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Hydro-Meteorological Data Consistency, Trend Detection, and Network Evaluation in the Upper Ganga Basin under a Changing Climate

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Abstract

The Himalayan region strongly influences India's climate and hydrology and serves as a major source of water for the Indo-Gangetic plains through rainfall, snowmelt, and glacial melt. Reliable long-term hydro-meteorological data are essential for effective water resources planning and climate change assessments. This study analyses hydro-meteorological data from the India Meteorological Department and the Central Water Commission for the Upper Ganga Basin (UGB) up to Rishikesh, using data validation, trend analysis, and network assessment techniques.

Spatial homogeneity analysis identified 24 abnormal rainfall events during 1972–2016, while double-mass curve analysis revealed significant inconsistencies at 8 of 30 stations. Trend analysis indicates an overall increase in precipitation during the monsoon season and at the annual scale across the UGB. Increasing trends in the number of rainy days were observed at several stations during the pre-monsoon and monsoon seasons. In contrast, decreasing trends were observed during the winter and post-monsoon seasons. Trends in temperature and river flows were also evaluated.

The hydro-meteorological network assessment indicates that the existing station network is generally adequate for capturing rainfall variability; however, reactivation of discontinued stations is recommended in accordance with WMO guidelines. Entropy analysis identified potential locations for new observation stations. Evaluation of gridded and reanalysis datasets showed that GPM-IMERG satisfactorily represents monthly precipitation over the UGB and can serve as a suitable alternative dataset. In contrast, ERA5-Land and IMDAA datasets exhibit a significant cold bias and underestimate local temperatures in the Himalayan region, limiting their direct applicability for local-scale temperature studies.

1.0 Introduction

The first important task in the entire hydrological analysis of a river basin is the collection of accurate, reliable, and consistent hydrological and hydro-meteorological data. In mountainous areas, significant variation in altitude, slope, aspect, soil, and land-use characteristics over short distances requires a high-density hydrometric network to reliably assess water resources. However, due to various operational problems, a proper hydro-meteorological network is not available in mountainous regions. Further, there is widespread concern about global climate change and its impact on various hydrological variables. This impact is not uniform globally, and mountainous regions are considered to be more susceptible to climate change (IPCC, 2007). Many organisations are involved in India in the collection of hydrological and meteorological data, and it becomes important to integrate the data related to different hydro-meteorological variables (say, precipitation, temperature, river flow, groundwater levels, etc.) in a database so that a comprehensive analysis of hydrological variables can be carried out. In addition to point observations, many satellite platforms (such as Resourcesat, Cartosat, MODIS, TRMM, APHRODITE, etc.) are providing spatial information across various observation windows, some of which are available online in the public domain. This information can be used in hydrological analysis for various purposes.

Ecological and hydro-meteorological data are unavailable in many Himalayan regions. Further, the station data also has consistency issues and missing records. Thus, it is quite complex to process data to determine various hydrological and ecological variables in the Himalayan region. Raw hydrologic data is not generally used; it is preferred to process the data to evaluate its accuracy. In this study, the Surface Water Data Entry System (SWDES), developed under Hydrology Project – I (DHV Consultants et al., 1999), and the HYMOS software (Delft Hydraulics, 1999) have been used for entry and processing of the hydrological database for the Upper Ganga basin up to Rishikesh.

Understanding average estimates and trends of water-related variables is crucial for assessing the potential impact of a changing climate on various hydrological processes for sustainable water management. Some studies have been carried out in the Indian Himalayan basins, which have documented trends in temperature, precipitation, snow cover area, and river flows. With respect to precipitation, there are no consistent or statistically significant future projections for the Himalayan region, although localised and seasonal trends have been observed (Shrestha, Wake, Dibb, & Mayewski, 2000). Precipitation is projected to increase by the end of the century in the Indus (Immerzeel et al., 2010), Ganges (Kumar et al., 2011) and Brahmaputra (Immerzeel, W. 2008) basins, although the magnitude of change varies from basin to basin. Shrestha et al. (2012) have prepared a pan-Himalayan view of the widespread trends in seasonal and annual precipitation across different eco-regions of the Himalaya. In most of the Himalayan arc, the authors predict that precipitation in the fall and winter seasons is declining, though a reverse trend is observed in the summer season. Further, annual precipitation also shows an increasing trend (of varying magnitude), except in the extreme north-eastern part of the Himalaya. Mixed trends in annual and seasonal rainfall have been observed at various stations in the Uttarakhand region by Singh and Mal (2014). In the Kashmir region, annual precipitation and the number of rainy days show a decreasing trend, though the rate of decrease varies considerably across stations (Kumar et al., 2013). Using data from 14 precipitation stations in the Chenab basin from 1975 to 2000, Arora et al. (2003) observed an increasing trend.

The temperature trends in the Himalayas have been studied in parts by some researchers. The upper Indus basin shows an increasing temperature trend over the past 50–100 years, although the trends are not homogeneous (Bhutiyani, Kale and Pawar, 2007). In the Ganges basin, there is a consistent increase in temperature with altitude (You et al., 2010). Shrestha *et al*. (2012) prepared a pan-Himalayan view of widespread trends of seasonal and annual temperature in different eco-regions of the Himalaya and inferred an increase in temperature in the spring season in the western part of the Himalaya (Central to western part), while the increase is more pronounced in the winter season in the Central to Eastern part of the Himalaya.

Glacier-melt runoff provides about 40% of total streamflow in the Upper Indus basin and about 10% in the Ganges basin (Immerzeel et al., 2010). Lutz et al. (2014 projected an increase in runoff at least until 2050, caused primarily by increasing precipitation in the Ganges and Brahmaputra basins and accelerated melt from the Indus basin. Singh & Bengtsson (2004) opined that changes in seasonal flow and its peak distribution may be more crucial than annual changes. Diminishing trends in seasonal flows in the Tawi River in the Jammu region have been observed by Kumar et al. (2013), while Arora et al. (2013) have observed decreasing trends in annual

flows in the upper parts of the Satluj basin. However, increasing flow trends have been observed in the upper parts of the Chenab basin (Arora et al., 2003).

It is well known that the density of hydro-meteorological stations is sparse over the mountainous terrain of the Himalayas. Further, harsh climatic conditions pose challenges for maintaining high-quality data records. Therefore, data scarcity, due to various reasons, is a major obstacle to analysing hydro-meteorological dynamics vis-à-vis the changing climate. With advances in technology, manual intervention and station-based data recording have been overcome to a greater extent, and an array of global gridded products has been developed by researchers worldwide using sophisticated techniques. Besides, satellite-based remotely sensed products have become increasingly available over the past few years. Openly available global datasets are easily accessible and have been widely used in a number of studies (Bharti et al., 2016; Ciabatta et al., 2016; Beria et al., 2017; Parida et al., 2017). Though the importance of station observations cannot be ignored, global estimates are useful for understanding historical climate and its changes over time, as well as for real-time applications. Some widely used open datasets from various sources include: CHIRPS, PERSIANN, PERSIANN-CCS, PERSIANN-CDR, SM2RAIN-CCI, APHRODITE, APHRODITE-2, CMORPH, MSWEP, GSMaP, TRMM-3B42, and GPM-IMERG. These datasets cover different time frames and have been developed using different techniques/ algorithms. Given the scarcity of data in the Himalayan region, it is important to evaluate the global datasets available from various satellite and other sources.

2.0 Description of Study Basin

The present study focuses on the Upper Ganga Basin (UGB) up to Rishikesh in the Indian Himalayan Region. The Ganga River Basin is one of the largest river basins in the world, covering nearly 1.086 million km² across India, Nepal, China, and Bangladesh. The basin supports a population exceeding 500 million and plays a vital role in the water, agriculture, and energy security of northern India.

The UGB extends between 29°45′N and 31°27′N latitude and 78°09′E to 80°15′E longitude, covering an area of approximately 21,763 km². The basin is predominantly mountainous, with elevations ranging from about 333 m near Rishikesh to over 7500 m in the higher Himalayan regions. Most of the basin lies within the state of Uttarakhand, while a small portion extends into the Kinnaur district of Himachal Pradesh. Rugged mountains, deep valleys, glaciers, snow-covered regions, and dense river networks characterise the terrain.

The basin's climate ranges from subtropical in the lower elevations to alpine conditions in the higher reaches. Annual precipitation ranges from about 550 mm to 2500 mm, strongly influenced by topography and the southwest monsoon. Most rainfall occurs during June–September, while higher elevations receive substantial snowfall during winter. Orographic effects drive significant spatial variability in precipitation across the basin.

The Upper Ganga Basin comprises two major Himalayan headwater systems: the Bhagirathi and the Alaknanda rivers (Figure - 1). The Bhagirathi River originates from the Gangotri Glacier near Gomukh at an elevation of about 3892 m, while the Alaknanda River originates from the Satopanth and Bhagirath Kharak glaciers at elevations around 4800 m. These two rivers merge at Devprayag to form the River Ganga, which subsequently flows through Rishikesh and enters the Indo-Gangetic plains at Haridwar. The Bhagirathi sub-basin covers approximately 8847 km² and includes major tributaries such as the Bhilangana and Asiganga rivers. The Alaknanda sub-basin covers about 11,065 km² and includes major tributaries, including the Mandakini, Pindar, Nandakini, and Dhauliganga. Streamflow in both river systems is sustained by monsoon rainfall, snowmelt, glacier melt, and groundwater contributions.

