Impact of Climate Change on Water Resources in View of Contribution of Runoff Components in Stream Flow: A Case Study from Langtang Basin, Nepal

Bikas Chandra Bhattarai[1], **Dhananjay Regmi**[2]

[1]*Central Department of Environmental Science, Tribhuvan University, Kathmandu Nepal*

[2]*Central Department of Geography, Tribhuvan University, Kathmandu, Nepal*

ABSTRACT

Observation and model-based studies suggest substantial hydrological flow pattern changes in mountain watershed where hydrology is dominated by cryospheric processes (IPCC 2007). The response of cryospheric processes to warming climate in mountain areas can be analysed by examining the responses in the seasonal and annual hydrologic regimes of rivers where snowmelt contributes significantly to the runoff. This study is carried out in Langtang basin, which aims to assess the impact of potential warming on snowmelt contribution and river discharge utilizes a Snowmelt Runoff Model (SRM), which is one of a very few models in the world today that requires remote sensing derived snow cover data as a model input. In this study, snow cover and hydrometric data were derived from Moderate Resolution Imaging Spectro-radiometer (MODIS) snow product and Snow and Glacier Hydrological Unit (SGHU) of Department of Hydrology and Meteorology, Government of Nepal. The model is calibrated for the year 2006 and validated in 2005. Different climatic scenarios are used (only change in temperature) to run the model in order to understand the impact of changing climate on runoff component and river discharge. In 2006, snow and glacier melt component contributes 35% in winter, 18% in summer and 19% annually in the stream flow. In this study, model predicts that snow and glacier melt contribution in stream flow will increase approximately at the rate of 2% in winter, 5% in summer and 4% in annual flow per 1°C temperature rise. Due to increase in snowmelt contribution, river discharge will also increase at the rate of 2% in winter, 6% in summer and 5% in annual flow under the projected temperature rise of 1°C.

***Key words**: Climate change, Himalayas, Langtang basin, MODIS snow, Snow Melt*

1. INTRODUCTION

Growing evidence indicates mountain glacier and snow covered area on average have decline on both hemispheres (IPCC 2007). Geographic areas where the water cycle is dominated by snow and glacier melt hydrology are expected to be more susceptible to climate change as it affects the seasonality of runoff (Adam et al. 2009). Changes in seasonal snow covered and glaciated regions may alter the variability of stream flow and hence water availability which sustains a large population downstream. Despite its regional importance, there is uncertainty associated with the rates and magnitude of climate change impacts on snow cover and snow and glacier melt hydrology. These climate driven responses of mountainous river hydrology when combined with potential land cover changes, population growth, and already stressed water resources may pose significant challenges for this region.

Since the negative impacts of climate change on water resources are expected to be greater than its benefits (Kundzewicz et al. 2007), it is important to understand the hydrologic variability particularly in mountain environment with respect to potential climatic changes. Regional climate projections by IPCC (2007) indicate Central Asia to be warmed by a median temperature of 3.7°C by the end of the 21st century, with largest warming over higher altitudes particularly in the Tibetan Plateau and the Himalayas. According to the IPCC (2007), the temperature increase in the Himalayan region has been greater than the global average of 0.74°C over the last 100 years. Several global and few local to regional scale hydrological studies have been conducted to assess impacts of a changing climate on snow and glacier melt hydrology.

