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ORIGINAL ARTICLE

Evaluating the Responses of Streamflow under Future Climate Change Scenarios in a Western Indian Himalaya Watershed

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Abstract

Water resources in the mountain ecosystem are very important in supporting the livelihood of the population. It is crucial to assess changes in climate variables and their effect on streamflow to determine water availability in a watershed. Thus, this paper aimed to understand the changes in climate variables and their effect on streamflow in the upper Beas basin of Western Himalaya by mid-21st century. The topographical details of the basin were taken from Cartosat digital elevation model (DEM). Non-parametric methods were applied for climate variability analysis of Manali, Bhuntar and Katrain stations. The decision tree technique was applied to the Landsat image in making land use/land cover (LULC) map of the study area. Soil and Water Assessment Tool (SWAT) was employed to simulate the future streamflow under different climate change scenarios. SWAT was calibrated and validated using observed streamflow data of Thalout station. The study found a rise (0.31% to 14.18%) in mean annual streamflow while seasonal flow was more pronounced in pre-monsoon and monsoon in the near future. However, there would be lesser streamflow in the latter half of this century due to reduction in snow cover consequent to rise in temperature. This will adversely affect the irrigation potential and hydroelectricity generation capacity in the region.

Keywords Climate change scenarios · Streamflow · Hydrological modelling · SWAT

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1 Introduction

One of the confronting issues around the world is climate change and its consequence on available water resources. Atmospheric temperature is considered as one of the key elements of climate change because it affects other climate variables. Furthermore, it is also one of the key inputs to hydrologic modelling (Boyer et al. 2010). An increase of about 0.89 °C was reported in the mean global surface temperature during 1901–2012. Nevertheless, its magnitude of change varied with regions (IPCC 2014). Air temperature changes have also been observed over different regions of India (Arora et al. 2005; Dash et al. 2007; Jhajharia and Singh 2011; Mondal et al. 2014; Rani and Sreekesh 2018). A rise in annual mean (0.51 °C/100 years), maximum (0.72 °C/100 years) and minimum temperature (0.27 °C/100 years) has been found at India level during 1901–2007 (Jain and Kumar 2012). Warming in air temperature has also been reported in the Western Indian Himalaya (Bhutiyani et al. 2007; Dash et al. 2007; Dimri and Dash 2012).

Variation in precipitation has also been reported around the world (Klein Tank et al. 2006; Westra et al. 2013). Reduction in precipitation has been found in the tropics since the 1970s, while an increase in mean monsoon rainfall has been predicted for South Asia (IPCC 2014). India has also experienced variability in rainfall (Guhathakurta and Rajeevan 2008; Ghosh et al. 2009; Kumar and Jain 2011; Pal and Al-Tabbaa 2011; Jain and Kumar 2012; Mondal et al. 2014; Rani and Sreekesh 2018). However, no significant trend has been found in rainfall at India scale (Kumar et al. 2010). The evidence of rising and decreasing trends has been observed in the pre-monsoon and monsoon precipitation, respectively, in the Western Himalaya (Bhutiyani et al. 2010).

These two factors of climate play a major part in determining the streamflow. Thus, understanding the interaction of these variables and streamflow is imperative, since it has many socio-economic implications. IPCC (2013) found concurrence in detected trends in streamflow with temperature and precipitation changes at a regional scale since the 1950s. Approximately one third of the top 200 rivers have shown significant changes in discharge during 1948–2004 (Dai et al. 2009). Evidences of the influence of climate change on streamflow have also been found in different areas of the world (Lu et al. 2010; Mishra and Lilhare 2016; Leta and Bauwens 2018; Wang et al. 2018; Tirupathi et al. 2018).

Evidence of change in temperature and precipitation is also reported in the proposed study area that is the upper Beas river basin in Kullu district (Himachal Pradesh, India). Precipitation in the Himachal Pradesh showed a decline over time. A decline in water availability in rivers was also found in the state (Government of Himachal Pradesh (GoHP) 2002a), though the amount of reduction in streamflow has not been estimated. Rainfall intensity has increased in the district and the rainfall has replaced snowfall due to rising temperature (Government of Himachal Pradesh (GoHP) 2012). A substantial decrease in observed streamflow at Bhuntar, Thalout and Pandoh has been reported in many studies (Bhutiyani et al. 2008; Kumar et al. 2009; Singh et al. 2014) but the contributing factors for the reduction in streamflow, especially changes in climate as well as land cover, have not been fully understood. The streams in the study area receive melt-water from the snow and glaciers. The reduction in the area of glaciers has also been reported (Kulkarni et al. 2005; Kumar et al. 2009; Dutta et al. 2012). The Beas Kund glacier, which is the source of origin of the Beas river, has shown retreat of 18.8 m/year during the period 1963–2000, and monsoon streamflow in the basin has shown a substantial reduction (Government of Himachal Pradesh (GoHP) 2002a). On the other hand, based on population projections, water demand in urban areas of the upper Beas basin is expected to increase from 2.99 million liters per day (mld) in 1999 to 4.82 mld in 2021, while in rural areas, it would increase from 23.61 to 38.89 mld in the corresponding period (Government of Himachal Pradesh (GoHP) 2002b). The rising water demand and the reduction in water availability at basin level would increase the dependency of the population on the surface water resources which may lead to water stress.

Based on these, it is imperative to quantify the effect of climate change on surface water and understand the possible changes in water availability in the future. Review of literature revealed the absence of a comprehensive study, which would examine the combined effect of changing temperature and precipitation on streamflow in the Beas basin. Hence, the present study is an attempt to provide a complete analysis of changes in future streamflow under different climatic conditions. Thus, the objective of the study was to analyze the response of streamflow to climate change in the near future (2015–2050), and further, to understand the recent changes in climate and construct climate change scenarios for the study area. The study also analyzed the trend in minimum temperature (T_{min}), maximum temperature (T_{max}), mean temperature (T_{mean}) and rainfall in the upper Beas basin during 1969–2010. This work is helpful for understanding the hydrological processes and water management to sustain the livelihood of the people.

2 Study Area

The study was conducted in the upper Beas basin, a branch of the Indus river, which originates at the Beas Kund at an elevation of about 4085 m (Fig. 1). Catchment area and length of the basin up to Pandoh dam are about 5300 km^2 and 116 km, respectively, out of which only 780 km^2 is under permanent snow (BBMB 1988). According to the latest report, the number of glaciers in Kullu district are six with the aerial extent of approximately 16 km^2, and 47 permanent snowfields cover an area of about 72.4 km^2 (Government of Himachal Pradesh (GoHP) 2012). Among Beas river tributaries, glacier-fed are: Pārbati river and Sainj Khad. Sabari Nala, Pārbati river, Tirthan, Sainj and Bakhli Khad are some of the major tributaries of Beas river above the Pandoh dam. Elevation in the basin varies between 840 m and 6500 m along the Pārbati sub-catchment (Fig. 1).

