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Application of HEC-HMS for the event and continuous simulation in high-altitude scarcely-gauged catchment under changing climate

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Abstract: Aim of this study was to examine the most suitable combination of different methods (transfer and loss) provided by a standard rainfall-runoff model (HEC-HMS), used for the event based and continuous streamflow simulation, in a high-altitude (snow- and glacier-fed) scarcely-gauged Jhelum River catchment (western Himalayan), under potential changing climate scenarios. The observed and remotely sensed Tropical Rainfall Measuring Mission (TRMM) data were utilized to simulate daily streamflows. Further, the land use land cover layers were utilized as input data to design initial curve numbers (CN) of the study area. The model were calibrated during 2000-2007 and validated during 2007-2012, for different combinations of transfer (Snyder Unit Hydrograph and Clark Unit Hydrograph method) and loss methods for event based (Soil Conservation Service Curve Number (SCS-CN) and Green and Ampt) and for continuous simulation (Soil Moisture Accounting (SMA) and deficit and constant loss method) for the selection of most suitable combination to forecast the daily streamflow under potential climate change scenarios. Overall, all the combinations performed within the acceptable range with least NS coefficient of 0.76 for event based and 0.68 for continuous simulation. The combination of Green and Ampt and Clark UH for event based and SMA and Snyder UH for continuous simulation showed best efficient results than any other combination, in high-altitude scarcely-gauged catchment. Further, the hypothetical climate change scenarios showed a significant increase of annual streamflows (21.87%) of the Jhelum River catchment by the increase of 20% precipitation in comparison with 3 ^{o}C temperature increase (10.79%).

Key words: HEC-HMS, Event based, Continuous simulation, Hydrological Modelling

1. INTRODUCTION

The application of hydrological models with accurate formulation is essential for the simulation and forecasting of streamflows in catchments characterized by high-altitude with limited data issues to manage the hydrological extremes such as droughts and floods, in relation with climate change. The hydrological models can be categories into rainfall-runoff and snowmelt-runoff models. The rainfall-runoff models showed their importance because of provision to incorporate snowmelt-runoff and can simulate both source of runoff i.e. rainfall or snowmelt (Azmat et al. 2016). However, the rainfall-runoff models are less efficient in high-altitude watersheds (Martinec 2008). In hydrological modelling the quality of climate data and selection of simulation methods significantly affects the accuracy of outcomes which further leads to the uncertainty in hydrological predictions under changing climate (De Silva et al. 2013). Therefore, the selection of appropriate methods by considering catchment characteristics is always been challenging for the hydrological community.

The Hydrologic Engineering Center–Hydrologic Modelling System (HEC–HMS) developed by the U.S. army Corps of Engineers, is a well-known rainfall-runoff model used for the dendritic watershed modelling, offers several methods for the modelling on lumped and distributed basis. This model is seldom calibrated and validated for the high-altitude Pakistani watersheds and essential to examine under local input data issues. The calibration of hydrological models by employing local observed or remotely sensed data is in fact useful to improve accuracy of predictions (Halwatura and Najim 2013).

The HEC-HMS offers total nine different loss and seven transfer methods to simulate streamflows and few of them are specifically designed for event based simulations, while others are for continuous simulation. Several researchers (Azmat et al. 2015; De Silva et al. 2013; Halwatura and Najim 2013; Shahid et al. 2017) have been applied HEC-HMS for the event based and continuous simulation by employing different methods. However, this study is an attempt to check the efficiency of different combinations of loss and transfer methods available in HEC-HMS model for event based and continuous simulation by the integration of remotely sensed data. Subsequently, a most efficient combination was applied to investigate the impact of climate change on streamflows of the Jhelum River basin.

