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Statistical analysis of precipitation, temperature and snow cover in Bhagirathi River basin

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सार – गंगा नदी बेसिन दुनिया की सबसे बड़ी नदी बेसिनों में से एक है। भागीरथी बेसिन जो इस गंगा बेसिन का हिस्सा है, इसलिए महत्वपूर्ण है क्योंकि ग्लेशियर (गंगोत्री) जिससे गंगा नदी निकलती है, वह इसी बेसिन में स्थित है। वर्तमान अध्ययन भागीरथी बेसिन के हिम आवरण और जल विज्ञान व्यवस्था की गतिशीलता पर बदलते जलवायु प्रभाव को प्रस्तुत करता है। मोडिस, टीआरएमएम और कार्टोसैट डीईएम से रिमोट सेंसिंग उपग्रह डेटा का उपयोग किया जाता है और वाटरशेड चित्रण, बर्फ आच्छादित क्षेत्र निष्कर्षण, प्रवृत्ति और सहसंबंध विश्लेषण क्रमशः ArcGIS और R सांख्यिकीय सॉफ्टवेयर में किया जाता है। प्रवृत्ति विश्लेषण के परिणाम वर्षा के आंकड़ों में एक नकारात्मक औरकमजोर संबंध तथा तापमान के आंकड़ों में सकारात्मक लेकिन कमजोर संबंध दिखाते हैं। हालांकि, जब बेसिन में विभिन्न स्टेशनों के लिए सहसंबंध विश्लेषण किया गया, तो केंडल (0.93), स्पीयरमैन (0.99) और पियर्सन (0.99) विधियों के लिए वर्षा और तापमान डेटा के बीच एक मजबूत सकारात्मक सहसंबंध पाया गया। केंडल (0.04), स्पीयरमैन (0.06) और पियर्सन (0.07) विधियों के लिए भागीरथी बेसिन में अंतर्वाह और प्रतिशत हिम आवरण क्षेत्र के बीच एक कमजोर सहसंबंध पाया गया। अध्ययन के निष्कर्ष सांख्यिकीय रूप से वर्षा, तापमान और हिम आवरण क्षेत्र के आंकड़ों में एक अंतर्दृष्टि प्रस्तुत करते हैं। इसके अलावा यदि उप-बेसिन स्तर का अध्ययन किया जाता है तो डेटा की बेहतर समझ स्थापित की जा सकती है।

ABSTRACT. One of the world's largest river basins is the Ganga River basin. Bhagirathi basin which is part of this Ganga Basin is important because the glacier (Gangotri) from which river Ganga originates is situated in this basin. The present study presents the changing climate impact on dynamics of snow cover and hydrological regime of the Bhagirathi basin. The remote sensing satellite data from MODIS, TRMM and Cartosat DEM are used and watershed delineation, snow cover area extraction, trend and correlation analysis are performed in ArcGIS and R statistical software respectively. The results of trend analysis show a negative and weak association in precipitation data and positive but weak association in temperature data. However, when correlation analysis was done for different stations in the basin a strong positive correlation was found among the precipitation and temperature data for Kendall (0.93), Spearman (0.99) and Pearson (0.99) methods. A weak correlation was found between inflow and percentage snow cover area in the Bhagirathi basin for Kendall (0.04), Spearman (0.06) and Pearson (0.07) methods. The study findings present an insight into the precipitation, temperature and snow cover area data statistically. Further a better understanding of the data can be established if sub-basin level study is performed.

Key words – Remote sensing, Precipitation, Temperature, Snow cover, Kendall, Spearman, Pearson.

1. Introduction

Patterns of changing climate govern the human economies and cultures and play a vital role in shaping the natural ecosystem. The changing climate with disruptive impacts is progressing faster than any seen event in the last 2000 years. (WHO, 2018) Temperature and precipitation (rainfall and snowfall) are the main governing variables of climate and any change in their pattern and distribution will affect human health, ecosystems, flora and fauna. (Karmeshuand Frederick, 2015) Earth orbiting satellites and other technologically advanced sources which have collected data over many years revealed the signals of changing climate. Climate change has caused increased variability of precipitation events which has resulted in increased frequency of severe floods and droughts which has led to alterations in the seasonal variation, timing and magnitude of precipitation.