The area lies on Dhauladhar and Pir-Panjal ranges of the Western Himalaya. Major water bearing formations of the area are semi-consolidated and consolidated sediments (Proterozoic) that cover a major part of hilly terrain. The unconsolidated porous sediments (River and Glacial deposits) cover the valleys (Kujur 2013). The soils of the area are categorized into Entisols, Inceptisols and Molisols (SLUSI 2013). Magar-Keran-kathel (coarse to fine loamy and well drained) soil series cover the majority of the study area, followed by Kippar-Urla, Dhamasan-Mamel and Bitohi-Urla (Fig. 2a). The major part of the area remains under frozen conditions during January–February. The forest is dominant land cover of the basin while the cultivated land covers very less area (Fig. 2b). Main cereal crop is wheat, while apple is the main horticultural crop grown in the basin. Total population in the catchment area is approximately 400,000 (Census of India 2011) and primarily depends on surface water sources for their domestic and agricultural water demand.

3 Material and Methods

The Soil and Water Assessment Tool (SWAT) hydrological model (Neitsch et al. 2002) was used to estimate the streamflow under different future climate change scenarios. It requires

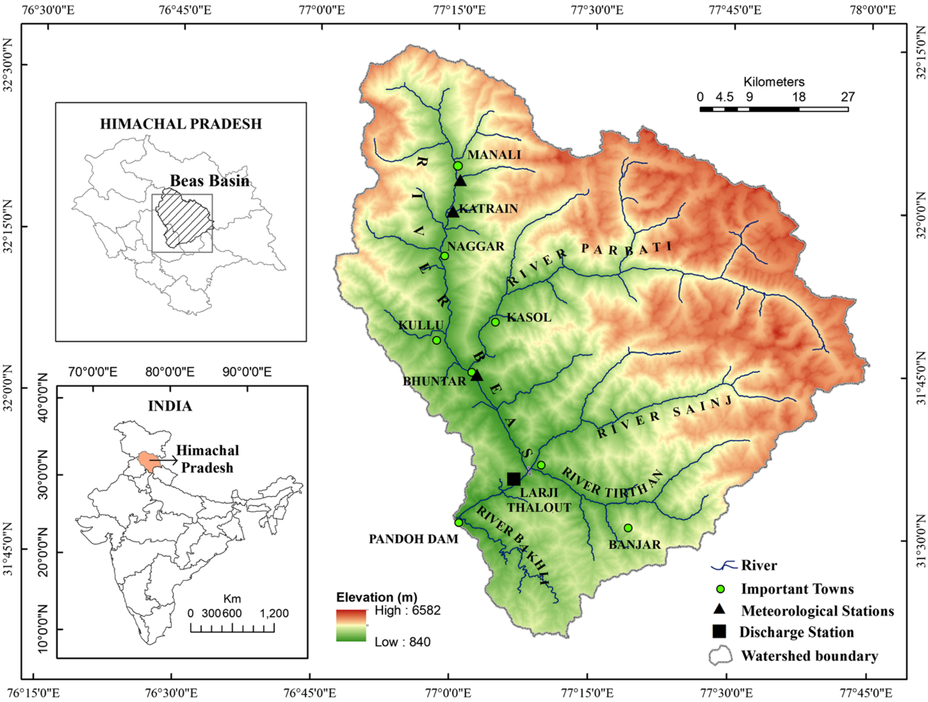

Fig. 1 Location of the upper Beas basin (up to Pandoh dam), Western Indian Himalaya

climate data within a GIS environment along with the data on elevation, land use/land cover (LULC), soil characteristics and streamflow (Table 1). Climate data of daily air temperature (T_{min} and T_{max}), rainfall, relative humidity and wind speed were acquired from the India Meteorological Department (IMD) for Manali (1969–2010) and Bhuntar (1969–2010), and for Katrain (1985–2010) from the Indian Agricultural Research Institute (IARI). Cartosat-1

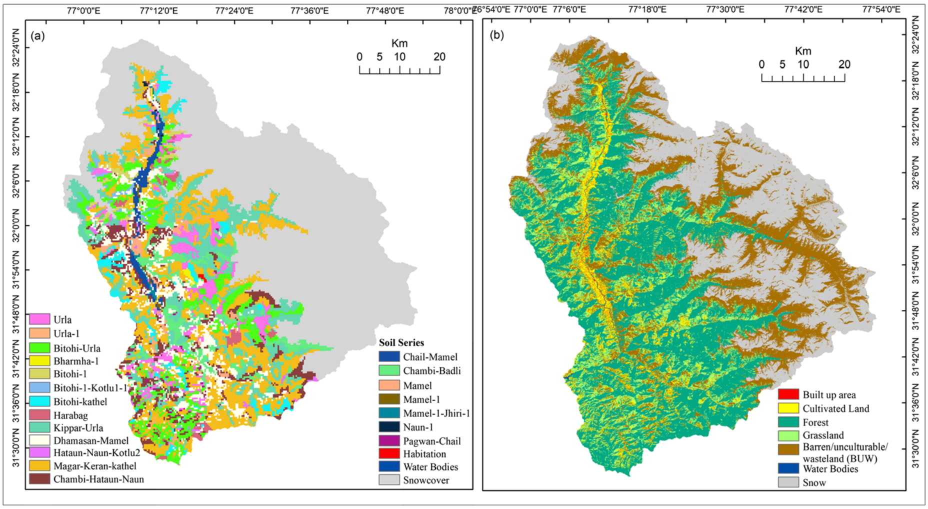

Fig. 2 **a** Soils; and (**b**) Land use/Land cover of 1991 of the upper Beas basin

Table 1 Data and sources of the study

S.No	Data	Sources
1	Metereological Variables: Daily min and max air temp (°C); daily min and max relative humidity (%); daily rainfall (mm); and daily average wind speed (m/s)	India Meteorological Department (Manali, Bhuntar) 1969–2010 and Indian Agricultural Research Institute (Katrain) 1985–2010
2	Discharge of Thalout station (1971–2002)	Ghorpa hydal project report
3	Topographic map at 1:50000	Survey of India (SOI)
4	Digital Elevation Model (DEM) 30 m	Cartosat-1 DEM, Bhuvan
5	Satellite Image (LANDSAT_5(TM), P/R 147/038 dated-11/16/1991)	Landsat Data from USGS Global Visualization Viewer (GloVis)
6	Soil map (Type of soils and their physical/ chemical properties)	Soil Resource Mapping District Kullu and Mandi, Himachal Pradesh, 2013, Soil and Land Use of Survey India (SLUSI)