2. STUDY AREA

This study was carried out in the Jhelum River basin originates from Northern Pakistan, a sub-basin of the Indus Basin, having an area of 33,867 km^2 up to Mangla dam located in Azad Kashmir, Pakistan. Due to transboundary river catchment, more than 50% catchment area is situated in India which is considered as ungauged part of the catchment because of data collection issues (Azmat et al. 2015). The elevation of the study area ranges between 300- 6182 m a.s.l. (mean elevation~ 2094 m a.s.l.) and only four (4) stations area located above the mean elevation. The Jhelum River basin is mainly a snow-fed catchment with slightly covered by perennial glaciers, approximately 3% (>5000 m a.s.l.) of the total area, as confirmed by the hypsometric analysis.

3. METHDOLOGY

3.1 Hydrometeorological data

The observed daily precipitation and temperature data were obtained from Water and Power Development Authority (WAPDA), and Pakistan Meteorological Department (PMD) for eleven (11) stations located within the boundary of Pakistani border, spanning 2000-2013. While, the daily streamflow data at Mangla dam were made available over the period of 2000-2013 from Surface Water Hydrology Project of WAPDA (SWHP-WAPDA).

3.2 Remotely sensed data

3.2.1 Precipitation data

Further, to cover the ungauged part of the catchment, two remotely sensed (Tropical Rainfall Measuring Mission (TRMM) and ERA-interim datasets were evaluated for the integrity in comparison with observed data. We utilized 3B42 version 7 daily precipitation at spatial resolution of 0.25°x0.25°. TRMM data were extracted at seven points located in ungauged part of the catchment. This dataset have been tested and successfully used by Azmat et al. (2016), in Jhelum River basin.

3.2.2 Topographic, soil and land use data

The Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global digital elevation model (GDEM) was utilized in this study to estimate physical characteristics such as catchment area, reach length and slope etc. The project was generated by the integration of ASTER

GDEM with the HEC-GeoHMS (an extension of ArcGIS).

The curve number values estimation is mainly based on the soil type and LULC information, therefore, both information were integrated for further analysis. In order to obtain the LULC data, the information extraction was performed by using data provided by two (European Space Agency (ESA) and classify images of Landsat 8) different agencies which further compared to assess the difference between both datasets. The comparison between the information obtained from both datasets was performed by considering ESA data as a reference because this data have been successfully used by Adnan et al. (2016), for this region. The results for both datasets were found very similar, therefore, the information extracted from Landsat 8 images were finally used to compute the initial Curve Number values with help of guidelines given in National Engineering Handbook of Hydrology (USDA-NRCS 2007). The soil types for the study basin was extracted by using Digital Soil Maps of World prepared by Food and Agriculture Organization (FAO) of the United Nations, during 2007 (FAO 2007).

3.3 HEC-HMS model application

HEC–HMS a standard rainfall-runoff model detail discussed by Azmat et al. (2016) and De Silva et al. (2013). In this study, event and continuous simulations by employing HEC-HMS was carried out on semi-distributed basis and the study catchment was divided into twenty two (22) sub-basins by using HEC-GeoHMS. To examine the event based simulation efficiency of the model, two flood events were selected in a year (one from each season i.e. winter (Sep-March) and summer (April-August)) during 2000-2007. The selection of events during different seasons was associated with the investigation of model capability for the simulation of events occurred during snow accumulation and monsoon season (extreme rainfall events). The event based calibration was carried out during 28 July–08 August 2000 and 07 July–26 July 2005, for summer season and 21–28 Feb. 2000 and 08 –19 Feb. 2005, for winter season. While, the validation was performed during 07 July–19 July, 2006 and 21 June–19 July, 2007, for summer season, and 23–05 March 2006 and 01–13 Dec. 2007, for winter season. Further, the calibration and validation for the continuous simulation was performed during April 2000–March 2007 (5 years) and April 2007–March 2012 (5 years), respectively.