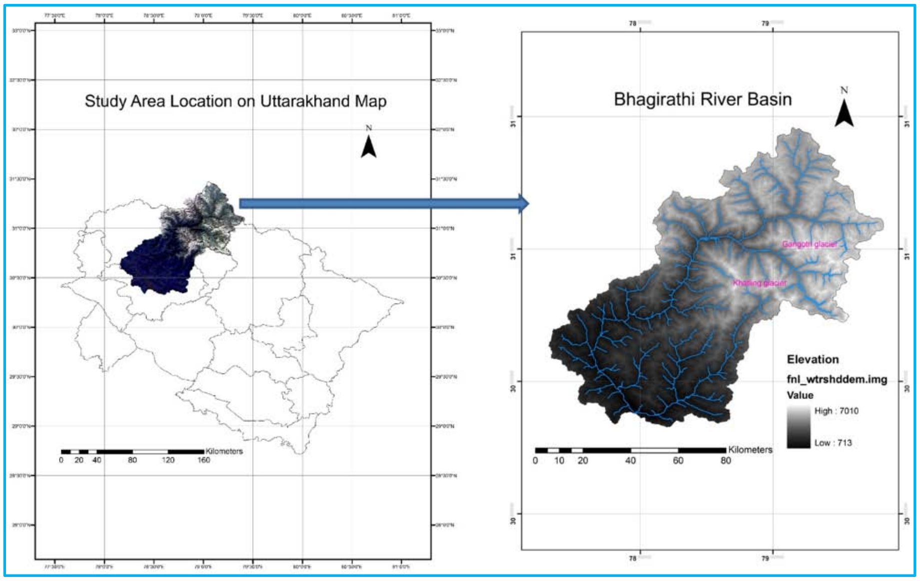

Fig. 1. Study area

(Onoz and Bayazit, 2002) The two variables, temperature and precipitation, governing the climate change are also interconnected in a way that any increase in Earth's temperature leads to more evaporation and cloud formation which in turn increases precipitation. The change in distributed patterns of precipitation and temperature are needed to be studied to access the impact of change on climate (Tabari *et al.*, 2011). To better understand the hydrological behavior of the basin preliminary analysis is a prerequisite. So, before going to hydrological modelling of the climate variables it is required to better understand them statistically. Correlation is a bivariate analysis that measures the strength of association between two variables and the direction of the relationship. Pearson correlation assumes variables should be normally distributed. Spearman rank correlation does not make any assumptions regarding the data. Studies of Sheng Yue and Paul Pillon have shown that rank-based tests should be applied for trend detection for their increased ability to detect trends (Yue *et al.*, 2002; Yue and Pillon, 2011). In order to better understand the hydrological regime of the basin under study various methods which have been suggested by researchers for trend and correlation analysis. The current study focuses on statistically studying the prevailing changes in precipitation (rainfall and snowfall) and temperature in Bhagirathi basin using readily available remote sensing precipitation (snow and rain) data and data products. (Hirsch and James 1984; Helsel and Hirsch, 2002; Reichl and Hack, 2017). Also, no comprehensive statistical study of the precipitation and temperature for studying the hydrological behavior has been carried out so far in the Bhagirathi basin (Negi and Purohit, 2012; Rautela *et al.*, 2002; SERB, DST status report, 2012).

2. Study area

The Bhagirathi basin which is a part of upper Ganga basin in lower Himalayas is taken up as study area. Tehri dam which is the highest dam in India is located on this Bhagirathi River at an elevation of 713 m above msl and withholds a reservoir of capacity 4 km^3. This multipurpose project caters water for irrigation, municipal water supply and generation of hydroelectricity. The mean annual discharge at Tehri Dam from entire Bhagirathi basin is 232.17 m/s^3 with minimum and maximum inflows of 81 m/s^3 and 998 m/s^3 respectively for the adequate working of the dam. The two major tributaries of Ganga River in the Bhagirathi basin are Bhagirathi and Bhilangana, which have their confluence at Tehri dam. Bhagirathi originates from Gaumukh (3,892 m elevation) at the foot of Gangotri glacier and Bhilangana originates from Khatling glacier (3,717 m elevation), situated south of Gangotri glacier (Fig. 1). The total area of the Bhagirathi basin is about 7208 m with elevation vary from 713m to 7010m above msl (seen as 'fnl_wtrshddem.img' in Fig. 1).