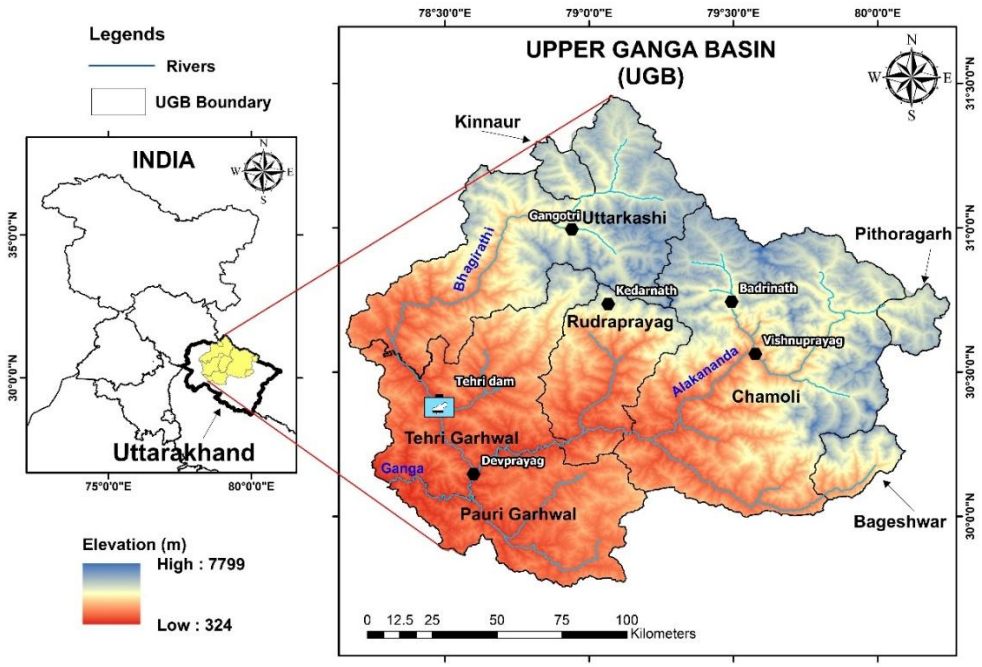


Figure - 1: Study Area Map of the Upper Ganga Basin Showing Topography and Drainage Network

The basin contains several important hydropower and water resources projects, including the Tehri Dam, located on the Bhagirathi River, one of the tallest dams in India. Owing to its complex terrain, climatic variability, glacial influence, and hydrological significance, the UGB is highly sensitive to climate change and extreme hydro-meteorological events, making it an important region for hydro-climatic investigations.

3.0 Preliminary Data Analysis

The preliminary data analysis for the Upper Ganga Basin (UGB) involved a comprehensive approach to developing a robust hydro-meteorological database, integrating observations from the India Meteorological Department (IMD) and the Central Water Commission (CWC). The initial dataset comprised long-term precipitation and temperature data from 47 IMD stations, of which 30 demonstrated sufficient continuity for subsequent analysis spanning from June 1972 to May 2016. Concurrently, CWC provided multi-parameter data, including rainfall, temperature, river discharge, cross-section geometry, and water quality, from 15 streamflow gauging sites and 11 meteorological stations. Access to restricted flow data from CWC was secured under specific project authorisation. The spatial distribution of IMD and CWC stations within and around the UGB is crucial for understanding the representativeness of the data: IMD stations predominantly cover precipitation and temperature, while CWC stations provide a broader suite of hydrological parameters. The locations of these IMD stations in the UGB are shown in Figure - 2. Stream network in the UGB showing major rivers and the location of CWC gauging sites is shown in Figure - 3.

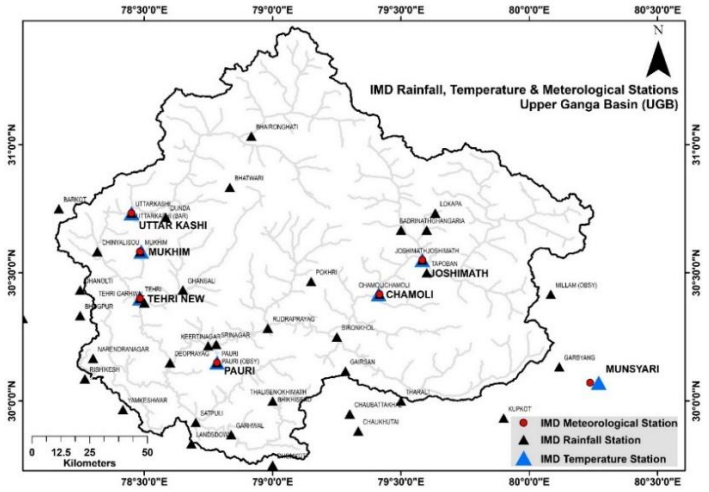


Figure - 2: IMD hydro-meteorological stations in/around the UGB



Figure - 3: CWC gauging stations in/around the UGB

Data processing adhered to standardised protocols, notably the Ministry of Jal Shakti's Manual on Rainfall Data Processing (DoJS, RD & GR, 2019). Primary data validation was performed using SWDES-3.0, a software developed under the World Bank Hydrology Project–I, while secondary validation and spatio-temporal integration were performed using HYMOS software from Delft Hydraulics. An assessment of data availability revealed that many IMD stations, though some were initiated in the early 20th century, often had sparse and discontinuous records, with many ceasing operations by the century's end. Conversely, most CWC stations, primarily established in the 1970s, exhibited greater continuity and fewer gaps. Consequently, a uniform analytical period from June 1972 to May 2016 was established, retaining only stations with ≥70% data completeness. This selection resulted in 19 IMD and 11 CWC precipitation stations being included for detailed data processing.

Correlation analysis was carried out, and correlated stations were identified, enabling the data from these stations to be used for data validation and to fill in missing period records. For this purpose, a correlation matrix was developed among all selected stations to identify those stations with similar rainfall characteristics. The correlation functions indicate similarities in the mechanisms that cause a phenomenon to exhibit. These functions use the covariance, defined as the expectation of the product of the respective deviations from their means. Cross-correlation is the normalised covariance (= correlation) between two stochastic variables, defined as the covariance divided by the product of the standard deviations of each series. The covariance between two stochastic variables is calculated as:

$$C(x_{1,}x_2) = \frac{1}{n-1}\sum_{i=1}^{n}\{[Z(x_{1,i}) - m_1][Z(x_{2,i}) - m_2]\} \quad \ldots(1)$$

where 'm' is the mean of Z(x) and 'n' are the number of measurements. The sample estimates $S(x_i)$ for the population standard deviation are computed as:

$$S(x) = \frac{1}{n-1}\sum_{i=1}^{n}[Z(x_1) - m_1]^2 \quad \ldots(2)$$

The equation for computing the sample correlation coefficient is:

$$r(x_{1,}x_2) = \frac{C(x_{1,}x_2)}{S(x_1)^* S(x_2)} \quad \ldots(3)$$

Using the 'Spatial Correlation' function of HYMOS, the correlation coefficients among different rainfall stations were worked out in the form of a correlation matrix, such that higher values of correlation coefficient for a station with surrounding stations represent identical precipitation characteristics. In addition, a distance matrix among stations was generated, representing the mutual spatial distances among them. For a particular station, the correlated stations are identified as those with a high correlation coefficient (e.g., >= 0.7) and located in close vicinity of the base station (e.g., within 70 km). Using these conditions and based on the availability of data series, correlated stations for selected 30 base stations were identified as given in Table 1.

Table – 1

Identified correlated stations for selected precipitation stations of IMD/CWC in UGB

S. No.	Base Station	Correlated Stations
1	Bhatwari	Dhanolti, Keertinagar, Mukhim, Tehri, Uttarkashi
2	Bhogpur	Keertinagar, Pauri, Narendranagar, Mukhim
3	Bironkhol	Mukhim, Pauri, Tehri
4	Chamoli	GG260A1, Keertinagar, Okhimath
5	Devprayag	GG100A1, GG260J4, Srinagar
6	Dhanolti	Bhatwari, Dunda, Tehri-Garhwal, GG000Y4
7	Dunda	Dhanolti, Tehri, Tehri-Garhwal, Mukhim, GG100K4, Keertinagar
8	GG000Y4- Rishikesh	Narendranagar, Keertinagar, Lansdowne
9	GG100A1- Devprayag	GG260A1, GG200D3, GG200G5
10	GG100K4- Uttarkashi	Uttarkashi, Tehri, Mukhim, Dunda
11	GG110A1- Koteshwar	Tehri, Tehri Garhwal, GG200D3, GG000Y4
12	GG200B5- Srinagar	Srinagar, Pauri, Thalisen, Dhomkot
13	GG200G5- Rudraprayag	Mukhim, Tehri, GG260J4, GG260A1, Gg100A1
14	GG200S3- Joshimath	Rudraprayag, Srinagar, GG260J4
15	GG200V5- Badrinath	No relation
16	GG260A1- Karanprayag	Keertinagar, Lansdowne, GG260J4, Chamoli
17	GG260J4- Nandkeshari	Rudraprayag, GG260A1, GG200S3, GG200G5
18	GGZ00D3- Marora	Keertinagar, Narendranagar, GG260A1, GG100A1
19	Joshimath	Okhimath
20	Keertinagar	GG260A1, Dunda, GG000Y4
21	Lansdowne	GG000Y4, GG260A1, Keertinagar, Mukhim, Tehri-Garhwal
22	Mukhim	Keertinagar, Tehri-Garhwal, GG100K4, GG200G5

S. No.	Base Station	Correlated Stations
23	Narendranagar	GG000Y4, GG100K4, Keertinagar
24	Okhimath	GG260A1, GG100K4
25	Pauri	GG200B5
26	Rudraprayag	GG200S3, GG200D3, GG260A1, GG260J4
27	Srinagar	Pauri, Tehri, Lansdowne, GG100A1
28	Tehri	Tehri-Garhwal, GG100K4
29	Tehri-Garhwal	Dunda, GG260A1, Tehri
30	Uttarkashi	GG100A1, GG100G4, Mukhim

Following gap-filling, a spatial homogeneity test was conducted to identify outliers within the precipitation data. This test involves estimating rainfall at a given station as an inverse-distance-weighted average of observations from its correlated neighbours. Discrepancies between observed and estimated values exceeding ±3 standard deviations (based on the residual distribution) were flagged as suspect. Notable outliers were identified at stations such as Chamoli (1991, 2012, 2016), Mukhim (1995), Narendranagar (1990, 1999, 2012), and several CWC stations (e.g., GG000Y4, GG100A1). Given the rugged, undulating terrain of the Himalayan region, where rainfall can exhibit significant spatial variability over short distances, these anomalies were treated as candidates for manual verification rather than automatic rejection. The complex topography of river basins, particularly in mountainous regions like the UGB, significantly influences rainfall patterns, making accurate data collection and validation challenging.

