Application of the Snowmelt Runoff Model in the Salang River Basin, Afghanistan Using MODIS Satellite Data

Hedayatullah Arian[1,2], Rijan B. Kayastha[1], Bikas C. Bhattarai[1], Ahuti Shrestha[1], Hafizullah Rasouli [1,3] Richard Armstrong[4]

[1] *Himalayan Cryosphere, Climate and Disaster Research Centre, Department of Environmental Science and Engineering, School of Science, Kathmandu University, Dhulikhel, Nepal*

[2] *Department of Hydro-Meteorology, Faculty of Geosciences, Kabul University, Kabul, Afghanistan*

[3] *Department of Geology, Faculty of Geosciences, Kabul University, Kabul, Afghanistan*

[4] *National Snow and Ice Data Centre, The University of Colorado, Boulder, USA*

ABSTRACT

This study is carried out on the Salang River basin, which is located at the northern part of the Kabul River basin, and in the south facing slope of the Hindu Kush Mountains. The basin drains through the Salang River, which is one of the tributaries of the Panjshir River. The basin covers an area of 485.9km2 with a minimum elevation of 1653 m a. s. l. and a maximum elevation of 4770 m a. s. l. The Salang River sustains a substantial flow of water in summer months due to the melting of snow. In this study, we estimate daily discharge of Salang River from 2009 to 2011 using the Snowmelt Runoff Model (SRM, Version 1.12, 2009), originally developed by J. Martinec in 1975. The model uses daily observed precipitation, air temperature and snow cover data as input variables from which discharge is computed. The model is calibrated for the year 2009 and validated for 2010 and 2011. The observed and calculated annual average discharges for the calibration year 2009 are 11.57m^3s^{-1} and 10.73m^3s^{-1}, respectively. Similarly, the observed and calculated annual average discharges for the validation year 2010 are 11.55m^3s^{-1} and 10.07m^3s^{-1}, respectively and for 2011, the discharges are 9.05 m^3 s-1 and 9.6m^3s^{-1}, respectively. The model is also tested by changing temperature and precipitation for the year 2009. With an increase of 1°C in temperature and 10% in precipitation, the increases in discharge for winter, summer and annually are 21.8%, 13.5% and 14.8%, respectively. With an increase of 2°C in temperature and 20% in precipitation, the increases are 48.5%, 43.3% and 44.1%, respectively. The results obtained suggest that the SRM can be used as a promising tool to estimate the river discharge of the snow fed mountainous river basins of Afghanistan and to study the impact of climate change on river flow pattern of such basins.

Keywords: *Snowmelt Runoff Model (SRM), Salang River basin, snowmelt, river discharge*

1. INTRODUCTION

Afghanistan is a country dominated by a dry climate with most of the area represented by arid land. The population of this country mostly uses mountain fed river water for irrigation, hydropower, and drinking water purposes. The

effect of global climate change on hydrologic systems, especially on mountain snow and glacier melt, can modify the timing and amount of runoff in mountainous watersheds. Therefore, accurate stream flow simulation and forecast is of great importance to water resources management and planning (Abudu et al., 2010).

The high mountain snow and glaciers of Afghanistan are at high risk due to the climate change phenomenon. In the summer season, there is high snow melt and retreat of snow cover. The great amount of this melt water reliably occurs at this particular time of the year. To minimize the risk and loss from floods caused by rapid snow and glacier melt, accurate forecasting is essential (Li and Williams, 2008). However, 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). In addition potential impacts of climate change on stream-flow regimes can be evaluated if valid snow-glacier models are available (Hong and Guodong, 2003).

There are three methods to estimate snow melt runoff: (a) degree day method, (b) energy budget method, and (c) combination method. Of these three methods, the degree day method has the most application, because of the simplicity and accuracy (Raghunath, 2006). The Snowmelt Runoff Model (SRM) also referred as the "Martinec Model" or "Martinec-Rango Model" originally developed by Martinec (1975) in small European basins. This model is based on the degree day model and is designed to simulate and forecast the daily stream flow in mountain basins where snowmelt is a major runoff factor.