TM, Thematic Mapper; P/R, Path/Row

digital elevation model (DEM 30 m) data was obtained from Bhuvan (Cartosat 1 DEM 2014) (National Remote Sensing Centre- NRSC/Indian Space Research Organization- ISRO Open data and product archive) to demarcate the drainage basin and develop a decision tree for LULC mapping (Ahmed et al. 2007). Landsat image of the study area was taken from the United States Geological Survey global visualization viewer (USGS GloVis) (NASA 2014). Soil physical and chemical properties were obtained from Soil and Land Use of Survey India (SLUSI) (2013). Mean monthly streamflow data of Thalout station (1971–2002) was obtained from the Ghorpa hydal project report of Himachal Pradesh State Electricity Board (HPSEB undated). The climate data was analyzed following the seasons identified for the area by Jain et al. (2009), i.e., pre-monsoon (April–June), monsoon (July–September), post-monsoon (October–November) and winter (December–March).

3.1 Climate Variability Analysis

The trend and its magnitude in temperature and rainfall was computed using Mann-Kendall test (Mann 1945; Kendall 1975) and Sen Slope estimator (Theil 1950; Sen 1968), respectively, because these are non-parametric tests and not influenced by outliers in the data.

3.2 LULC Mapping

Land cover map of the basin is an essential input to SWAT model and prepared from Landsat image. Dark Object Subtraction (DOS) was used for atmospheric correction of the image (Chavez Jr 1988). The study area base map was prepared from the Survey of India (SoI). Spectral separability analysis and indices such as normalized difference built-up index (NDBI), normalized difference vegetation index (NDVI), water ratio index (WRI), and normalized difference snow index (NDSI) were applied to classify the image (Supplementary material, Fig. S1). Following the NRSC/ ISRO (2011) LULC classification scheme, seven LULC types were recognized using a decision tree method in the ENVI 5.2 software, namely built-up area, cultivated land, forest, grassland, barren/unculturable/wasteland (BUW), water bodies and snow (Fig. 2b). Kappa (K) coefficient (Cohen 1960) and an error matrix/contingency table (Congalton 1991) were employed for assessing the accuracy of classified maps. Overall accuracy and kappa coefficient of LULC map were 85% and 0.82, respectively

(Supplementary material, Table S1). User's accuracy among the LULC classes varied from 71% to 100%, while producer's accuracy varied from 68% to 95%.

3.3 Hydrological Model

SWAT model, a watershed scale hydrological model was used for calculating the effect of future climate change on streamflow in the present study (Neitsch et al. 2002). This model has been widely used around the world for understanding the effect of climate change on streamflow and find it also suitable for water resource management applications (Mishra and Lilhare 2016; Leta and Bauwens 2018; Wang et al. 2018; Tirupathi et al. 2018). In the present study, a total of 180 hydrological response units (HRUs) in 57 sub-basins were created by using land use, soil and slope parameters (Figs. 1 and 2). The slope of the basin, derived from DEM, was categorized into four classes (<10%, 10–15%, 15–25% and > 25%). On the basis of analysis of snow cover area (SCA) under different elevation zones in the basin (Rani 2017), eight (850 class intervals) elevation bands (for estimating orographic effects on both air temperature and rainfall) were chosen for use in SWAT, because elevation bands are helpful in bringing reliable changes in distribution of water within a watershed hydrological cycle (Grusson et al. 2015). The Penman-Monteith method was used for evapotranspiration computation because it takes into account most of the weather parameters and was considered appropriate for computing the effects of climate change on streamflow (Neitsch et al. 2011). The Soil Conservation Service (SCS) curve number technique was chosen to model surface flow in the basin (Neitsch et al. 2011).

The model calibration and validation for the basin was done with help of mean monthly streamflow data of Thalout station (Fig. 1). The SWAT model was run for the period 1974–2010 excluding the first 5 years (1969–1973) which were used as a warm-up period to initialize the model hydrological conditions. The periods 1985–1995 and 1996–2002 were used for calibration and validation, respectively. Eighteen parameters related to elevation band, snow and hydrology were selected by taking into consideration the hydrological behaviour of the Beas basin (Table 2). Elevation band and snow-related parameters were calibrated manually in the model, based on observed data (Table 2). The sensitivity of the remaining parameters was analyzed by using the Latin hypercube one-factor-at-a-time (LH-OAT) technique of the SWAT Calibration and Uncertainty Programs (SWAT-CUP) before running the calibration (Abbaspour 2015). Eight sensitive parameters were selected, based on the guidelines of Abbaspour et al. (2015), which were optimized by using the Sequential Uncertainty Fitting (SUFI2) algorithm in the SWAT-CUP (Table 2). These parameters were primarily related to streamflow, groundwater, snow and evapotranspiration (ET) of the basin hydrology. The Nash-Sutcliffe (NS) and coefficient of determination (R^2) were applied for assessing the uncertainty in simulated streamflow of the basin (Nash and Sutcliffe 1970; Moriasi et al. 2007).

4 Results and Discussion

4.1 SWAT Model Calibration and Validation

The results of the model calibration and validation shown satisfactory performance in representing the hydrological behavior of the basin (Fig. 3). The p-factor (refers to the

Table 2 SWAT model parameters and fitted values after calibration

Optimized Parameters	Fitted Value
Elevation band related parameters-	
a) Precipitation lapse rate (PLAPS) v	20 mm/km
b)Temperature lapse rate (TLAPS) v	6 °C/km
c) Snow water content (SNOEB) v	30–200 mm
Snow related parameters-	
a) Rain/snow threshold (SFTMP) v	0 °C
b) Maximum melt coefficient (SMFMX) v	5 °C/mm/day
c) Minimum melt coefficient (SMFMN) v	2 °C/mm/day
d) Snowpack temperature lag factor (TIMP) v	0.68
e) Snowpack temperature melt factor (SMTMP) v	1
f) Areal snow coverage threshold CV100 (SNOCOVMX) v	0.68
g) Areal snow coverage threshold CV50 (SNO50COV) v	0.5
Hydrological parameters	
a) r__CN2.mgt	−0.15
b) v__GW_DELAY.gw (days)	11.9
c) v__SURLAG.bsn (days)	9.6
d) v__OV_N.hru	4.2
e) r__HRU_SLP.hru (m/m)	−1.8
f) v__GWQMN.gw (mm)	23
g) v__REVAPMN.gw (mm)	964.5
h) v__GW_REVAP.gw	0.04