Finally, the temporal consistency of the rainfall records was assessed using a double mass curve (DMC) analysis. This technique evaluates whether the location and exposure conditions of a rain gauge station have changed significantly over its period of record, which could introduce inconsistencies due to altered rainfall capture conditions or other factors, such as station relocation or observational errors. For each station, cumulative annual rainfall was plotted against the cumulative mean annual rainfall from its correlated neighbour group, ordered in reverse chronological sequence. A breakpoint in the slope of the resulting plot indicates a change in the precipitation regime at the test station. Eight stations exhibited statistically significant breakpoints ($p < 0.01$, Chow test, including Dhanolti (1986), Lansdowne (1996), Uttarkashi (1999), Srinagar-CWC (1985), Badrinath-CWC (2003), Karanprayag-CWC (1991), Marora-CWC (2000), and Nandkeshari-CWC (2006). These breakpoints indicated regime shifts likely attributable to instrumentation changes, relocation, or micro-environmental alterations. To ensure homogeneity, pre-breakpoint records were adjusted using the pre-change slope, as defined by Equation 4

$$P_X(i) = m \times C_A(i) - C_X(i-1) \quad \ldots(4)$$

This rigorous process of consistency correction ensures that the final dataset accurately reflects rainfall observations throughout the 1972–2016 period, laying a solid foundation for subsequent trend, frequency, and hydrological modelling analyses. Such meticulous data preparation is foundational for reliable climate change impact assessments on hydrometeorological extremes

4.0 Trend analysis of rainfall in UGB

The precipitation and temperature are the two major influential variables in the hydrological and climate change studies. The trend analysis of processed and gap-filled data of 30 rainfall stations of IMD and CWC from June 1972 to May 2016 was carried out in the UGB at monthly, seasonal and annual time scales.

Two widely used non-parametric tests (Bisht et al. 2017; Dhage et al. 2016; Jena et al. 2014; Pingale et al. 2014; Taxak et al. 2014; Duhan and Pandey, 2013; Kumar and Jain, 2011; Basistha et al., 2009; Partal and Kahya, 2006), namely, Mann-Kendall and Theil-Sen's estimator, were used for detecting the trend and change in the magnitude in time series data. Mann-Kendall (Mann 1945; Kendall 1948) is a rank-based test. However, the trend detection is reported to be affected by the presence of negative or positive autocorrelation in the time series (Hamed and Rao 1998; Yue et al. 2002), and pre-whitening is often employed to detect the trend in serially

autocorrelated time series (Cunderlik and Burn 2004; Machiwal and Jha 2016). Yue et al. (2003) reported that pre-whitening reduces the detection rate of significant trends in the Mann-Kendall test that are inherent in the time series dataset. Therefore, the Modified Mann-Kendall test (Hamed and Rao 1998; Rao et al. 2003) was employed for detecting trends in autocorrelated time series, which is otherwise expected to protect the required correlation within the dataset. Theil-Sen approach (TSA) (Theil 1950; Sen 1968) is used to determine the magnitude of change. The trend results for all stations have been summarised in Table - 2.

Table – 2

Results of trend analysis of rainfall amount at various stations of IMD/CWC in UGB

Z - statistic	Shade	Trend at different confidence levels
Z >= 1.96		Significant increasing trend at 95% confidence level
Z >= 1.645 & < 1.96		Significant increasing trend at 90% confidence level
Z < 1.645		No significant trend
Z <= - 1.96		Significant decreasing trend at 95% confidence level
Z <= - 1.645 & Z > - 1.96		Significant decreasing trend at 90% confidence level
Z > - 1.645		No significant trend

Station	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Annual	Pre_mon.	Monsoon	Post_mon.	Winter
Z-statistic of trend analysis of rainfall in the Bhagirathi Sub-basin																	
Bhatwari-IMD	0.47	0.54	0.34	0.32	-0.69	0.62	-0.48	-1.55	1.03	-0.32	1.07	1.96	0.55	1.67	0.67	-1.00	-0.59
Bhogpur-IMD	1.86	2.87	2.03	1.76	2.00	1.02	0.72	1.28	2.24	1.19	2.14	1.32	2.13	1.97	2.36	1.44	0.52
Dhanolti-IMD	0.49	2.50	1.88	1.51	0.29	0.95	-0.52	-0.17	0.15	-0.40	0.47	-0.08	2.10	0.23	2.44	0.00	-0.96
Dunda-IMD	0.61	0.00	-0.04	-0.39	-1.20	-0.87	-0.75	-1.21	1.46	-0.44	1.66	0.79	0.40	1.32	0.62	-2.18	-0.74
Mukhim-IMD	0.72	1.38	0.87	0.04	-0.48	-0.17	-0.21	-1.59	1.24	-0.98	1.11	1.34	0.98	1.02	1.40	-1.27	-1.51
Narendranagar-IMD	0.50	1.36	0.65	1.11	1.33	1.31	-1.13	0.47	1.06	0.37	1.89	-0.27	1.48	0.45	1.48	1.13	-0.40
Tehri-IMD	0.34	1.76	0.21	0.01	-1.38	0.03	-0.25	-0.33	0.76	-0.26	1.36	2.82	1.23	2.33	1.10	-1.57	-0.04
Tehri-Garhw-IMD	0.40	3.09	1.53	1.62	-0.41	0.61	0.03	-0.05	1.17	0.38	1.63	1.95	2.12	2.24	1.99	-0.59	0.31
Uttarkashi-IMD	1.36	1.09	0.80	-0.12	0.40	0.96	0.38	-0.83	1.33	0.16	1.60	1.21	1.09	1.89	1.51	-0.18	-0.34
Uttarkashi-CWC	1.09	1.90	2.01	0.40	0.39	0.23	-0.50	-1.30	0.63	-0.77	1.84	1.27	2.05	1.97	1.86	-0.17	-1.04
Koteshwar-CWC	0.74	1.93	0.74	-0.06	-1.99	0.56	-0.23	-0.17	1.17	0.59	1.32	1.99	1.40	1.76	1.21	-1.91	0.06
Z-statistic of trend analysis of rainfall in the Alaknanda Sub-basin																	
Bironkhol-IMD	1.75	2.25	1.37	0.99	0.50	0.27	0.92	0.71	0.81	1.29	2.10	1.83	1.82	2.05	2.72	-0.11	-0.09
Chamoli-IMD	1.44	2.60	1.28	1.29	0.04	-1.01	-0.66	-1.34	0.68	-0.60	-0.31	-0.72	2.10	-0.27	2.40	-1.09	-0.79
Joshimath-IMD	3.13	1.54	0.27	-1.13	0.01	0.76	1.61	1.25	-0.03	-0.82	0.09	1.55	1.75	1.32	2.01	0.82	0.09
Keertinagar-IMD	0.78	-0.15	-0.45	0.24	-0.06	-0.71	-1.23	-0.99	0.07	-0.53	0.84	0.62	-0.31	1.06	0.00	-0.88	-1.14
Okhimath-IMD	0.97	1.70	0.91	1.69	0.97	-1.44	-0.83	-1.47	0.24	-0.54	0.12	-0.04	1.29	0.16	1.59	-0.09	-1.14
Pauri-IMD	1.44	1.47	0.67	2.26	1.31	0.69	-0.21	0.85	1.67	1.35	2.35	1.91	1.55	2.09	1.67	1.30	1.05
Rudraprayag-IMD	2.10	2.63	2.01	2.01	-0.14	-1.14	-0.68	-1.97	-0.19	-0.73	2.00	0.47	2.82	1.09	2.86	-1.19	-1.61
Srinagar-IMD	3.03	3.62	1.48	2.45	0.61	-0.08	0.24	0.88	1.68	1.31	1.85	1.54	1.69	1.55	3.50	0.88	1.51
Srinagar-CWC	2.12	2.27	1.14	2.44	0.54	0.78	0.04	0.75	1.21	1.13	1.77	1.85	1.33	1.49	2.71	0.93	1.15
Rudraprayag-CWC	0.63	1.42	0.28	1.29	0.38	1.29	-1.11	-0.74	0.34	0.18	0.89	-0.25	1.86	0.09	1.89	-0.05	-0.78
Joshimath-CWC	1.21	3.35	1.97	0.95	-1.80	-1.17	0.22	-0.91	0.17	-0.98	1.12	-0.68	1.69	0.55	3.02	-2.14	-1.06
Badrinath-CWC	0.08	1.18	0.81	1.00	-0.97	-0.37	-0.19	-1.83	-0.55	-1.46	0.36	-0.29	0.87	0.17	1.34	-0.96	-2.20
Karanprayag-CWC	2.06	4.25	3.32	2.24	0.42	-1.14	-0.73	-2.04	0.00	-0.02	1.38	0.36	3.96	1.51	4.09	-0.76	-0.94
Nandkeshari-CWC	2.56	4.05	3.75	2.65	-0.67	-2.40	-2.09	-2.05	-1.15	-1.69	0.27	0.38	4.32	0.81	4.77	-1.63	-2.48
Marora-CWC	-0.49	0.83	2.42	2.29	0.00	0.35	-0.92	-1.57	0.23	-0.13	0.24	0.30	1.14	0.11	2.88	-0.67	-1.31
Z-statistic of trend analysis of rainfall in the UGB d/s of Devprayag up to Rishikesh																	
Devprayag-IMD	-0.34	1.63	0.58	1.49	-0.06	0.26	-0.96	0.39	1.52	0.23	1.22	0.62	1.36	0.94	1.74	-0.35	0.08
Lansdowne-IMD	0.43	0.31	1.90	-0.37	-0.31	-1.35	-1.13	-0.11	1.56	0.75	0.93	1.40	0.89	1.55	1.25	-1.03	-0.16
Rishikesh-CWC	1.55	1.36	2.92	0.04	1.49	-0.51	-0.03	-0.23	1.35	0.34	0.73	0.31	2.18	0.80	2.29	0.99	0.02
Devprayag-CWC	0.22	1.89	2.06	1.80	0.63	0.27	-0.63	-0.60	1.22	0.47	1.36	1.69	1.54	1.57	1.89	0.43	0.02