The model was applied by using different combinations of loss and transfer methods available in HEC-HMS in order to examine the most suitable combination for event and continuous streamflow simulation in high-altitude scarcely-gauged catchment (Table 1). The selection of loss and transfer method was chosen by considering their specific application i.e. event or continuous. In this study, we employed two loss methods i.e. Green and Ampt and Soil Conservation Services (SCS) Curve Number (CN) for event based, while, soil moisture accounting (SMA) and deficit and constant for continuous simulation. Further, two different transfer methods i.e. Snyder Unit Hydrograph and Clark Unit Hydrograph, were adopted for both event and continuous simulations, as adopted by Azmat et al. (2015).

Further, to incorporate snowmelt contribution, the model offers temperature index and gridded temperature index method. The gridded temperature index method is complicated and its application is limited in scarcely-gauged catchments, therefore, temperature index method was adopted in this study. The optimized range and detail of source of initial parametric values is given in Table 1.

Further, the model efficiency was evaluated by using three well-known statistical descriptors such as normalized objective function (NOF), the Nash–Sutcliffe efficiency (NS), and the percentage bias (δb).

3.4 Climate change scenarios

The climate change hypothetical scenarios were established by considering outcomes of previous studies for this region such as Akhtar et al. (2008); IPCC (2014). In this study, two scenarios were considered for the climate change analysis, as follows:

First, for the precipitation scenarios we considered an increase by 10 and 20%, while decrease by 10%, in base precipitation (2000-2005). Second, an increase by 2 and 3 ^{o}C, while decrease by 2 ^{o}C, in base temperature.

Table 1. Range of estimated and calibrated values for the calibration and validation of event based and continuous streamflows, for the twenty two (22) sub-basins of Jhelum River basin.

Parameter	Range of Optimized values	Source of Initial Values
Soil Moisture Accounting (SMA) Loss Method		
Canopy storage (mm)	7.5 – 20	HEC-HMS Help manual (Scharffenberg and Fleming 2006)
Surface storage (mm)	8 – 12	HEC-HMS Help manual (Scharffenberg and Fleming 2006)
Max infiltration (mm/h)	8 – 10	GIS data (Landsat 8)
Imperviousness	21 – 30	GIS data (Landsat 8)
Soil storage (mm)	28 – 55	FAO soil data
Tension storage (mm)	15 – 30	HEC-HMS Help manual
Soil percolation (mm/h)	25 – 50	FAO soil data
Ground water 1 storage (mm)	125 – 200	Calibration trial and error
Ground water 1 percolation (mm/h)	1.0 – 1.50	Calibration trial and error
Ground water 1 coefficient (h)	80 – 200	Calibration trial and error
Ground water 2 storage (mm)	140 – 180	Calibration trial and error
Ground water 2 percolation (mm/h)	1.0 – 1.50	Calibration trial and error
Ground water 2 coefficient (h)	1.0 – 1.50	Calibration trial and error
Deficit and Constant Method		
Initial Deficit (mm)	10 – 35	HEC-HMS Help manual (Trial and Error)
Constant Rate (mm/hr)	0.30 – 3.25	HEC-HMS Help manual (Trial and Error)
Impervious (%)	18 – 35	GIS data (Landsat 8)
Curve Number Method		
Initial Abstraction (mm)	18 – 37	Trial and error
Curve Number	41.85 – 49.39	GIS and FAO data (Trial and error)
Green and Ampt Method		
Initial loss (mm)	2 – 8	GIS data (Landsat 8), Calibration trial and error
Moisture deficit	0.21 – 0.58	FAO soil data and De Silva et al. (2013), (trial and error method)
Suction head (mm)	195.39 – 225	FAO soil data and De Silva et al. (2013), (trial and error method)
Conductivity (mm/h)	2.5 – 3.0	FAO soil data and De Silva et al. (2013), (trial and error method)
Impervious (%)	25 – 35	GIS data (Landsat 8), Calibration trial and error
Snyder UH Transfer Method		
Standard Lag (hr)	2.98 – 23.66	US Soil Conservation Service equation for time of concentration
Peaking Coefficient	0.5 – 0.75	HEC-HMS help manual, Trial and error
Clark UH Transfer Method		
Time of Concentration (hr)	4.23 – 36.22	SCS log equation, Calibration trial and error
Storage Coefficient (hr)	8.41 – 35.63	Streamflow at inflection point of hydrograph divided by the time derivative of flow, calibration trial and error
Temperature Index Method		
Px Temperature (^{o}C)	2.5 – 3.0	HEC-HMS help (constant for each sub-basin but varies over simulation time window)
Base Temperature (^{o}C)	0	HEC-HMS help (constant for each sub-basin but varies over simulation time window)
Lapse Rate (^{o}C /100 m)	-0.65 – -0.15	By using observed temperature data (WAPDA)
Degree Day Factor (DDF) (mm/ ^{o}C-day)	4.2 – 7.4	Extract from previous studies conducted on Himalayan Range (Azmat et al. 2016)
Evapotranspiration (mm/month)	3.0 – 78	By using Hamon method

