Trends of Extreme Climatic Events in Kumaon Lesser Himalaya: A Case Illustration of Ramgad Watershed

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Abstract: ***The paper analyzed the variability of the precipitation pattern and interpreted the frequency and intensity of the high - intensity rainfall and drought over the Ramgad Watershed, Kumaon Lesser Himalaya, India over the past five decades. The study used the ground observed climatic data of the Automated Weather Station [AWS] of India Meteorological Department situated in the watershed for the last 50 years. The study observed an increasing trend in the decadal rainfall but an overall declining trend in decadal rainy days with few exceptions between 1971 and 2020. The study investigated that the decadal rainfall has increased during the winter, summer and monsoon seasons, whereas it shows a declining trend in the post - monsoon months. However, the decadal rainy days indicated a declining trend in all seasons except during the summer months. Further, the watershed recorded a progressively increasing trend in the events of high - intensity rainfall during monsoon months with a considerably large proportion of high - intensity rainfall events falling in the category of severe rainfall events. Whereas, the events of high - intensity rainfall have shown a declining trend during winter, summer and post monsoon seasons in the watershed. However, the number as well as the intensity of drought have been observed increasing in monsoon season if compared to other seasons when the incidences as well as the intensity of drought have shown a declining trend. The study concluded that climate change induced extreme events of high - intensity rainfall and drought have emerged the major environmental threats undermining the sustainability of the socio - ecological system and thus increasing vulnerability of a large proportion of population to water, food, health and livelihood insecurity in the rain - fed and densely populated Lesser Himalayan mountains.***

Keyword: High - intensity rainfall, drought, rainy days, hydrological system, subsistence farming, food and livelihood security

1. Introduction

Climate is referred to as a long - term average of varying the weather phenomena; whereas, weather is interpreted as the state of the atmosphere with respect to wind, temperature, cloudiness, moisture and wind pressure in a geographical region for a short period of time (Balasubramanian, 2018). Extreme events are swift, occur in the present, and are highly visible as opposed to long - term climate change trends that seem abstract, distant, slow and complicated (Herring et al., 2021; FAO, 2018; Donat et al., 2013; Howe et al., 2014; IPCC, 2012). Both the extreme weather and extreme climatic events are termed 'climate extremes' (Balasubramanian, 2018; IPCC, 2012 and 2018). However, the main difference between these two phenomena is related to the specific time scale of the event (National Academies of Sciences, Engineering, and Medicine, 2016). An 'extreme weather event' is referred to as an unexpected, unusual and severe weather condition that occurs within time frames of less than a day to a few weeks; whereas an 'extreme climate event' takes place on a longer time span (IPCC, 2012 and 2014). It has been observed that the rapidly changing climatic conditions are changing the frequency, intensity, spatial extent, duration, and timing of both the weather and climate extremes, and are resulting into unprecedented extremes (Huggel et al., 2020; Khatiwada and Pandey, 2019; Everard et al., 2018; World Bank, 2018; FAO, 2015; Aase et al., 2013; Government of India, 2009; ICIMOD, 2007a and 2007b; Alexander et al., 2006). It has been observed that both the frequency and intensity of extreme events have been increasing all across the world for the past some decades (Dimri et al., 2021; Donat et al., 2013; IPCC, 2012, 2014, 2018 and 2021).

Himalaya which is one of the most densely populated and rapidly urbanizing mountains of the world (Heath et al., 2020; Tiwari et al., 2019 and 2021; Tiwari and Joshi, 2012 and 2015) has been experiencing an unprecedented increase in the frequency and intensity of both the weather and climatic extremes, more particularly the hydrological extremes due to climate change (ICIMOD, 2007a, IPCC, 2018; Wester et al, 2019; Mohanti, 2020). These events are not only disrupting the fragile mountain ecosystem and natural resource base; but also causing loss of human lives, the devastation of community livelihood and agricultural and food system, damage of houses and critical infrastructure at a large scale (Rusk et al, 2021; Grainger et al., 2021; South Asia Network on Dams, Rivers and People, 2021; Mishra and Singh 2010; Shrestha et al.2000, Goswami et al.2007). The intensity and severity of these hydrological weather extremes are evinced by the events of high - intensity rainfall followed by the Glacial Lake Outburst Flow [GOLF] in the valley of Mandakini river in which the important holy Hindu Shrine of Kedarnath is situated, in June 2013; flash - flood in the Great Himalayan mountains in February 2021; and the event of catastrophic rainfall in the densely populated Lesser Himalayan ranges in the post - monsoon month of October 2021, in the Himalayan State of Uttarakhand, India (Indian Express, 2021; South Asia Network on Dams, Rivers and People, 2021; Sati, 2013). These observations clearly indicate that the frequency, intensity and severity of the climate change - induced weather and climatic extremes have been increasing in Himalaya for the last some decades (Sharma et al.2021; Rasul et al., 2019; Shrestha et el.2015; Nandargi et al.2016).

However, a few studies have been conducted so far to understand and analyze the trends and variability of extreme weather and climatic events, particularly at local levels. Rekhcha and Pisharoty (1996) investigated the trends and persistence of extreme rainfall events analyzing 80 - year rainfall data (1991 - 1980) collected from 316 locations using the standard statistical test technique over India. Mirza (2003) analyzed the inter - linkages between climate change and extreme weather events in the context of developing countries. Samra (2004) presented a comprehensive review and analysis of drought monitoring, declaration and management process in India. De et al. (2005) presented a detailed scientific analysis of extreme weather events over India over the last 100 years. Whereas, Shewale and Kumar (2005) studied the trends of climate change - induced drought across India by using 130 years of data series (1877 - 2004). The study observed that hydrological droughts are widespread and more frequent in most of the parts of India; and the authors attributed these extreme events with the increase in temperature and changes in the precipitation patterns across the country. Goswami et al. (2006) used a gridded dataset from 1951 to 2004 to demonstrate the frequency and intensity of extreme rainfall events over India and observed a significant increase in extreme rainfall events. Mall and Kumar (2011) presented a comprehensive overview of the extreme weather events and climate change policy in India. Balasubramanian (2018) has taken into account both weather and climatic extremes as climatic extremes and presented a scientific interpretation of extreme climatic events. More recently, Mohanti (2020) attempted to analyze the pattern, frequency and intensity of extreme weather and climate events such as high - intensity rainfall and drought on a decadal basis using a gridded exposure sheet at the district level in India. This study provided a detailed assessment of the impact of extreme events at the district level for a long period from 1970 to 2019.

