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Trends of Extreme Climatic Events in Kumaun Lesser Himalaya: A Case Illustration of Kujgad Watershed

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Abstract:

The present study analyzed the variability of the precipitation pattern and interpreted the frequency and intensity of the high-intensity rainfall and drought over the Kujgad Watershed, Kumaun Lesser Himalaya, India, over the past 5 decades, used the climatic data of the Uttarakhand Forest Department Tarikhet (Ranikhet), situated in the middle of the Watershed. The study observed a decreasing trend of rainfall (i.e., 0.25mm/year) and the data indicate that most of the rain amounts below the mean value (897.76mm ± 220.86 mm). Moreover, the study investigated that the decadal rainfall has increased during the winter, summer and monsoon seasons, whereas it shows a decreasing trend in the post-monsoon season. Likewise, the decadal rainy days indicated a declining trend in all seasons except the summer. Further, the Watershed recorded a progressively increasing trend in high-intensity rainfall events during monsoon months, with a considerably large proportion of high-intensity rainfall events falling in the category of severe rainfall events. At the same time, high-intensity rainfall events have shown a declining trend during winter, summer and post-monsoon seasons in the Watershed. However, the numbers as well as the intensity of drought have been observed to increase in the monsoon season compared to other seasons. The study concluded that climate change-induced extreme events of high-intensity rainfall and drought have emerged as the major environmental threats undermining the sustainability of the socio-ecological system and thus increasing the vulnerability of a large proportion of the population to water, food, health and livelihood insecurity in the rain-fed and densely populated Lesser Himalayan mountains.

Keywords: *High-intensity Rainfall, Drought, Rainy Days, Hydrological System, Livelihood security, Kumaun Lesser Himalaya, Kujgad Watershed*

1. Introduction:

Recent investigations observed that the changing climatic conditions are increasing the severity and frequency of extreme weather events such as storms, cyclones, heavy snowfall and drought, which are causing drought, flash floods, floods, landslides, avalanches and Glacial Lake Outburst Flow (GLOF) all across the world (WHO, 2014; IPCC, 2014 and 2018; ICIMOD, 2012 and

2017). Extreme events are swift, occur in the present and are highly visible as opposed to long-term climate change that seems abstract, distant, slow and complicated, and have devastating impacts on the natural environment, natural water resources, agricultural resources, urban and rural infrastructure, agriculture, food and livelihood security, health and supply chains worldwide (Balasubramanian, 2018; Nainwal, 2021; IPCC, 2012 and 2018; Herring et al., 2021; FAO, 2018; IPCC, 2012).An 'extreme weather/climatic event' is an unexpected, unusual and severe weather condition that occurs within time frames of less than a day to a few weeks or a longer time span (IPCC, 2012 and 2014). The frequency and intensity of extreme events have been increasing worldwide for decades Dimri et al., 2021; Donat et al., 2013; IPCC, 2012, 2014, 2018 and 2021). 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 in 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).

Himalaya, which is one of the most densely populated and rapidly urbanizing mountains of the world, 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 (Heath et al., 2020; Tiwari et al., 2019 and 2021; 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, and damage of houses and critical infrastructure at a large scale (Rusk et al., 2021; Grainger et al., 2021; Mishra and Singh, 2010; Shrestha et al., 2016; 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 months 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 climate change-induced extremes have been increasing in the Himalayan region 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. The most recent assessment report (AR6) of the IPCC observed that mountains are highly significant regions in the context of climate change and sustainable development.

Mountains have experienced above-average warming, which is expected to continue in the future (IPCC, 2021 and 2022a). The observed changes in mountain ecosystems include increasing temperatures, changing seasonal rainfall patterns, reductions in snow cover extent and duration at low elevations, loss of glacier mass, increased permafrost thaw, and an increase in the number and size of glacier lakes (IPCC, 2021 and 2022a). The hydro-meteorological monitoring system needs to be better developed across the Himalayan region; consequently, a vast gap in climatic information exists in the entire Himalayan region (ICIMOD, 2009a and 2012). As a result, there exists a significant knowledge gap in the understanding of the trends of climate change and its association with weather and climatic extremes. Due to terrain constraints, climatic complexities and the lack of adequate hydro-meteorological data, the Himalayan region has yet to be included in many important research works (ICIMOD, 2019). However, the frequency of extreme weather events, particularly high-intensity rainfall and drought, has increased in the Himalayan region over the past decades (Government of Uttarakhand, 2014; ICIMOD, 2012). The Himalayan Mountains receive 80% and 20% of the annual rainfall, respectively, in the summer months (June-September) and the winter and spring seasons between October and April (India Metrological Department, 2005a and 2005b). The summer rainfall is brought by the southwest monsoon, whereas the western disturbances constitute the main source of winter and spring rainfall in the Himalayan region.