There are 11 stations in the Bhagirathi sub-basin. 7 stations in the pre-monsoon (April - May) season and 4 stations in the monsoon season (June – September) show a rising trend of rainfall. 4 stations in the higher reaches (Uttarkashi, Tehri, Dhanolti, and Bhogpur) also show a rising rainfall trend at the annual time step. However, 2 stations show a decreasing trend of precipitation in the post-monsoon (October – November) season. Similarly, there are 15 stations in the Alaknanda sub-basin, and 9 stations show a rising trend of rainfall at the annual time step, while 12 out of 15 stations show a significantly rising trend of rainfall in the monsoon season. In the pre-monsoon season, 2 stations show a significantly rising trend. These results suggest that the monsoon season, as well as annual rainfall, is rising in the Alaknanda sub-basin. However, 1 station in the post-monsoon season and

2 stations in the winter season show significant declining precipitation in this sub-basin. In the downstream part of the UGB up to Rishikesh, there are 4 stations and 3 stations show significant rising trend in the monsoon season while 1 station show significant rising trend at annual time step. At monthly time step, most of the stations in monsoon months in the Alaknanda and Bhagirathi sub-basin show significant rising trend of rainfall. In the downstream part of the UGB, significant precipitation rise is observed at 3 stations in August month.

Based on these observations, it can be broadly inferred that precipitation in the UGB is increasing in the monsoon season and at the annual time step. 9 stations also show significant rising rainfall trend in the pre-monsoon season. On the other hand, significant decreasing precipitation trend is observed only at 1 station in post-monsoon season and 2 stations in the winter season in the basin.

Trend analysis of number of rainy days in UGB

In addition to the rainfall amount, number of rainy days is an important variable that is considered to be affected by the climate change. As per IMD guidelines, a day is considered as a 'Rainy Day' if the rainfall on a day equals or exceeds 2.5 mm. The rainy days were computed for all the stations and the trend analysis was carried out. The trend results for number of rainy days are summarized in Table – 3.

Table – 3

Results of trend analysis of number of rainy days at IMD/CWC stations in UGB

Z - statistic	Shade	Trend at different confidence levels
Z >= 1.96		Significant increasing trend at 95% confidence level
Z >= 1.645 & < 1.96		Significant increasing trend at 90% confidence level
Z < 1.645		No significant trend
Z <= - 1.96		Significant decreasing trend at 95% confidence level
Z <= - 1.645 & Z > - 1.96		Significant decreasing trend at 90% confidence level
Z > - 1.645		No significant trend

Stations	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Annual	Pre_mon.	Monsoon	Post_mon.	Winter
Z-statistic of trend analysis of rainy days in the Bhagirathi Sub-basin																	
Bhatwari-IMD	-1.060	-0.038	-0.420	-0.513	-1.272	-0.047	-0.478	-2.423	-0.076	-0.695	1.799	1.408	-0.796	2.630	-0.446	-1.277	-1.435
Bhogpur-IMD	2.865	3.313	0.676	1.245	1.204	0.000	0.113	0.997	2.106	0.775	2.009	1.650	2.227	2.211	2.359	1.072	0.988
Dhanolti-IMD	-0.287	1.978	0.808	1.408	0.680	0.462	-0.437	0.048	-0.038	-0.877	0.386	-0.182	0.749	0.067	1.490	0.579	-0.699
Dunda-IMD	-1.162	-1.416	-1.362	-1.219	-1.153	-0.718	-0.914	-2.320	-0.479	-0.773	2.260	0.276	-1.394	1.529	-1.242	-1.535	-1.777
Mukhim-IMD	1.037	2.658	2.320	1.780	-0.833	-0.944	-1.001	-1.621	-0.019	-1.259	1.707	1.685	2.039	2.254	2.834	-1.528	-1.930
Narendranagar-IMD	0.848	0.826	-1.285	-0.010	0.887	0.195	-1.615	0.560	0.920	-0.010	1.634	0.048	0.673	0.534	0.417	0.715	0.096
Tehri-IMD	-1.350	-0.124	-0.741	-0.694	-1.299	0.188	-0.126	-0.957	0.403	-1.489	0.665	1.953	-1.384	1.873	-1.203	-0.980	-0.788
Tehri-Garhwal-IMD	-0.200	0.768	1.226	1.237	-0.239	-0.062	0.110	-0.221	0.115	-0.335	1.260	1.554	0.979	1.996	0.806	-0.302	-0.278
Uttarkashi-IMD	1.264	0.612	1.035	0.086	0.000	0.011	-0.266	-0.948	0.972	0.524	3.000	1.276	2.113	2.853	1.175	-0.288	0.076
Uttarkashi-CWC	-0.133	0.733	0.276	-0.248	-0.138	-0.053	-0.844	-2.338	-0.106	-1.113	1.665	0.706	0.047	1.805	0.446	-0.511	-1.890
Koteshwar-CWC	-1.342	0.799	0.000	-0.362	-1.953	0.224	-0.130	-0.469	0.430	-0.680	0.559	1.662	-0.493	1.387	-0.294	-1.502	-0.391
Z-statistic of trend analysis of rainy days in the Alaknanda Sub-basin																	
Bironkhol-IMD	1.741	2.615	0.950	0.931	-0.555	-0.866	-0.331	1.197	0.632	1.149	2.595	2.369	2.265	2.619	2.000	-0.474	0.266
Chamoli-IMD	0.475	0.504	-0.611	-0.352	-0.108	-1.778	-0.580	-1.677	0.134	-0.615	0.382	-0.172	-0.581	0.323	0.015	-0.717	-0.986
Joshimath-IMD	2.931	2.521	0.057	-1.050	-0.030	0.463	1.849	0.924	0.791	0.591	0.000	2.334	2.985	1.569	2.238	0.443	1.081
Keertinagar-IMD	0.371	-0.938	-1.177	-0.371	0.182	-0.493	-0.839	-1.022	-1.372	-0.863	1.050	0.715	-0.812	1.216	-0.896	-0.187	-1.527
Okhimath-IMD	0.865	0.209	-0.486	0.725	0.963	-1.490	-1.069	-1.413	0.172	-0.791	0.801	0.495	0.143	1.265	0.351	0.173	-1.623
Pauri-IMD	1.152	0.961	1.016	2.103	0.943	-0.082	-0.350	1.462	1.357	1.236	1.621	2.201	2.198	2.113	1.725	0.871	1.073
Rudraprayag-IMD	1.133	0.921	-0.336	0.524	-0.615	-0.907	-0.292	-1.874	-1.772	-1.030	1.749	0.647	-0.106	1.677	0.583	-1.421	-1.977
Srinagar-IMD	0.942	2.118	0.931	1.845	1.102	1.008	0.520	0.961	1.371	0.924	0.992	1.386	1.407	1.220	2.152	1.092	0.837
Srinagar-CWC	1.124	1.342	1.092	2.581	1.120	1.899	0.454	1.430	1.576	1.382	1.398	2.359	2.426	2.234	2.077	1.448	1.597
Rudraprayag-CWC	1.188	-0.285	0.010	0.866	-0.089	0.645	-0.293	-1.219	-0.391	-0.181	1.723	0.877	0.711	1.266	0.720	-0.318	-0.979
Joshimath-CWC	0.334	2.690	1.341	0.477	-1.946	-1.763	-0.458	-1.584	-0.362	-1.868	1.574	-0.898	0.320	0.391	1.579	-2.091	-2.189
Badrinath-CWC	0.514	1.477	0.143	0.457	-1.311	-0.897	-0.783	-2.471	-0.812	-2.152	0.967	0.220	-0.389	0.609	0.529	-1.464	-2.895
Karanprayag-CWC	0.628	2.389	0.101	0.672	0.175	-1.393	0.000	-2.002	-1.011	-0.784	2.420	0.601	0.627	1.962	0.785	-0.816	-1.474
Nandkeshari-CWC	0.343	0.629	-0.581	0.513	-1.032	-2.001	-2.257	-3.426	-2.546	-2.881	0.344	-0.685	-2.078	0.105	0.265	-2.282	-3.778
Marora-CWC	0.286	1.057	1.924	0.115	-0.217	-1.045	-0.849	-1.344	-0.612	-0.880	0.683	0.536	0.797	0.953	1.236	-0.930	-1.344
Z-statistic of trend analysis of rainy days in the UGB d/s of Devprayag up to Rishikesh																	
Devprayag-IMD	-2.703	1.549	0.171	1.202	-0.394	0.358	-0.774	0.435	-0.375	-0.221	0.822	1.063	0.920	1.430	0.360	-0.374	-0.285
Lansdowne-IMD	0.703	0.000	0.038	-0.789	-0.308	-1.009	-1.573	0.222	0.642	0.359	1.254	1.339	0.048	1.759	-0.057	-0.799	-0.551
Rishikesh-CWC	1.076	0.589	1.154	-0.228	1.388	-1.048	-0.041	-0.706	1.108	0.010	1.338	0.913	1.204	1.566	1.224	0.632	0.019
Devprayag-CWC	-0.352	2.522	1.754	2.091	0.244	0.255	-0.228	-0.356	-0.029	-0.634	1.517	2.544	2.636	2.665	2.704	0.279	-0.066

In the Bhagirathi and Alaknanda sub-basins, 12 out of 26 stations show rising trend of rainy days in the pre-monsoon (April - May) season while 8 stations show rising number of rainy days in the monsoon (June – September) season and at annual time step. However, significant decreasing trend in number of rainy days is observed at 7 stations in the winter season and at 2 stations in the post-monsoon season. In the UGB d/s of Devprayag up to Rishikesh, 1 station shows significant increasing rainy days in pre-monsoon and monsoon seasons and at annual scale while 1 station shows rising trend in pre-monsoon season only. July month shows increasing rainy days at 9 stations while the January month shows decreasing number of rainy days at 8 stations.