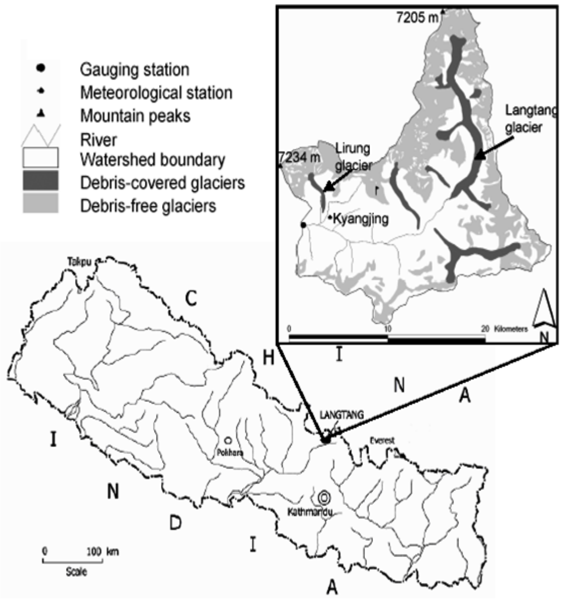

Figure 1: Location map of Langtang basin, Nepal

Analytical studies representing temperature increases of 1-3°C in the western Himalayan region suggest an increase in glacial melt runoff by 16-50% (Singh and Kumar 1997), regression of the annual maximum spring stream flow period by a month, and increased sensitivity of snowfed basins in terms of reduction in water availability (Singh and Bengtsson 2005). Water resource management and the evaluation of impacts of climatic change require quantification of stream flow variability and hydrologic models provide a framework to investigate these relationships (Leavesley 1994). Poor accessibility and inadequate network of hydro-meteorological station in high altitude regions is a major impediment to runoff modeling and as a result only a few studies have explored snow and glacier melt runoff models in Himalayan sub basins (Akhtar et al. 2008; Braun et al. 1993; Shrestha et al. 2004). The impact of potential climate change on snowmelt hydrology in the Himalaya, therefore, remains an active area of research (Figure 2). The objective of this paper is to assess the impact of potential warming on

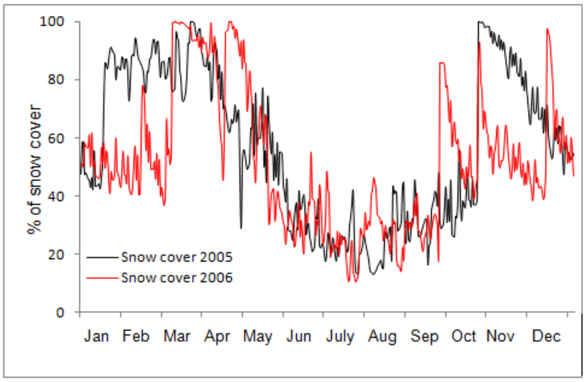

Figure 2: Snow covered area in 2005 and 2006

stream flow. As there is no significant change in annual and monsoon precipitation amount in Nepal (APN 2007, Shrestha et al. 2000) only temperature is increased from 1-3°C for assessing impact of changing climate in snowmelt contribution and river runoff.

2. STUDY AREA

Langtang River basin is situated at about 60 km north of Kathmandu at the border to China, and is the head water area of Trisuli River in the Narayani River System as shown in Figure 1. The total basin area of Langtang River is 363.5km2 (watershed delineation is based on the (Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Model (DEM) of 30 m resolution by taking the outlet at Department of Hydrology and Meteorology gauging site (85^0 32' E 28^0 12'N)). The catchment reaches from the 3800 m a.s.l. up to the Langtang Lirung at 7234 m a.s.l. with two other peaks above 7000 m a.s.l. The average altitude is 5169 m. a.s.l. with mean slope of 26.7° which reflects the high potential relief energy of the catchment. At the meteorological station the mean daily air temperature for the hydrological years 2001/02 to 2005/06 is -0.7 °C in the dry season from October to June and 6.9 °C in the Monsoon season. The highest annual precipitation falls during monsoon season i.e. 74% in the period from 1988 to 2009 with average annual precipitation of 722.05 mm at SGHU station.