The increase in temperature increases the variability of the western disturbances affecting the precipitation pattern over the western Himalayan region during the winter and spring seasons (Huggel et al., 2020; Dimri et al., 2021). As a result, precipitation in the western Himalayas is declining and the region is facing frequent and prolonged drought and semi-drought in the winter and spring months (ICIMOD, 2012; Krishnan et al., 2019; IPCC, 2021 and 2022a). Further, these changes in the temperature and precipitation pattern are increasing the events of high-intensity rainfall as well as drought both in pre-monsoon and monsoon seasons (Beniston, 2005; Basistha et al., 2009; Bhutiyani et al., 2010; Huggel et al., 2020). The sharp increase in average annual temperature and erratic and unreliable rainfall pattern is affecting the biophysical and socio-economic systems and causing hydrological disruptions and reduced water availability, which are not only eroding the traditional integrated farming system but also depleting the diversity of traditional crops in the entire region (IPCC, 2012, 2014, 2018, 2021 and 2022; ICIMOD, 2009a, 2012; Huggel et al., 2020; World Bank 2018; FAO, 2015a and 2015b).

2. Study Area:

Kujgad Watershed situated in district Almora in the State of Uttarakhand, the Kumaun Lesser Himalayan region has been selected as the area of study for the present study (Figure 1). The watershed is located between 29°30’00’’ to 29°35’00’’ North Latitudes and 79°21’00’’ and 79°30’00’’ East Longitudes; and encompasses a geographical area of nearly 99.61 Km^2 between

964m and 2066m altitude above the mean sea level. The total population of the Watershed is 24321 persons as per the Census of India 2011 and calculated density of population 244 persons/Km^2. Kujgad is one of the principal tributaries of river Kosi, which is one of the major, rains fed river of Kumaun and drains to the Ganges system in Kumaun Himalaya. The entire Watershed is characterized by diversified terrain and geomorphic landscape which are clearly reflected in varying magnitudes of slopes and their aspects, variety of soils, natural vegetation and hydrological parameters, and the climatic complexities. As in other parts of Kumaun Himalaya, the traditional resource use structure is changing fast mainly in response to growth of population and resultant increased demand of food, fodder and fuel wood. Consequently, the activities of cultivation, grazing and deforestation are extended over large areas of the region. 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 food security and livelihood. This further increases the vulnerability of the natural and socio-economic system to the risks of extreme weather and climate events in the study region.