5.0 Processing and trend analysis of temperature data in UGB

Data of maximum and minimum temperature at different stations in UGB on daily time scale was obtained from the IMD and CWC. However, the data availability was quite limited for the IMD stations with limited years of observations while long-term series could be obtained for the CWC stations. The data of maximum and minimum temperature were prepared at regular daily time step and the daily values were averaged at monthly, seasonal, and annual time steps. For a particular month, the temperature values were averaged if the data length of 15 or more days was available. Otherwise, the month was reported with no temperature data.

In view of the long-term and continuous data availability of temperature data at CWC stations in the UGB, only such data has been used for the trend analysis. Some discrepancies in the data due to human errors (say, due to typographical data entry errors or due to interchange of maximum and minimum temperature columns by mistake) were observed using graphical plot of data and were corrected. The results of trend analysis for maximum/minimum temperatures are summarized in Table – 4.

Table – 4

Results of trend analysis of maximum/minimum temp. at CWC stations in UGB

Z - statistic	Shade	Trend at different confidence levels
Z >= 1.96		Significant increasing trend at 95% confidence level
Z >= 1.645 & < 1.96		Significant increasing trend at 90% confidence level
Z < 1.645		No significant trend
Z <= - 1.96		Significant decreasing trend at 95% confidence level
Z <= - 1.645 & Z > - 1.96		Significant decreasing trend at 90% confidence level
Z > - 1.645		No significant trend

Station	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Annual	Pre_mon.	Monsoon	Post_mon.	Winter
Z-statistic of trend analysis of maximum temperature in Bhagirathi Sub-basin																	
Uttarkashi-CWC	-1.79	-2.63	-1.63	-1.20	1.41	2.09	2.03	2.06	1.99	1.91	1.07	-1.01	1.50	0.36	-2.06	2.13	2.36
Z-statistic of trend analysis of maximum temperature in Alaknanda Sub-basin																	
Chandrapur-CWC	-4.07	-4.60	-4.89	-4.97	-4.68	-3.59	-2.64	-2.11	-0.54	-2.32	-2.85	-2.85	-4.77	-3.01	-5.60	-4.38	-2.14
Joshimath-CWC	-0.20	0.05	-0.18	0.28	0.42	-2.90	-2.32	-2.00	-0.75	0.85	-0.30	0.04	-1.46	-0.27	-0.07	-1.50	-1.49
Karanprayag-CWC	2.36	0.14	-0.10	1.27	1.62	0.42	0.93	1.37	2.45	4.20	3.52	3.53	1.96	3.49	0.77	0.91	2.30
Marora-CWC	-3.10	-2.45	-1.63	-1.70	-2.46	-3.72	-3.42	-2.38	-1.27	-1.74	-2.77	-2.49	-3.03	-2.79	-2.61	-3.22	-2.15
Z-statistic of trend analysis of maximum temperature in UGB d/s of Devprayag up to Rishikesh																	
Devprayag-CWC	-2.24	-1.87	-1.59	-2.40	-3.24	-3.50	-3.26	-2.19	-1.65	-1.38	-2.56	-2.56	-3.04	-2.62	-2.08	-3.55	-2.41
Z-statistic of trend analysis of minimum temperature in Bhagirathi Sub-basin																	
Uttarkashi-CWC	-1.35	-1.88	-1.83	-1.56	-1.89	-1.12	0.16	0.24	-0.03	-0.99	-1.92	-1.91	-1.78	-1.98	-2.06	-0.63	2.36
Z-statistic of trend analysis of minimum temperature in Alaknanda Sub-basin																	
Chandrapur-CWC	-0.90	-2.43	-2.99	-2.77	-0.63	0.34	-1.32	-0.60	0.69	0.03	-0.16	-0.26	-1.78	-0.32	-3.01	-0.74	-0.73
Joshimath-CWC	0.82	1.44	0.47	1.63	1.82	0.76	0.87	0.28	1.56	2.12	1.54	2.37	1.41	1.63	1.04	1.34	1.93
Karanprayag-CWC	0.71	0.13	-0.65	-0.90	-0.47	-1.24	-1.14	0.17	1.75	2.50	2.16	1.40	2.06	2.03	-0.03	-0.54	1.32
Marora-CWC	2.65	2.90	2.49	2.03	0.56	-0.14	0.36	-0.23	1.87	2.35	1.36	1.90	1.93	1.65	2.85	0.00	1.30
Z-statistic of trend analysis of minimum temperature in UGB d/s of Devprayag up to Rishikesh																	
Devprayag-CWC	-2.38	-1.96	-2.48	-1.77	-2.18	-1.80	-1.35	-1.87	-0.83	-0.42	-0.99	-1.73	-1.52	-1.30	-2.75	-1.96	-1.13

The results of trend analysis for maximum temperature indicate that out of 6 stations in UGB, 3 stations are showing significant reduction at annual scale and in all seasons while 2 stations are showing significant rise in post-monsoon/winter seasons. With regard to minimum temperature, the trend analysis results indicate that 3 stations are showing significant reduction in monsoon season and at annual time step, while 2 stations are showing rising trend in pre-monsoon season and at annual scale. Most stations in the Alaknanda sub-basin show rising trend of minimum temperature from February to May.

6.0 Processing of flow data in UGB

Daily observed flow data are recorded by CWC in the UGB at 11 locations. Different data lengths are available for various stations but available data from June, 1972 onwards has been used in the present study. Data at Karanprayag are available from December, 1976 while data at Koteshwar are available from July, 2011 onwards. At Badrinath, the data were available for the monsoon months from June to October. At Devprayag, flow is recorded at Bhagirathi (before confluence of Alaknanda) and at main Ganga river (after confluence of Alaknanda). Similarly, flow is recorded in Mandakini river at Rudraprayag before confluence with Alaknanda and at the main Alaknanda river after confluence with Mandakini river. For these sites, combined plots have been prepared to assess the relative contribution of the tributaries with respect to the main river. Very small data gaps (of the order of 1 to 2 days) were recorded in various data series and the same were filled using linear interpolation.

It is observed that operation of Tehri dam has significantly altered the monthly distribution of flows in the d/s parts of Bhagirathi river and the main Ganga river. As the dam absorbs significant part of the flow during the monsoon season and releases the water during non-monsoon period, monthly and seasonal flows show significant changing trends at Devprayag station on the Bhagirathi river and the Rishikesh station. At most sites, monsoon flow is around 70% of the annual flows except at Uttarkashi where monsoon flows are 48% of the annual flows and around 29% is the contribution during the winter months because of the release of stored water from the Tehri dam in non-monsoon months. At Rishikesh, the average annual flow is computed close to 24 BCM (billion cubic meters). Since the Tehri dam redistributes the flows in different months, average seasonal computations have been made for two periods: from 1972 to 2005 (without the Tehri dam), and from 2006 to 2017 (with the Tehri dam). It is observed that without the Tehri dam, the flows in pre-monsoon, monsoon, post-monsoon, and winter seasons were of the order of 7.3%, 76.5%, 8.5%, and 7.8%, respectively, of the annual flows, which changed to 9.1%, 68.3%, 9.9%, and 12.7% after the operation of the Tehri dam.

The trend analysis of flow data has also been carried out at different temporal scales (monthly, seasonal, and annual) for 10 stations (except Badrinath station). Uttarkashi station shows significantly low flows during the period from 1986 to 2009 (except for year 1995) for the pre-monsoon, post-monsoon and winter months, which needs further investigation. Trend results of river flows at various CWC stations are summarised in Table 5.

