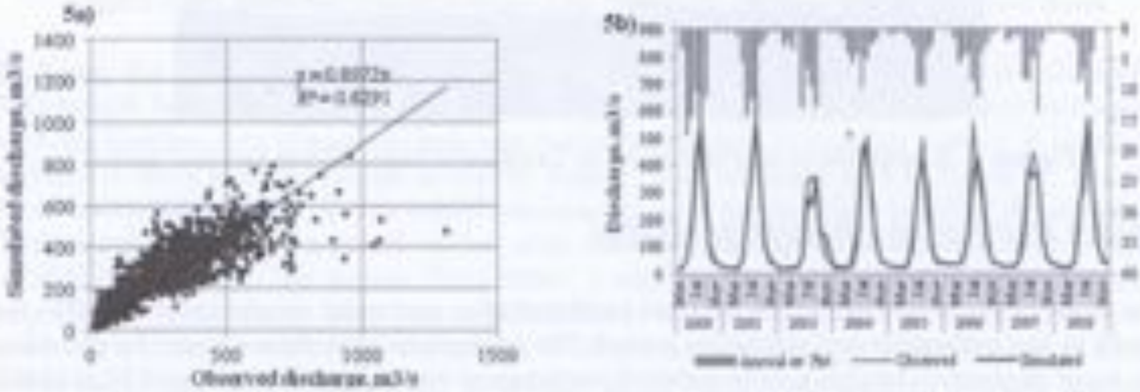

Figure 5. (a) Scatter plot of observed and simulated discharge for the period of 2000-2008. (b) Monthly simulated hydrograph for observed and simulated discharge.

With the mean SCA of 742 km^2 in the basin, snowmelt contributes an average of 26.5% to the total flow in Tamakoshi basin. Khadka, et al. (2014) estimated an annual contribution of 18% to the total flow for their baseline period of 2000-2009. Also Shilpakar et al. (2009) estimated an annual contribution of 9% to the total flow for his two years of calibration (2003) and validation (2002). The total contribution of snowmelt to stream flow highly depends on the precipitation gradient (Immerzeel et al., 2014) used in the basin; that is used for extrapolating precipitation according to each elevation zones. Extrapolation of data from the stations located at lower elevation also leads to uncertain water balance of the system. These differences are also due to different range of parameters optimized for the basin. Since the melt is estimated based on degree-day approach, using different ranges of input for degree day factor certainly provides a different analysis. Emphasis on need for parameterization in mountain catchments has also been suggested and conducted by Immerzeel et al. (2011) and Pellicciotti et al. (2012). Therefore, a sensitivity analysis for the SRM parameters needs to be conducted to define an optimum range of parameters for the basin. Annual hydrograph of snow melt shows two peak-first during the spring season when snow melt begins to rise after a winter minimum and second during the monsoon season when the temperature is its peak (Figure 6). Seasonally, maximum snowmelt in Tamakoshi basin was found during monsoon season, which contributes 14.41% to the total flow. However, the percentage of maximum contribution is observed during the month of post-monsoon season (Mar, Apr and May), 67.80 % of the total water produced from snowmelt for runoff followed by the winter season (Dec, Jan and Feb) with 34.45%. The highest contribution during the post monsoon season indicates more contribution from ice melt, when air temperature and solar radiation exert a strong forcing in snow-free ice area.

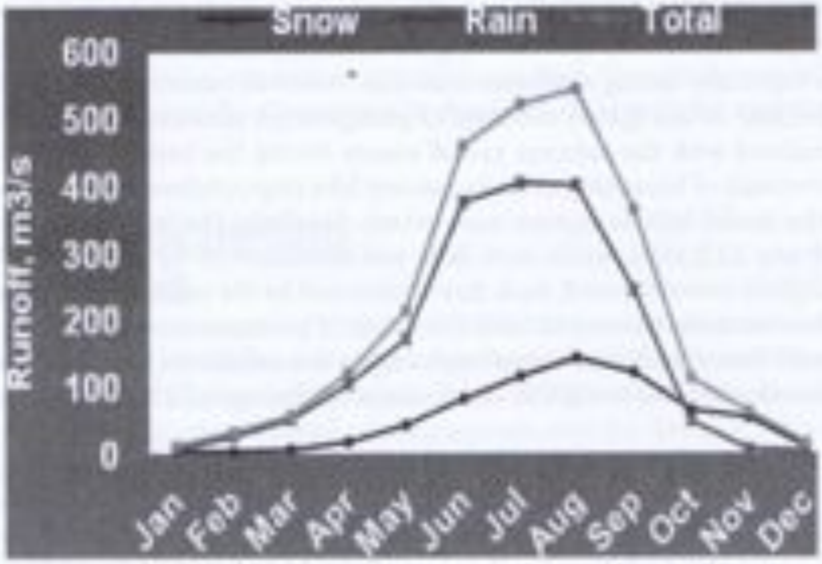

Figure 6. Runoff due to rain and snow in Tamakoshi basin during baseline period

Flows in climate change scenario

The flows for the period of 2021 to 2060 are predicted after successful simulation of runoff by the model in the calibration and validation period. The projections were then allowed by providing the input of climate data i.e. a daily series of temperature and precipitation data of ECHAM05. Results of annual average flow for the period of 2021 to 2060 indicate an increase in flow at a rate of 1.72mm/year as shown in Figure 7. Analysis of mean annual flow in four decades with respect to the simulated flow ($126m^3/s$) in the baseline period is also expected to rise, with more prominent increase observed at the end of the decade, where the flow tends to increase nearly by double. A similar projection of increase in flow after 2050s, incorporating PRECIS: ECHAM05 and PRECIS: HadCM3 data, had been experienced in Koshi basin by the use of SWAT model (NDRI, 2013).