r, relative change (%); v –replace; CN2-SCS runoff curve number for moisture condition II; GW_DELAY-Groundwater delay; SURLAG- surface run-off lag time; OV_N- Manning's roughness for overland flow; HRU_SLP- average slope steepness; GWQMN-threshold depth of water in the shallow aquifer required for return flow to occur; REVAPMN- threshold depth of water in the shallow aquifer for "revap" or percolation to deep aquifer to occur; GW_REVAP-ground revap coefficient

percentage of observations covered by the 95% prediction uncertainty) (0.67) and r-factor (refers to the thickness of the 95% prediction uncertainty envelop) (0.63) indicate the reliability of the SWAT model in simulating the basin streamflow (Fig. 3a). The model correctly tracked the mean monthly streamflow during the simulation period, although some peak streamflow months were under-predicted during calibration (Fig. 3b). Comparatively, under-prediction in streamflow was low during validation period, probably due to low variation in precipitation of the basin. The statistics suggest a good arrangement between observed and simulated mean monthly streamflow. Literature suggests that the SWAT model is unable to capture extreme events and often under-predicts the major streamflow events (Tolson and Shoemaker 2004; Chu and Shirmohammadi 2004; Wang and Melesse 2005). R^2-values of the mean monthly observed and simulated streamflow in the baseline, calibration and validation periods were 0.64, 0.61 and 0.61, respectively (Table 3) (Supplementary material, Fig. S2). The NS coefficients for mean monthly observed and simulated streamflow were 0.65, 0.61, and 0.63 for the calibration, validation and baseline period, respectively, suggesting a better model performance. Overall, the SWAT model was found appropriate to simulate well the actual hydrological conditions in the upper Beas basin.

4.2 Changes in Air Temperature and Rainfall

The basin experienced an annual T_{mean} ranging between 13.1 °C and 17.8 °C during the study period. Lowest and highest T_{mean} was found at Manali and Bhuntar, respectively. The majority of the area remains under frozen conditions from January to February. Seasonal trend analysis

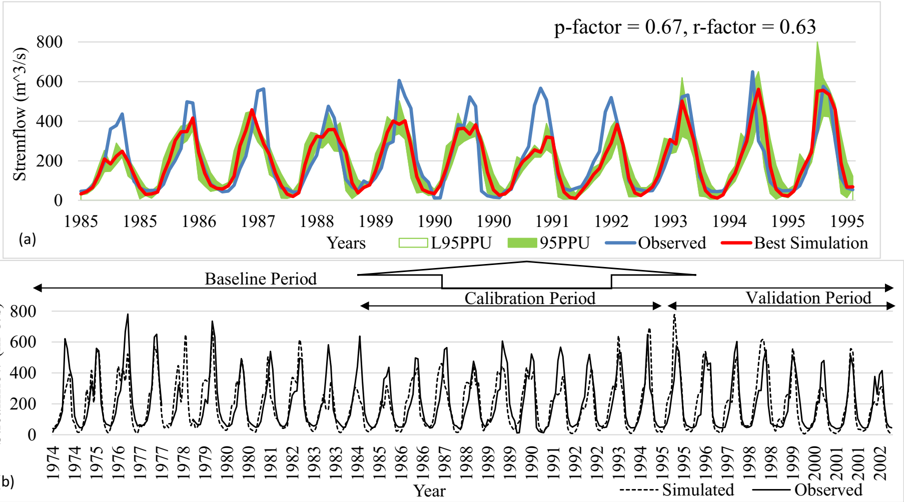

Fig. 3 **a** Observed and simulated mean monthly streamflow at Thalout during calibration period; **b** Observed and simulated mean monthly streamflow at Thalout

showed a significant rise in mean T_{min} at Manali and Katrain. The rate of rise in mean T_{min} was slightly higher than the rate observed at Manali (Table 4). The mean T_{max} at Manali showed a significant decline while Bhuntar showed a significant rise in mean T_{max} in winter. Consequently, T_{mean} also showed a significant rise at Bhuntar in winter. The maximum rate of the rising trend in T_{mean} at Katrain was observed during the post-monsoon. Both stations have experienced a rise in T_{mean} during winter, though the magnitude of rise was higher at Katrain. The annual mean T_{min} has shown a significant rise only at Manali whereas annual mean T_{max} was more or less stable in the basin. The annual T_{mean} showed a significant rise at Bhuntar and Katrain during the study period. Rise in annual T_{mean} of all the stations were found particularly after the year 2000. The IPCC (2014) has also concluded that the decade of the 2000s has been the warmest at the global scale. The trend of air temperature in the basin is consistent with previous studies (Arora et al. 2005; Dash et al. 2007; Bhutiyani et al. 2007; Dimri and Dash 2012). It may be attributed to increasing greenhouse gases in the atmosphere linked to rapid urbanization/industrialization but there is a need to study their changes in relation to climatic change (Bhutiyani et al. 2007). Rising air temperature leads to a shift in

Table 3 Statistics of mean monthly streamflow at Thalout during the calibration and validation periods

Type	Period	Time Scale	Mean Flow (m^3/s)				R^2	NS
			Observed		Simulated			
			Mean	SD	Mean	SD		
Default	1974–2002	Monthly	207	176	175	155	0.24	−0.39
Baseline	1974–2010	Monthly	207	176	198	165	0.64	0.63
Calibration	1985–1995	Monthly	217	186	207	166	0.61	0.65
Validation	1996–2002	Monthly	207	173	202	164	0.61	0.61