4. RESULTS AND DISCUSSION

This study suggests the best suitable combination of methods offered by HEC-HMS for the simulation of event and continuous based streamflows to improve the modelling efficiency.

4.1 Event based simulations

The extreme events during winter and summer of 2000 and 2005 were selected for the event based streamflow simulations. Table 2 depicted that the model performed efficient during calibration and validation period with least values 0.22, 0.86 and 13.59 of NOF, NS and δb (%), respectively, for the calibration of summer season (28–08, August 2000) by employing C3 (SCS CN and Snyder UH) combination. However, during winter season (21 – 28 Feb. 2000) the model performed slightly less efficient for the extreme events with least NOF, NS and δb (%) values of 0.21, 0.84 and 14.17, respectively, by employing C3 combination. The results showed that the C2 (Green and Ampt and Clark UH) combination showed best simulation efficiency with values 0.12, 0.96 and 10.18 of NOF, NS and δb (%), respectively, during both calibration periods of summer season (07–26 July, 2005). The results obtained during validation period showed slightly poor efficiency of HEC-HMS with highest NS coefficient value of 0.86 during summer season (07–19 July, 2006) for C2 combination. Moreover, Figure 1 showed a substantial difference in streamflows during winter and summer season. It observed that the HEC-HMS reproduce streamflows efficiently against observed by employing all the combinations, however, C2 produced best results. Overall, it noticed that the HEC-HMS performed slightly less efficient during winter with comparison of summer season. This may be associated with low efficiency of the HEC-HMS with the simulation of snowmelt runoff. During winter season, the precipitation occurs in low elevation part of the catchment generate runoff, however, in high elevation part, the precipitation occurrence in form of solid snow resulting delay in hydrological response.

4.2 Continuous streamflow simulation

The results for the calibration and validation of continuous streamflow by employing different combinations of loss (SMA and Deficit and Constant) and transfer (Snyder UH and Clark UH) is presented in Table 2. The results showed that the HEC-HMS performed fairly well with least NS coefficient value of 0.75 and 0.68 during calibration and validation period, respectively. Although, the simulation efficiency for all combinations were found very similar, however, C5 (SMA and Snyder UH) combination was found most efficient during both calibration and validation with NS coefficient value of 0.78 and 0.73, respectively. Figure 2 depicted that the HEC-HMS reproduce streamflows fairly well against observed during both summer and winter season. The streamflows during winter season are not substantial in comparison with summer season, nevertheless, few non exiting peaks against observed data were produced by HEC-HMS by employing C5 combination in contrast to C7. However, it observed that the C5 combination performed slightly better to reproduce rapid streamflow peaks in comparison with C7 (Deficit and constant and Clark UH). The similar results were found for C6 and C8 combinations. Overall, during summer season, the simulated streamflows were overestimated under all combinations. This may be associated with the limitation of HEC-HMS which is poor to properly capture some rapid streamflow peaks generated by extreme rainfall events and snowmelt generated runoff. Since, the Jhelum River basin is influenced by two precipitation patterns (monsoon and westerlies circulations), therefore, the streamflow generate by rainfall are overlapped by snowmelt runoff particularly during early summer season.

