Estimation of Discharge From Upper Kabul River Basin, Afghanistan Using the Snowmelt Runoff Model

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ABSTRACT

In this study, we estimated discharge from Upper Kabul River basin in the Hindu Kush Mountain (Paghman range) in Afghanistan. The Upper Kabul River basin covers an area of 1633.8km2 with a maximum elevation of 4522 m and minimum elevation of 1877 m. The Kabul River is one of the main rivers in Afghanistan and sustains a significant flow of water in summer months due to the melting of snow. In this study, daily discharge from Upper Kabul River basin, west of Kabul basin, for 2009 and 2011 is estimated by using Snowmelt Runoff Model (SRM) (Version 1.12, 2009), originally developed my J. Martinec in 1975. Daily precipitation, air temperature, discharge and snow cover data are used in the model as input variables. We calibrated the model for 2009 and validated in 2011. The observed and calculated annual average discharges in 2009 are 5.7m^3/s and 5.6m^3/s, respectively; and in 2011 are 1.33m^3/s and 1.31m^3/s, respectively. The model results are in good agreement with the measured daily discharges. With an increase of 1°C in temperature and 10% precipitation, the increase in discharge in winter, summer and annually relative to 2009 discharge are 39%, 18.5% and 17.9%, respectively. Similarly, with an increase of 2°C in temperature and 20% in precipitation, modeled discharge increases by 51.2%, 40.8% and 47.3%, respectively. The results obtained suggest that the SRM can be used efficiently for estimating discharge in the snow fed sub-catchment of the Upper Kabul River basin and other mountain basins in Afghanistan.

Keywords: *Snowmelt, Snowmelt Runoff Model, Upper Kabul River basin, MODIS*

1. INTRODUCTION

Afghanistan is dominated by a dry climate with most of the area represented by arid land. Only 20% of the population has access to tap water (Hoben et al., 2009) supplied by authority. The rest directly depends on shallow wells and rivers. Therefore, the population mostly uses snow-fed river water for irrigation, hydropower, and drinking water. Water supply from snow or ice melt represents a major contribution to discharge during the summer months. Consequently, a shortage of snow and ice in mountain regions might have far-reaching economic, ecological and societal implications. Runoff due to snowmelt from mountain regions is important for a sustained water supply (Nestler et al., 2014). Snow is thus an important water resource, because unlike rainfall, it is released gradually in the form of melt water over a long period (Hatta et al., 1995) and provides sustained flow during dry seasons to fulfill the water requirements. The presence of snow in a basin strongly affects the moisture that is stored at the surface and is available for future runoff (Tahir et al., 2011).

The hydrology of mountainous regions is largely dependent on the climatic conditions of the region, as mountains usually receive large amounts of precipitation, which may be stored in the form of snow (e.g. Upper Kabul River basin, Afghanistan). Mountains also represent unique areas for the detection of climatic change and the assessment of climate-related impacts (Beniston, 2003). The complexity and mutual inter-dependency of mountain environmental and socio-economic systems pose significant problems for climate impact studies (Diaz et al., 1997). Climate change is expected to contribute to the increased variability of river runoff due to changes in the timing and intensity of precipitation, as well as the melting of snow. Runoff will initially increase as snowmelts and will then decrease after the snowmelt is completed (Fang & Pomeroy, 2007). The detailed investigation of snow and ice processes or their relevance to climate has taken place only in limited areas of the Himalayan and other high ranges (Dahri et al., 2011). The limited study in the Himalayan and other high ranges indicating the clear gap in knowledge of economic impacts of climate change (Gautam et al., 2013). This knowledge gap persists in the Hindu-Kush of Afghanistan as well.

In this study, the SRM is used for estimating discharge in the context of climate change in mountain catchments (Martinec et al., 1975; Ma et al., 2013). This is complicated due to the large climatic variability and the dynamic response of snowmelt runoff. The SRM is an appropriate tool, for estimating discharge in the region with limited data and successfully tested by the World Meteorological Organization with regard to runoff simulation (WMO, 1986). Snowmelt runoff varies with day-to-day variation in hydro-meteorological conditions of the basin (MacDonald et al., 2009). Therefore, model structure for the forecast of snowmelt on the short-term basis becomes most useful in efficient management and planning of water resources (Dey & Rango, 1989). The SRM requires less data for daily simulation than other hydrological models (Abudu et al., 2012) so it is appropriate to use it in the upper Kabul River basin where there is limited data. This model estimates snow and ice melt and its relative contribution to the basin runoff from daily air temperature and precipitation. The main aim of this study is to simulate the daily discharge from the snow cover area of Upper Kabul River basin in Afghanistan by applying SRM.