Table 2. Percentage change in total flow in four decades based on simulated flow

Season/Decade	21-30	31-40	41-50	51-60
Average	41	45	59	82
Winter	-6	-3	-1	-1
Pre-monsoon	88	84	114	158
Monsoon	44	43	63	86
Post-monsoon	23	20	35	55

**Winter=DJF, Pre-monsoon=MAM, Monsoon=JJAS, Post-monsoon=ON*

Along with annual average flow, seasonal changes in flow in four different decades were carried out (Table 2) as it is imperative to understand the seasonal variations of flow for future water management activities. Result in Table 2 indicates considerable increase in stream flow during all season except in winter months. A significant rise is expected during pre-monsoon months, with over more than 100% increase after 2040. This increasing pattern of runoff in Tamakoshi basin was found to highly correlate with the projected precipitation data with a Pearson correlation coefficient of 0.85. Also the increase during pre-monsoon months might be due to increased contribution from snowmelt. Moreover, a slight decrease in flows is expected during winter season, which however, tends to decline with the progressive decade i.e. from -6 to -1 %.

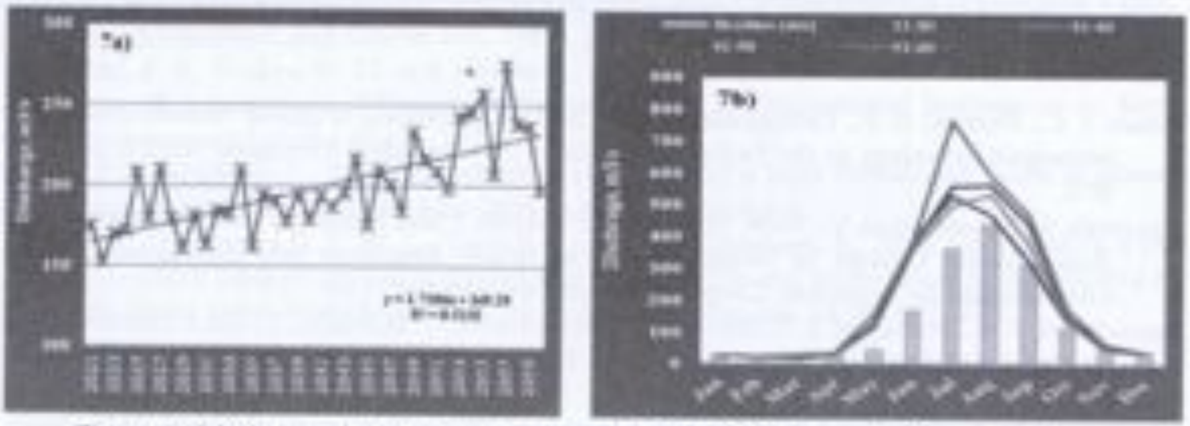

Figure 7. (a) Projected annual average flow (m³/s); (b) Hydrograph of projected flows

In Nepal, the peak flows are observed during the month of August. To assess the changes in hydrograph, future flows were divided into four decades. Analysis comparing this four hydrograph with the baseline data (Figure 7b) indicates noticeable changes in monthly pattern. A significant increase in flows from the month of May to August could be clearly seen in Figure 7b. The peak flows of August however, shows varied responses in each decade. Flow in initial decade (2021-2030) is expected to shift a month earlier, while it resumes back to its normal state for the period of 2031-2050. But, in 50s decade (2051-2060), a visible shift in the peak flow from August to July (Figure 7b) is clearly seen. The amplification of stream flow (Table 2, Figure 7) especially after 2050s is thus predicted by the model. With the coupled effect of positive trend in annual precipitation and temperature, water availability in the basin is not likely to decrease in overall until 2060, though initial decline during winter season is projected. Therefore it is expected to sustain, increasing demands of water in basin.

Conclusions

The research analyses flow characteristic in Tamakoshi basin for the future period incorporating a bias corrected climate data of ECHAM05, using a snow melt runoff model. The model performed adequately for the period of 2000-2008. Though parameters like runoff coefficient and recession coefficient were found to be sensitive, a sensitivity analysis for other parameters is required to set an optimal range for the model parameters to reduce the uncertainty. The bias corrected data in the basin indicates more warming with an average increase of temperature by 0.057°C and also with an increasing precipitation trend of 12.21 mm/year. A significant contribution of snowmelt is observed during post-monsoon season in the basin. Annual flows at Busti gauging station is expected to increase at a rate of 1.72mm/year, while such flows are expected to rise especially during pre-monsoon months. Though shift in flows, a month earlier is not significant in initial three decades i.e. for the period of 2021-2050, this shift is highly marked after 50s decade. Therefore, based on climate model, we conclude an increase in annual flows in the future, mostly because of the contribution from monsoon rains, increased melt from snow and glaciers in the region; it is thus, expected to sustain the water demand at least until 2060.

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