SRM also successfully underwent tests by the World Meteorological Organization (WMO) with regard to runoff simulation (WMO, 1986) and to simulated conditions of real time runoff forecasts (WMO, 1992). The SRM with the progressive use of remote sensing data for snow cover is widely applied in practice by various agencies, institutes and universities in different parts of the world (Martinec et al., 1983). SRM or variations of it have been applied in over 100 basins in 25 countries around the world with basin sizes varying from <1 to 120,000km2 (Seidel and Martinec, 2004). With input of climatic variables and parameter selection methods, SRM has a potential in forecasting stream flow and evaluating the effects of climate change on runoff in mountainous watersheds, especially data-scarce watersheds in high-elevation regions. Therefore, we use this SRM model in Salang River basin having limited data.

2. STUDY AREA

The Salang River basin is located at the northern part of the Kabul River basin and in the south facing slope of the Hindu Kush Mountains. It lies between the Panjshir and Ghorband Valleys, which drain water from the central Hindu Kush Mountains (Favre and Kamal, 2004). It

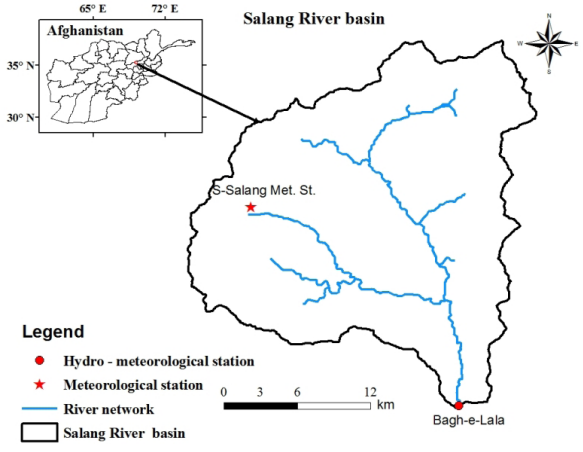

Figure 1 : Location map of Salang River basin, Afghanistan.

covers a total area of 485.9km^2 and is situated between latitude 35.7°N and 35.25°N and longitude 69.0°E and 69.45°E. The minimum and maximum elevation of the basin ranges from 1653ma.s.l. to 4770ma.s.l., respectively, with an average elevation of 2953ma.s.l. The basin has one hydro-meteorological station and one meteorological station, namely, Bagh–e–ala hydro-meteorological station (1653ma.s.l.) and South Salang meteorological station (3172ma.s.l.). Figure 1 shows the location of the major river systems in the basin and the hydro-meteorological stations present in the basin.

The annual mean temperature recorded in Bagh–e–Lala hydro-meteorological station from January 2009 to May 2013 was 14.8°C with a maximum monthly mean temperature of 26.8°C in August 2009 and a minimum monthly mean temperature of -1.9°C in February 2012. Similarly, the annual total precipitation for the year 2009 was 587.4 mm. The annual mean discharge recorded in this station from January 2009 to December 2012 ranged from 9m^{3}s^{-1} to 12m^{3}s^{-1}, with a maximum monthly mean discharge of 41m^{3}s^{-1} recorded in April 2012 and a minimum monthly mean discharge of 1m^3 s^{-1} in January 2012.

3. DATA COLLECTION AND METHODS

3.1 Data Collection

3.1.1 Basin area and elevation distribution

The Digital Elevation Model (DEM) downloaded from *http://gdex.cr.usgs.gov/gdex/*, with horizontal resolution of 30 × 30 m obtained from the United States Geological Survey (USGS) is used in this study. ArcMap 9.3 is used to calculate the area and the area-elevation distribution of the basin. As the physical environment varies drastically with increasing altitudes, the basin's great elevation range is divided into several zones to better describe the physical environment (Tahir et al., 2011). Hence, the study area is divided into 16 elevation zones, each with a vertical difference of 200m (Table 1). The area-elevation curve (Figure 2) is used to determine the zonal