Moreover, there exists a large knowledge gap in the understanding of weather and climatic extremes and their association with climate change in Himalaya. Owing to constraints of terrain, climatic complexities and the lack of adequate hydrometeorological data the Himalayan region has not been included in many important research works (Wester et al., 2019). Basistha et al. (2009) explored the changes in rainfall pattern in the Indian Himalaya region during the 20th century using 80 - year data from 30 rain - gauge stations maintained by the India Meteorological Department (IMD) across the region. Bhutiyani et al. (2009) interpreted the interlinkage between climate change and the precipitation variations in the north - western Himalaya. They analyzed the spatial and temporal patterns of rainfall using the long - term climatic data [1992 - 2005] of two meteorological stations located in Nainital and Almora districts in the State of Uttarakhand. The study interpreted the rainfall variability and trend of extreme rainfall events and concluded that the events of extreme rainfall were increasing while the low and moderate rainfall events were declining significantly in the region over the past 50 years. Ghimire et al. (2010) studied the household level vulnerability to drought in hill agriculture of Nepal. Nandargi and Dhar (2011) analyzed the frequency of extreme one - day rainfall for 475 stations for the period of 1871 - 2007 across the Indian Himalaya region. Joshi et al. (2013) examined the trends of rainfall by correlating it with different indices of extreme rainfall in Uttarakhand Himalaya.

Wang et al. (2013) examined the climatic factors of winter droughts in western Nepal Himalaya during recent years. Kafle (2015) analysed the spatial and temporal variation of drought in the Middle and Western Himalayan region of Nepal. Kotal et al. (2014) analyzed the observational aspects of catastrophic heavy rainfall event in the Great Himalayan Ranges in Uttarakhand occurred in June 2013. Nandargi et al., (2016) analyzed the frequency and magnitude of 1 - day extreme rainfall event in Uttarakhand region during 1991 - 2013 using 100 years of daily rainfall data. Kumar et al. (2016) studied the pattern and trend of meteorological drought in the western part of Uttarakhand employing the Standardized Precipitation Index (SPI) and using 60 years of daily rainfall data. Dahal et al. (2016) made a comprehensive temporal and spatial assessment of drought risks in central Nepal. Shekhar et al. (2017) analyzed the trends in extreme precipitation events over western Himalayan mountains in India. Moreover, Xavier et al. (2018) investigated the instability and dynamics of abnormal circulation pattern and intensification of the trough in the upper troposphere observed during the extreme rainfall event which occurred in the early phase of the 2013 summer monsoon in the State of Uttarakhand based on the dataset of European Centre for Medium - range Weather Forecasts [ECMWF]. Adhikari (2018) attempted to evolve drought impact and adaptation strategies for the mid - hill farming system of western Nepal Himalaya. Xavier et al. (2018) analyzed the dynamics of an extreme rainfall event that triggered devastating flash - flood in the Greater Himalayan ranges in Uttarakhand in 2013. Krishnan et al. (2019) presented a comprehensive overview of the weather and climatic extremes related to climate change across the Himalaya.

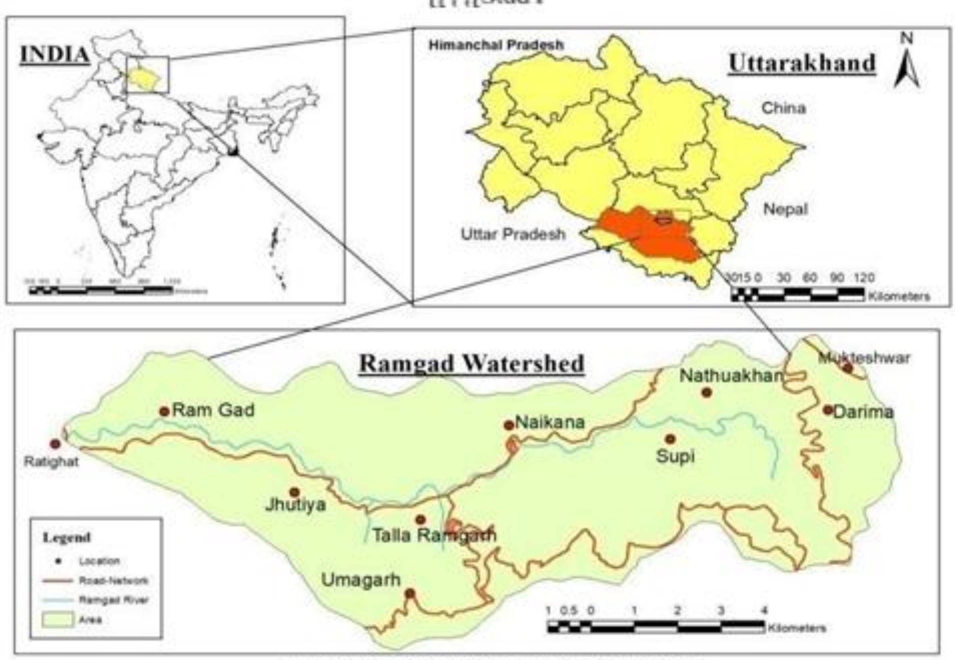
The preceding discussion clearly indicates that there exists a vast knowledge gap in the scientific understanding of weather and climatic extreme events, particularly at the local level in the Himalaya which is now being considered as one of the climate change hot - spots of the planet. In view of this, the present work that aims to analyze the trends and variability of the most prevalent extreme climate events all across the Himalayan mountains - the high - intensity rainfall and droughts - would help in developing a preliminary scientific understanding of the spatio - temporal pattern of climate change - induced hydrological extremes at watershed level in the region. The work presented in the paper is based on the interpretation of ground observed daily rainfall data of the past 50 years [1971 - 2020] over the Ramgad Watershed situated in Kumaun Lesser Himalaya, Uttarakhand, India.