2. STUDY AREA

This study is carried out on Upper Kabul River basin (Figure 1) which is also a sub-basin of Kabul River basin and includes the headwaters of it. It starts from 80 km west of Kabul city, from Paghman mountain range (Sanglakh mountains region) and belongs to the Hindu-Kush Mountains range in Afghanistan. Its total basin area is 1630.8km2. The elevation of Tangi

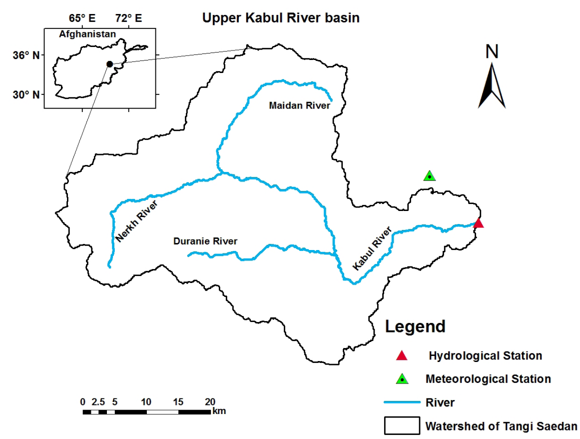

Figure 1: Location map of Upper Kabul River basin, Afghanistan

Saedan hydrological station at Mt. Sanglakh is 1869 m a.s.l.

We used discharge data from the Tangi Saedan hydrological station (34.857° N, 69.077° E). The maximum monthly mean discharge at this station was 34.36 $m^3 s^{-1}$ in April 2012 based on the observed data from June 2008 to September 2013. The annual mean discharge for the year 2009 and 2011 are 5.6 and 1.31 $m^3 s^{-1}$.

Similarly, we used temperature and precipitation data from Qalay Malak station. The observed precipitation data from June 2008 to October 2013 at this station shows a maximum of 147.18 mm in February 2013. Similarly, the maximum and minimum temperature recorded are 23.46 °C (July 2008) and -6.60 °C (February 2012), respectively. For the linear extrapolation of temperature lapse rate, data from 2009 to 2013 of Banda Qargha and Qalay Malak meteorological stations are averaged for each month (Table 2).

3. MODEL DESCRIPTION AND DATA

The SRM is designed to simulate and forecast daily stream flow in mountain basins where snowmelt is a major runoff contributor. Recently, it has also been applied to evaluate the effect of climate change on seasonal snow cover and runoff (Rango et al., 2008).

3.1 Snowmelt Runoff Model (SRM)

In this study, we used Snowmelt Runoff Model (SRM) to simulate the snowmelt runoff in the study basin, as it requires limited data. The SRM model developed by J. Martinec in 1975 is a conceptual, deterministic and degree-day based model that estimates snowmelt as a linear function of average air temperature for periods of a day or longer. The SRM estimates snowmelt, superimposes it on calculated recession flow, and transforms it into daily discharge from the basin using equation (1) given by Martinec et al. (2008):

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

Where, Q_n is discharge on day n ($m^3 s^{-1}$), C_S and C_R refers to runoff coefficient expressing the loss as a ratio for snowmelt and rain, respectively, a_n is degree-day factor (cm °$C^{-1} d^{-1}$) indicating the snowmelt depth resulting from 1 degree-day temperature increase. T is number of degree-days (°C d), ΔT is the adjustment using a temperature lapse rate to extrapolate the temperature from the station to the average hypsometric elevation of the basin or zone (°C d), S is ratio of the snow cover to the total area, and P is precipitation contributing to runoff (cm). A preselected threshold temperature, T_{CRIT}, determines whether the precipitation is rainfall and the contribution to discharge is immediate. If precipitation is determined by T_{CRIT} to be new snow, it is kept as storage over the hitherto snow free area until melting conditions occur, where A is area of the basin or zone (km^2). K is the Recession coefficient indicating the decline of discharge in the period without snowmelt or rainfall, where $K = \frac{Q_{n+1}}{Q_n}$ and n is the sequence of days during the discharge computation period. Equation (1) is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. In this case, the number of degree-days measured on the nth day corresponds to the discharge on the n+1 day. Various lag times can be introduced by a sub-routine, using $\frac{10000}{86400}$ = as the conversion from depth (cmkm2 d^{-1}) to discharge ($m^3 s^{-1}$). In the SRM, T, S and P are variables to be measured each day, while C_S, C_R, the lapse rate to determine ΔT, T_{CRIT}, k and the lag time are parameters which are characteristic for a given basin or, more generally, for a given climate.