3. Data used

The climate and hydrological gauge data are taken from stations located within or close to the basin. There are two stations within the basin (Tehri and Uttarkashi) and one station close to the basin boundary (Rudraprayag)

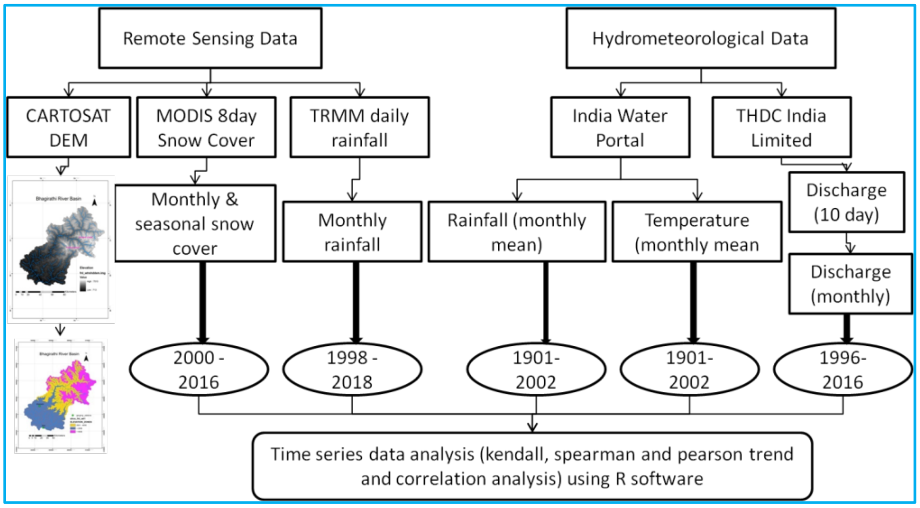

Fig. 2. Methodology

TABLE 1

Location of gauging and climate stations within the Bhagirathi Watershed

Station	Station type	Period of record	Basin Area, km^2	Mean flow, m^3/s	Annual total rainfall, mm
Tehri	Flow Gauging	2000-2017	7208	231.1	-
Uttarkashi	Climate	1901-2002	4555	-	1354 (fluctuating)
Tehri	Climate	1901-2002	7208	-	898 (fluctuating)

TABLE 2

Satellite data used

Satellite data used	Period of record	Data version	Sources
Cartosat DEM	2015	V3	BHUVAN portal
MODIS 8-day Snow Cover	2000-2016	MOD 10 A2 (V005)	https://search.earthdata.nasa.gov/
TRMM precipitation	1997-2017	3B42 (v7)	https://giovanni.gsfc.nasa.gov/giovanni

(Table 1). This clearly shows that the basin under study is a scarcely gauged basin and remote sensing data and data products can prove to be a reliable source for understanding the hydrological regime of this basin. The precipitation (snow and rain) data play an important role for the hydrological analysis. During the last decade, the precipitation data derived from remote sensing has been considered a reliable source for estimating the hydrological regime in ungauged or scarcely gauged basins of the Himalayas (Singh *et al.*, 2009; Yanming *et al.*, 2011; Zhang *et al.*, 2017). Also, hydro-meteorological study is essential in this high-altitude area where the precipitation occurs in the form of snow as well as rainfall. Therefore, remote sensing tools are a suitable approach to investigate cryosphere dynamics and its impact on the hydrological behavior of the Bhagirathi basin effectively and efficiently in this inaccessible area for better water resources management in the region (Navalgund *et al*., 2011).

Remote sensing satellite data obtained from different satellite sources is listed in Table 2. Cartosat DEM obtained from BHUVAN site of National Remote Sensing Agency (NRSA) is used for watershed and drainage

TABLE 3

Characteristics of the three elevation zones in the Bhagirathi Basin

Zones	Elevation range (m)	Mean Elevation (m)	Area (%)	Area (km^2)
1	<2000	1356	37.89	2767
2	2001-4000	3000	33.87	2473
3	>4000	5505	28.24	2062

delineation. MODIS 8-day snow cover available at NASA's earth data center, is used to obtain snow cover area in the Bhagirathi basin. Apart from this precipitation and temperature data are also collected from India Water Portal, which provides data for last 100 years (1901-2002). Precipitation data for the entire Bhagirathi basin is also obtained from TRMM precipitation data available at GIOVANNI. The reservoir inflow and outflow data were provided by Tehri Hydropower Development Corporation India Limited for the year 2000-2017 (inflow) and 2005-2017 (outflow).