2. Study Area

Ramgad Watershed situated in the Lesser Himalayan mountains of district Nainital, in Uttarakhand State has been selected as the site of study for the present work (Figure - 1). The Watershed lies between 29°24' to 29°29' N latitudes and 79°29' to 79°39' E longitudes and encompasses a geographical area of approximately 75.02 km2 between an elevational transect of 1025 and 2525 m from the mean sea level. Since Ramgad watershed is one of the most densely populated areas of Kumaon Lesser Himalaya and is located almost centrally in the region, it has been considered a representative watershed for the present study. Ram Gad is one of the principal tributaries of River Kosi which is one of the most important rain - fed rivers of Kumaon Himalaya. The area of the watershed is characterized by diversified terrain and geomorphic landforms which are reflected in varying magnitudes of slopes and their aspects, variety of soils, natural vegetation and hydrological parameters, and the climatic complexities observed across the region. Geologically, the area is very complex and constituted by several formations and shows evidence of landslides, displacement of rocks, slope failure and multi - cyclic river terraces.

The Watershed is marked with varying natural and socio - economic characteristics with sharp variations in both absolute and relative relief which are clearly reflected in the availability of natural resources and their utilization pattern all across the area. The total population of the watershed was 22085 persons in 2020, which are inhabited in 30 villages. These physical and social characteristics render the entire watershed highly vulnerable to the impacts of climate change as well as climate change - induced weather and climatic extremes. Moreover, the susceptibility of the socio - ecological system of the watershed to climate change has direct implications on the availability, carrying capacity and utilization pattern of natural resources, particularly water, land and forests, and community livelihood. This further increases the vulnerability of the natural and socio - economic system to the risks of extreme weather and climate events in the watershed. This is substantiated by the event of high - intensity rainfall that devasted most of the farm - land, roads and irrigation canals, houses and other rural infrastructure and community livelihood besides taking the toll of hundreds of human lives in October 2021 (Indian Express, 2021; South Asia Network on Dams, Rivers and People; 2021). Moreover, the Adaptation to climate change demands an integrated approach between the natural ecosystem and socio - economic system at the watershed level in mountain regions (FAO, 2015 and 2018). In view of this, an attempt has been made in the present work to analyze the trend and variability of extreme weather events following the watershed approach.

Figure Number 1: Location Map of Ramgad Watershed



Location Map of Ramgad Watershed

3. Data Source and Methodology

As in other parts of Himalaya the events of high - intensity rainfall and incidences of droughts have been considered as major weather and climatic extremes in the watershed. However, in the present work, both the 'extreme weather events' and 'climatic extremes' have been termed and studied as 'climatic extremes. Firstly, because almost all the studies carried out in the Himalayan region and also in other parts of the world (referred in the present work) have clearly attributed both the climatic and weather extremes to climate change. Secondly, several research publications have used the term 'climatic extremes' for both the weather and climatic extremes (Balasubramanian, 2018; Herring et al., 2021; FAO, 2015 and 2018; Donat et al., 2013; Howe et al., 2014; World Bank, 2018; FAO, 2015; Khatiwada and Pandey, 2019; IPCC, 2012, 2014, 2018 and 2021). The ground observed rainfall data of the past 50 years [1971 - 2020] has been analyzed for the identification and interpretation of the trends of high - intensity rainfall and droughts in the region. The method recommended by India.

Meteorological Department (2005a, 2005b and 2015) has been used for the determination and classification of the events of high - intensity rainfall and incidences of droughts in the watershed. As in other parts of India the annual weather cycle of the Ramgad Watershed has been divided up into the following three seasons following the approach of the Indian Institute of Tropical Meteorology (Joshi et al.1983): [i] the cold and dry winter season [from December to February]; [ii] the hot and dry summer season [from March to May]; [iii] the hot and wet rainy season [from June to September]; and [iv] the post - monsoon season [from October to November]. The above - mentioned seasonal cycle has been adopted to analyze the temporal pattern and distribution of rainfall in Ramgad Watershed.

The rainfall data have been obtained from the Indian Meteorological Department Automated Weather Station [AWS] located at Mukteshwar in Ramgad Watershed. Besides analyzing the daily rainfall pattern, the arithmetic average has been used for the construction of monthly mean rainfall data in the watershed. The daily rainfall data has been used for determining the number of total monthly and annual rainy days and events of high - intensity rainfall, whereas the monthly average rainfall has been used for the identification and classification of droughts. The days when the rainfall exceeded 0.1 mm in 24 hours were included in rainy days over the watershed (India Meteorological Department, 2015). The amount of rainfall [in mm] and its percentile have been considered as parameters to determine the events of high - intensity rainfall over the watershed. The high - intensity rainfall events have been classified into the following three categories adopting the criteria of India Meteorological Department (2015): [i] heavy rainfall when the total rainfall ranges between 64.5 mm and 115.5 mm/day with a percentile range between 95 and 99; [ii] very heavy rainfall ranges between 115.6 mm/day and 204.4 mm/day with a percentile range between 99 and 99.9; and

[iii] Extremely heavy rainfall above 204.4 mm/day with percentile range of above 99.9.

Further, the temporal pattern of ‘rainfall deficiency' has been used as a tool for determining the events of droughts in the Watershed. The method developed and used by the India Meteorological Department has been employed for the identification and classification of droughts in the present work (India Meteorological Department, 2015). The India Meteorological Department refers drought to as a meteorological condition in which the rainfall deficiency in an area is more than 26% of its long time normal. The drought is classified into ‘moderate’ and ‘severe’ respectively when the rainfall deficiency is between 26 to 50% and more than 50% (India Meteorological Department). In view of this, the droughts in the Ramgad Watershed have been classified into the following two categories: [i] ‘moderate drought' when the rainfall deficit lies in the range between 26% and 50%; and [ii] 'severe drought' when the rainfall deficit exceeds above 50% of its long time normal in the area.