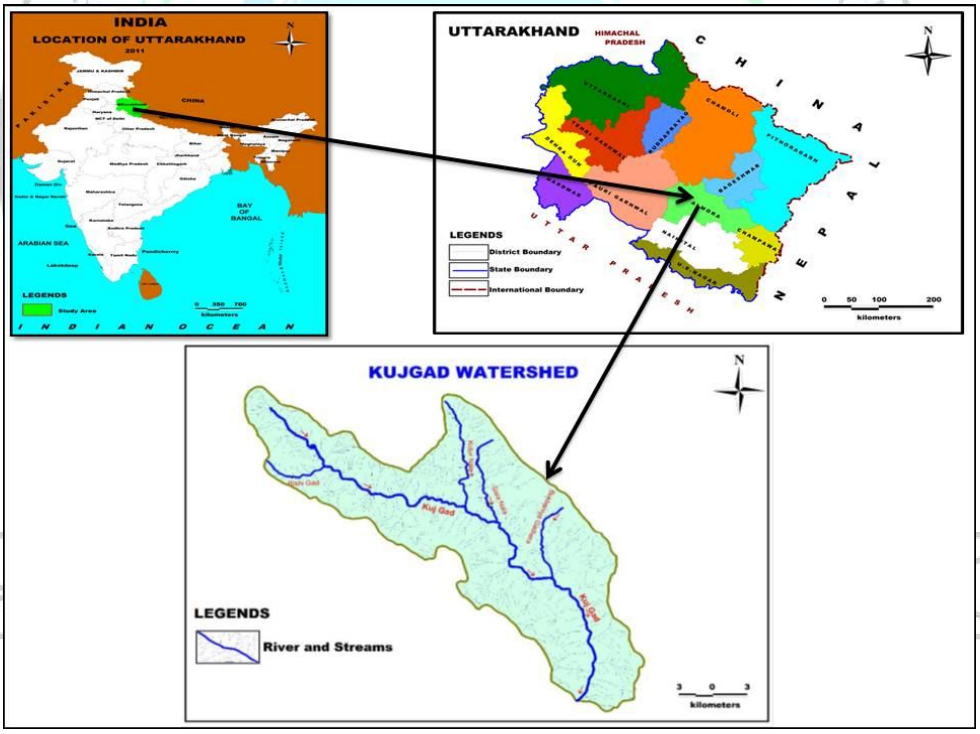

Figure 1: Location Map of Kujgad Watershed, Kumaun Lesser Himalaya

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 Kujgad Watershed. However, in present study, both the 'extreme weather events' and 'climatic extremes' have been termed and studied as 'climatic extremes or climate shocks. The ground observed rainfall data of the past 50 years (1972-2021) 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 (IMD) (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 study region. As in other parts of India, the annual weather cycle of the Kujgad Watershed has been divided up into the following four seasons following the approach of the Indian Institute of Tropical Meteorology (Joshi et al.1983): [i] winter season [from December to February]; [ii] pre monsoonal or summer season [from March to May]; [iii] monsoonal or rainy season [from June to September]; and [iv] autumn or post-monsoon season [from October to November]. The above mentioned seasonal cycle been adopted to analyze the temporal pattern and distribution of rainfall in study region.

The rainfall data have been obtained from the Uttarakhand Forest Department Tarikhet (Ranikhet) located at middle of the watershed Tarikhet. 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 its daily, monthly and seasonal variability, and the number of rainy days. Since Kujgad Watershed is situated in the Kumaun Lesser Himalaya ranges and rainfall is the most prominent form of precipitation in the study region. 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 75-80% of the total annual rainfall occurs during the monsoon normally between mid of June to mid of September.

Table 1: Decadal Trends of Rainfall Variability and Rainy Days in study region (1972-2021)

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
1972-1981	9503	-	950	-	898	-
1982-1991	8766	-7.76%	877	-7.68%	604	-32.74%
1992-2001	8378	-4.43%	838	-4.47%	676	+11.92%
2002-2011	8622	+2.91%	862	+2.86%	675	-0.15%
2012-2021	9619	+11.56%	961	+11.48%	588	-12.89%
Total	**44888**	**+0.57%**	**897.6**	**+0.55%**	**3441**	**-8.47%**

Source: Forest Range Office Tarikhet

Table- 1 shows the decadal trends of rainfall variability and rainy days in Kujgad Watershed over the past 5 decades from 1972 to 2021. The Table makes it clear that the Watershed received a total rainfall of 44888mm with an annual average of 897.6mm during the past 5 decades. Moreover, study region observed an overall increasing trend of decadal rainfall over the past 50 years. The average decadal rainfall decreased by 7.76% and 4.43% between 1982-1991 and 1992-2001, respectively. While, the average rainfall increased by 2.91% and 11.56% during last two decades 2002-2011 and 2012-2021 with an overall average increase of 0.57% (Table- 1, Figure- 2). However, in number of rainy days, a slightly decreasing trend (8.47%) has been observed over the last 50 years. Where the number rainy days decreased by 32.74%, 0.15% and 12.89% during the period 1982-1991, 2002-2011 and 2012-2021, respectively, while only one decade, 1992-2001 shows a decadal increase by 11.92% (Table- 1, Figure- 3).