3.2 Basin characteristics

Areas of basin and elevation zones are determined by using Digital Elevation Model (DEM) of the study basin. In this study, DEM of 30 m resolution is downloaded from the USGS (http://gdex.cr.usgs.gov/gdex/) and used for differentiating the study area into different elevation zones. The study area is divided into ten elevation zones with an altitude difference of 264 m between each zone (Table 1). The area-elevation curve and zonal mean hypsometric elevation is derived from the DEM (Figure 2).

Table 1. Elevation zone, elevation range, mean elevation and zonal area for the ten elevation zones of the Upper Kabul River basin

Elevation Zone	Elevation range (m a.s.l)	Mean elevation of zone (m a.s.l)	Zonal area (km^2)
A	1877 - 2141	207 9	48.6
B	2141 - 2405	2402	306.8
C	2405 - 2670	2664	352.7
D	2670 - 2934	2929	272.2
E	2934 - 3198	3194	227.5
F	3198 - 3462	3459	183.8
G	3462 - 3726	3722	131.9
H	3726 - 3991	3987	77.6
I	3991 - 4255	4262	26.9
J	4255 - 4519	4422	2.8

Table 2. Calibrated model parameters for 2009

Date	Monthly lapse rate (°C/100m)	T_{CRIT} (°C)	a_n (cm/°C/ day)	Lag Time (hour)	C_s	C_R	RCA	X Coeffi.	Y Coeffi.
Jan	0.359	2	0.9	12	0.129	0.3	1	0.861	0.097
Feb	0.399	2	0.6	12	0.129	0.3	1	0.861	0.097
Mar	0.680	2	0.9	12	0.129	0.3	1	0.861	0.097
Apr	0.705	2	0.9	12	0.129	0.3	1	0.861	0.097
May	0.556	2	0.9	12	0.129	0.3	1	0.861	0.097
Jun	0.574	2	0.12	12	0.129	0.3	1	0.861	0.097
July	0.627	2	0.12	12	0.129	0.3	1	0.861	0.097
Aug	0.495	2	0.12	12	0.129	0.3	1	0.861	0.097
Sep	0.572	2	0.12	12	0.129	0.3	1	0.861	0.097
Oct	0.361	2	0.12	12	0.129	0.3	1	0.861	0.097
Nov	0.260	2	0.12	12	0.129	0.3	1	0.861	0.097
Dec	0.279	2	0.6	12	0.129	0.3	1	0.861	0.097

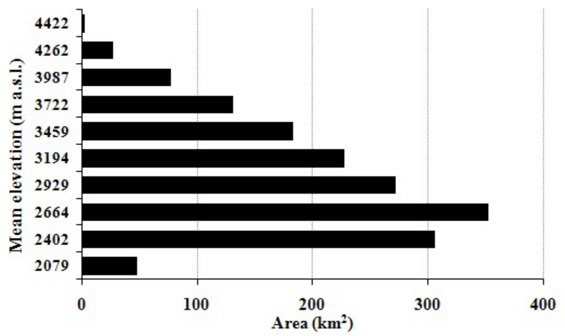

Figure 2: Area-elevation distribution of the Upper Kabul River basin

3.3 Model variables

3.3.1 Temperature and degree-days

The positive degree-days are used to compute snowmelt using mean air temperature. The adjustment value of degree-days for each elevation zone is computed as:

$$\Delta T = \Upsilon . (h_{st} - \bar{h}) . \frac{1}{100} \quad \text{..................(2)}$$

where, ΔT is the difference in temperature at the respective zone, ϒ (°C per 100 m) is temperature lapse rate, h_{st} is the elevation of the base station, and $\bar{h}$ is mean height of the respective zone.

3.3.2 Precipitation

We assume the altitudinal variation of precipitation in this study by increasing precipitation by 20% above 4000 m a.s.l. and using the same precipitation of Qalay Malak station below 4000 m a.s.l. During snowmelt season, precipitation usually occurs in one of two forms, rain or snow. A critical temperature is incorporated to decide whether the precipitation event will be as rain or snow.