3. MODEL STRUCTURE

Numerous snowmelt forecasting models have been developed to outfit specific needs and hydrologic conditions. These are either data intensive and/or complex to handle. Very few models can handle diverse hydrologic conditions in general. The popular ones are SAARR (1972), Snowmelt Runoff Model (SRM) (Martinec, 1975), Precipitation Runoff Modelling System (PRMS) (Leavesley, 1983) and UBC (Quick and Pipes, 1997) (Rao et al., 1996). Among several models, SRM, which uses the snow cover information as input, has been the most widely used one both in simulation and forecasting (Ferguson, 1999; Hall and Martinec, 1985; Rango and Martinec, 1979; Rango and van Katwijk,1990; WinSRM, 2003). SRM or variations of it were applied over 100 basins in 25 countries at latitudes 32–60 N, 33–54 S with basin sizes varying from less than $1km^2$ to 120,000km2 and accepted in about 80 scientific journals (Seidel and Martinec, 2004).

SRM is a conceptual model which is used to simulate and/or forecast daily runoff resulting from snowmelt and rainfall in mountainous regions. SRM requires daily temperature, precipitation and daily snow-covered area values as input parameters. Based on the input values, SRM computes the daily stream flow for a lag time of 18 h by equation 1.

$$Q_{n+1} = [C_{S.n} \, . \, a_n (T + \Delta T) S_n + C_{R.n} P_n] A . \frac{10000}{86400} . (1 - k_{n+1}) + Q_n k_{n+1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

According to equation 1, the daily average discharge on day n +1 is computed by summation of snowmelt and precipitation that contributes to discharge with the discharge on the preceding day. Snowmelt from the preceding date is found by multiplication of the degree day factor, a, (cm° C^{-1} d^{-1}), zonal degree days (T +ΔT) (°C) and the snow covered area percentage (S). To determine the percentage that contributes to runoff, the result of the above multiplication is further multiplied with C_s, snowmelt runoff coefficient and the total area of the zone, A (km^2). Measured/forecasted precipitation is multiplied by C_r, rainfall runoff coefficient and the zonal area to calculate the precipitation contributing to runoff. 10000/86400 is conversion from runoff depth to discharge. Discharge computed on preceding date is multiplied by recession coefficient (k) to calculate the effect on today's runoff. Eq. (1) is applied to each zone of the basin when the model is applied in semi-distributed manner, the basin is subdivided into zones, and then the discharges are summed up. SRM adjusts the input data if lag time other than 18 h is used (WinSRM, 2003). For accuracy assessment of the model performance, Nash and Sutcliffe efficiency statistic NSE (R^2) (equation 2) and volume difference Dv (%) (equation 3) are used.

$$R^2 = 1 - \frac{\sum_{i=i}^{n}\left(Q_i - Q_i'\right)^2}{\sum_{i=1}^{n}(Q_i - Q^-)^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots. (2)$$

Where:

Q^- is the average measured discharge of the given year to snowmelt season.

Q_i' is the computed daily discharge

Q_i is the measured daily discharge

n is the number of daily discharge values

$$D_v[\%] = \frac{V_R - V_R'}{V_R} . 100 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (3)$$

Where: V_R is the measured yearly or seasonal runoff volume

V_R' is the computed yearly or seasonal runoff volume

R^2 approaches to 1 as the root mean square prediction error decreases to zero. Volume difference (Dv), which is the percentage difference between the observed and simulated/forecasted mean or total discharge, reduces to zero as the observed and modeled values approach to each other. SRM was successfully applied to upper Euphrates Basin for simulation of water years 1997 and 1998 by Kaya (1999) and Tekeli (2000). The accuracies obtained from the above studies are determined, varying from 0.95 to 0.85 for R^2 and 0.56 to 9.3 for Dv, respectively.