4. Results and Discussion

4.1 The Temporal Pattern of Rainfall

The temporal pattern of rainfall is reflected by it’s daily, monthly and seasonal variability, and the number of rainy days. Since Ramgad Watershed is situated in the Lesser Himalaya ranges, the rainfall is the most prominent form of precipitation in the region as most of the precipitation in the watershed is received in the form of rainfall. As in other parts of Himalaya the south - facing slopes which come first to the contact of monsoon winds, receive a higher amount of rainfall compared to north - facing slopes in the watershed. Most of the rainfall is governed by the southwest monsoon, and nearly 75% of the total annual rainfall occurs during the monsoon season normally between 15 June and 15 September. Table - 1 shows that the decadal trends of rainfall variability and rainy days in Ramgad Watershed over the past 5 decades between 1971 - 2020. The Table makes it clear that the watershed received a total rainfall of 62596 mm with an annual average of 1252 mm during the past 5 decades. Ramgad Watershed observed an overall increasing trend of decadal rainfall over the past 50 years. The average decadal rainfall increased by 20% between 1981 - 1990 and 1991 - 2000, by 8% between 1991 - 2000 and 2001 - 2010 and by 4.29% between 2001 - 2010 and 2011 - 2020 with an overall average increase of 2.34% during the past 5 decades. However, the decadal rainfall declined by 23% between the decades 1971 - 1980 and 1981 - 1990 (Table - 1, Figure No.2.1). However, in general, a slightly declining trend has been observed in the temporal distribution of rainy days in the watershed over the last 50 years (Table - 1, Figure No.2.2). This is indicated by an overall average decrease of 1.05% in the annual number of rainy days in the watershed during the period. Table - 1 explains that the number of rainy days declined by more than 11% during the decades 1971 - 1980 and 1981 - 1990; while the rainy days increased respectively by 2.85%, 0.44% and 4.06% between 1981 - 1990 and 1991 - 2000, 1991 - 2000 and 2001 - 2010 and 2011 - 2020 respectively in the watershed (Table - 1, Figure No. 2.2).

Table 1: Decadal Trends of Rainfall Variability and Rainy Days in Ramgad Watershed [1971 – 2020]

Decades	Total Rainfall (mm)	% Change in Total Rainfall	Annual Average Rainfall (mm)	% Change in Annual Average Rainfall	Number of Rainy Days	% Change in Rainy Days
1971 - 1980	13228	-	1323	-	754	-
1981 - 1990	10203	- 23.00	1020	- 23.00	667	- 11.54
1991 - 2000	12220	+20.00	1222	+20.00	686	+02.85
2001 - 2010	13189	+8.00	1319	+8.00	689	+00.44
2011 - 2020	13756	+4.29	1376	+4.20	717	+04.06
Total	**62596**	**+2.32**	**1252**	**+2.30**	**3513**	**- 01.05**

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Table - 2 illustrates the decadal distribution and trends of seasonal rainfall and seasonal rainy days during winter and summer seasons in the watershed from 1971 to 2020. The Table shows that the winter rainfall [from December to February] which is extremely useful for Rabi crops and horticultural farming in the region has increased by 11% over the period. The winter rainfall increased by respectively by 24% and 33% between the decades 1971 - 1980 and 1981 - 1990 and 2001 - 2010 and 2011 - 2020; while it declined by 7.22% between 1981 - 1990 and 1991 - 2000, and by 7% between the decades 1991 - 2000 and 2001 - 2010 (Table - 2, Figure No, 3.1). However, the watershed recorded an overall average decline of 1% rainy days in the winter season over the past 50 years. The number of winter - season rainy days declined continuously during the first 4 decades (from 1971 - 1980 to 2001 - 2010) while the number of rainy days increased almost by 20% between the decades 2001 - 2010 and 2011 - 2020 (Table - 2, Figure No.3.3). Table - 2 and Figure No.3.2 shows that the overall average summer rainfall increased by 6% with a clear increasing trend over all the decades except during 1981 - 1990 and 1991 - 2000 when the watershed recorded a 4% decline in summer rainfall. Ramgad Watershed enjoyed total of 622 rainy days during the summer seasons over the past 5 decades. The interpretation of rainy days revealed a clearly increasing trend in the number of rainy days in the watershed during summer month throughout all 5 decades with an overall average increase of 8.33 rainy days (Table - 2, Figure No.3.4). The number of rainy days increased by 1%, 5% and 19% respectively between the decades 1981 - 1990 and 1991 - 2000, 1991 - 2000 and 2001 - 2010, and 2001 - 2010 and 2011 - 2020.

Table 2: Seasonal Rainfall Variability and Rainy Days in Ramgad Watershed [1971 – 2020]

Decades	Winter Season (December - February)						Summer Season (March - May)					
	Total Rainfall (mm)	% Change in total Rainfall	Annual Average Rainfall (mm)	% Change in Annual Average Rainfall	Number of Rainy Days	% Change in Rainy Days	Total Rainfall (mm)	% Change in Total Rainfall	Annual Average Rainfall (mm)	% Change in Annual Average Rainfall	Number of Rainy Days	% Change in Rainy Days
1971 - 1980	1085	-	108	-	89	-	1481	-	148	-	118	-
1981 - 1990	1342	+24.00	134	+24.00	88	- 1.00	1632	+10.19	163	+10.19	118	-
1991 - 2000	1245	- 7.22	124	- 7.22	82	- 6.00	1560	- 4.41	156	- 4.41	119	+1.00
2001 - 2010	1159	- 7.00	116	- 7.00	65	- 17.00	1759	+13.00	176	+13.00	124	+5.00
2011 - 2020	1538	+33.00	154	+33.00	74	+20.00	1828	+4.00	183	+4.00	143	+19.00
Total	**63696**	**+11.00**	**127**	**+11.00**	**398**	**- 1.00**	**8260**	**+6.00**	**165.2**	**+6.00**	**622**	**+8.33**

Table 3: Seasonal Rainfall Variability and Rainy Days in Monsoon and Post Monsoon Seasons in Ramgad Watershed [1971 – 2020]

Decades	Monsoon Season (June - September)						Post - Monsoon Season (October - November)					
	Total Rainfall (mm)	% Change in Total Rainfall (mm)	Annual Average Rainfall (mm)	% Change in Annual Average Rainfall	Number of Rainy Days	% Change in Rainy Days	Total Rainfall (mm)	% Change in Total Rainfall	Annual Average Rainfall (mm)	% Change in Annual Average Rainfall	Number of Rainy Days	% Change in Rainy Days
1971 - 1980	10192	-	1019	-	517	-	470	-	47	-	30	-
1981 - 1990	7976	- 25.00	798	- 25.00	426	**- 17.60**	564	+20.00	56	+20.00	27	- 3.00
1991 - 2000	9048	+13.44	905	+13.40	459	**+7.7**	283	- 50.00	28	- 50.00	26	- 1.00
2001 - 2010	7738	- 14.47	774	- 14.40	471	**+2.61**	403	+42.00	40	+42.00	23	- 3.00
2011 - 2020	11054	+45.00	1105	+45.00	495	**+5**	239	- 42.00	23	- 42.00	19	- 4.00
Total	**46009**	**+5.00**	**920**	**+5.00**	**2368**	**- 0.57**	**1959**	**- 7.50**	**20**	**- 7.50**	**125**	**- 3.00**

Table - 3 shows the decadal distribution and trends of seasonal rainfall and seasonal rainy days during monsoon and post - monsoon months in Ramgad Watershed over the past 5 decades.