Table 1 Elevation zone, elevation range, hypsometric mean elevation and zonal area for the 16 elevation zones of Salang River basin

Elevation zone	Elevation range (m a.s.l.)	Hypsometric mean elevation (m a.s.l.)	Zonal area (km^2)
1	1653 - 1853	1748	3.5
2	1853 - 2053	1940	11.8
3	2053 - 2253	2150	26.8
4	2253 - 2453	2355	46.4
5	2453 - 2653	2540	57.2
6	2653 - 2853	2738	67.0
7	2853 - 3053	2955	63.1
8	3053 - 3253	3215	51.5
9	3253 - 3453	3370	45.2
10	3453 - 3653	3583	38.5
11	3653 - 3853	3783	29.7
12	3853 - 4053	3978	21.2
13	4053 - 4253	4178	15.8
14	4253 - 4453	4404	5.8
15	4453 - 4653	4620	1.9
16	4653 - 4770	4711	0.3

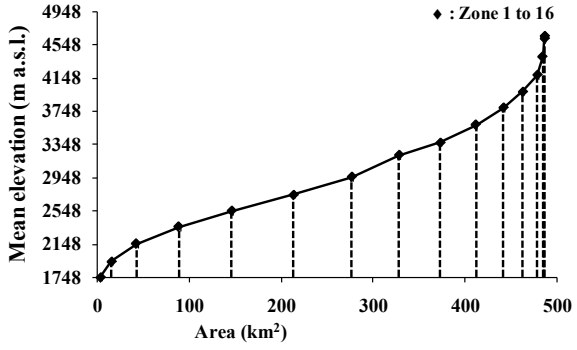

Figure 2 : Area – elevation curve of Salang River basin

mean hypsometric elevations. Temperature and precipitation of each elevation zone are extrapolated for the calculation of zonal degree-days and zonal precipitation.

3.1.2 Temperature

In order to compute the daily snowmelt from the SRM, the number of degree-days must be determined from mean temperature data for each zone. In this study, the temperature obtained from Bagh–e–Lala hydro-meteorological station is used to estimate the mean temperature corresponding to the mean elevation of each zone using the temperature lapse rate. Due to the lack of historical data, the temperature lapse rate of Panjshir River basin situated nearby to the Salang River basin is used, which is calculated from the temperature data of two hydro-meteorological stations: Gul Bahar hydro-meteorological station (1605 m a.s.l.) and Du Ab hydro-meteorological station (2065 m a.s.l). The calculated average lapse rate of 0.91 ˚C per 100 m is used.

3.1.3 Precipitation

Extrapolating precipitation is particularly difficult in mountainous watersheds because of the lack of weather stations in the watershed and local factors, such as topography, which strongly influence the spatial distribution. In this study, precipitation recorded at Bagh–e–Lala hydro-meteorological station and South Salang meteorological station are used to calculate the precipitation gradient, which is found to be 1.7% increase per 100 m elevation rise. The calculated precipitation gradient is then used to estimate the precipitation at each elevation zone.

Precipitation usually occurs in two forms, i.e. rain or snow, which can be determined by a critical temperature in this model. When temperature is higher than the critical temperature, the precipitation is determined to be rain; otherwise, the precipitation is determined to be snow. The distinction between rain and snow is important in the SRM because the rain contribution to runoff occurs at about the same time as when rain occurs, whereas snow contribution to runoff is usually delayed until conditions for melt occur.

3.1.4 Snow Cover

Satellite-derived snow covered area is the best routinely available input for SRM, especially in remote and data-scarce mountain watersheds. Compared with other satellite platforms, the Moderate Resolution Imaging Spectro-radiometer (MODIS) derived snow cover area is the most suitable for use in snowmelt models because of a higher spatial resolution (500 m) and location accuracy (Tekeli et al., 2005). In this study, MODIS/Terra Snow Cover 8 – Day L3 Global 500 m (MOD10A2) data set is downloaded from National Aeronautics and Space Administration's Earth Observing System Data and Information System. It is considered to be one of the best resources for remotely sensed information on the distribution of snow covered area over eight-day periods (Hall et al., 2002).