4. Methodology

The overview of methodology followed is given in Fig. 2. From CARTOSAT DEM watershed is delineated and stream map is generated. Also watershed boundary map is prepared which is further used with MODIS 8-day snow cover data to extract 8-day snow cover for the Bhagirathi basin. From these data annual and seasonal percent snow cover area (%SCA) is obtained for years 2000-2016 and is further used for statistical analysis by Kendall, Spearman and Pearson. The entire basin is further divided into three elevation zones (Table 3) and snow cover area is extracted zone wise. It is found that major snow cover area lies in zone 3 (elevation> 4000m) and very less or no snow cover is present in lower zones 1 (elevation< 2000m) and 2 (2001m< elevation≤ 4000m).

TRMM precipitation data is compared with the precipitation data obtained from India Water Portal and is found to be in good agreement. All these data from different sources are prepared at month-wise timeframe and is analyzed statistically and correlation is found by Kendall, Spearman and Pearson methods in R statistical software. R is an integrated suite of software for data manipulation, calculation and graphical display.

Correlation is a bivariate analysis in statistics that measures the strengths of association between two variables. The value of the correlation coefficient varies between +1 and -1 where ±1 indicates a strong association while 0 indicates weak association between the variables. Usually, in statistics, we measure three types of

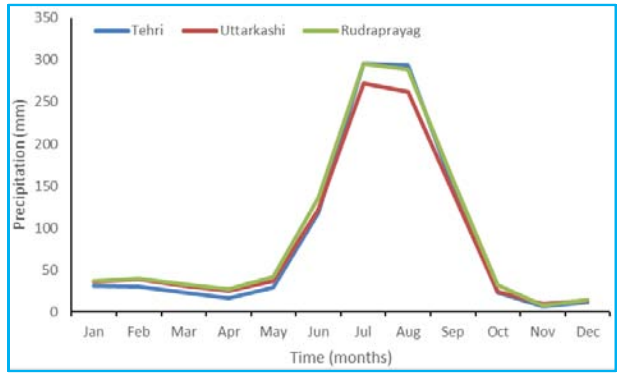

Fig. 3. Rainfall variation in the region governed by southwest monsoon rainfall

Correlations: Pearson correlation, Kendall rank correlation and Spearman correlation. Pearson r correlation is widely used in statistics to measure the degree of the relationship between linear related variables. For the Pearson r correlation, both variables should be normally distributed. Kendall rank correlation is a non-parametric test that measures the strength of dependence between two variables. Spearman rank correlation is a non-parametric test that is used to measure the degree of association between two variables. The assumptions of Spearman rho correlation are that data must be at least ordinal and scores on one variable must be monotonically related to the other variable (Karmeshu and Frederick, 2015).

A detailed correlation analysis is carried out between climate variables (precipitation and temperature), discharge (at the Tehri Dam) and snow cover dynamics based on remotely sensed MODIS snow cover data (MOD10A2) over a period of 10 years in the Bhagirathi Basin. Also, the spatial and temporal variations in snow cover are obtained and the correlation analysis between snow cover and stream flows on annual basis in Bhagirathi Basin at the Tehri dam reservoir.

5. Results and discussion

The time series trend analysis of the precipitation and temperature data is performed at different stations (Tehri, Uttarkashi and Rudraprayag) to understand the changing behavior of climate in the Bhagirathi Basin. These climate stations in Bhagirathi basin are situated at elevations of 742 m (Tehri) and 1127 m (Uttarkashi). The total annual precipitation received at Tehri is about 85 mm and at Uttarkashi is about 84 mm which is almost the same even though these stations are at different elevations. The entire Bhagirathi Basin is substantially influenced by the southwest monsoon rainfall (Fig. 3). The maximum rainfall occurs in the months of July - August during the southwest monsoons. However, this precipitation data