Ramgad Watershed recorded a continuously increasing trend of rainfall during monsoon months with an overall average increase of 5% over the past 50 years. The monsoon rainfall increased by13.44% and 45% respectively between the decades 1981 - 1990 and 1991 - 2000 and 2001 - 2010 and 2011 - 2020. However, the decadal monsoon season rainfall recorded a decline of 25% between 1971 - 1980 and 1981 - 1990 and 14.47% between 1991 - 2000 and 2001 - 2010 (Table - 3, Figure No.4.1). Whereas, the number of monsoon rainy days decreased by 0.57 % in the watershed for the past 5 decades (Table - 3, Figure No.4.3). Ramgad Watershed received a total rainfall of 1959 mm in 125 rainy days during post - monsoon season over the period of last 5 decades. The interpretation of post - monsoon season rainfall data revealed that the watershed experienced an overall decrease of 7.5% in the post - monsoon season rainfall over the past 50 years. Table - 3 shows that the post - monsoon season rainfall increased by 20% and 40% respectively between the decades 1971 - 1980 and 1981 - 1990 and 1991 - 2000 and 2001 - 2010, whereas it declined respectively by 50% and 42% between the decades 1981 - 1990 and 1991 - 2000 and 2001 - 2010 and 2011 - 2020 (Table No.3, Figure No.4.2). However, the watershed witnessed a continuously decreasing trend of post - monsoon months rainy days throughout the last 50 years with an average decline of 3% (Table - 3, Figure No.4.4).

Decadal and seasonal Changes in Rainfall variability and rainy days over Ramaged Watershed [1971 - 2020]

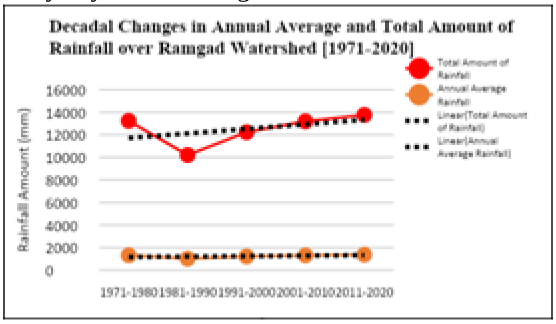
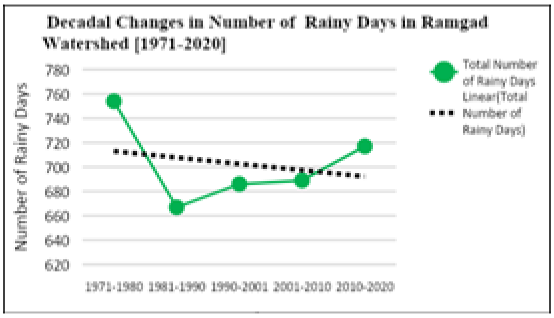


Figure 2.1



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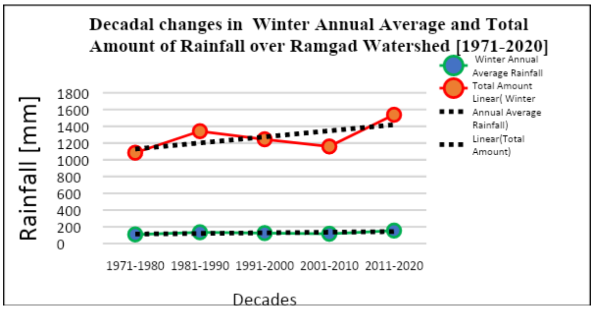

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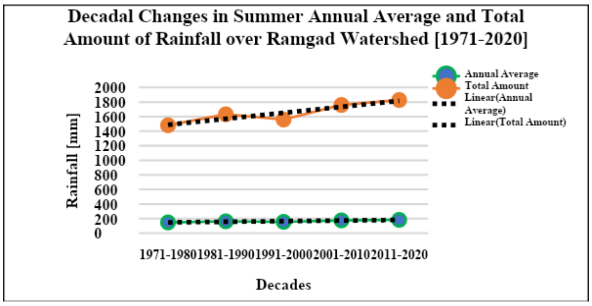

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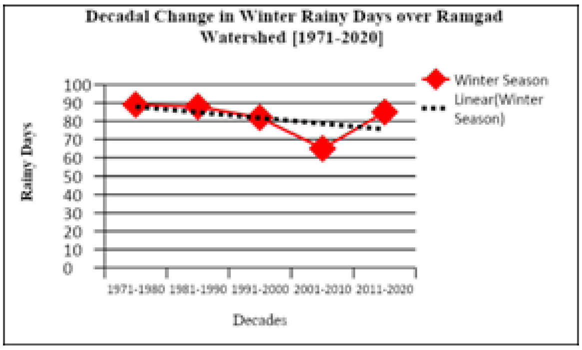

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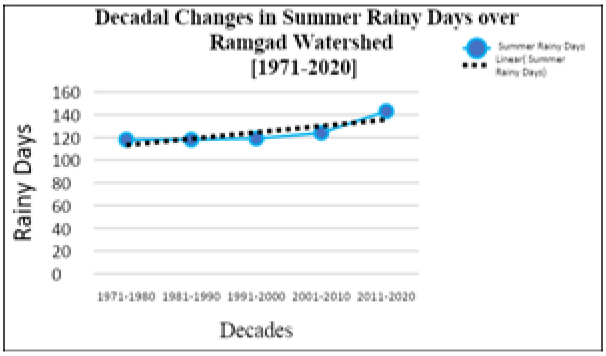