Although MODIS provides both daily and 8-day snow cover products, the 8 – day maximum snow-cover extent product is used to minimize cloud cover effect. The data sets thus obtained are processed through a MODIS Re-projection Tool (MRT) (Dwyer and Schmidt, 2006) with the WGS 1984 UTM Zone 42N projection system

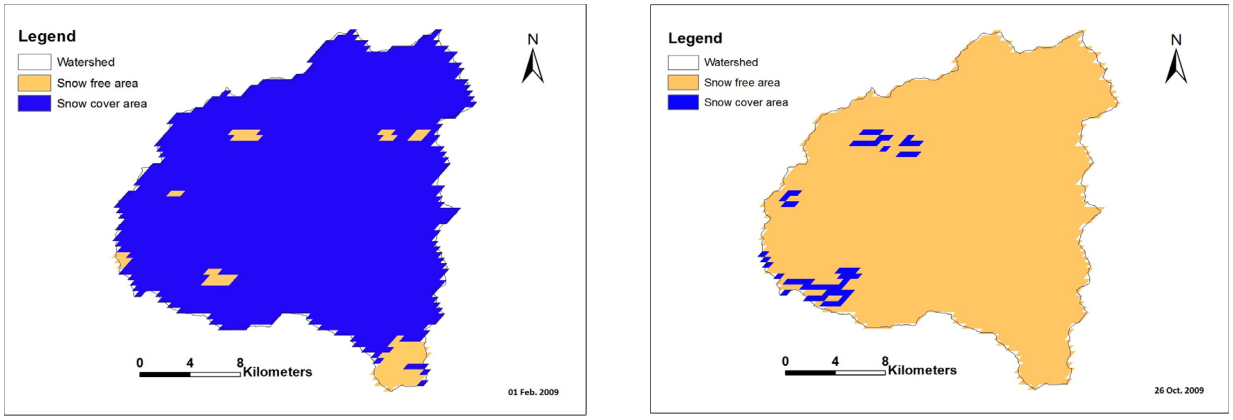

Figure 3 : Snow covered area in 2009

to get the 8 – day maximum snow covers for the Salang River basin, which are then interpolated to get daily snow cover data required to run the SRM. The snow covered area is calculated for the sixteen different altitudinal zones for snowmelt runoff modeling. We calculate the percentage of annual average snow covered area in 2009, 2010 and 2011 as 47%, 30% and 41%, respectively. The snow covered area for 2009 is shown in Figure 3.

3.2 Methods

3.2.1 Snowmelt Runoff Model (SRM)

The SRM is one of the very few models in the world today that require remote sensing derived snow cover as model input. Owing to its simple data requirements and use of remote sensing to provide snow cover information, SRM is ideal for use in data sparse regions, particularly in remote and inaccessible high mountain watersheds (Hong and Guodong, 2003).

Daily temperature and precipitation data along with daily snow cover are the three basic input variables required for the operation of the model; and temperature lapse rate, runoff coefficient (for rain and snow), degree-day factor, recession coefficient, critical temperature, rainfall-contributing area, and lag time are the eight model parameters (Table 2).

In SRM, the runoff produced from snowmelt and rainfall is computed, superimposed on the calculated recession flow and transformed into

Table 2

Parameters	Description	Value
ϒ	Temperature lapse rate (°C per 100 m)	0.91 °C per 100 m
T_{Crit}	Critical temperature (°C)	0 °C
a_n	Degree day factor (cm $°C^{-1}day^{-1}$)	0.9 cm $°C^{-1}$ day^{-1}
Lag time	Time lag (hour)	6 hour
Cs	Runoff coefficient for snow	0.34
Cr	Runoff coefficient for rain	0.15
X	x – coefficient	1.2
Y	y – coefficient	0.1
RCA	Rainfall contributing area (option)	1

daily discharge from the basin according to the equation (1) given by Martinec et al. (2008):