SD- Standard Deviation,NS-Nash-Sutcliffe coeffecient

Table 4 Trend in minimum, maximum and mean air temperature in the basin

Time Scale	Manali						Bhuntar						Katrain					
	T_{min}		T_{max}		T_{mean}		T_{min}		T_{max}		T_{mean}		T_{min}		T_{max}		T_{mean}	
	MK(Z)	SS (°C/yr)	MK(Z)	SS (°C/yr)	MK(Z)	SS (°C/yr)	MK(Z)	SS (°C/yr)	MK(Z)	SS (°C/yr)	MK(Z)	SS (°C/yr)	MK(Z)	SS (°C/yr)	MK(Z)	SS (°C/yr)	MK(Z)	SS (°C/yr)
Jan	1.65	0.02	−0.61	0	1.29	0.01	0.06	0	2.91**	0.06**	3.56**	0.04**	2.64**	0.09**	−0.43	−0.01	1.73	0.06
Feb	2.76**	0.04**	0.28	0	1.69	0.03	2.32*	0.02*	1.34	0.03	1.61	0.03	2.98**	0.10**	−0.39	−0.02	1.39	0.05
Mar	1.78	0.02	0.94	0.02	1.55	0.03	0.59	0.01	1.09	0.05	1.11	0.03	3.54**	0.16**	2.11*	0.11*	2.92**	0.15**
Apr	0.92	0.01	−1.43	−0.03	−0.8	−0.01	−0.02	0	0.21	0.01	0.23	0.01	3.13**	0.14**	0.56	0.01	2.43*	0.09*
May	2.15*	0.03*	−0.15	0	1.37	0.02	1.2	0.02	−0.06	0	0.9	0.02	2.74**	0.14**	−0.1	0	2.19*	0.09*
Jun	1.97*	0.03*	−1.43	−0.02	0.12	0	−0.29	−0.01	−0.92	−0.02	−0.21	0	3.20**	0.11**	−1.51	−0.05	1.53	0.04
Jul	1.55	0.02	−0.58	0	0.43	0.01	1.11	0.01	0.43	0	0.94	0.01	3.60**	0.12**	0.65	0.02	3.18**	0.07**
Aug	2.39*	0.04*	0.18	0	1.69	0.02	0.36	0	0.35	0.01	0.96	0.01	3.60**	0.12**	−0.15	−0.01	1.77	0.05
Sep	3.02**	0.06**	−1.96*	−0.02	1.29	0.01	0.77	0.02	−0.94	−0.01	0.81	0.01	3.68**	0.13**	−0.93	−0.03	2.50*	0.06
Oct	3.21**	0.04**	−2.38*	−0.03*	−0.39	0	−0.04	0	0.61	0.01	1.15	0.01	3.50**	0.18**	−0.59	−0.02	2.57*	0.10*
Nov	3.11**	0.05**	−2.85**	−0.04**	0.68	0.01	0.82	0.01	0.35	0	1.87	0.02	3.16**	0.14**	0.02	0	2.73**	0.08**
Dec	3.52**	0.04**	−1.15	−0.02	−0.7	−0.01	−0.7	−0.01	1.19	0.02	1.86	0.01	2.30*	0.08*	0.36	0.01	1.16	0.04
Winter	2.95**	0.04**	0.38	0	1.44	0.02	0.77	0.01	2.41*	0.04*	3.04**	0.03**	1.68	0.11	0.34	0.01	2.65**	0.07**
Pre Monsoon	1.64	0.03	−0.89	−0.01	1.4	0.01	0.36	0.01	−0.08	0	0.96	0.01	1.91	0.13	−0.49	−0.02	2.07*	0.06*
Monsoon	3.80**	0.04**	−1.53	−0.01	0.44	0	1.3	0.01	0	0	1.36	0.01	1.63	0.12	−0.37	−0.02	3.06**	0.06**
Post Monsoon	3.59**	0.04**	−3.57**	−0.03	0.11	0	0.35	0	0.73	0.01	1.93	0.02	2.31*	0.17*	−0.48	−0.02	3.14**	0.09**
Annual	3.35**	0.04**	−1.6	−0.01	1.12	0.01	1.28	0.01	1.36	0.01	2.09*	0.02*	1.74	0.13	−0.54	−0.02	2.84**	0.06**

T_{min}-Mean minimum temperature; T_{max}-Mean maximum temperature; T_{mean}-Mean temperature; MK(Z)-Mann-Kendall Test (Z); SS-Sen's Slope; Significant at 0.01** and 0.05* level precipitation from snowfall to rainfall, which reduces the accumulated snow cover over the years. A significant negative trend was found in snowfall (Bahang, Solang and Dhundi) (Bhutiyani et al. 2010) and snow cover in the upper Beas basin (Rani and Sreekesh 2016).

The basin received a mean annual rainfall of 1100 mm over the study period and about 38% is received during monsoon. The monthly trend analysis has shown a statistically significant decline in the rainfall of January and July at Manali (Table 5). Reduction in rainfall in January may be due to decline in the rainy days (Rani 2017). In contrast, Katrain showed a significant rise in rainfall in June during the study period. The seasonal rainfall showed a statistically significant decline during winter (Manali) that may be due to the decline in rainy days (Rani 2017). However, annual rainfall has shown a significant decline at Manali while rise was found at Bhuntar. Results at Manali are consistent with other studies (Rani and Sreekesh 2016). Bhutiyani et al. (2010) found no trend in precipitation during winter and significant decline in monsoon precipitation in the Western Himalaya.

4.3 Climate Change Scenarios

Studies emphasize the significance of regional climate data in downscaling General Circulation Models predictions (GCMs) at smaller spatial scale for better predictions (Skoulikaris and Ganoulis 2011; Pellicciotti et al. 2012; Kumar et al. 2013; Dimri et al. 2013; Mishra 2015; Anagnostolpoulou et al. 2016; You et al. 2017; Dimri 2018). Due to lack of reliable regional meteorological data of the upper Beas basin, which are needed for the downscaling of GCMs outputs at regional scale, the use of a synthetic method was selected. This approach refers to a scenario that is based on incremental (or decremental) changes in climate variables (from the baseline climate data of the study area) such as temperature and precipitation (Feenstra et al. 1998). For instance, temperature changes of +1 °C and + 2 °C, which can be combined with 5%, 10% or no change in rainfall to create a synthetic scenario. This method is well accepted in

Table 5 Trend in the amount of rainfall in the basin

Time Scale	Manali		Bhuntar		Katrain	
	MK(Z)	SS (mm/yr)	MK(Z)	SS (mm/yr)	MK(Z)	SS (mm/yr)
Jan	−2.50*	−2.18*	−1.77	−1.38	0.11	0.13
Feb	−1.31	−1.08	0.69	0.66	0.61	1.21
Mar	−1.56	−2.34	0.13	0.13	−1	−1.87
Apr	−1.25	−1.05	0.23	0.13	−0.07	−0.06
May	−0.34	−0.19	0.27	0.08	0.03	0.03
Jun	0.02	0.01	0.57	0.25	2.55*	2.39*
Jul	−1.98*	−2.31*	−0.59	−0.42	−0.43	−0.9
Aug	−1.59	−1.86	−0.5	−0.29	0.2	0.5
Sep	−0.16	−0.07	1.41	0.69	0.18	0.33
Oct	−1.36	−0.33	−1.23	−0.17	0.23	0
Nov	−0.17	0	0.37	0	0.15	0.03
Dec	0.02	0	−0.15	0	0.34	0.25
Winter	−2.57**	−5.97**	0	0	0.24	1.19
Pre Monsoon	−1.32	−2	0.12	0.1	1.12	2.82
Monsoon	−1.57	−3.1	0.65	1.22	−0.41	−1.33
Post Monsoon	−1.13	−0.55	0.01	0	−0.3	−0.27
Annual	−1.97*	−10.81*	2.72**	4.66**	−0.19	−0.71

MK(Z)-Mann-Kendall Test (Z); SS-Sen's Slope; Significant at 0.01** level and 0.05* level the current literature (Lirong and Jianyun 2012; Schwank et al. 2014; Liu et al. 2012; Pervez and Henebry 2015; Musau et al. 2015).