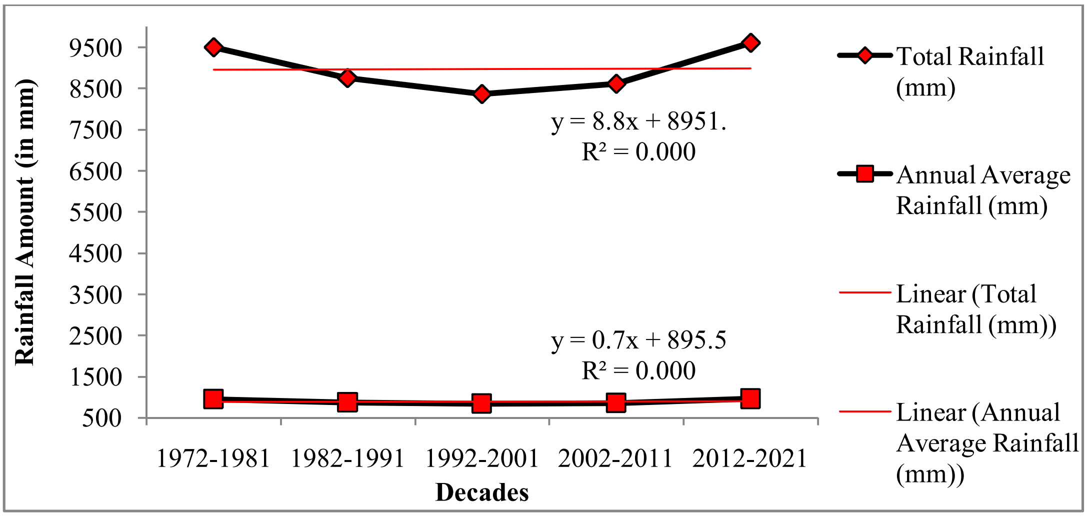

Figure2: Decadal Changes in Annual Average and Total Amount of Rainfall over Kujgad Watershed (1972-2021)

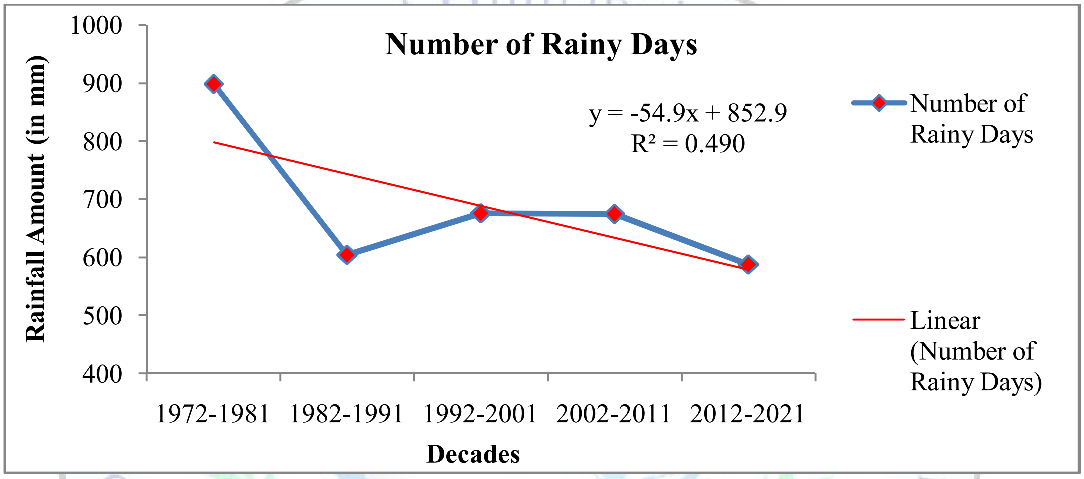

Figure3: Decadal Changes in Number of Rainy Days in Kujgad Watershed (1972-2021)

Table- 2 (A, B, C and D) illustrates the decadal distribution and trends of seasonal rainfall and rainy days during winter, summer, monsoon and post-monsoon seasons in the study region from 1972 to 2021. 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 1.59% over the period. The winter rainfall increased by 1.16%, 12.20 and 15.92% between 1972-1981 and 1982-1991, 1992-2001 and 2012-2021, while it declined by 22.92% between 1992-2001 and 2002-2011 [Table- 2 (A)]. The number of winter-season rainy days declined continuously during the first 2 decades (from 1972-1981 and 1982-1991), while the number of rainy days increased between the decades 1992-2001, 2002-2011 and 2012-2020 [Table- 2 (A)]. However, the Watershed recorded an average increase of 0.37% on rainy days in the winter over the past 50 years.