Table 1: Elevation zone, zonal area, elevation range, and mean elevation for the nine elevation zones of Langtang River basin

Elevation zone	*Elevation Range /m a.s.l.*	*Elevation Area/km²*	*Zonal /basin area (%)*	*Hypsometric Elevation of zone/ m a.s.l.*
A	3600-4000	18.1	4.9	3933
B	4000-4400	33.9	9.3	4246
C	4400-4800	51.8	14.2	4655
D	4800-5200	84.8	23.3	5005
E	5200-5600	78.7	21.6	5385
F	5600-6000	61.6	16.9	5766
G	6000-6400	25.4	6.9	6141
H	6400-6800	7.7	2.1	6575
I	6800-7200	1.5	0.4	6861
Total		363.5	100	

3.1 Model variables and parameters

(i) Basin characteristics

1) Zonal characteristic: The area elevation curve is used in SRM to determine the zonal mean hypsometric elevation (i.e. elevation dividing the area in to equal half), and the value of the hypsometric elevation is then used as the elevation to which base station temperatures are extrapolated for the calculation of zonal degree days. This area elevation curve and zonal mean hypsometric elevation can also be derived from Digital Elevation Model (DEM) by using the spatial analysis capabilities provided in a Geographical Information Systems (GIS). For the Langtang River basin, the basin and elevation zone areas, elevation ranges, and mean hypsometric elevations for each of nine zones are computed and listed in Table 1 and elevation zones are delineated in equal intervals of 400 m.

(ii) Model variables

(1) Temperature and number of degree-day*:* In SRM the number of degree-day is expressed in the form of temperature. Temperature is a comprehensive index for calculating snowmelt. Moreover, temperature is a routine meteorological observation and easy to acquire, extrapolate and forecast. In order to compute the daily snowmelt depth, the average number of degree-day for each elevation zone is computed as:

$$\Delta T = \gamma.\left(h_{st} - \overline{h}\right).\frac{1}{100} \text{..........................(4)}$$

Where γ is temperature lapse rate; h_{st} is altitude of the temperature base station; h is mean hypsometric elevation for a giver zone. The lapse late in this research is taken as 0.53 °C/100m (Kayastha et al., 2005).

(2) Precipitation: During the snow melt season, precipitation usually occurs in two forms, rain or snow. A critical temperature in SRM is adopted to decide whether a precipitation event will be as rain or snow. When temperature is higher than critical temperature, the precipitation is determined to be rain; otherwise, the precipitation is determined to be snow. The precipitation increases with altitude is usually true mountain areas in Nepal Himalayas (Higuchi et al., 1982). According to Seko, (1987), there is 1.3 times greater precipitation at 5000 m than that at elevation 4000 m which is used for the spatial distribution of the precipitation with in different elevation zone.

$$P_{j,n} = P_{BH,n} \qquad \text{For } h_j < 4000 \text{ m}$$

$$P_{j.n} = P_{BH,n}\left[1 + 0.0003\left(h_j - 4000\right)\right] \text{ For, } 4000\text{m} \leq h_j \leq 5000 \text{ m}$$

$$P_{j.n} = 1.3.P_{BH.n} \text{For } h_j > 5000m$$

Where P_j is precipitation at hypsometric elevation h_j of the zone j, $P_{BH,n}$ is the precipitation at base station in the nth day.

(3) Snow Covered Area (SCA): It is a typical feature of mountain basins that the areal extent of snow cover gradually decreases as the snowmelt season progresses. In this study, the information on SCA is obtained from the MODIS daily product and these images were processed with the MRT tool. Then the snow cover area is calculated with the help of ARC Map 9.3. For the calculation of SCA in each zone, first elevation zones with an equidistance of 400 m are derived from basin's DEM, resulting in a map layer of elevation zones. Step two overlay the map layer of elevation zones on the map layer of snow cover. The result of this process is the snow coverage per elevation zone.

(iii) Model parameters

(1) Runoff coefficient: The SRM accepts separate values of runoff coefficient for snow and rain, because runoff coefficient is usually different for snowmelt and for rainfall. For the Langtang River basin, the runoff coefficients of snow and rainfall are determined from the basin characteristics. The adjustment of runoff coefficient is always required in the initial stage of model simulation, especially when a runoff simulation is not at once successful. In this study the runoff coefficient is treated as the parameter to be calibrated.