Considering the results of the present study and other studies, eleven future climate change scenarios were decided (Table 6). The first two scenarios indicate a daily increase in mean air temperature by 2 °C and 3 °C over the baseline scenario. These scenarios correspond with the trend analysis in the present study that found a rise in T_{mean} at the rate of 0.031 °C/year in the basin, which may lead to about 1.27 °C rise in T_{mean} by mid-21st century as well as other studies (Table 4). For the same period, other studies have estimated T_{mean} ranging from 1 °C (RCP 2.6) to 2.62 °C (RCP 8.5) in Western Indian Himalaya (larger spatial scale than that of the present study) using different regional climate models (RCPs) (Kumar et al. 2013; Niu et al. 2015; Bal et al. 2016; Krishnan and Sanjay 2017; Wu et al. 2017; Dimri et al. 2018). Bal et al. (2016) predicted a rise of 2.4 °C in T_{mean} and by 2050 in state of Himachal Pradesh, where the upper Beas basin is located. The next three scenarios represented an increase of 5, 10 and 15% in rainfall over the baseline scenario. These scenarios are selected by considering the predicted 10.2% change in annual rainfall by 2050 (Bal et al. 2016). Remaining scenarios indicate simultaneous changes in air temperature and rainfall, and are decided based on combination of first five scenarios. S2 and S11 scenarios represent extreme climate change under high emissions scenarios, which will help to understand the extreme hydrological conditions in the basin. The scenarios are based on change in mean monthly temperature (additive factor) and percentage change in monthly rainfall (multiplicative factor) in the future period relative to the baseline period (1974–2010). Each scenario was run for the period 1974–2010, with modified climate parameter inputs, i.e., air temperature and rainfall using the weather adjustment tool of SWAT (Neitsch et al. 2011).

4.4 Effect of Climate Change on Streamflow

SWAT was used to understand the possible changes in the streamflow in the basin by mid-21st century (2015–2050). LULC of 1991 was used in the model which corresponds with the calibration period. Forest and snow covered an area of about 34% and 26%, respectively, while BUW is about 23% of the basin, indicating most influential land covers on the basin hydrology (Table 7 and Fig. 3). The snow cover area is sensitive to temperature changes and determines the seasonal streamflow fluctuations. Area under BUW at high altitudes varies with snow coverage and influences streamflow. Built up area and cultivated land together constitute

Table 6 Climate change scenarios for the study area for 2015–2050

Climate Change Scenarios	Air Temperature (°C)	% Change in Rainfall
S1	2	0
S2	3	0
S3	0	5
S4	0	10
S5	0	15
S6	2	5
S7	2	10
S8	2	15
S9	3	5
S10	3	10
S11	3	15

Table 7 Area of different LULC classes of the study area, 1991

LULC Classes	Area	
	km^2	%
Built up area	14	0.26
Cultivated land	268	4.98
Forest	1831	34.03
Grassland	605	11.24
Barren/unculturable/wasteland (BUW)	1262	23.44
Waterbodies	7	0.12
Snow	1396	25.93

around 5% of the area and are confined in the valleys of the basin. These land uses have negligible effect on streamflow. Only marginal changes in the LULC were observed during 1974–2015 (Rani 2017). Thus, the study has assumed it as constant in future simulations of the model for estimating the effect of climate change on streamflow. It also helps in reducing complexities while deriving inferences.

During the baseline period (1974–2010), the mean annual water yield and annual evapotranspiration (ET) were 27.7 and 1086 mm, respectively. Snowmelt begins from April and continues up to October in the basin. The rising limb of the hydrograph starts from April onwards, as the basin starts receiving water from snowmelt, and reaches a peak in July, because of the combined effect of monsoon rainfall and snowmelt. The descending limb of the hydrograph reaches its lowest in December because the snowmelt flow ceases. The contribution of snowmelt to streamflow is negligible during December to March (winter) since it is the frozen period in the upper Beas basin. During this period, streamflow in the basin consists of approximately 7.2% of the annual streamflow (Kumar et al. 2007). Hence, during this period impact of snowmelt on streamflow could be ignored because there is hardly any snowmelt to streamflow in the basin.

The rise in air temperature would mainly lead to changes in forms of precipitation, increase in snowmelt runoff and evapotranspiration rate in the basin. These processes collectively modify the streamflow in the basin. A slight increase of 0.4% and 1.8% in the predicted mean streamflow would occur during pre-monsoon months in response to 2 °C (S1) and 3 °C (S2) rise in T_{mean}, respectively (Fig. 4). Rising predicted streamflow in winter and pre-monsoon indicates the basin sensitivity to the effect of decreasing snowpack level due to changes in forms of precipitation (from snow to rainfall during winter) and successive increase in snowmelt streamflow (pre-monsoon). Unlike annual streamflow, monthly streamflow is the most sensitive parameter to warm conditions, especially during winter (Thayyen and Gergan 2009; Liu et al. 2012). An increase in annual runoff by 7–12% by 2050 has been estimated because of accelerated snow melting with increasing precipitation (Lutz et al. 2014).

The consistent linear rise in predicted mean monthly streamflow with reference to the baseline would happen in response to 5% (S3), 10% (S4) and 15% (S5) increase in rainfall in the basin during 2015–2050 (Fig. 4). The increase in the predicted streamflow would be more pronounced in the monsoon months, which indicates that inconsistency in streamflow would increase with increasing rainfall by mid-twenty-first century. Rise in predicted mean monthly streamflow would vary from 1.9% to 16.5% under scenarios from S3 to S5 (Fig. 4). This also indicates that rainfall variation played a major role in increasing the streamflow in the study area, compared to air temperature. With the rise