3.3.3 Snow covered area

The snow-covered area is an input variable in the SRM. For this research, Moderate Resolution Imaging Spectroradiometer (MODIS) Snow Cover Daily L3 Global Grid containing snow cover data (Hall et al., 2006) in HDF-EOS format along with corresponding metadata are used. MOD10A1 consists of 1200 km by 1200 km tiles of 500 m spatial resolution and daily temporal data gridded in a sinusoidal map projection. We projected the MODIS images using WGS 1984 UTM ZONE 42N. The Upper Kabul River basin area delineated based on the extent of the study basin area and then extracted from this image to assess the percentage of snow cover. We calculated snow-covered area for ten different altitudinal zones. We found that the percentage of annual average snow cover for the study area in 2009 and 2011 were 27% and 15%, respectively. The snow-covered area for 2009 is shown in Figure 3.

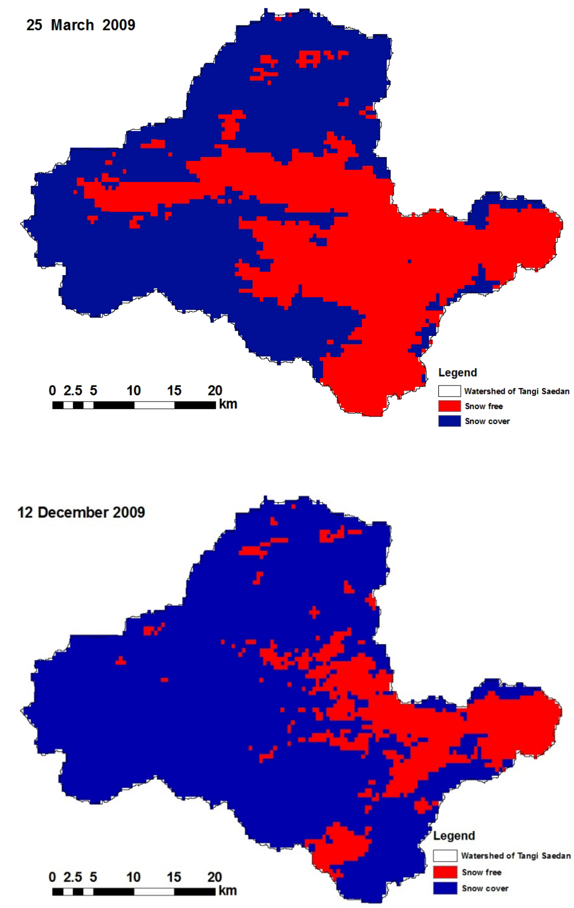

Figure 3: Extremes of Upper Kabul River basin snow covered area in 2009

3.4 Model parameters

3.4.1 Runoff coefficient

The SRM accepts separate values of the runoff coefficient for snow (Cs) and rain (C_R), because the runoff coefficient is usually different for snowmelt and rainfall and this allows the appropriate value to be used. The following equations are used to calculate Cs and Cr:

$$Cs = \frac{\text{Volume of snowmelt contributing to runoff}}{\text{Total volume of snow melt}} \quad \ldots\ldots (3)$$

$$C_R = \frac{\text{Volume of rain fall contributing to runoff}}{\text{Total volume of rain}} \quad \ldots\ldots (4)$$

The calibrated values of Cs and C_R used in this study are shown in Table 2.

3.4.2 Degree-day factor (a)

The degree-day factor in SRM is the key parameter for calculating snowmelt expressed as depth of water. Snowmelt (M) in depth of water (cm day^{-1}) is calculated using the following equation:

$$M = a_n \times T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In this study the value of degree-day factors are taken from Dey et al., (1989). We calibrated degree-day factors, which is given in Table 2.

3.4.3 Critical temperature and temperature lapse rate

Critical temperature is an important parameter in SRM. It is usually higher than the freezing point and diminishes to close to 0^{o}C as the snowmelt season progresses. In this study, we calibrated critical temperature (Table 2).

3.4.4 Rainfall Contributing Area (RCA)

The RCA is a parameter used in SRM to determine whether runoff from rainfall is added to runoff due to snowmelt either from snow free area only (option 0) or from the entire basin or zonal area (option 1). If option 0 is set in SRM simulation, runoff from rainfall is added to runoff due to snowmelt only from the snow free area; otherwise, if option 1 is set, runoff from rainfall is added to runoff due to snowmelt from the entire basin. In the present study option 1 (Table 2) is used for RCA which means the runoff from rainfall is added to runoff due to snowmelt.