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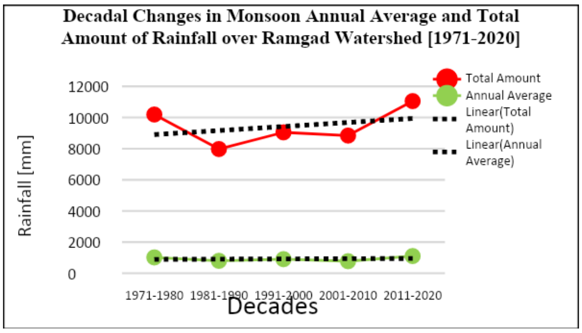
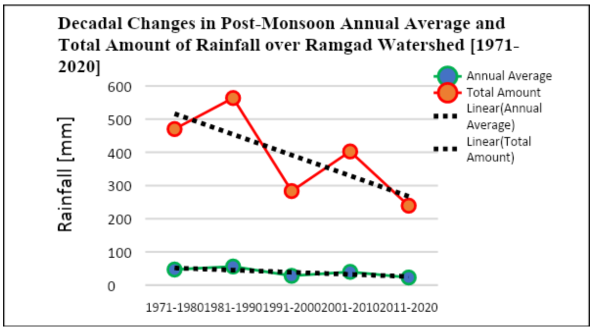


Figure 4.1



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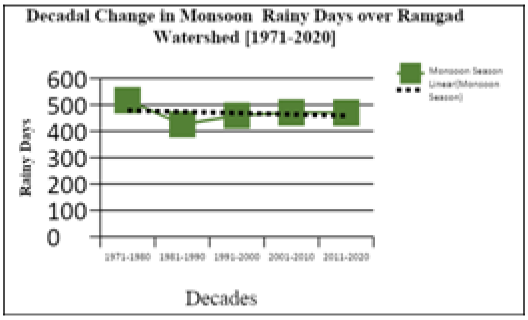

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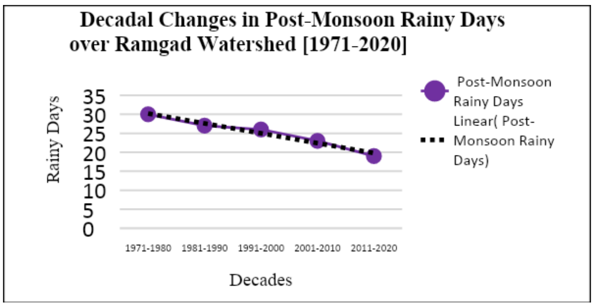

Figure 4.4

The High - Intensity Rainfall Events:

The interpretation of ground observed climatic data revealed that the events of high - intensity rainfall have been increasing in the watershed for the past five decades. As in other parts of Himalaya this increasing trend in the incidences of high intensity rainfall have been attributed to climate change (Wester et al., 2019; International Centre for Integrated Mountain Development, 2007a and 2007b). Flash - floods are generally caused by high - intensity rainfall which triggers a series of hazards such as, rock falls, landslides, debris and mudflow in the mountain environment (ICIMOD, 2007a and 2007b). Table - 4 and Figure No.5.1 presents the trends and temporal distribution of the events of high - intensity rainfall over the watershed on a decadal basis from 1971 to 2020. The watershed recorded total of 123 days of high - intensity rainfall over the past 5 decades. Out of total of 123 events of high – intensity rainfall respectively 91, 29 and 3 have been categorized as heavy, very heavy and extremely heavy rainfall events. Table - 4 indicates a progressive increase in the frequency of the incidences of high - intensity rainfall in the region over the period. The events of high - intensity rainfall increased from 18 during 1971 - 1980 to as many as 29 events in 2001 - 2010 in Ramgad Watershed. However, the events of high - intensity rainfall declined slightly between the decades 2001 - 2010 and 2011 - 2020 in the watershed. Table - 3 also indicates a continuously increasing trend in the events of heavy rainfall except between the decades 2001 - 2010 and 2011 - 2020 when the incidences of heavy rainfall declined marginally in the region. Although the number of very heavy and extremely heavy rainfall events does not seem significant compared to the number of heavy rainfall events, yet it is alarming that the incidences of very heavy and extremely heavy rainfall have been rising for the period of 50 years. More particularly the events of extremely heavy rainfall have emerged only during the past 2 decades (Table - 4). This further indicates that not only the events of high - intensity rainfall are increasing, but the frequency of both heavy and extremely heavy rainfall events has also been rising over the past 5 decades in the region (Table - 4).

Table 4: Decadal Trend of High Intensity Rainfall Events in Ramgad Watershed [1971 - 2020]

Decadal Change	Total Rainfall (mm)	Days of High Intensity Rainfall	Categories of High - Intensity Rainfall Events		
			Heavy rainfall Events	Very Heavy Rainfall Events	Extremely - Heavy Rainfall Events
1971 - 1980	13228	18	14	4	0
1981 - 1990	10203	22	15	7	0
1991 - 2000	12220	27	20	7	0
2001 - 2010	13189	29	22	6	1
2011 - 2020	13756	27	20	5	2
Total	62596	123	91	29	3

Table 5: Seasonal Trends of High - Intensity Rainfall Events in Ramgad Watershed (1971 - 2020)

Seasons	Total Rainfall (mm)	Days of High - Intensity Rainfall Events	Categories of High - Intensity Rainfall Events		
			Heavy Rainfall Events	Very Heavy Rainfall Events	Extremely Heavy Rainfall Events
Winter Season (December - February)	6370	6	4	2	0
Summer Season (March - May)	8259	2	1	1	0
Monsoon Season (June - September)	46009	109	81	25	3
Post - Monsoon Season (October and November)	1959	6	5	1	0
Total	62596	123	91	29	3