$$Q_{n+1} = [C_{Sn} a_n (T_n + \Delta T_n) S_n + C_{Rn} P_n] + \frac{A.1000}{86400}(1 - K_{n+1}) + Q_n K_{n+1} \quad \ldots\ldots\ldots\ldots (1)$$

where Q is average daily discharge ($m^3 s^{-1}$); C_S and C_R are the runoff coefficients that expresses the losses to discharge (ratio of volume of snowmelt (rain) contributing to runoff to the total volume of snowmelt (rain)); *a* is degree-day factor (cm $^oC^{-1}$ d^{-1}); T is number of degree days (^oC d); ΔT is the adjustment by temperature lapse rate (^oC d); S is ratio of the snow cover to the total area; P is the precipitation contributing to runoff (cm); T_{CRIT} is the critical temperature that determines whether this contribution is rainfall and immediate runoff. If precipitation is determined by T_{CRIT} to be new snow, it is kept on storage over the hitherto snow free area until melting conditions occur; A is area of the basin or zone (km^2); n is sequence of days during the discharge computation period; $\frac{10000}{86400}$ = conversion from runoff depth (cmkm2 d^{-1}) to discharge ($m^3 s^{-1}$). K is a recession coefficient indicating the decline of discharge in the period without snowmelt or rainfall, $K = \frac{Q_{m+1}}{Q_m}$ (m, m+1 are the sequence of days during a true recession flow period). The recession coefficient 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 based on the following equation:

$$K_{n+1} = x.Q_n^{-y} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where Q_n is discharge on day *n*; *x* and *y* are two constants. For the determination of *x* and *y*,

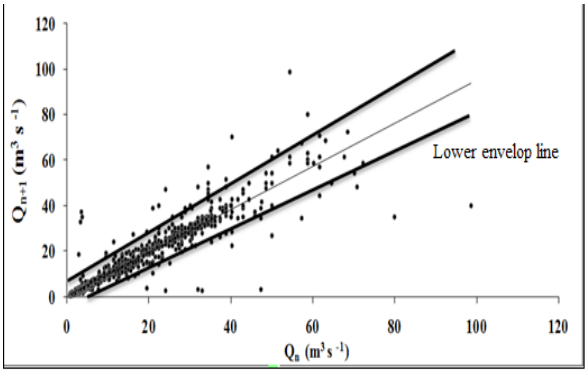

Figure 4 : Recession flow plot Qnvs Q n+1 forSalang River basin

daily discharge on a given day, Q_n, is plotted against the value on the following day, Q_{n+1}. Figure 4 illustrates the plotting of Q_n and Q_{n+1} for the *K* value of the Salang River. For this basin, the lower envelop line, which passes through the lower discharge values, is used to calculate x and y. The lowest and highest values of Qn that lie along the lower envelop line are used for the determination of Q_1 and Q_2. Based on the relation $K = \frac{Q_{n+1}}{Q_n}$, it is derived that k_1=1.23 for Q_1=72.3 $m^3 s^{-1}$ and K_2= 1.73 for Q_2=12.2$m^3 s^{-1}$. Using these values in equation (2), the x and y are calculated which is given in Table 2. Equation (1) is for a time lag between the daily temperatures cycle and the resulting discharge cycle of 18 hours. Various lag times can be introduced by a sub-routine and for this basin; a lag time of 6 hrs is used for simulation which can be fed into the model

Another parameter called Rainfall Contribution Area (RCA) is used in this model to know whether runoff from rainfall is added to runoff due to snowmelt only from the snow free area (option 0) or from the entire basin or zonal area (option 1). In the present study option 1 is used for RCA, which means the runoff from rainfall is added to runoff due to snowmelt from the entire basin as shown in Table 2.