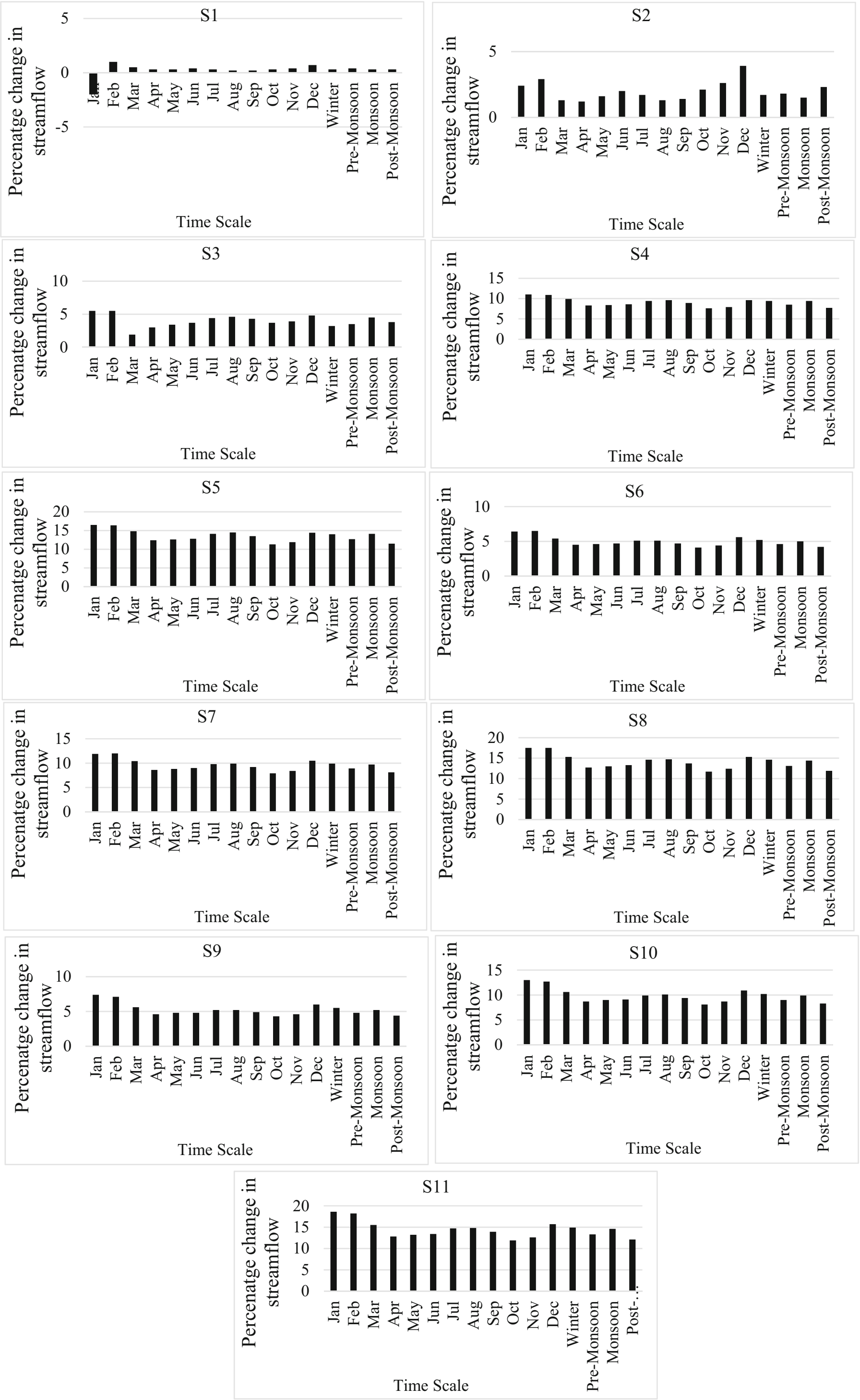

Fig. 4 Percentage change in predicted mean streamflow (2015–2050) with reference to baseline period (1974–2010)

in T_{mean} to 2 °C and 5%, 10% and 15% (S6 to S8) increase in rainfall, winter and monsoon months show the highest increase in the predicted mean streamflow during 2015–2050. Predicted mean monthly streamflow would vary from 5% to 14% under S6 to S8 scenarios in the basin. The rise in T_{mean} would lead to changes in the form of precipitation from snow to rainfall, resulting in lesser snowfall and snow-covered area. In addition, early melting of snow would also occur due to rise in T_{mean} in the basin. Both these factors lead to increase in the predicted mean streamflow in the basin during winter. Furthermore, the basin receives maximum rainfall during monsoon followed by winter, pre-monsoon and post-monsoon (Rani and Sreekesh 2017). This means that increases in rainfall have a major effect on the predicted mean streamflow during monsoon. Subsequently, predicted mean streamflow during winter and monsoon would increase in the basin under scenarios S6 to S8. An increase in surface runoff for the monsoon months with increasing rainfall intensities was also found in the upper Yamuna River basin during 2071–2100 (Narula and Gosain 2013). An increasing trend was also projected for surface runoff in summer monsoon in most central Indian River basins (Raje et al. 2014), Brahmaputra basin (Pervez and Henebry 2015) and sub-continental river basin of India (Mishra and Lilhare 2016).

With a rise in T_{mean} by 3 °C and an increase in rainfall by 5% to 15% in the scenarios (S9-S11), the mean monthly streamflow would increase by mid-twenty-first century (Fig. 4). Increasing predicted mean monthly streamflow would vary from 4.3% to 18.6% under these scenarios during 2015–2050. This shows that increase in streamflow is more prominent under these scenarios compared to the previous three scenarios (S6-S8) due to high increase in both T_{mean} and rainfall. The rise in T_{mean} would obviously lead to changes in precipitation from snow to rain that would lead to a decline in snow-covered area in the near future (2015–2050). At the same time, early snowmelt runoff will happen in the basin, which contribute to an overall increase in the predicted mean streamflow in the watershed.

The increase in predicted mean annual streamflow in the basin would vary between 0.31% and 1.66% under 2 °C and 3 °C rise in T_{mean}, respectively (Table 8). During 2015–2050, with a 5% increase in rainfall, the mean annual streamflow was predicted to increase to 3.9% and with a 10% and 15% increase in rainfall, average annual streamflow would rise by 9% and 13.5%, respectively (Table 8). With an increase in both T_{mean} and rainfall, annual streamflow would increase between 4.91% (S6) and 14.18% (S11) in the basin by mid-twenty-first century. In an extreme scenario of rise

Table 8 Change in mean annual streamflow with reference to baseline (1974–2010) under different climate change scenarios during 2015–2050

Climate change Scenarios	Mean Annual Flow (m^3/s)	% Change in Mean Annual Flow
Baseline	198.4	
S1	199.0	0.31
S2	201.7	1.66
S3	206.1	3.9
S4	216.4	9.07
S5	225.3	13.59
S6	208.1	4.91
S7	217.1	9.45
S8	226.1	13.98
S9	208.5	5.1
S10	217.5	9.65
S11	226.5	14.18

in rainfall and T_{mean}, predicted mean annual streamflow would increase between 13.5% (S5) and 14.1% (S11) in the basin (Table 8). Overall change in predicted mean annual streamflow in the basin ranged between 0.31% and 14.18%. Narsimlu et al. (2013) showed an increase of about 16.4% in mean annual streamflow by the mid-twenty-first century of the upper Sind River basin, and also indicated a drastic rise in streamflow in the monsoon. An increase in mean precipitation was projected to be 5.4, 5.6 and 12.7% that would bring an increase in mean runoff by 6.7, 11.3 and 19.1% in the Brahmaputra, Ganges and Meghna basin, respectively, by the mid of the twenty-first century (Masood et al. 2014), and a substantial increase in the streamflow in the Teesta River basin in eastern Himalaya was also reported (Singh et al. 2017).