Table 2. Statistical descriptors for the event based and continuous streamflow simulation by using different combinations of loss and transfer methods, at Mangla dam.

Event Based Simulation			**NOF**	**NS**	**δb (%)**	**NOF**	**NS**	**δb (%)**
For Calibration Events			**Summer Events**			**Winter Events**		
			28 July – 08 August 2000			**21 Feb. – 28 Feb. 2000**		
C1	Green and Ampt	Snyder UH	0.20	0.88	17.43	0.21	0.85	12.48
C2	Green and Ampt	Clark UH	0.18	0.94	11.82	0.14	0.91	10.18
C3	SCS CN	Snyder UH	0.22	0.86	13.59	0.21	0.84	14.17
C4	SCS CN	Clark UH	0.20	0.92	12.28	0.15	0.86	10.87
			07 July – 26 July 2005			**08 Feb. – 19 Feb. 2005**		
C1	Green and Ampt	Snyder UH	0.20	0.87	12.12	0.22	0.85	12.48
C2	Green and Ampt	Clark UH	0.12	0.96	10.18	0.11	0.93	9.48
C3	SCS CN	Snyder UH	0.17	0.89	12.42	0.18	0.85	11.57
C4	SCS CN	Clark UH	0.13	0.93	10.55	0.14	0.90	10.38
Average for Validation Event			**07 July – 19 July 2006**			**23 Feb. – 05 March 2006**		
C1	Green and Ampt	Snyder UH	0.26	0.81	13.63	0.32	0.78	15.67
C2	Green and Ampt	Clark UH	0.16	0.86	12.17	0.24	0.83	13.65
C3	SCS CN	Snyder UH	0.25	0.78	19.35	0.36	0.76	15.39
C4	SCS CN	Clark UH	0.23	0.80	16.66	0.36	0.76	16.33
Continuous Simulation		**Calibration April 2000 – March 2005**						
C5	SMA	Snyder UH	0.40	0.78	21.27	–	–	–
C6	SMA	Clark UH	0.42	0.77	22.39	–	–	–
C7	Deficit and Constant	Snyder UH	0.44	0.75	25.63	–	–	–
C8	Deficit and Constant	Clark UH	0.42	0.76	24.21	–	–	–
		Validation April 2007 – March 2012						
C5	SMA	Snyder UH	0.45	0.73	31.33	–	–	–
C6	SMA	Clark UH	0.48	0.70	32.51	–	–	–
C7	Deficit and Constant	Snyder UH	0.46	0.72	30.28	–	–	–
C8	Deficit and Constant	Clark UH	0.49	0.68	32.88	–	–	–