3.3 Evaluation of model performance

The computed and measured hydrographs show at the first glance whether the simulation is successful or not. In addition, SRM uses two accuracy criteria to evaluate model performance, namely, the coefficient of determination (R^2), and the volume difference D_v (Martinec and Rango, 1989). The R^2 is computed as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q'_i)^2}{\sum_{i=1}^{n}(Q_i - \bar{Q})^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where, Q_i is measured daily discharge (m^3s^{-1}), Q'_i is simulated daily discharge ($m^3 s^{-1}$), $\bar{Q}$ is average measured discharge of the given year or snowmelt season ($m^3 s^{-1}$) and n is the number of daily discharge values. Similarly, the volume difference (D_v) in percentage is computed as:

$$D_v = \frac{V_R - V'_R}{V_R} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where V_R is the measured runoff volume (m^3) and V'_R is the simulated runoff volume.

4. RESULTS AND DISCUSSION

4.1 Model calibration and validation

In this study, the model has been calibrated for 2009 due to its good hydro-meteorological records and validated for 2010 and 2011. Parameter adjustment is carried out manually by using a trial-and-error method. The values of the main parameters for SRM in the Salang River basin are listed in Table 1. The measured and computed discharge hydrographs for the calibration year 2009 are shown in Figure 5. The observed and calculated annual average discharges for 2009 are 11.57 $m^3 s^{-1}$ and 10.73m^3s^{-1}, respectively and the results are good with an R^2 value and D_v of 0.87 and 7.18%, respectively.

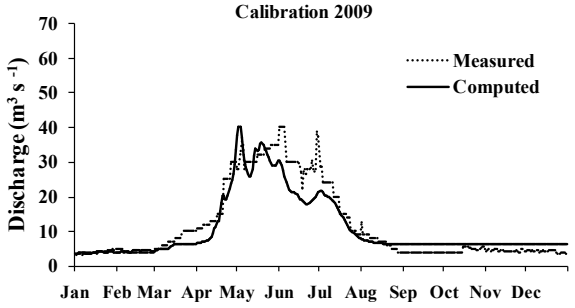

Figure 5 : Observed and computed discharges of Salang River basin (2009)

After getting good results from the calibration period, the model is validated for 2010 and 2011 as shown in Figure 6. The observed and calculated annual average discharges for 2010 are 11.55 $m^3 s^{-1}$and 10.07 $m^3 s^{-1}$, respectively and the resulting R^2 and D_v values are 0.43 and 12.8%, respectively. Similarly, for 2011 the observed and calculated annual average discharges are 9.05 $m^3 s^{-1}$ and 9.6 $m^3 s^{-1}$, respectively and the resulting R^2 and D_v values are 0.69 and -6.9%, respectively.

In our study, the model did not simulate the peak stream flows well in summer months. The relatively low R^2 values and the high volume differences in the validation years obtained in our study are attributed to the underestimates of those peak flows and contribution of ground water in the hydrographs. As there is very little or no precipitation during the summer season in this basin, the peaks obtained in the observed discharge hydrographs may be due to the sudden hydrologic events such as flash

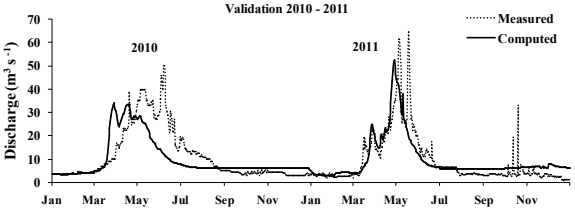

Figure 6 : Observed and computed discharges of Salang River basin (2010 - 2011)

floods that could not be simulated by the model. Hence, considering the limited measurements available, the performance of the SRM is found to be satisfactory.

4.2 Impact of change in temperature and precipitation on river discharge

It is very important to study the changing pattern of river flow in the changed temperature and precipitation scenario, not only for future planning of new water resources projects but to maintain and operate the existing water schemes. The snow-fed sources of water are extremely sensitive to the changing precipitation and temperature parameters over the time. Hence, after good calibration of the model, it is also used to study the change in stream flow due to change in temperature and precipitation (Figure 7). Four climate scenarios are considered for discharge simulation, namely i) increase in 1°C temperature and 10% precipitation, ii) increase in 2°C temperature and 20% precipitation, iii) decrease in 1°C temperature and 10% precipitation, and iv) decrease in 2°C temperature and 20% precipitation. However, the snow cover area for this analysis is kept constant in all these scenarios due to difficulty in predicting future snow cover data.