(2) Degree-day factor: The degree-day factor in SRM is a key parameter for calculating snowmelt expressed in depth of water:

$$M = a \cdot T \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where, M is snowmelt in depth of water (cm); a is degree-day factor; and T is number of degree-days. The degree day factors for snow and ice ablation used in this research are 7.0 and 8.0 mm $d^{-1}°C^{-1}$ respectively at the altitude up to 5000 m a.s.l. And above 5000 m a.s.l the factors are 10.5 and 9.5 mm $d^{-1}°C^{-1}$ are used respectively from Kayastha et al. (2005).

(3) Critical temperature: The critical temperature is an average value of temperature used in SRM to determine whether the precipitation is rain or snow. Critical temperature is usually higher than freezing point and close to 0°C as snow melt season progresses. The estimation of critical temperature for determination of snowfall amount during precipitation events is carried out using the relation obtained on glacier AX010, east Nepal. The relation was obtained by plotting calculated monthly mean air temperature (Kayastha et al., 2005).

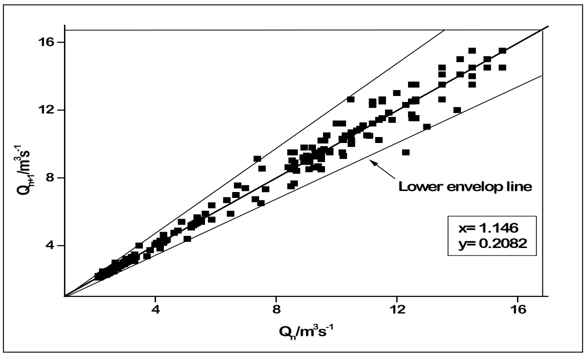

Figure 3: Recession flow plot Qn vs. Qn+1 for Langtang River basin

(4) Rainfall contributing area: Rainfall contributing area is a parameter used in SRM to determine whether rainfall runoff is added to snowmelt runoff only from snow-free area (option 0) or from entire basin or zone area (option 1). If option 0 is set in SRM simulation, rainfall runoff is added to snow melt runoff only from the snow-free area; otherwise if option 1 is set, rainfall runoff is added to snowmelt runoff from the entire basin or zone area. For simplicity, the option 1 is assumed in this research. The melting effect of rain is neglected because the additional heat supplied by the liquid precipitation is considered to be small (Wilson, 1941).

(5) The recession coefficient: It is an important model parameter since (1-*k*) is the proportion of the daily melt-water of snow contributing to the daily runoff. Recession coefficient can be obtained by the analysis of historical discharge data according to the equation (6)

$$k_{n+1}=x.Q_n^{-y}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Where, Q_n is discharge on day n, x and y are two constant. For the determination of x and y, daily discharge on a given day, Q_n is plotted against the value on the following day, Q_{n+1}. As illustrated in Figure 3. In this study, the lower envelop line of all points is considered to indicate the k value. Based on the relation $k = Q_{n+1}/Q_n$, it can be derived that $k_1 = 0.937$ for $Q_1 = 2.47\ \frac{m^3}{s}$ and $k_2 = 0.723$ for $Q_2 = 9.12\ \frac{m^3}{s}$ According to the equation (7) it follows, $x = 1.146$ and $y = 0.2082$, the recession equation for the Langtang River using the lower envelop line thus becomes

$$k_{n+1}=1.146Q_n^{-0.2082} \quad \text{……………………} \quad (7)$$

4. MODEL CALIBRATION AND VALIDATION

Model is calibrated for 2006 with the above parameters. After calibrating the model, model accuracy is evaluated by calculating the coefficient of determination (R^2) and volume difference. Figure 4 shows the calculated and observed hydrographs for the calibration period of 2006. There is a statistically significant relationship between the calculated and observed discharges and the calculated river flow captures the inter-annual variation well. The simulation results are encouraging with and R^2 of 0.91 and a volume difference of 0.1%.