The streamflow variation is minimal in the upper reaches of the basin, whereas the lower reaches of the basin are likely to experience maximum streamflow variations (Fig. 5). There are spatial variations in the pattern of changes in mean annual streamflow in the sub-basins under different climate change scenarios. Major rise in streamflow was observed in the sub-basins, located in the valleys as remaining sub-basins are snow-covered and have very low streamflow. Streamflow in the present study was found to be more sensitive towards precipitation changes. Mishra and Lilhare (2016) also found surface runoff more sensitive towards changes in precipitation of monsoon rather than air temperature in Ganga river basin.

The increasing streamflow in the study area due to rising air temperature and rainfall with varying magnitude by mid-twenty-first century would be beneficial for agriculture and hydro-power generation in the area. The increased water availability due to early snow melting would be helpful especially for irrigation. However, reduction in snow cover (Rani and Sreekesh 2016) and glacier (Kulkarni et al. 2005; Dutta et al. 2012) due to warming may increase streamflow in the near future, but this continuous decline will lead to reduction in the water availability possibly by the end of this century

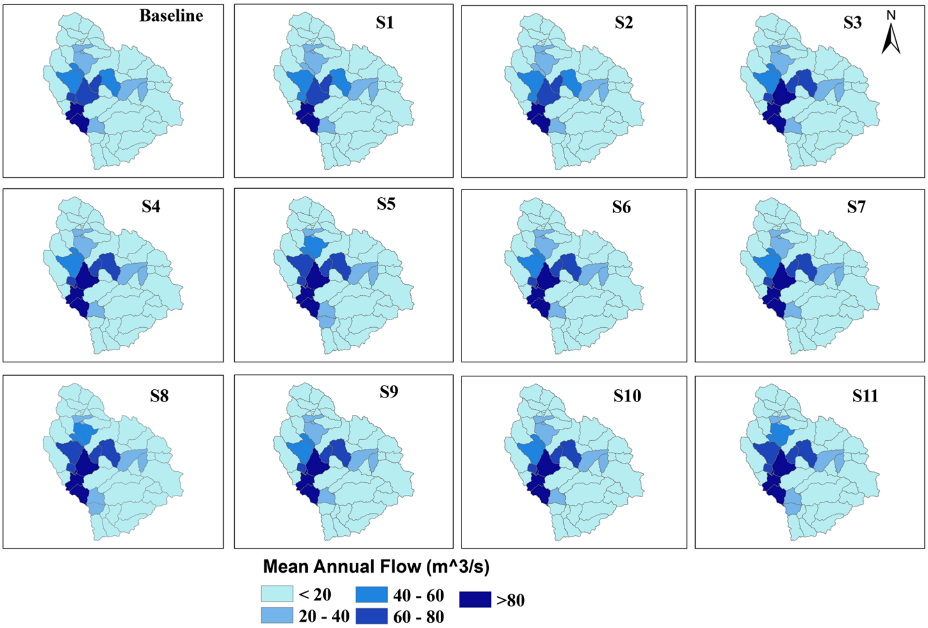

Fig. 5 Sub-basin wise baseline (1974–2010) and predicted (2015–2050) mean annual streamflow

(Nepal and Shrestha 2015). Although total annual water availability may rise in the short term, seasonal shift in streamflow will occur where there is shortfall in post-monsoon. The present study considered no change in land use in the near future but influence of land cover changes especially snow cover (due to snowfall reduction) and progression of agriculture as well as horticulture to higher altitudes on streamflow needs to be studied, because it is more sensitive towards changes in temperature. Uncertainty in the hydrological components of the basin in the present study needs to be considered because of lack of climate data at higher elevations, streamflow data, future climate situations, emission scenarios and errors/limitations. Hence, the interpretation of the model results in this study requires consideration of these uncertainties. Therefore, the study reiterates the need of regional water studies with a broader network of meteorological data for narrowing the uncertainties in the anticipation of future water resource availability (Barnett et al. 2005).

5 Conclusions

The present study found a warming trend in the basin during the study period. The rise in T_{mean} was at the rate of 0.031 °C/year in the basin during the study period, which may lead to about 1.27 °C rise in T_{mean} by mid-twenty-first century. This is coherent with the global air temperature changes. Although the magnitude of trends in the air temperature is not high, slight changes in the temperature in an area like the Himalaya, in the long run, can influence the availability of water resources. The study has found a rise in winter and pre-monsoon streamflow under rising temperature and stable rainfall. Monsoon streamflow will increase more if there is an increase in rainfall and temperature is stable. If both change simultaneously, winter streamflow will increase more due to the increase in snowmelt. The predicted increase in mean annual streamflow, with reference to baseline streamflow, in the upper Beas basin was found between 0.31% and 14.18% by mid-twenty-first century. The effect of climate change on streamflow was predicted to be more pronounced at the seasonal scale than the annual scale. Streamflow was found to be more sensitive towards changes in precipitation than air temperature. An increase in streamflow would mostly concentrate in the pre-monsoon months since it results from rise in temperature and rainfall. Hence, there will be a higher seasonal concentration of streamflow and lower flow conditions in other seasons, which in turn will affect the water availability in downstream areas. Increase in mean streamflow in the near future will be beneficial to the population. However, with the slow disappearance of snow cover, the consequent to the rise in temperature and change in the form of precipitation will be lesser streamflow in the latter half of this century. This will contribute to a decrease in water availability in the latter half of this century, which is a matter of concern.

Furthermore, assessments of climate change impact on water availability should be taken as indicative because of uncertainty in hydrological model application in the area like Himalaya. Climate projection is also a major uncertainty, which has a greater effect on the simulated streamflow in the future. Therefore, this study emphasizes the need of regional studies with finer meteorological data, snow/glacier properties and improved RCMs for understanding the climate-basin hydrological interaction in mountain areas under changing climate conditions and also for minimizing the uncertainties in computed future water resource availability.

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