Table- 2 (B) shows that the overall average summer rainfall increased by 0.42% with a clear increasing trend over all the decades except during 1992-2001 and 2012-2021, when the Watershed recorded 19.63% and 5.08% decline, respectively. Kujgad Watershed enjoyed a total of 868 rainy days during the summer seasons over the past 5 decades. The number of rainy days declined during the decades 1972-1981 and 1982-1991 and 2002-2011, and 2012-2021 while the number of rainy days increased between the decades 1992-2001 and 2002-2011 [Table- 2 (B)].

Table 2: Seasonal Rainfall Variability and Rainy Days in study region (1972-2021)

	A						**B**					
Decades	**Winter Season**						**Pre monsoon or Summer Season**					
	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**
1972-1981	1120.2	-	112	-	162	-	1182.5	-	118.25		217	
1982-1991	1133.2	1.16	113	0.89	129	-20.37	1444.6	22.16	144.46	22.16	147	-32.26
1992-2001	1271.4	12.2	127	12.39	133	3.1	1161	-19.63	116.1	-19.63	150	2.04
2002-2011	980	-22.92	98	-22.83	113	15.04	1210	4.22	121	4.22	203	35.33
2012-2021	1136	15.92	113	15.31	109	3.7	1148.5	-5.08	114.85	-5.08	151	-25.62
Total	**5640.8**	**+1.59**	**563**	**+1.44**	**646**	**+0.37**	**6146.6**	**+0.42**	**614.66**	**+0.42**	**868**	**-5.12**
	C						**D**					
Decades	**Monsoon or Rainy Season**						**Autumn or Post-Monsoon Season**					
	Total Rainf	**% Ch**	**Annual**	**% Chan**	**Numbe**	**% Cha**	**Total**	**% Cha**	**Annual**	**% Chan**	**Numb**	**% Cha**

	all (mm)	ang e in Tot al Rai nfal l	Aver age Rainf all (mm)	ge in Ann ual Aver age Rain fall	r of Rai ny Day s	nge in Rai ny Day s	Rai nfall (m m)	nge in Tot al Rai nfall	Ave rage Rai nfal l (m m)	ge in Annu al Aver age Rainf all	er of Rai ny Da ys	nge in Rai ny Day s
1972-1981	6841.7	-	684.17	-	486	-	300.7	-	30.07	-	33	-
1982-1991	5760.5	-15.80	576.05	-15.80	314	-35.39	470.6	56.50	47.06	56.50	14	-57.58
1992-2001	5571.5	-3.28	557.15	-3.28	364	15.92	374.3	-20.46	37.43	-20.46	29	107.14
2002-2011	6248	12.14	624.8	12.14	329	-9.62	199	-46.83	19.9	-46.83	30	3.45
2012-2021	7144.5	14.35	714.45	14.35	323	-1.82	149	-25.13	14.9	-25.13	5	-83.33
Total	**31566.2**	**+1.85**	**3156.62**	**+1.85**	**1816**	**-7.73**	**1493.6**	**-8.98**	**149.36**	**-8.98**	**111**	**-7.58**

Source: Forest Range Office Tarikhet

Kujgad Watershed recorded an increasing rainfall trend during monsoon months, with an overall average increase of 1.85% over the past 50 years. The decadal monsoon rainfall increased by 12.14% and 14.35%, respectively, between the decades 1992-2001 and 2002-2011 and 2002-2011 and 2012-2021. However, the decadal monsoon rainfall recorded a decline of 15.80% between 1972-1981 and 1982-1991 and 3.28% between 1982-1991 and 1992-2001 [Table- 2 (C)]. Whereas, the number of monsoon rainy days decreased by 7.73% in the Watershed over the past 5 decades [Table- 2 (C)].

Kujgad Watershed received a total rainfall of 1493.6mm on 111 rainy days during the post-monsoon season over the last 5 decades. The interpretation of post-monsoon season rainfall data revealed that the watershed experienced an overall decrease of 8.98% in the post-monsoon season rainfall over the past 50 years. Table- 3 (D) shows that the post-monsoon season rainfall increased by

56.50% between the decades 1972-1981 and 1982-1991, whereas it declined respectively by 20.46%, 46.83% and 25.13% between the decades 1982-1991 and 1992-2001 and 2002-2011 and 2012-2021 [Table- 3 (D)]. However, the watershed witnessed decreasing trend with an average decline of 7.58% [Table- 3 (D)].