Table - 5 and Figure No.5.2 shows the distribution and trends of the events of season - wise high - intensity rainfall over the watershed from 1971 to 2020. The watershed recorded the highest number of events (109) of high - intensity rainfall in the monsoon season followed by winter (6), post - monsoon (6) and summer season (2) over the past 50 years. This clearly indicates that the monsoon season is the most critical for the incidences high - intensity rainfall and their associated risks in the region. Out of the total 109 events of high - intensity rainfall that occurred during the monsoon months respectively 81, 25 and 3 have been characterized as heavy, very heavy and extremely heavy rainfall events. Nevertheless, not a single event of extremely heavy rainfall was experienced in the winter season, summer and post - monsoon seasons in the region over the past 5 decades (Table - 5). The increasing incidences of high - intensity rainfall are disrupting the life, livelihood, infrastructure and subsistence agricultural economy of the fragile Himalayan ecosystem in the watershed through disruption of hydrological processes, depletion of water sources, and frequent crop failures. Similar observations have also been made in the studies carried out in other parts of Himalaya including Nepal Himalaya (ICIMOD, 2007a). The synthesis of research produced by the International Centre for Integrated Mountain Development (ICIMOD) revealed that most serious changes in the socio - ecological system in Himalaya are probably related to the frequency and magnitude of extreme weather events, such as high intense rainfalls leading to flash floods, landslides and debris flows (ICIMOD, 2007a and 2007b). The climate change - induced extreme rainfall events are triggering the process of natural disasters all across the Himalayan mountains (Grainger et al., 2021; Rusk et al., 2021; Rasul et al., 2019; World Bank, 2028; ICIMOD, 2007a and 2007b; Sati, 2013). The two devastating events of cloudburst triggered flash - floods that occurred in the Kedarnath and Badrinath valleys during pre - monsoon season in Uttarakhand Himalaya in 2013 substantiate these observations (Bhutiyani et al., 2009; Sati, 2013; Xavier et al., 2018). Further, the increasing incidences of climate change - induced high - intensity rainfall and the associated devastation have been evinced by the abnormal rainfall episode in the post - monsoon month of October 2021 in the Himalayan State of Uttarakhand, particularly in Ramgad Watershed. This extreme rainfall event has been termed as the highest rainfall recorded in the history of the region as per the India Meteorological Department (South Asia Network on Dams, Rivers and People, 2021; Indian Express, 2021).

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Decadal and seasonal changes in High- Intensity Rainfall Events over Ramgad Watershed [1971- 2020]

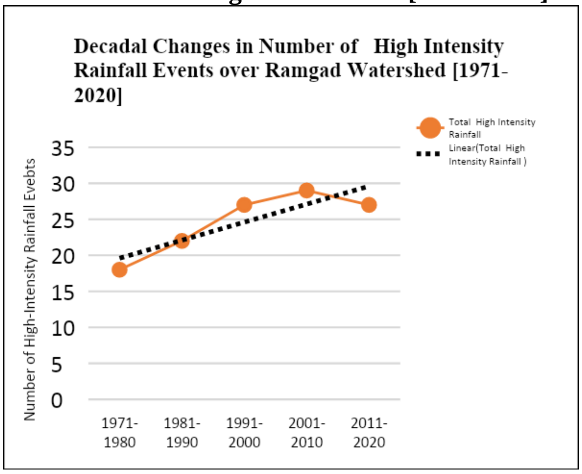

Figure 5.1

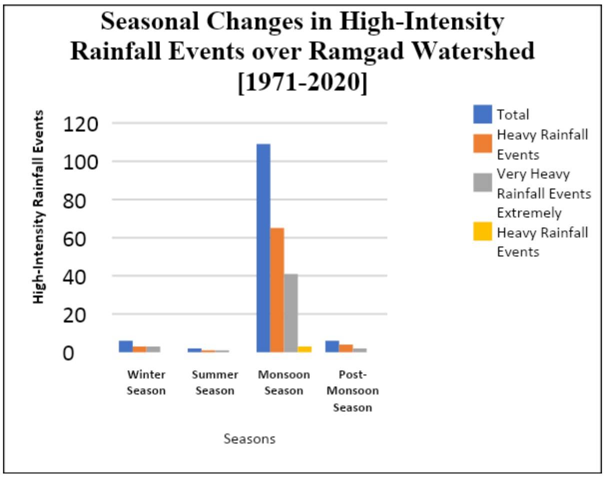

Figure 5.2

Drought Events

Drought has been conceptualized and defined as an extended period of deficient precipitation resulting into widespread depletion of water resources, disruption of the natural environment, and a significant loss of farm production (FAO, 2018). Drought is generally referred to as the deficiency in precipitation over an extended period that often results in a water shortage causing adverse impacts on vegetation, soils, livestock, and people (Wilhite, 2000; Khatiwada and Pandey, 2019). Further, drought is generally considered as the condition of acute water shortage due to lack of rains over a protracted period of time affecting natural as well as socio - economic systems (Mishra and Singh, 2010). Further droughts are referred to as an extended period of low precipitation that results into the shortage of water (Wilhite, 2000). Droughts are a creeping phenomenon that is difficult to be precisely identified as these events develop slow in time, but their impacts generally last for a long period (FAO, 2018). Drought leads to the disruption of hydrological processes, depletion of water and forest resources, loss of soil moisture, and decline in agricultural productivity and crop failure (Government of India, 2009). Further, drought is a usual, recurring feature of climate and characterized in terms of its geographical coverage, intensity and duration (Government of India, 2009). Conditions of drought appear when the rainfall is deficient over a region to the statistical average for an extended period (FAO, 2018). Drought may reduce the availability of water and reduce food and fodder productivity for a longer period (Narasimhan and Srinivasan, 2005; Dahal et al., 2016).

As discussed in the preceding sections the number of rainy days has been declining in Ramgad Watershed for the last 50 years. This is resulting into the temporal deficiency in rainfall and widespread conditions of soil moisture loss, decrease in groundwater recharge and resultant acute water shortage over protracted period affecting natural as well as socio - economic systems all across the watershed. Table - 6 and Figure No.6.1 presents the trend and distribution of drought events over the Ramgad Watershed during the period 1971 - 2020. The Table shows that the incidences of drought have been increasing with some fluctuations. The watershed recorded as many as 495 events of drought during the last 50 years with an average occurrence of nearly 10 droughts each year. The highest number of drought incidences [103] were recorded in the decade 2011 - 2020 followed by 1981 - 1990 (102), 1991 - 2000 (99), 2001 - 2010 (96) and 2001 - 2010 (95). A close observation of Table - 6 makes it clear that the events of drought have increased from 95 to 102 between the decades of 1971 - 1980 and 1981 - 1990, but the drought events declined slightly in the following two decades. Further, Table - 6 also explains clearly that the intensity of droughts has increased over the last five decades in the region. This is brought out by the fact that out of the total 495 drought events as many as 407 (more than 82%) have been characterized as severe droughts and only 88 (18%) classified as moderate drought events. Moreover, the frequency of both the normal and severe drought events have been observed increasing in the watershed (Table - 6).