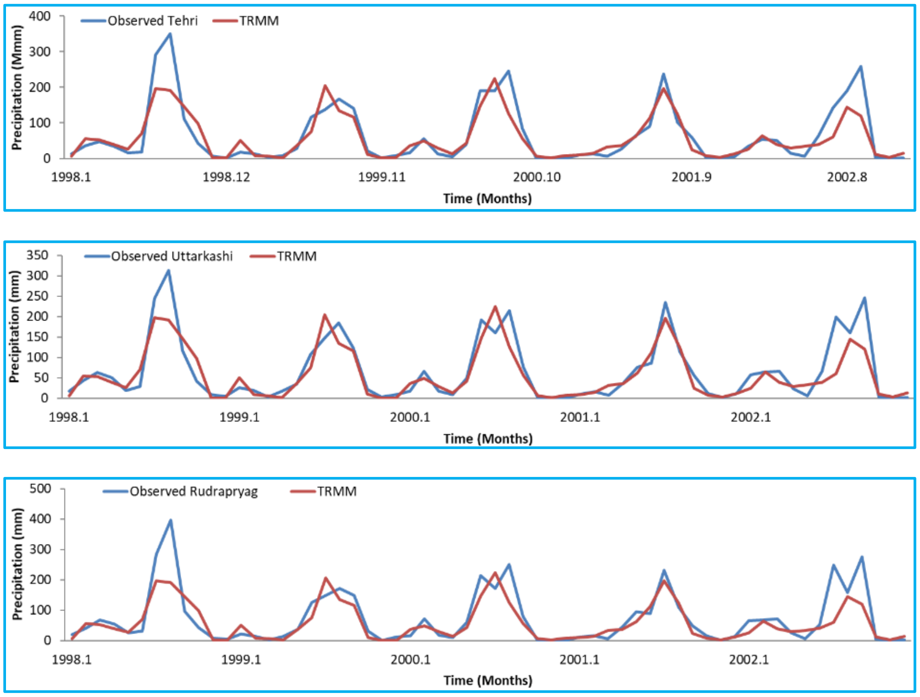

Fig. 4. Monthly variation of precipitation over 5-year period (1998-2002) for the climate stations in and around the Bhagirathi Basin

records are not the actual representation of the Bhagirathi River flows (Bhagirathi Basin) at Tehri Dam for the lack of adequate number of climate stations installed in the high altitudes of the basin. A hypothesis is made that the precipitation gauge observations from each station are able to provide the relative trend from one month to the next. Therefore, the correlation analysis is carried out on a monthly basis.

The lower and middle elevation zones (1 &2) of the basin are largely dominated by rainfall events and the higher elevation zone (3) part is dominated by snowfall events. The monthly variation of precipitation provided by India Water Portal at Tehri, Uttarkashi and Rudraprayag are shown in Fig. 3. Fig. 4 shows a comparison of precipitation data derived from India Water Portal and TRMM data sources, from 1998-2002 and one can see the TRMM data agrees well with the Tehri, Uttarkashi and Rudraprayag station data but under predicts the extreme rainfall events. Fig. 5 shows the variation of average temperature in the Bhagirathi basin for the period of 1901-2002 at Tehri, Uttarkashi and Rudraprayag.

Trend analysis of total monthly mean precipitation, maximum, minimum and average temperature is carried out using Kendall's tau (τ) trend test at Tehri, Uttarkashi and Rudraprayag climate stations of the Bhagirathi basin. The tau (τ) value and *p*-value derived for respective method and different climatological parameters are shown

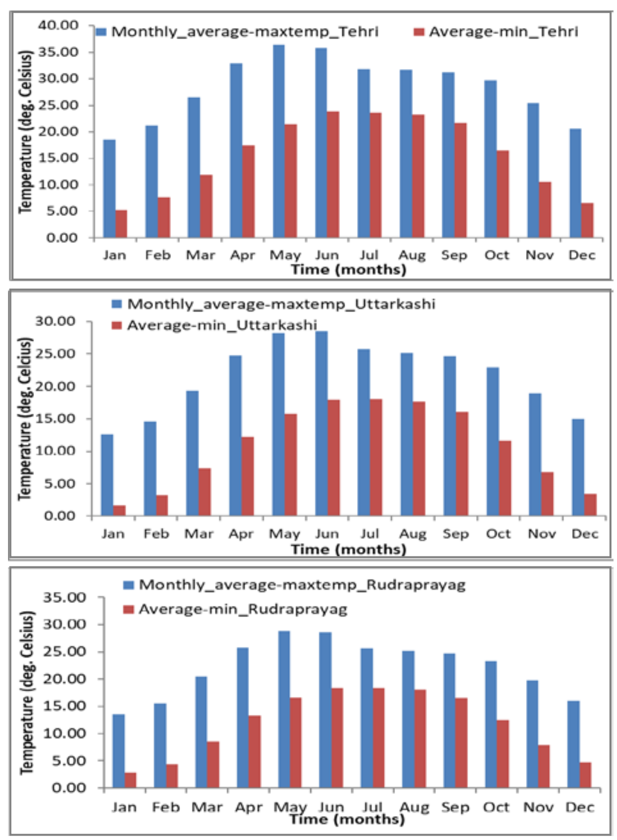

Fig. 5. Monthly average temperature variation at Tehri, Uttrakashi and Rudraprayag stations in and around Bhagirathi Basin