Table – 5

Results of trend analysis of observed flows at various CWC stations in UGB

Z - statistic	Shade	Trend at different confidence levels
Z >= 1.96		Significant increasing trend at 95% confidence level
Z >= 1.645 & < 1.96		Significant increasing trend at 90% confidence level
Z < 1.645		No significant trend
Z <= - 1.96		Significant decreasing trend at 95% confidence level
Z <= - 1.645 & Z > - 1.96		Significant decreasing trend at 90% confidence level
Z > - 1.645		No significant trend

Station	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Annual	Pre_mon.	Monsoon	Post_mon.	Winter
Z-statistic of trend analysis of observed flows in the Bhagirathi Sub-basin																	
Uttarkashi – CWC	-0.511	0.757	1.761	-0.530	-1.698	-1.556	-1.542	-1.553	-1.334	-1.220	-1.375	-1.420	-0.511	-1.837	0.379	-1.461	-1.393
Devprayag-Bhagirathi - CWC	-2.670	-3.373	-3.594	-3.068	-1.572	1.360	1.663	1.017	1.478	1.501	1.403	-0.492	-1.382	1.023	-3.318	0.133	1.353
Z-statistic of trend analysis of observed flows in the Alaknanda Sub-basin																	
Rudraprayag-Mandakini - CWC	0.530	2.216	2.253	1.155	1.231	1.363	1.931	2.386	1.894	1.212	-0.814	-0.682	2.178	-0.947	2.500	1.307	2.121
Rudraprayag-Alaknanda - CWC	2.803	4.147	4.753	3.258	3.124	2.500	2.727	2.140	1.913	0.227	-0.625	0.568	4.980	0.473	3.915	2.954	2.045
Joshimath - CWC	-0.473	-0.644	-0.852	-1.837	-1.818	-2.064	-1.610	-1.099	-0.577	-1.085	-1.837	-1.439	-0.795	-1.530	-1.060	-2.121	-1.147
Marora - CWC	-0.909	-0.360	-0.606	-0.151	-0.114	0.114	0.682	-0.966	-0.644	-0.454	-0.038	-0.568	-0.322	-0.360	-0.151	-0.151	-0.151
Karanprayag - CWC	0.146	0.461	-1.382	0.371	1.988	3.740	2.550	0.955	1.786	0.505	-0.663	-1.988	0.101	-1.471	-0.685	2.752	1.337
Devprayag-Alaknanda - CWC	-0.890	0.549	0.606	-0.030	1.704	1.704	2.159	3.238	1.955	2.221	-0.322	-1.174	0.771	-0.852	0.376	1.894	2.473

Z-statistic of trend analysis of observed flows in UGB d/s of Devprayag up to Rishikesh																
Devprayag-Ganga - CWC	-1.666	-1.136	-1.420	-1.085	1.023	1.648	1.704	2.104	1.977	1.974	0.789	-0.852	0.606	0.057	-1.284	1.799	1.993
Rishikesh - CWC	-1.382	-2.954	-2.670	-1.988	0.852	2.443	3.663	2.088	2.186	3.181	1.780	0.303	-2.253	0.947	-2.897	1.610	2.334

Mixed trends are observed at different gauging stations at various time steps. Because of significantly low flows during 1986 to 2009 (needs further investigation), Uttarkashi shows a significant decreasing trend in pre-monsoon months. Tehri dam impact is visible at d/s sites (Devprayag at Bhagirathi, Devprayag at Ganga, and Rishikesh), resulting in a significant rise in flows in post-monsoon and winter months at the cost of monsoon months. However, annual flows at Rishikesh show a significant decreasing trend. Though the trend for most of the time appears reasonable, there are 12 years (1986, 1987, 1988, 1989, 1991, 1998, 1999, 2012, 2014, 2015, 2016, and 2017) when the annual flows at Rishikesh are less than at Devprayag-Ganga. After the year 2012, non-monsoon flows at Rishikesh are quite less as compared to Devprayag-Ganga, which could be due to intermediate diversion of water for various purposes.

Flow observations at Rudraprayag (Mandakini and Alaknanda) show a significant rising trend at annual scale and in the post-monsoon and winter seasons. Karanprayag shows a significant rise in the post-monsoon season. Since the flow at Devprayag-Ganga and Devprayag-Bhagirathi is affected by the Tehri dam releases, the flow from Alaknanda at Devprayag is estimated by deducting the flow at Devprayag-Bhagirathi from the flow at Devprayag-Ganga and trend analysis is carried out for the computed flow of the Alaknanda River at Devprayag. Flows at Devprayag (Alaknanda and Ganga) show a significant increase in post-monsoon and winter months.

Overall, it can be inferred that flows are increasing in the Alaknanda basin as a whole with a significant increasing trend in post-monsoon and winter months. In the Bhagirathi sub-basin, the Tehri dam has redistributed the flows with a significant increase in the non-monsoon months at the cost of monsoon months.

7.0 Analysis of the hydro-meteorological network in UGB

A hydro-meteorological network is an organised system for the collection of information of a specific kind, such as precipitation, temperature, relative humidity, wind speed, solar radiation, etc. and other climate parameters. Availability of adequate, relevant, and accurate hydrologic information reduces the chances of under-design or over-design and thus minimises the economic losses, which leads to the overall increase in the benefit/cost ratio. Setting up a station requires investment for infrastructure equipment, logistics, operation and maintenance. Scientific planning is necessary for network design so that the desired results can be achieved with minimum cost. Hydro-meteorological data networks are operated by a number of independent agencies (say, IMD, CWC, State agencies, etc.) and good coordination among them is important for optimisation of cost and utilisation of data.

Rainfall data are a fundamental input for effective planning, design and operation of water resources projects. Increasing network density with additional rain gauge stations has been the main underlying criterion in the past to reduce error and uncertainty in rainfall estimates. Since the catching area of a rain gauge is very small compared to the aerial extent, it is obvious that to get a representative picture of a storm over a catchment, the number of rain gauges should be as large as possible. However, due to economic and other considerations such as topography, accessibility, etc., a limited number of rain gauges are installed. Hence, one aims at an optimum density of gauges from which reasonably accurate information about the storm can be obtained. WMO (2008) has recommended an ideal density of 100 - 250 sq. km per station (acceptable density is 250-1000 sq. km per station) as the network density for precipitation stations in mountainous areas, with 10% of the stations equipped with self-recording gauges. The area of the UGB below the 4000 m elevation is 14000 sq. km, and it is expected that 56 stations (considering a density of 250 sq. km per station) would be able to capture the rainfall variation in the basin.

Bureau of Indian Standards (*IS: 4986-1968 guidelines*) suggests one rain gauge for 500 sq. km in non-orographic regions, while in regions of moderate elevation (up to 1000 m above mean sea level), the recommended network density is one rain gauge for 260 - 390 sq. km, and in predominantly hilly areas with heavy rainfall, the recommended density is 130 sq. km per station. As per this criterion, the required number of stations in the area below 4000 m works out to be 108.

The problem of ascertaining the optimum number of rain gauges in a basin is of a statistical nature and depends on the spatial variation of rainfall. Thus, the coefficient of variation of rainfall from existing stations is utilised to determine the optimum number of raingauges. If there are already some rain gauges in the catchment, the optimal number of stations that should exist to have an assigned percentage of error in the estimation of mean rainfall is obtained by statistical analysis as:

$$N = \left(\frac{C_v}{P}\right)^2 \qquad \ldots(6)$$

where 'N' is the optimal number of stations, 'p' is the allowable degree of error in the estimate of mean rainfall (usually taken as 8 to 10%) and 'C_v' is the coefficient of variation of rainfall values at existing stations. In this study, the average annual rainfall, standard deviation, and coefficient of variation were computed for 30 stations and using equation 6, the number of required rainfall stations was computed as 11.

Based on this 'Coefficient of Variation (C_v)' analysis, it is found that the present network of stations is sufficient to capture the variability of rainfall in UGB. All these stations can also be equipped with sensors for measurement of maximum and minimum temperature, relative humidity, wind speed and solar radiation.

7.1 Evaluation of rain gauge network using the entropy approach

One of the important objectives of network design is to estimate the probable magnitude of error or regional hydrological uncertainty arising from network density, distribution and record length. In entropy method, the hydrological information and regional uncertainty associated with a set of precipitation stations are estimated using the Shannon's entropy concept. Since time series of rainfall data can be represented by gamma distribution due to the presence of skewness, the entropy term is derived using single and bivariate gamma distribution. Let **X** represents the rainfall measured at a station with events $\mathbf{x_1}, \mathbf{x_2}, \ldots\ldots \mathbf{x_n}$ and with the probability of occurrence of $\mathbf{j^{th}}$ event denoted by $\mathbf{p(x_j)}$. Shannon and Weaver (1949) defined the average uncertainty, also known as entropy, with **n** event as:

$$H(X) = -\sum_{j=1}^{n} p(x_j)\log_2 p(x_j) \qquad \ldots(7)$$

where, **H(X)** is the uncertainty or entropy of variable X. For details of the entropy method of network design, one can refer to *National Hydrology Project – Hydro-Meteorological Network Design* (https://nhp.mowr.gov.in/HIS/Entropy_Method.aspx). In this study, the distribution of rain gauges used for entropy based analysis in the UGB is shown by blue star in Figure – 4 along with the station names and IDs.

Total annual rainfall at each station for all the available years were computed. Using the basic time series data, the mean, variance, and the scale and shape parameters for each station were estimated. Out of 25 selected stations, only those stations were identified which can be joined through obtuse angle triangles which is one of the requirement for selection of stations. For selected stations, entropy of rainfall, H(X), is computed. Using the mean and variance of time series, the rainfall at each station were transformed into normal variates and the correlation coefficient for each pair of station were computed from the normal variates. Subsequently, the information transmission, for all feasible combination of stations was computed.

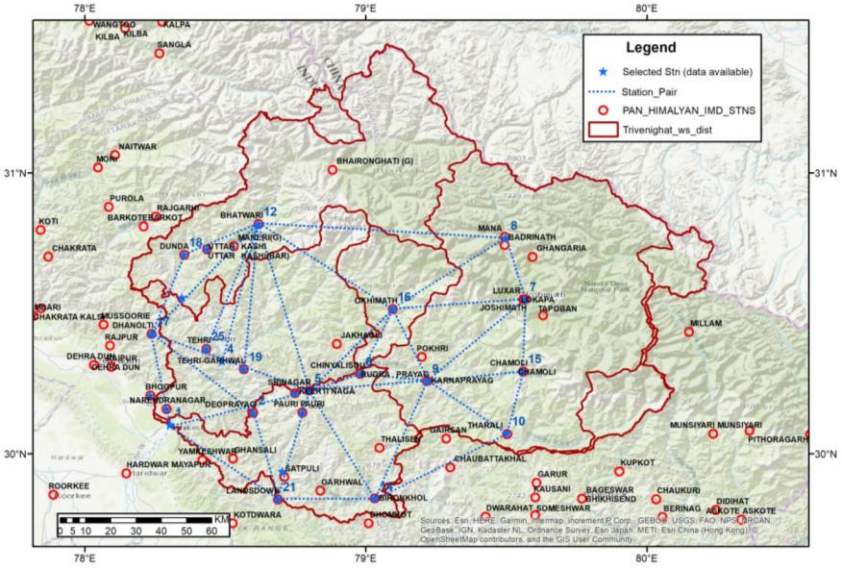


Figure – 4: Selection of rain gauge stations for entropy analysis

The study basin was divided into twenty-one triangles. Vertices of the triangles were decided such that the correlation between all three stations at the vertices exist and none of triangles has any obtuse angle. The selection of triangles is shown in Figure - 4 with blue dotted lines. Information transformation at 10 points (equally spaced) along each side of all the triangles are then computed. Using this information, information transmission grids at every 200 m grid interval are generated. The overlay of the information grid over topographical map is shown in Figure – 5. This figure also shows the information contours over the study area. The high information grids (entropy > 6) are shown by green shades while the low information grids are shown in various shades of red color. The darker red color patch are the patches where sufficient information is not available and could be probable site for new rainfall stations.