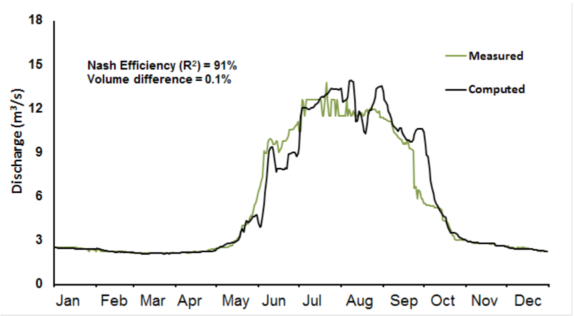

Figure 4: Calculated and Measured Discharge in calibration year (2006)

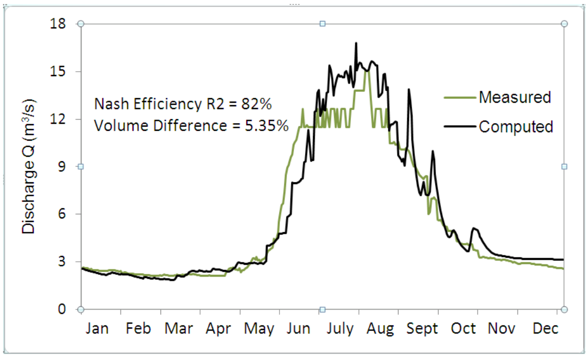

Figure 5: Calculated and measured discharge in validation year (2005)

Since the qualities of data (i.e. snow cover, precipitation and temperature) are good in the year 2005, validation is done in this year. The calculated and observed discharges matched quite well in the validation year too with the R^2 and volume difference of 0.82 and 5.35%, respectively as shown in Figure 5. Few stream flow peaks could not be generated in calculated runoff, which is possibly due to sudden release of stored water at some location in the glacier body, and such events are clearly identified because they are not supported by climate condition (Singh et al., 2008).

In validation year the volume difference is higher than in calibration year. This higher volume difference in validation year might be due to the following reasons:

i) The measured discharge in the year 2005 is 173.8 Million meter cube (Mm^3) which is more than in year 2006 (i.e.171.2 Mm^3).

ii) Precipitation in base year (2006) was 10.3% less than in the validation year i.e. 2005.

5. CONTRIBUTION OF SNOWMELT IN STREAM FLOW

The contribution of snowmelt in stream flow is still considerable though there is high

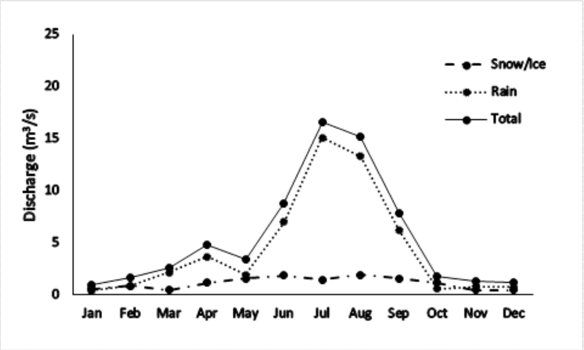

Figure 6: Contribution of Snow melt in Stream flow in 2006

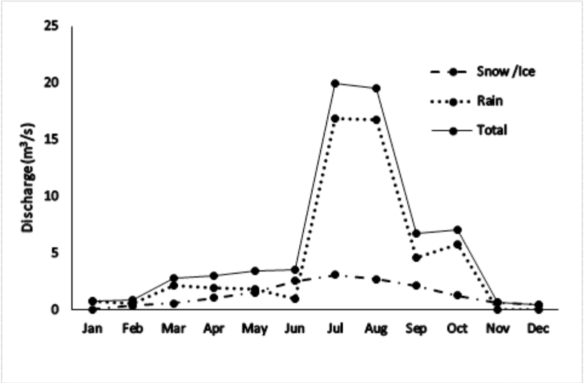

Figure 7: Contribution of Snowmelt in stream flow in 2005

precipitation (320.1 M m^3) than the runoff (171.2 M m^3). From the calculation it is found that, snowmelt contribution in stream flow in winter season is 31.5% while 17.7% in summer season and altogether 19.4% of contribution to the annual flow (Figure 6) in year 2006. The low snowmelt contribution in January is because of low temperature recorded during that period i.e. -0.37 ^{0}C which is comparatively lower than the average temperature of other months.