TABLE 4

Trend Analysis of different climatological parameters in Bhagirathi Basin

Parameters	Tehri		Uttarkashi		Rudraprayag	
	tau value	*p* value	tau value	*p* value	tau value	*p* value
Precipitation	-0.0003	0.9887	-0.005	0.7792	-0.011	0.5798
Max. Temp.	0.006	0.7398	0.011	0.5581	0.011	0.5536
Min. Temp.	0.011	0.5786	0.016	0.4117	0.016	0.4118
Avg.Temp.	0.121	0.0712	0.165	0.0140	0.156	0.0201

TABLE 5

Precipitaiton correlation coefficient between climate stations located in and around Bhagirathi Basin

Stations	Kendall			Spearman			Pearson		
	Tehri	Uttarkashi	Rudraprayag	Tehri	Uttarkashi	Rudraprayag	Tehri	Uttarkashi	Rudraprayag
Tehri	1.00	0.93	0.93	1.00	0.99	0.99	1.00	0.99	0.99
Uttarkashi	0.93	1.00	0.94	0.99	1.00	0.99	0.99	1.00	0.99
Rudraprayag	0.93	0.94	1.00	0.99	0.99	1.00	0.99	0.99	1.00

TABLE 6

Temperature correlation coefficients between climate stations in and around Bhagirathi Basin

Stations	Kendall			Spearman			Pearson		
	Tehri	Uttarkashi	Rudraprayag	Tehri	Uttarkashi	Rudraprayag	Tehri	Uttarkashi	Rudraprayag
Temperature (Maximum)									
Tehri	1.00	0.92	0.95	1.00	0.99	1.00	1.00	0.99	1.00
Uttarkashi	0.92	1.00	0.95	0.99	1.00	0.99	0.99	1.00	1.00
Rudraprayag	0.95	0.95	1.00	1.00	0.99	1.00	1.00	1.00	1.00
Temperature (Minimum)									
Tehri	1.00	0.96	0.95	1.00	1.00	1.00	1.00	1.00	1.00
Uttarkashi	0.96	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00
Rudraprayag	0.95	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Temperature (Average)									
Tehri	1.00	0.88	0.86	1.00	0.98	0.97	1.00	0.98	0.98
Uttarkashi	0.88	1.00	0.90	0.98	1.00	0.98	0.98	1.00	0.99
Rudraprayag	0.86	0.90	1.00	0.97	0.98	1.00	0.98	0.99	1.00

in Table 4. The Kendall tau (τ) values and *p*-values (shown in bracket) for total monthly mean precipitation are -0.0003 (0.9887), -0.005 (0.7792) and -0.011 (0.5798) respectively for Tehri, Uttarkashi and Rudraprayag. The tau (τ) values show that there is a negative trend and very weak association in the precipitation data at all the three stations. The Kendall tau (τ) values and *p*-values (in bracket) for maximum temperature are 0.006 (0.7398), 0.011 (0.5581) and 0.011 (0.5536) respectively for Tehri, Uttarkashi and Rudraprayag. The Kendall tau (τ) values and *p*-values (in bracket) for minimum temperature are 0.011 (0.5786), 0.016 (0.4117), 0.016 (0.4118) respectively for Tehri, Uttarkashi and Rudraprayag. And, for average temperature the Kendall tau (τ) values and

TABLE 7

Correlation coefficients for correlation analysis between precipitation and temperature by Kendall, Spearman and Pearson methods in the Bhagirathi basin

Kendall	Tehri_Tmax	Uttarkashi_Tmax	Rudraprayag_Tmax	Tehri_Tmin	Uttarkashi_Tmin	Rudraprayag_Tmin
Tehri_P	0.203	0.242	0.208	0.394	0.391	0.380
Uttarkashi_P	0.208	0.245	0.212	0.394	0.389	0.379
Rudraprayag_P	0.220	0.257	0.223	0.404	0.400	0.389
SPEARMAN	Tehri_Tmax	Uttarkashi_Tmax	Rudraprayag_Tmax	Tehri_Tmin	Uttarkashi_Tmin	Rudraprayag_Tmin
Tehri_P	0.353	0.410	0.362	0.599	0.593	0.579
Uttarkashi_P	0.358	0.410	0.365	0.594	0.587	0.574
Rudraprayag_P	0.376	0.428	0.382	0.607	0.600	0.586
PEARSON	Tehri_Tmax	Uttarkashi_Tmax	Rudraprayag_Tmax	Tehri_Tmin	Uttarkashi_Tmin	Rudraprayag_Tmin
Tehri_P	0.316	0.377	0.333	0.572	0.575	0.559
Uttarkashi_P	0.316	0.374	0.330	0.566	0.566	0.551
Rudraprayag_P	0.326	0.384	0.340	0.573	0.574	0.558