Table 6: Decadal Changes in Drought Events over Ramgad Watershed (1971 - 2020)

Decades	Annual Number of Drought Events	Categories of Drought Events	
		Moderate Drought	Severe Drought
2001 - 2010	95	15	80
1981 - 1990	102	21	81
1991 - 2000	99	20	79
2001 - 2010	96	16	80
2011 - 2020	103	16	87
Total	495	88	407

Table 7: Seasonal Variability of Drought Events in Ramgad Watershed (1971 - 2020]

Seasons	Moderate Drought	Severe Drought	Total
Winter Season (December - February)	20	86	106
Summer Season (March - May)	28	89	117
Monsoon Season (June - September)	24	145	169
Post - Monsoon Season (October and November)	16	87	103
Total	88	407	495

Table - 7 and Figure No.6.2 shows the seasonal variations in the occurrence of drought events in the watershed over the last five decades. Out of the total drought events (495) as many as 169 were observed during the monsoon season followed by summer (117), winter (106) and post - monsoon (103) months. This clearly indicates that precipitation

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deficiency as well as its temporal variability has been increasing in the rainy season in the watershed. The interpretation of the intensity of drought events in terms of their severity indicated that the occurrence of severe drought events is much more compared to the incidences of normal drought events in all the three seasons over the watershed during the past 5 decades. Further, the monsoon months experienced the highest events (145) of severe drought in comparison to the drought events that occurred in the watershed during summer (89), post - monsoon (87) and winter (86) seasons over the past 50 years (Table - 7, Figure no.6.2).

Decadal and seasonal changes in Drought Events over Ramgad Watershed [1971- 2020]

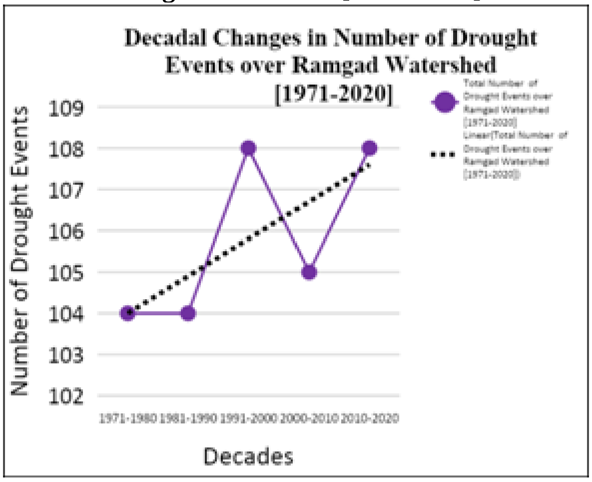

Figure 6.1

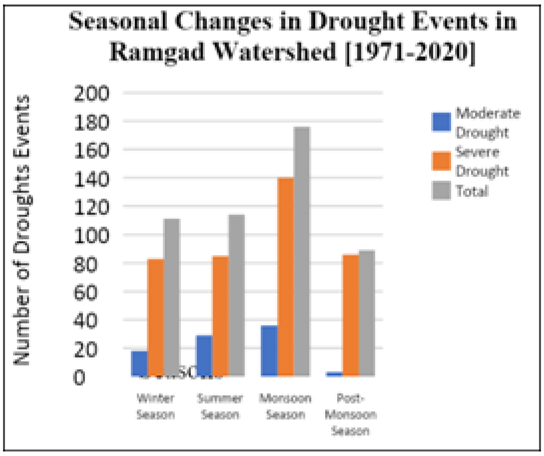

Figure 6.2

This clearly indicates that climate change - induced drought has emerged as one of the major threats to the subsistence farming system and rural food and livelihood security in the rain - fed middle Himalayan mountains (Adhikari, 2018; Dahal et al., 2016; Government of India, 2009). The rising temperature and the resultant increase in the rate of evapotranspiration and soil moisture loss accelerating the frequency and severity of meteorological drought all across the Himalayan mountains (Sharma et al., 2021; Khatiwada and Pandey, 2019; Kafle et al., 2015; Ghimire et al., 2010). The studies conducted in Nepal Himalaya also indicated that climate change - induced droughts have emerged as major climatic extremes, and the occurrences of drought are more frequent during the last 20 - 30 years intensifying their severity and duration in the region (Dahal et al., 2016; IPCC, 2012; Mishra and Singh, 2010; ICIMOD, 2007a and 2007b).

5. Conclusion

The study investigated that climate change has altered the precipitation pattern and transformed the hydrological regimes of the Himalayan watersheds over the past five decades. This is resulting into increasing frequency and intensity of climatic extremes, particularly the events of high - intensity rainfall and drought. Ramgad Watershed exhibited sharp variability in the temporal distribution of rainfall as both the amount of rainfall and the number of rainy days fluctuated unsteadily over the period. The events of high - intensity rainfall are not only increasing during monsoon months, but they are also becoming more severe. However, the watershed experienced fewer incidences of high - intensity rainfall during the winter season in comparison to the monsoon months. Moreover, the frequency, as well as the severity of drought, is much higher during monsoon months compared to other normally dry seasons in the region. The above - mentioned observations indicate clearly that climate change - induced events of high - intensity rainfall and drought have emerged as one of the major threats to subsistence farming system and food and livelihood security in the densely populated rain - fed middle Himalayan mountains over the past some decades.

The increasing frequency and severity of weather, as well as climatic extremes in combination with poverty and marginality have increased the vulnerability of the poor and other weaker sections of society to climate change and climate change - induced natural risks across the Himalayan mountains. These extremes are likely to have serious implications not only for a range of ongoing rural development and other programmes, but also on the implementation of climate change adaptation plans and attainment of United Nations Sustainable Development Goals in high mountains. Moreover, increasing stress of weather and climatic extremes may further increase the trends of rural outmigration resulting into draining away of human resource and further retarding the process of sustainable development in mountains. Further, the adverse effects of these extreme events are expected to disrupt the hydrological system of rain - fed Himalayan watersheds and affect the availability of fresh water both in the mountains and in the densely populated plains of South Asia. In view of this, there is an urgent need to close the knowledge gap by establishing and strengthening hydro - meteorological system for monitoring hydrological processes and downscaling climate models at the watershed level. In view of this, it is expected that the present work would contribute towards improving the understanding of the characteristics of weather and climatic extremes and the controlling factors of their variability at the watershed level.

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