- **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 5 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 3 and Figure- 4 present the trend and temporal distribution of high-intensity rainfall events over the study region on a decadal basis from 1972 to 2021. The Watershed recorded 136 days of high-intensity rainfall in the past 50 years. Out of a total of 136 events, 123, 9 and 4 have been categorized as heavy, very heavy and extremely heavy rainfall events, respectively. The high-intensity rainfall events increased from 16 between 1972 and 1981 to 37 between 2012 and 2021. The data indicate a progressive increase in the frequency of the incidences of high-intensity rainfall in the region over the period (Table- 3). However, the high-intensity rainfall events declined slightly between 1982-1991 and 1992-2001. Table- 3 also indicates a continuously increasing trend in the events of heavy rainfall except between the decades 1982-1991 and 1992-2001, 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, it is alarming that the incidences of very heavy and extremely heavy rainfall have been rising for the period of 50 years. More particularly, extremely heavy rainfall events have emerged only during the past decade (Table - 3). 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 - 3).

Table 3: Decadal Trend of High Intensity Rainfall Events in Tarikhet (1972-2021)

Decadal Change	Total Rainfall (mm)	Days of High Intensity Rainfall	Categories of High-Intensity Rainfall Events		
			Heavy Rainfall	Very Heavy Rainfall	Extremely Heavy Rainfall
1972-1981	9503	16	15	1	0
1982-1991	8766	31	30	1	0
1992-2001	8378	24	22	2	0

2002-2011	8622	28	25	3	0
2012-2021	9619	37	31	2	4
Total	**44888**	**136**	**123**	**9**	**4**

Source: Uttarakhand Forest Department Tarikhet (Ranikhet)

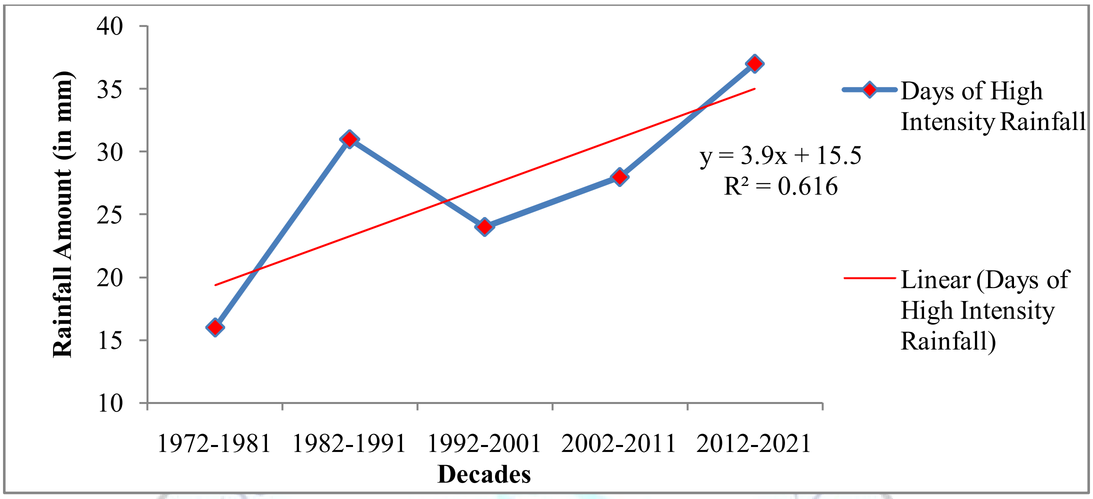

Figure 4: Decadal Trend of High-Intensity Rainfall Events in Kujgad Watershed

Table 4: Seasonal Variability of High-intensity Rainfall Events in Tarikhet (1972-2021)

Seasons	**Total Rainfall (mm)**	**Days of High Intensity Rainfall**	**Categories of High-Intensity Rainfall Events**		
			Heavy Rainfall	**Very Heavy Rainfall**	**Extremely Heavy Rainfall**
Winter season	5640.8	7	7	0	0
Summer season	6146.6	6	6	0	0
Monsoon season	31562.2	102	94	6	2
Post-monsoon season	1493.6	21	18	3	0
Total	**44843.2**	**136**	**125**	**9**	**2**

Source: Uttarakhand Forest Department Tarikhet (Ranikhet)