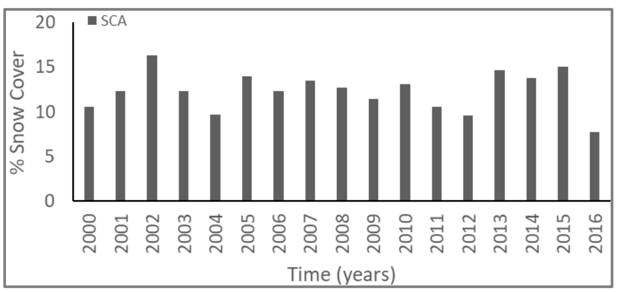

Fig. 6. Basin wide Average % Snow Cover Area variation in Bhagirathi basin (2000-2016)

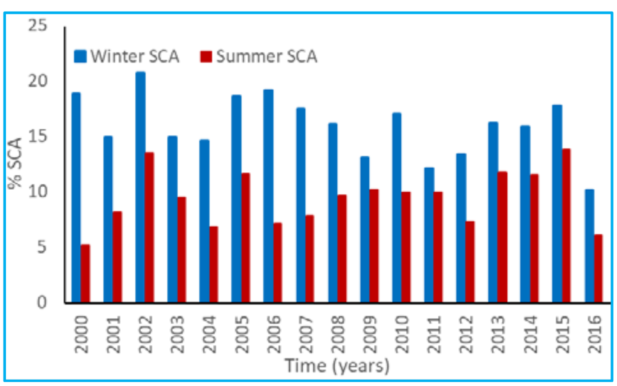

Fig. 7. Seasonal % SCA variation in Bhagirathi basin (2000-2016)

p-values (in bracket) are 0.121 (0.0712), 0.165 (0.0140), 0.156 (0.0201) respectively for Tehri, Uttarkashi and Rudraprayag. All these tau (τ) values for temperatures show a positive trend and very weak association present in the data at stations in Bhagirathi basin. The variations in temperatures (minimum and maximum) at these stations (Tehri, Uttarkashi and Rudraprayag) indicate that the runoff in the Bhagirathi basin is controlled by seasonality of the temperature (minimum and maximum) and melting of the seasonal snow due to rise in temperatures during summers.

Further, correlation analysis was performed using Kendall, Spearman and Pearson methods on precipitation and temperature data and the results are shown in Table 5 and Table 6 respectively. It is found that a strong and positive correlation exists among the climate stations present in and around the study area for climate variables of precipitation (Table 5) and temperature (Table 6). The coefficients range from 0.93 to 1.0 for precipitation and 0.86 to 1.00 for temperature. This indicates that the regionhas a well distributed variation in precipitation and temperature.

However, when the correlation analysis was performed between precipitation and temperature data by Kendall, Spearman and Pearson methods at climate staions (Tehri, Uttarkashi and Rudrapryag) present in the Bhagirathi basin to obtain the correlation coefficients (Table 7), it was found to have week correlation. The correlation coefficients (ranges from 0.2 - 0.6) obtain shows that there is weak but positive correlation between precipitation and maximum and minimum temperature data for all the three methods used. The positive correlation means that as one variable increase or decreases the other also tends to increase or decrease. A