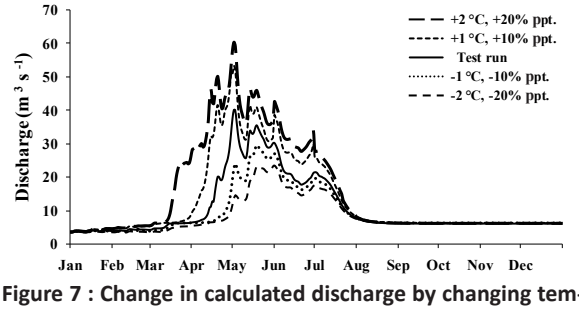

Figure 7 : Change in calculated discharge by changing temperature and precipitation (2009)

From the result shown in Figure 6, among these four scenarios, the increase in discharge is highest when the temperature and precipitation is increased by 2°C and 20%, respectively, whereas the decrease in discharge is more when the temperature and precipitation is decreased by 2°C and 20%, respectively. With the increase of 1°C temperature and 10% precipitation, the annual discharge is increased by 14.8%, whereas with increase of 2°C temperature and 20% precipitation, annual discharge is increased by 44.1%. Similarly, the results for other climate scenarios are shown in Table 3 and Figure 8.

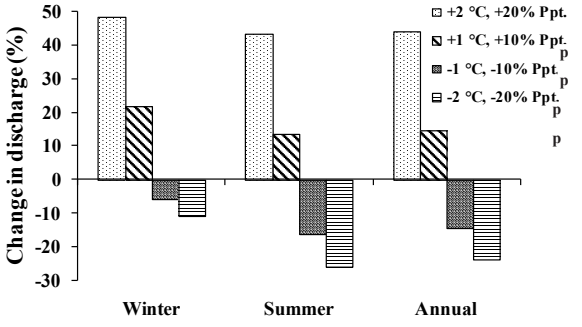

Figure 8 : Percentage change in discharge for different climate scenarios with the test run (2009)

From the analysis, we found that the stream flow in winter season is likely to increase more with the increased temperature and precipitation, whereas the stream flow in summer season is likely to decrease more with the decreased temperature and precipitation. However, the increase of temperature will melt snow earlier only if precipitation remains the same.

Table 3

	-1 °C, -10% Ppt.	-2 °C, -20% Ppt.	+1 °C, +10% Ppt.	+2 °C, +20% Ppt.
Winter	-5.8	-10.9	21.8	48.5
Summer	-16.2	-26.0	13.5	43.3
Annual	-14.6	-23.6	14.8	44.1

5. CONCLUSION

In this study, the SRM is used to estimate discharge from the Salang River basin, Afghanistan. The model is calibrated for 2009 and validated in 2010 and 2011. The observed and calculated annual average discharges for the calibration year are 11.57 $m^3 s^{-1}$ and 10.73m^3s^{-1}, respectively with R^2 and D_v values of 0.87 and 7.18%, respectively. The observed and calculated annual average discharges for the validation year 2010 are 11.55 $m^3 s^{-1}$and 10.07 $m^3 s^{-1}$, respectively and the resulting R^2 and D_v values are 0.43 and 12.8%, respectively. Similarly, for 2011, the observed and calculated annual average discharges are 9.05$m^3 s^{-1}$ and 9.6$m^3 s^{-1}$, respectively and the resulting R^2 value and D_v are 0.69 and -6.9%. The model shows good results in the calibration year, however, it could not simulate the peak stream flows well in the validation years, thus the R^2 values in these years are relatively lower. The model also estimates discharge of the basin by changing temperature and precipitation. When the temperature is increased by 1 ^oC and precipitation by 10%, the annual discharge will increase by 14.8%. Similarly, when the temperature is increased by 2 ^0C and precipitation by 20%, the increase in annual discharge is by 44.1%. The results obtained suggest that the SRM can be used to estimate the river discharge of snow fed mountainous river basins of Afghanistan.

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