Similarly in year 2005 the contribution of snowmelt in stream flow is 23.9% in the annual flow with 36.6% in winter and 24.47% summer season (Figure7). High snowmelt contribution in validation year (2005) is due to high average daily temperature and more snow coverage in year 2005. This is also justified by more runoff in year 2005 than in 2006.

6. IMPACT OF CLIMATE CHANGE

In addition to model calibration and validation, we also carried out several experimental runs. After validation of the model in the year 2005, SRM is used to study the change in snowmelt runoff component in river discharge by increasing the temperature by 1-3 °C. The calculated snowmelt contribution in stream flow for 2006 i.e. calibration year is used as reference for the present climate.

From the calculation, model predicts that by increasing 1°C temperature, snowmelt contribution in stream flow approximately increases at the rate of 4% in the annual, 2% in winter and 5% in summer, respectively. Increasing snowmelt contribution in stream flow, due to increase in temperature by 1-3 °C are shown in Table 2. From this analysis it is clear that, the increasing temperature have significant impacts on river discharge of glacierized basin due to increase in snow and glacier melt. Similar study was also carried out by Silpakar et al., (2009) in Tamakoshi basin of Nepal. They found that by increasing average temperature of 1 °C, annual snowmelt contribution in river discharge is increased by 3%.

Table 2: Impact of climate change in snowmelt contribution in stream flow

Season/Period	Present	T+1°C	T+2°C	T+3°C
Winter Season	35%	37%	38%	44%
Summer Season	18%	23%	27%	32%
Annual	19%	23%	28%	33%

Table 3 shows the impact of increasing temperature on river runoff volume. It is estimated that by increasing temperature of 1°C, river runoff volume approximately increases at the rate of 2% in winter, 6% in summer and 5%

Table 3: Impact of increasing temperature on runoff volume

Season	Measured	Present	T+1˚C		T+2˚C		T+3˚C	
	M m^3	M m^3	M m^3	Increase in%	M m^3	Increase in%	M m^3	Increase in%
Winter	34.2	34.6	35.2	2%	36.3	4%	37.7	8%
Summer	137.0	138.8	147.0	6%	155.6	11%	167.9	17%
Annual	171.2	173.4	182.2	5%	192.0	10%	205.6	16%

in annual, respectively. The main factor for such increase in snowmelt contribution and river runoff volume is because of melting of snow and glacier in the basin. The changes in discharge with different temperature scenarios in summer winter and annually are given in Table 3.

7. CONCLUSION

The result shows that the SRM can be well applied in rugged and remote Himalayan catchment like Langtang River basin with limited data. The study area is glacierized basin with more than 50% annual snow coverage. The average discharge for the year 2005 and 2006 are 5.5 m^3/s and 5.3 m^3/s, respectively. The average contribution of snow and glacier melt in 2005 and 2006 on stream flow are found 33.9% in winter, 20.8% in summer and 21.5% annually. From this study, it is found that the snow and glacier melt contribution in stream flow increases approximately at rate of 2% in winter, 5% in summer and 4% in annual flow per 1°C temperature rise. This study shows an extensive analysis of a glacierized catchment in the central Himalayas but the results are not representative for the entire Himalayas. To arrive at a comprehensive assessment on how climate change is affecting the hydrology of the Himalayas it is recommendable to perform this analysis in reference catchments covering the east–west and north–south gradient in climatology and glacier and hydrological dynamics. This study demonstrates that the impact of climate change (increasing temperature) in river discharge is significant. Hence, the outputs of this study are important guidance for water resources managers to make and implement appropriate strategy for water resources management and hydropower development. It is also useful tool for adoptive planning i.e. more and efficient use of winter flow and mitigative and preventive measure for high flow periods.

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