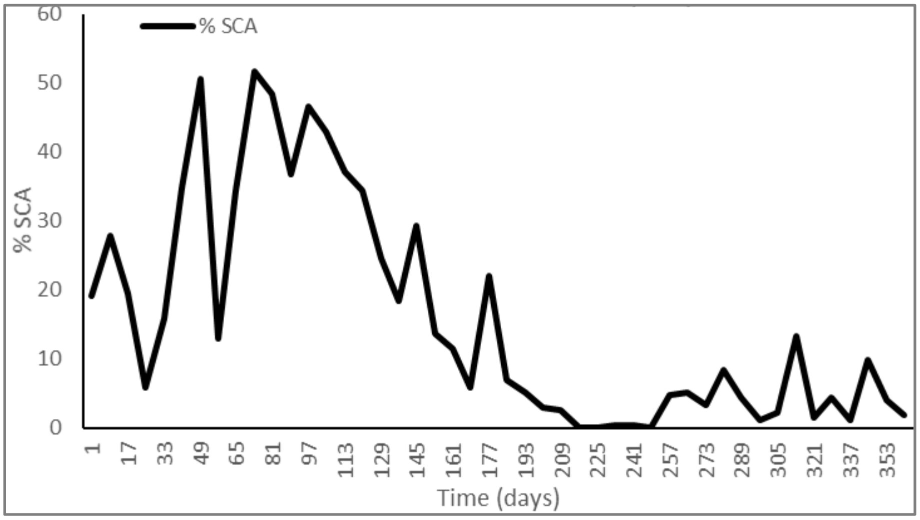

Fig. 8. Daily variation of SCA over the year 2015

TABLE 8

Correlation Analysis for seasonal Snow Cover Area (SCA)

S_SCA	Kendall		Spearman		Pearson	
	Winter	Summer	Winter	Summer	Winter	Summer
Winter	1.00	0.22	1.00	0.27	1.00	0.34
Summer	0.22	1.00	0.27	1.00	0.34	1.00

TABLE 9

Correlation analysis for SCA and inflow at the Tehri dam resservoir

Inflow-SCA	Kendall		Spearman		Pearson	
	Total-Inflow	SCA	Total-Inflow	SCA	Total-Inflow	SCA
Total-Inflow	1.00	0.04	1.00	0.06	1.00	0.07
SCA	0.04	1.00	0.06	1.00	0.07	1.00

significant correlation is found between the climate stations (Tehri and Uttarkashi) and at the neighboring Rudraprayag station for the minimum, maximum and mean temperature.

The yearly and seasonal variation of % SCA is shown in Figs. 6&7. It is found that the basin receives maximum snowfall during the months of February and March. Trend analysis for percentage seasonal Snow Cover Area (SCA) for the Bhagirathi basin by Kendall, Spearman and Pearson methods is shown in the Table 8. The trend coefficients were found to be 0.22 (Kendall), 0.27 (Spearman) and 0.34 (Pearson). The trend analysis of (SCA) shows a positive trend and weak association in the snow cover data extracted from MODIS data product. Further a correlation analysis was performed between percentage SCA and discharge in the Bhagirathi basin by Kendall, Spearman and Pearson methods (Table 9). The correlation coefficients obtained are 0.04 (Kendall), 0.06 (Spearman) and 0.07 (Pearson). The correlation coefficient obtained shows a very weak association and positive trend in the data. This indicates that percentage snow cover area has substantial contribution towards discharge in the basin due to its long melting time. The snow cover area depletes continuously as the mean temperature of the basin increases during the summer and contributes to stream flows. The zone 3 (elevation > 4000 m) is the most active zone in terms of availability of snow cover because of the presence of two major glaciers, Gangotri and Khantling. The Snow Cover Area (SCA) falls from 100% in winters (February-March) to 20% in summers (May- June) which indicates that snowmelt contributes significantly to runoff in this high elevation zone area. This zone is also responsible for the shifting of winter precipitation (snowfall) to runoff during summers. There are some variables which are important in influencing the river discharge, like sublimation, evapotranspiration, debris-free glaciers and melting permafrost, but these factors are not considered in this study.

6. Conclusions

This paper investigates the precipitation pattern in Bhagirathi basin, over a period of 20 years using time series analysis through R software. Snowfall pattern were evaluated season wise while both rainfall and temperature pattern were evaluated month wise. This study touches an important aspect of climate factor and hydro economics of the region and following conclusion can be drawn from this study:

(*i*) Use of TRMM precipitation data can efficiently addressed the scarcely gauged problem in the basin.

(*ii*) The trend analysis of precipitation data indicates a negative and weak association among the three stations while the trend analysis of temperature data indicates a positive and weak association.

(*iii*) The correlation analysis between the stations indicates that the region has a well distributed variation in precipitation and temperature. Also, the correlation analysis between precipitation and temperature indicates weak but positive correlation between them.

(*iv*) The correlation analysis between SCA and discharge in the basin indicates a positive and weak association between them. this indicates that melting snow has considerable contribution towards discharge in the basin.

The findings of this study have presented an understanding of temporal variations of precipitation and temperature which lead to variation in climate. However further study is required at sub-catchment level using longer time series of precipitation and temperature to forecast future scenarios. Modeling and simulation-based study shall be performed to understand the climate variation and impact on flora and fauna of the region.

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