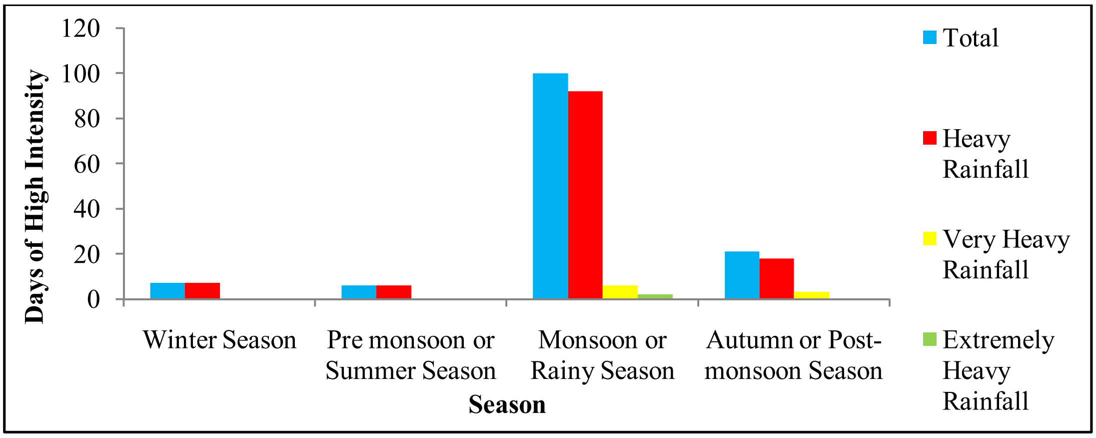

Figure 5: Seasonal Variability of High-intensity Rainfall Events in Tarikhet (1972-2021)

- **Drought Events:**

As discussed in the preceding sections, the number of rainy days has declined in the study region. The temporal deficiency in rainfall is leading to the loss of soil moisture, widespread depletion of groundwater and acute shortage of water over a protracted period. These changes in the hydrological regime and soil properties negatively affect the study region's natural and socio-economic systems. Table 5 presents the trends and temporal distribution of drought events over the study region on a decadal basis from 1972 to 2021. The watershed recorded 1956 days of drought in the past 50 years. Out of 1956 drought events, 446 (23%) and 1510 (77%) have been categorized respectively as moderate and severe. The highest numbers of drought incidences (569) were recorded in the decade 1972-1981, followed by 1992-2001 (399), 2002-2011 (368), 1982-1991 (336) and 2012-2021 (9284).

Table 5: Decadal Changes in Drought Events in Kujgad Watershed (1972-2021)

Decades	**Decadal Number of Drought Events**	**Categories of Drought Events**	
		Moderate Drought	Severe Drought Events
1972-1981	569	107	462
1982-1991	336	82	254
1992-2001	399	85	314
2002-2011	368	98	270
2012-2021	284	74	210
Total	**1956**	**446**	**1510**

Source: Uttarakhand Forest Department Tarikhet (Ranikhet)

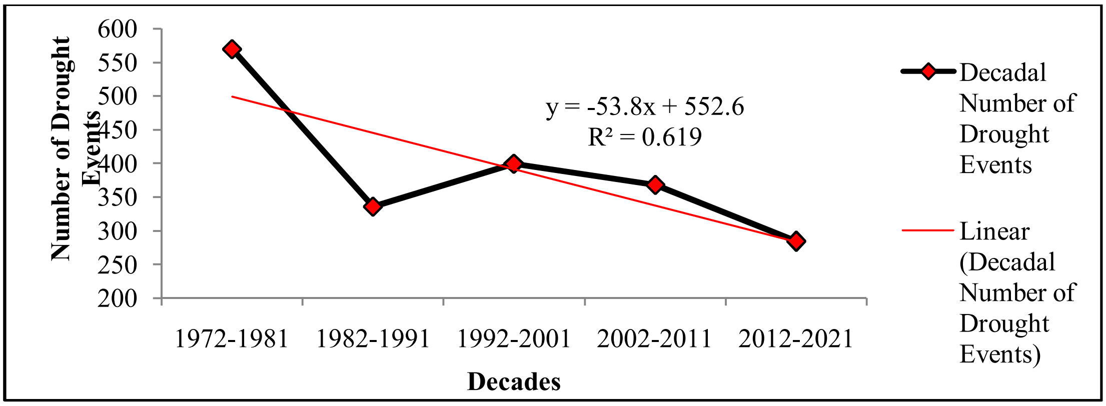

Figure 6: Decadal Changes in Drought Events in Kujgad Watershed (1972-2021)