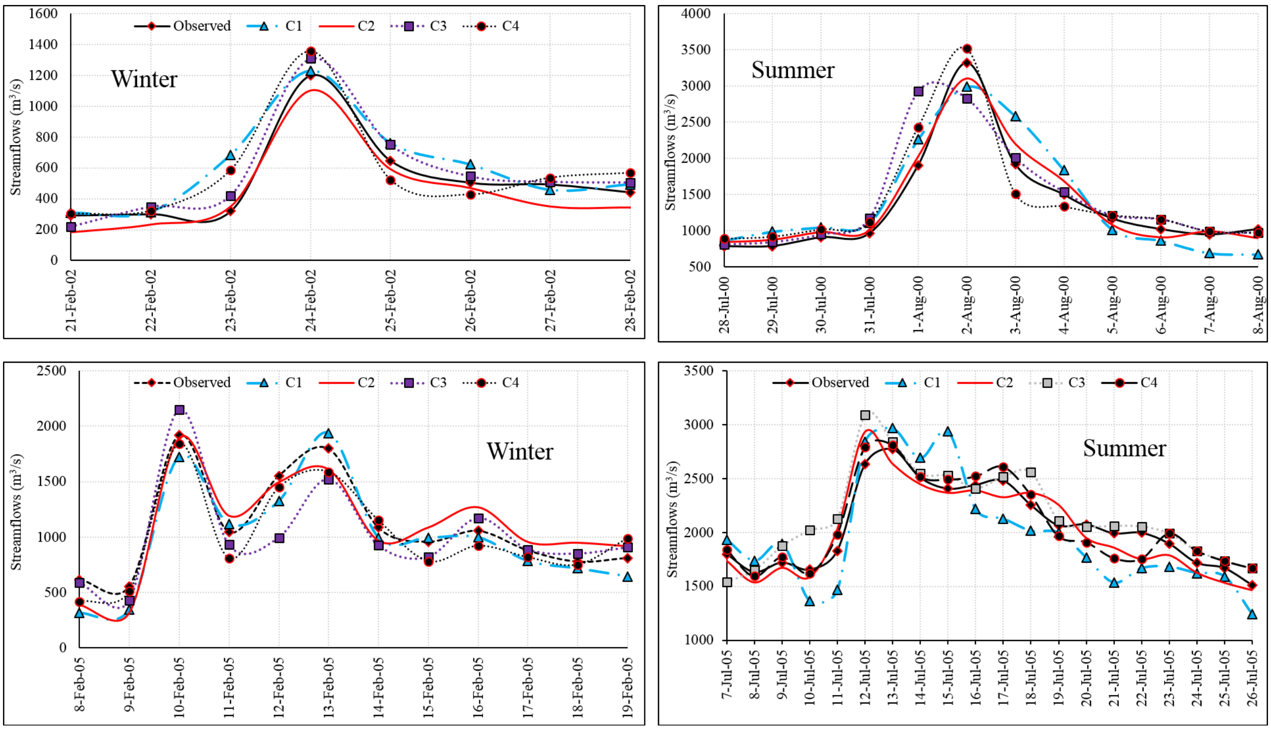

Figure 1. Observed and event based simulated streamflow for the combination of C1, C2, C3 and C4 at Mangla dam (Jhelum River basin), during the calibration periods.

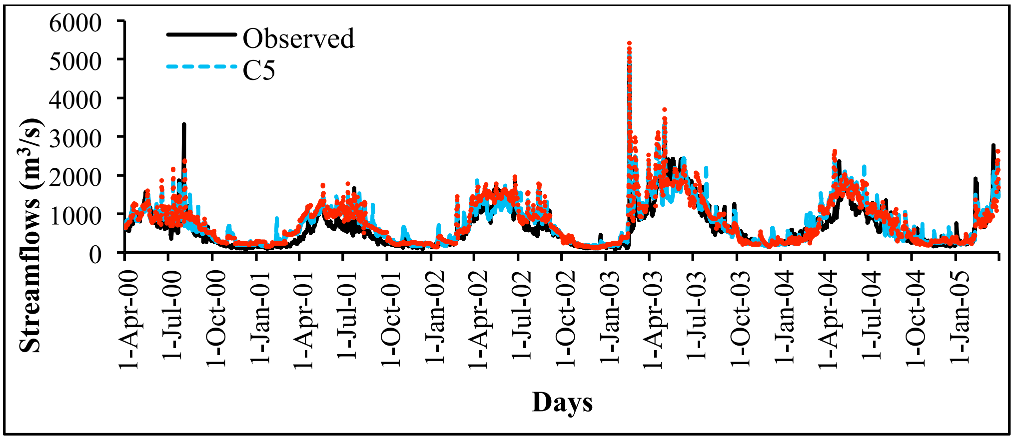

Figure 2. Observed and continuous daily simulated hydrograph for the combination of C5 and C7 at Mangla dam (Jhelum River basin), during the calibration period of five (5) years (April 2000 – March 2005).