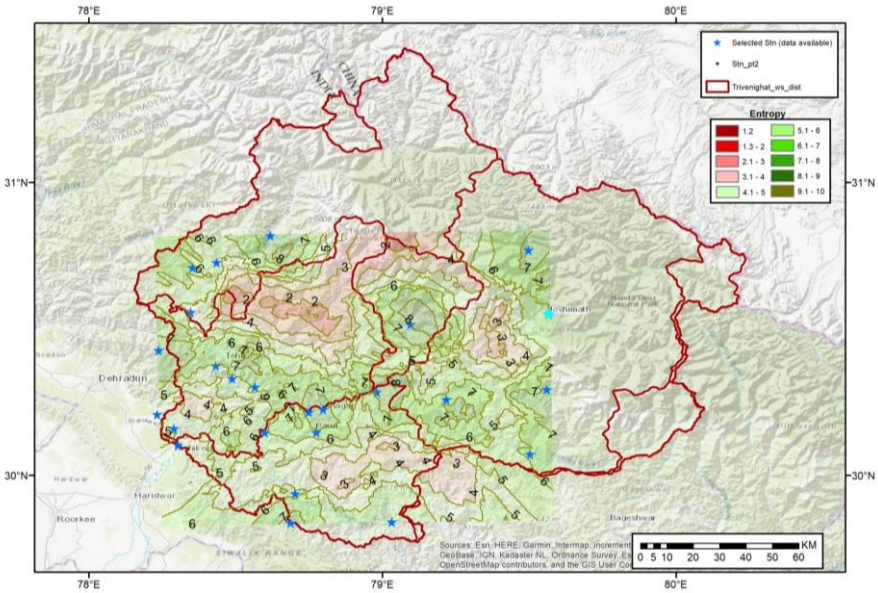


Figure - 5: Overlay of entropy information over topographical map

8.0 Investigation of spatial database from various sources

With the advancement in technology, manual intervention and station-based data recording have been overcome to a greater extent, wherein an array of precipitation products has been developed by researchers across the globe using sophisticated techniques and made available to the scientific community. Besides, remotely sensed

precipitation products have been further available over the past few years from satellite-based observations. Open available global precipitation datasets are easily accessible and have been widely used in a number of studies (Bharti et al. 2016; Ciabatta et al. 2016; Beria et al. 2017; and Parida et al. 2017). Though the importance of station data cannot be ignored, global precipitation estimates are useful in understanding the climate and its evolution with time and aid in real-time applications. Some of the widely used open datasets from various sources are: CHIRPS, PERSSIANN, PERSSIANN-CCS, PERSSIANN-CDR, SM2RAIN-CCI, APHRODITE, APHRODITE-2, CMORPH, MSWEP, GSMaP, TRMM-3B42 and GPM-IMERG. These datasets cover different time frames and spatial/temporal resolution (given in Table 6) and have been developed using different techniques/algorithms.

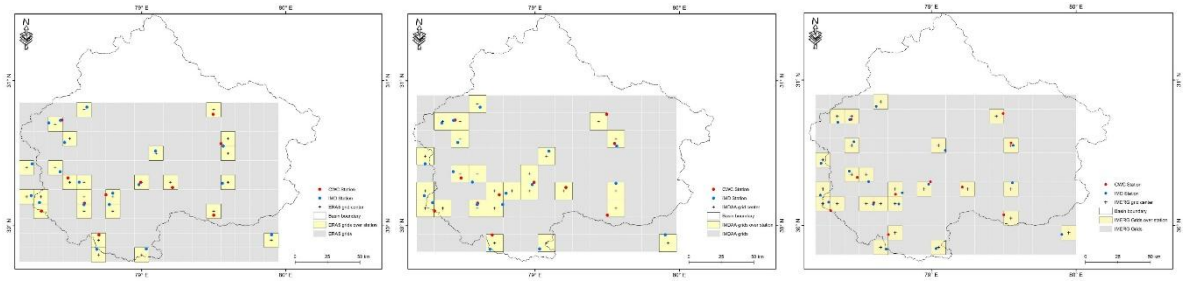
Table – 6

Description of various global precipitation estimates

S. No.	Dataset	Availability period	Resolution	
			Spatial	Temporal
1	CHIRPS	Jan 1981 - May 2019	0.25° x 0.25°	Daily
			0.05° x 0.05°	
2	PERSSIANN	Mar 2000 - Present	0.25° x 0.25°	Sub-daily, Daily
3	PERSSIANN-CCS	Jan 2003 - Present	0.04° x 0.04°	Sub-daily, Daily
4	PERSSIANN-CDR	Jan 1983 - Dec 2017	0.25° x 0.25°	Daily
5	SM2RAIN-CCI	Jan 1998 - Dec 2015	0.25° x 0.25°	Daily
6	APHRODITE	Jan 1951 - Dec 2007	0.25° x 0.25°	Daily
		Jan 2007 - Dec 2015		
7	APHRODITE-2	Jan 1998 - Dec 2015	0.05° x 0.05°	Daily
8	CMORPH	Dec 2002 - Oct 2017	0.25° x 0.25°	Sub-daily, Daily
9	MSWEP	Jan 1979 - Dec 2017	0.1° x 0.1°	Sub-daily
10	GSMaP_Gauge_RNL	Mar 2000 - Feb 2014	0.1° x 0.1°	Sub-daily
11	TRMM-3B42 Research Product	Jan 1998 - Present	0.25° x 0.25°	Daily
12	GPM-IMERG Research Product	Mar 2014- Present	0.1° x 0.1°	Daily

To use any global dataset, it is essential to assess its skills in resolving local climatology and capturing extreme events, and a comprehensive statistical approach needs to be adopted for such evaluation. To explore the potential usage of global precipitation estimates available from reanalysis products or satellite estimates, two reanalysis products, i.e. ERA5-Land hourly data, IMDAA daily dataset, and precipitation estimates from GPM-IMERG, were utilised. These products are available for different time durations and offer fine-scale spatial resolution. Therefore, these products were evaluated for their skills in resolving regional climatology using station-based records available from IMD and CWC.

ERA5 is the fifth-generation ECMWF atmospheric gridded reanalysis product of global climate. Reanalysis hourly precipitation is basically available in the form of total precipitation accumulated at the end of model time steps of every hour. The Indian Monsoon Data Assimilation and Analysis (IMDAA) product is the outcome of a formal collaboration between the Met Office (MO), United Kingdom; the National Centre for Medium Range Weather Forecasting (NCMRWF), India; and the India Meteorological Department (IMD) in the National Monsoon Mission (NMM) project of the Ministry of Earth Science (MoES), Government of India. The total precipitation that corresponds to total accumulated precipitation during the previous day IST 08:30 Hrs to the current day IST 08:30 Hrs from the IMDAA single-level dataset was downloaded from the NCMRWF website (https://rds.ncmrwf.gov.in/) for the study domain. The Integrated Multi-satellitE Retrievals (IMERG) for the Global Precipitation Mission (GPM) algorithm combines the information from the GPM satellite constellation to estimate precipitation over the majority of the Earth's surface. Earlier, the IMERG precipitation estimates were available from 2014 onwards. However, in the latest Version 06 of IMERG, the algorithm fuses the early precipitation estimates collected during the operation of TRMM satellite (2000 - 2015) with more recent precipitation estimates collected during the operation of the GPM satellite (2014 - present). IMERG estimates are reported to represent the mean monsoon rainfall and its variability more realistically, with fewer missed and false precipitation bias and improvements in the precipitation distribution over low rainfall rates for the Indian subcontinent. The distribution of ERA5-hourly data grids, IMDAA precipitation grids, and the GPM-IMERG data grids corresponding to 19 IMD and 11 CWC raingauge stations are shown in Figure - 6 (a - c), respectively.



(a) (b) (c)

Figure - 6 (a – c): Location of IMD and CWC stations corresponding to ERA5 grids, IMDAA grids, and GPM-IMERG grids

To analyse the skills of these three precipitation estimates, the comparison was done at a monthly scale wherein the areal monthly rainfall time series were created and analysed for UGB by creating the mean areal estimates and in a grid-wise manner. Different performance indices, viz. Pearson correlation coefficient (r), Nash-Sutcliffe efficiency (*NSE*), per cent bias (PBIAS), and Root-mean-squared-error (RMSE) were employed to assess the skills, along with a graphical method to visualise the skills of these products in resolving seasonal precipitation climatology. The skill assessment was carried out for varying periods of records, as the IMERG, ERA5, and IMDAA precipitation estimates are available for different durations. For IMERG, the time period covering the hydrological year since June 2000 - May 2018 (18 hydrological years) was used, whereas for ERA5 and IMDAA, the records from June 1981 – May 2018 (37 hydrological years) and June 1979 - May 2018 (39 hydrological years), respectively, were used. Though all these products were found to capture the seasonality of precipitation regime of UGB [Figure - 7 (a - f)], only IMERG is found to satisfactorily represent the monthly magnitudes.