3.4.5 Recession coefficient (k)

Recession coefficient (k) is determined through historical discharge data where the observed stream flow on day n+1 is divided by discharge on day n ($k = Q_{n+1}/Q_n$). The SRM uses x and y coefficients to estimate the recession coefficient using Equation 6. The recession coefficient can be obtained by the analysis of historical discharge data as shown in the following equation (Martinec et al., 2008):

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

Where x and y are two constants. 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. For the Upper Kabul River basin the daily discharge plotted is from 2008 to 2013. The lower line of all plotted points is considered to indicate the recession coefficient (k) value. The estimated values of x and y for each month are shown in Table 2. Based on the relation $k = \frac{Q_{n+1}}{Q_n}$, it is derived that $k_1 = 0.553$ for $Q_1 = 12.7\ m^3\ s^{-1}$ and $k_2 = 1$ for $Q_2 = 0.03\ m^3\ s^{-1}$. According to the equation (6), it follows: x = 0.86 and y = 0.097, the recession equation for the Upper Kabul River basin using the lower envelope line is:

$$k_{n+1} = 0.86\ Q_n^{-0.097} \quad \ldots\ldots\ldots\ldots\ldots (7)$$

4. RESULTS AND DISCUSSION

4.1 Model calibration and validation

The SRM is calibrated for 2009 with the above parameters. After calibrating the model, model accuracy is evaluated by calculating the coefficient of determination (R^2) and volume difference. Figure 4a shows the calculated and observed hydrographs for the calibration period of 2009. There is a statistically significant relationship between the calculated (5.6 $m^3 s^{-1}$) and the observed (5.7 $m^3 s^{-1}$) discharges, and the calculated river flow captures the inter-annual variations well. The simulation results are encouraging with R^2 of 0.904 and a volume difference of 0.5%. Since the quality of the hydrological and meteorological data is not good due to missing data in 2010, validation is carried out for 2011 (Figure 4b). The calculated (1.31 $m^3 s^{-1}$) and the observed (1.33 $m^3 s^{-1}$) discharges matched quite well in the validation year too with the R^2 and volume difference

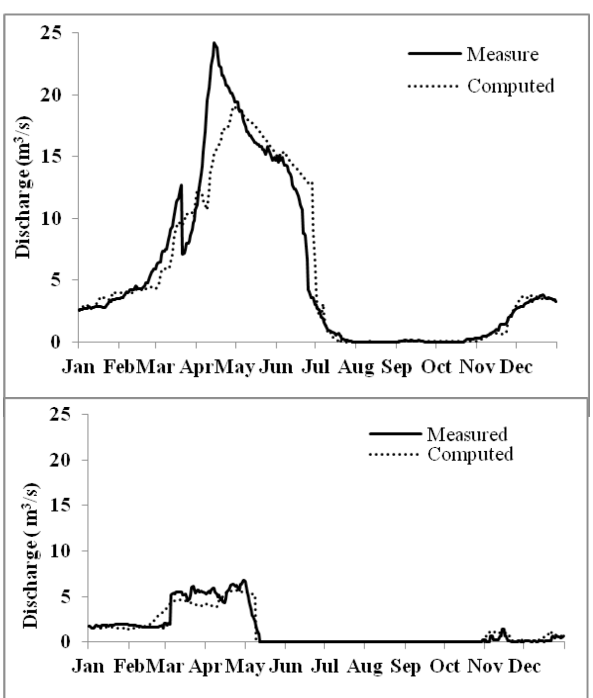

Figure 4 a): Distribution of discharge calculated from SRM for calibration year 2009 and b) validation year 2011

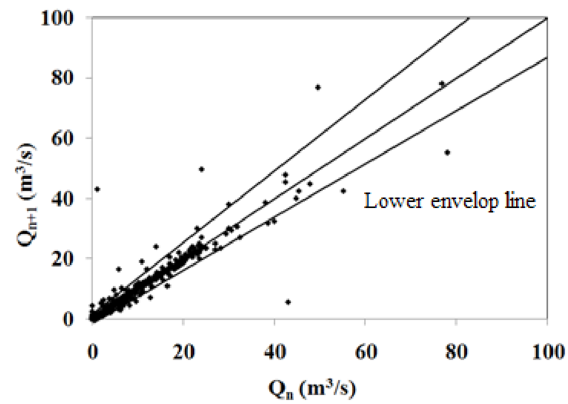

Figure 5: Recession flow plot of 2008 - 2013 for the Upper Kabul River basin in Afghanistan

of 0.903 and 2.4%, respectively. The best performance of the model is found in May, and worst performance of the model is found in February with the lowest R^2 value of 0.001. The observed discharge is high compared to the calculated in April 2009, which may be due to significant contribution of ground water in that month compared to other months. The average ground water contribution in April is 13.94 $m^3 s^{-1}$ (Akbari et al., 2010) based on the data from 2005 to 2007 in the basin. This is the same order of magnitude as the difference between observed and calculated discharge in the SRM for April 2009.