Table 6 shows the seasonal variations in the occurrence of drought events in the watershed over the last five decades. In Tarikhet, out of the total drought events (1956), as many as 1287 were observed during the monsoon season, followed by summer (348), winter (238) and post-monsoon (83) months. This clearly indicates that precipitation deficiency as well as its temporal variability has been increasing in the monsoon season in the study region. The interpretation of the intensity of drought events in term 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 seasons over the study region.

Table 6: Seasonal Variability in Drought Events in Kujgad Watershed(1972-2021)

Seasons	Categories of Drought Events		Total
	Moderate Drought	Severe Drought	
Winter Season	47	191	238
Summer Season	103	245	348
Monsoon Season	285	1002	1287
Post-monsoon Season	11	72	83
Total	**446**	**1510**	**1956**

Source: Uttarakhand Forest Department Tarikhet (Ranikhet)

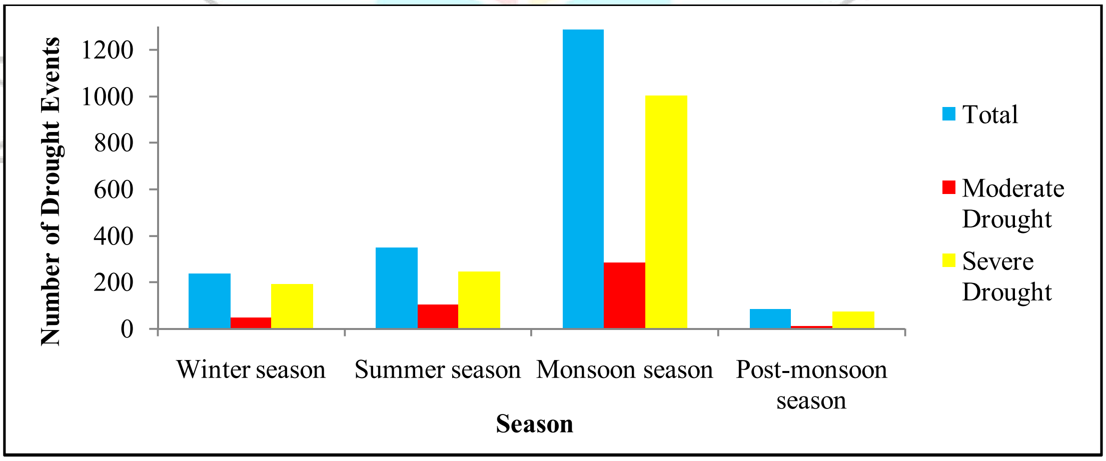

Figure 7: Seasonal Variability in Drought Events in Kujgad Watershed (1972-2021)

The rising temperature and the resultant increase in the rate of evapotranspiration and soil moisture loss accelerate the frequency and severity of meteorological drought across the Himalayan mountains (Sharma et al., 2021; Khatiwada and Pandey, 2019; Ghimire et al., 2010). 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 Lesser Himalayan Mountains (Adhikari, 2018; Dahal et al., 2016; Government of India, 2009). The studies conducted in Nepal Himalaya also indicated that climate change-induced droughts have emerged as major climatic extremes, and the occurrences of drought have been 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 some decades. The events of high-intensity rainfall are increasing not only during monsoon months but are also becoming more severe. This is resulting into increasing frequency and intensity of climatic extremes, particularly the events of high-intensity rainfall and drought. Kujgad 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. However, the watershed experienced fewer incidences of high-intensity rainfall during the winter season compared to the monsoon months. The abovementioned observations indicate that climate change-induced events of high-intensity rainfall and drought have emerged as one of the major threats to the subsistence farming system and food and livelihood security in the densely populated rain-fed Lesser Himalayan Mountains over the past some decades. Moreover, the frequency and severity of drought are much higher during monsoon months compared to other normally dry seasons in the region. The increasing frequency and severity of the 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 for implementing climate change adaptation plans and attaining United Nations Sustainable Development Goals in high 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 systems for monitoring hydrological processes and downscaling climate models at the watershed level. In view of this, 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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