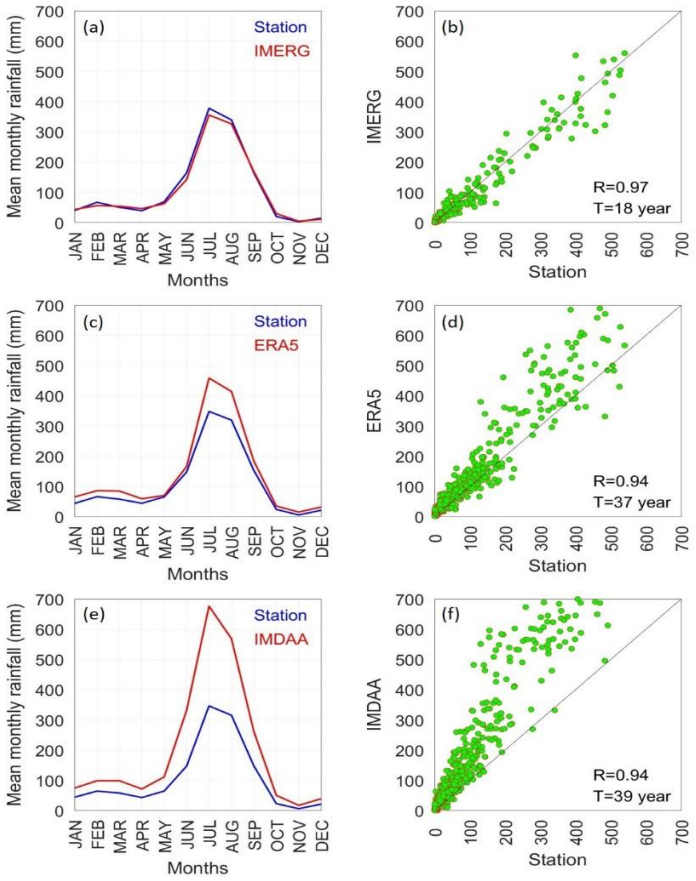
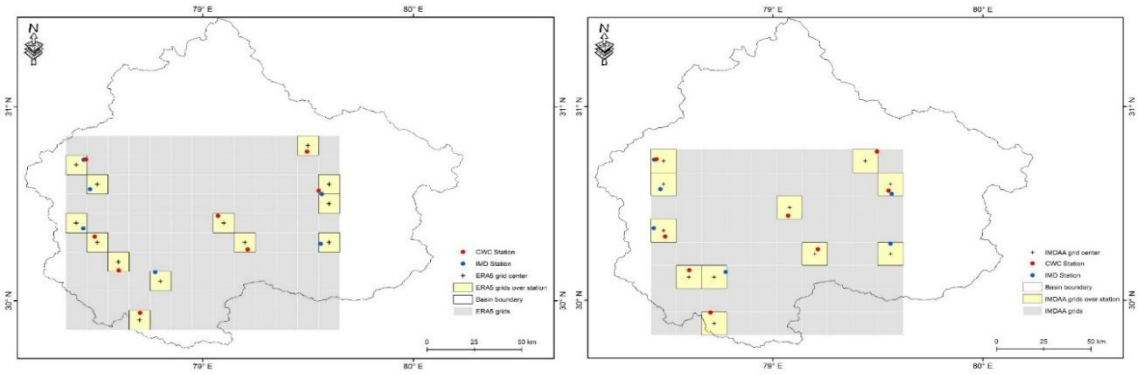


Figure - 7 (a – f): Comparison of station data of IMD and CWC with global and regional precipitation estimates of IMERG, ERA5, and IMDAA

To analyse the station-wise (or grid-wise) accuracy of IMERG, ERA5, and IMDAA rainfall estimates, the total monthly rainfall time series for each grid was compared with the corresponding station estimates. The IMERG precipitation estimate was found to show higher correlation with station records of IMD and CWC for different locations in comparison to the precipitation estimates of ERA5 and IMDAA. Based on the analysis, IMERG is found to be the most suitable alternative for the UGB for assessing the seasonal water availability.

8.1. Comparison of reanalysis and satellite temperature with station record

In addition to precipitation, comparison of the temperature products with the observed max./min. temperature in the UGB has also been investigated. ERA5-Land hourly temperature data is a gridded reanalysis product that provides global coverage and is available in regular latitude-longitude grid projection at 0.1 degree spatial resolution and a temporal coverage of January 1981 to present. The reanalysis air temperature is available at 2 m above the Earth's surface in Kelvin. Owing to the fine-scale spatial resolution and hourly records over a long period, ERA5-Land hourly air temperature was utilised for comparison with the station records. The minimum and maximum temperatures from the IMDAA single-level dataset at 2 m height above the ground were downloaded from the NCMRWF website (https://rds.ncmrwf.gov.in/) for the UGB. Observed maximum (T_{max}) and minimum (T_{min}) temperature data were available for 14 stations of IMD (6) and CWC (8). The ERA-5 and IMDAA temperature grids corresponding to CWC and IMD stations are shown in Figure - 8 (a – b).



(a) (b)

Figure – 8 (a-b): Location of IMD and CWC stations w.r.t. ERA5 and IMDAA grids

Different performance indices, viz. Pearson correlation coefficient (*R*), Nash-Sutcliffe efficiency (*NSE*), per cent bias (*PBIAS*), Mean absolute error (*MAE*), and Root-mean-squared-error (*RMSE*) were employed to assess the skills of ERA5 and IMDAA datasets against the station observations. The analysis revealed that the ERA5-Land hourly data cannot be used directly for local studies, as it did not match the station record and heavily underestimates the local temperature. The consistent under-estimation of temperature by ERA-5 infers that the reanalysis product has a cold bias, which should be treated prior to its application in local studies.

The analysis revealed that IMDAA data also cannot be used directly for local studies, as it also heavily underestimates the local temperature and does not match the station record. IMDAA temperature records are also found to have an inherent cold bias for the Himalayan region, which eventually results in poor skills demonstrated by large *MAE*, large *RMSE*, smaller *NSE* and poor *R* values.

9.0 Concluding remarks

In this study, processing and analysis of hydro-meteorological data of IMD and CWC (from June, 1972 to May, 2016) have been carried out, and some suspect values in observations have been identified. Trend analysis has been carried out on different hydro-meteorological variables. Network analysis has been carried out, and areas of probable new instrumentation have been identified using the entropy analysis. Gridded reanalysis and satellite spatial data products have been investigated for use in UGB.

It is inferred that the importance of hydrological data should be duly recognised by the team associated with its observation and processing. Further, the observed data should be put to primary validation and checking/correction in the proximity to the gauging sites. Long-term data series need to be developed at observation stations, and the gaps, if any, should be filled using suitable methods by collecting/processing organisations (rather than by the user agency). Abnormal occurrence of events (say, a cloudburst) may be associated with special remarks about the event. From the trend analysis of rainfall, it can be broadly inferred that rainfall is increasing in the UGB in the monsoon season and at the annual time step. Out of 30 stations, 9 stations also show a significant rising trend in the pre-monsoon season. On the other hand, a significant decreasing trend is observed only at 1 station in the post-monsoon season and 2 stations in the winter season. With regard to the trend of rainy days, it is observed that 12 out of 26 stations in the Bhagirathi and Alaknanda sub-basins show a rising trend of rainy days in the pre-monsoon (April - May) season, while 8 stations show a rising number of rainy days in the monsoon (June – September) season and at an annual time step. However, a significant decreasing trend in the number of rainy days is observed at 7 stations in the winter season and at 2 stations in the post-monsoon season. July shows increasing rainy days at 9 stations, while January shows decreasing number of rainy days at 8 stations. The results of trend analysis for the maximum temperature indicate that out of 6 stations in UGB, 3 stations show a significant reduction at the annual scale in all seasons, while 2 stations show a significant rise in the post-monsoon/ winter seasons. With regard to the minimum temperature, 3 stations show a significant reduction in the monsoon season and at the annual time step, while 2 stations show a rising trend in the pre-monsoon season and at the annual scale. Most stations in the Alaknanda sub-basin show a rising trend of minimum temperature from February to May. From the trend analysis of flow data at 10 stations in UGB, it is inferred that flows are increasing in the Alaknanda basin as a whole, with a significant increasing trend in the post-monsoon and winter months. In the Bhagirathi sub-basin, the Tehri dam has redistributed the flows with a significant increase in non-monsoon months at the cost of monsoon months.

Network analysis with the 'Coefficient of Variation (C_v)' method indicates that the present network of stations is sufficient to capture the variability of rainfall in the UGB. However, as per WMO criteria, it is expected that around 56 stations would be required in the basin. In this light, it would be desirable if all discontinued stations of IMD could be operationalised. Such stations (or some of them) can also be equipped with sensors for measurement of maximum/minimum temperature, relative humidity, wind speed and solar radiation. Entropy analysis has been carried out to find out the desirable areas of probable new stations in the UGB. It is also recommended that the new stations in the Bhagirathi and Alaknanda sub-basins be set up in the upper and lower portions of UGB as self-recording stations to capture the rainfall intensity.

The potential usage of global precipitation estimates from two reanalysis products (ERA5-Land hourly data and IMDAA daily dataset) and precipitation estimates from GPM-IMERG was also investigated. It was found that GPM-IMERG data satisfactorily represent the monthly magnitudes of precipitation and can be used as a suitable alternative for the UGB. For the temperature estimation in UGB, the analysis reveals that ERA5-Land hourly and IMDAA data cannot be used directly for local studies, as these heavily underestimate the local temperature and have a cold bias for the Himalayan region. However, there is a need to carry out further investigations with different sets of data and to validate the station records, particularly the minimum temperatures.

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