4.2 Discharge prediction by changing temperature and precipitation

In addition to model calibration and validation, we also carried out several experimental runs. After validation of the model in the year 2011, the SRM is used to study the change in river discharge by using different scenarios in the Upper Kabul River basin. The calculated discharge in 2009 i.e calibration year is used as reference for the present climate. Four scenarios are considered in this study. The combinations of these scenarios used in SRM are ±1 °C with ±10% precipitation, and ±2 °C with ±20%

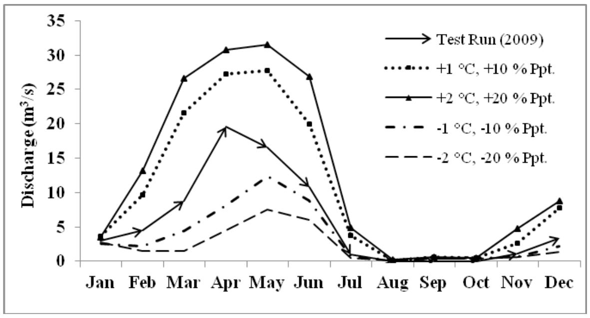

Figure 6: Distribution of monthly discharge for different scenarios of temperature and precipitation

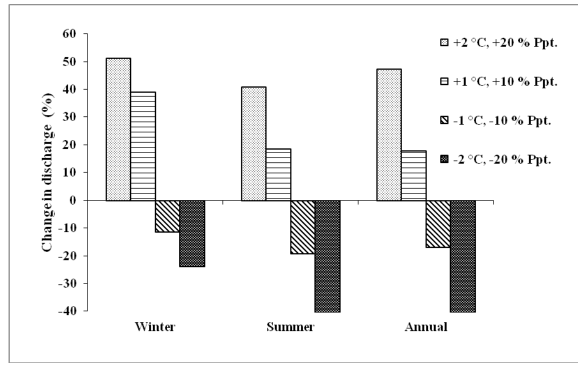

Figure 7: The changes in discharge with different temperature and precipitation scenarios in summer, winter and annually

precipitation. The combination of increase in temperature by 2 °C and 20% precipitation show the highest change in discharge as shown in Figure 5. When air temperature increases by 1°C and precipitation by 10%, annual discharge increases by 17.4%. Similarly, when we increase temperature by 2°C and precipitation by 20% then annual discharge will increase by 47.3%. The changes in discharge with different temperature and precipitation scenarios in summer, winter and annually are given in Table 3 and Figure 6.

Table 3. Change in calculated discharge by changing temperature and precipitation

Scenario	Change in discharge (%)		
	Winter	Summer	Annual
+1°C, +10% ppt.	39	18.5	17.9
+2 °C, +20% ppt.	51.2	40.8	47.3
-1°C, -10% ppt.	-11.4	-19.2	-17.0
-2°C, -20% ppt.	-23.9	-43.0	-40.4

5. CONCLUSION

The SRM is used to estimate discharge from the Upper Kabul River basin in Afghanistan. The SRM is calibrated for the year 2009 and validated in 2011. The calculated and observed mean discharges in 2009 are 5.6 $m^3 s^{-1}$ and 5.7 $m^3 s^{-1}$, respectively; and 1.31 $m^3 s^{-1}$ and 1.33 $m^3 s^{-1}$ in 2011, respectively. The model calibration and validation shows good results with significantly high R^2, 0.904 and 0.903, and volume differences, 0.5% and 2.4%, respectively. Then the discharge is calculated by changing temperature and precipitation. When air temperature increases by 1°C and precipitation by 10%, annual discharge increases by 17.4%. Similarly, when we increase temperature by 2 °C and precipitation by 20% then annual discharge will increase by 47.3%. The results obtained suggest that the SRM can be used efficiently in the other snow fed sub-catchments of the Upper Kabul River basin and other mountain basins in Afghanistan.

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