4.3 Impact of climatic variations on streamflows

The impact of climate change on streamflow was investigated under hypothetical scenarios of change in precipitation and temperature by employing calibration period of C5 (SMA and Snyder UH) combination, as shown in Figure 3. A significant change was observed by the change of climate variables. It observed that the winter streamflows were significantly influenced by the change in temperature as compare to summer. This change is slightly different in case of change in precipitation. With the increase of 10% (P+10%) and 20% (P+20%) precipitation, the streamflows during summer season were found increased by 16.96% and 22.82%, respectively. With the decrease in precipitation by 10% (P-10%), the streamflows were found decreased by -22.18% during summer season. This may be associated with fact that the HEC-HMS is largely sensitive to the precipitation and less to the temperature. Therefore, the model response fairly well to the precipitation change. Moreover, the Jhelum River basin is mainly influenced by the monsoon precipitation pattern and slightly by westerlies circulation, therefore, a slight increase in precipitation could largely effects the summer streamflows. Figure 3 depicted that the increase in precipitation by 10 and 20% resulting significant increase in streamflow during June, July and August (summer months).

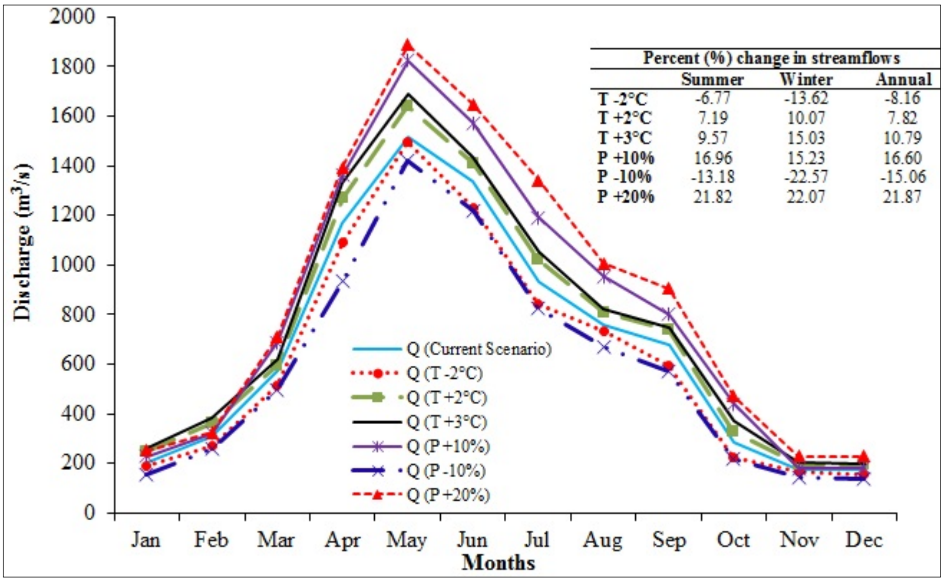

Figure 3. Percent change in streamflows under different hypothetical scenarios of change in precipitation and temperature.

5. CONCLUSIONS

This study suggests that the combination of different loss and transfer methods are effective to improve the continuous and event based hydrological modelling in a high-altitude scarcely-gauged catchment. The application of different combinations shows the capability of HEC-HMS to reproduce streamflows by the integration of different datasets of soil and land use land cover to improve the parametrization of the model. Moreover, the remotely sensed TRMM (3B42) precipitation data could be useful alternative for the scarcely-gauged Himalayan catchments. The climate change analysis shows a significant change in streamflows by the change in climate variables, in Jhelum River basin. Moreover, the Jhelum River streamflow is mainly responded by monsoon rainfall as compare to temperature during the end summer months, therefore, a significant increase in streamflow is expected in future.

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