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Assessment of Rainfall Variability and the Impact of Drought on Crop Growth in the Plain and Hill Zones of Uttarakhand, India

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

The rainfall data for the two stations *i.e*., Pantnagar (1981-2020) and Ranichauri (1985-2020) have been utilized to study the climate suitable for the growth and development of the crops in the plain and hill zones of Uttarakhand. The pentadal weekly, monthly and seasonal rainfall & rainy days have been calculated for these regions. An increasing trend in the pentadal mean rainfall and rainy days was experienced in the winter and southwest monsoon season and a decreasing trend could be observed in the summer and northeast monsoon season for both the stations. The frequency of meteorological drought for the plain zone is more as compared to hill zone. The Agricultural drought (Kharif & Rabi season) & Heavy rainfall events (at particular date of year) were assessed

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and there is no drought in the Rabi season for both these regions. The study underscores the importance of continuous climate monitoring, improved irrigation planning, and flood control measures to mitigate the impacts of rainfall variability in Uttarakhand. Adaptive climate strategies must be implemented to ensure sustainable water resource management and agricultural productivity in the region.

Keywords: Pentadal, drought; monsoon; meteorological drought.

1. INTRODUCTION

According to the Intergovernmental Panel on Climate Change (2007), future climate change will have a direct impact on agriculture, heightening the risks of hunger and water scarcity while accelerating the melting of icebergs. This, in turn, contributes to an increase in hydro-meteorological disasters such as floods and droughts (Kisaka et al., 2015b). Ensuring the sustainable development of agriculture in India requires robust research that identifies and quantifies climate change, a key driver of rainfall variability (Meshram et al., 2017). Chandrashekar and Shetty (2018) highlight that long-term rainfall variability is primarily influenced by deforestation, global warming, and rapid urban expansion. Similarly, Karuna Sagar et al. (2017) caution that these changes will result in heavy precipitation and intense rainstorms, increasing the likelihood of natural disasters such as landslides and floods.

Drought-prone districts in India comprise nearly 1/6th of this country in terms of area. These areas receive an annual rainfall of around 60 cm or less (Kisaka et al., 2015a). The Irrigation Commission of 1972 had identified nearly 67 Indian districts that were prone to droughts. These include 326 talukas situated in eight Indian states. These situations can be attributed due to human malpractices such as over-irrigation, deforestation, pollution, urbanization etc. as well as natural causes such as poor rainfall, climatic conditions, high temperature, etc (Boubacar, 2012; Hlavinka et al., 2009). The purpose of this study was to analyze the patterns of rainfall at both the plain and hill zones of Uttarakhand so that the agromet advisories could be given more precisely to the farmers, regarding irrigation scheduling, type of crop and other management practices.

Pantnagar is the town and a university campus, Govind Ballabh Pant University of Agriculture &

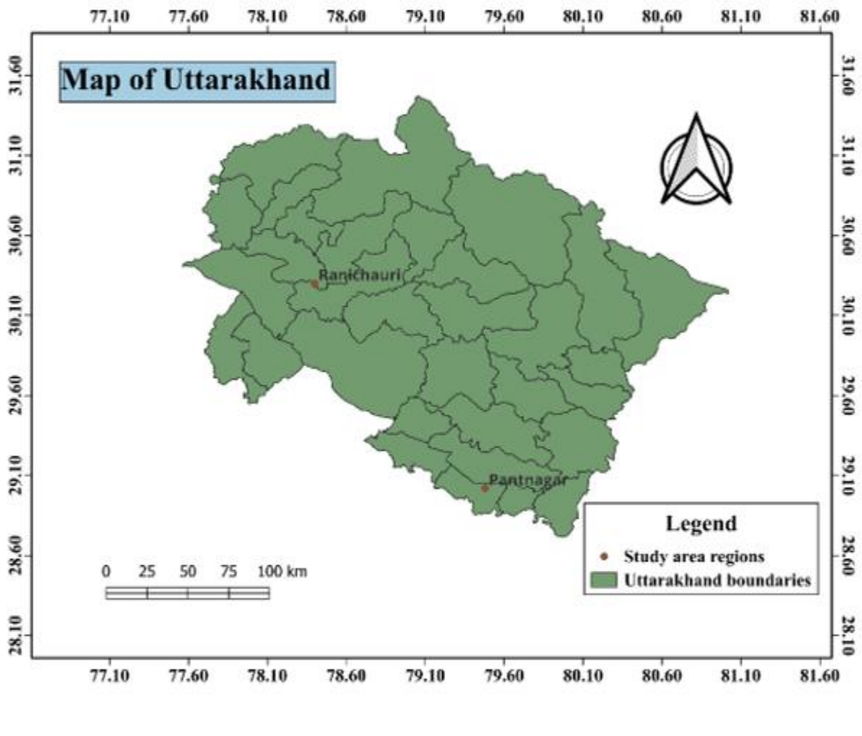

Fig. 1. The study area depicting Pantnagar (plain) and Ranichauri (hill) regions of Uttarakhand

Technology which is the state agricultural University that lie in Udham Singh Nagar district, Uttarakhand. Nainital, Kashipur, Rudrapur and Kiccha, Haldwani are the major cities surrounding Pantnagar. The area falls under the sub-humid subtropical climate of the *Tarai* belt, located in the foothills of the Himalayas at 29.02^{0}N latitude, 79.48^{0}E longitude (Goel et al., 2024) and at an altitude of 244.0 m above the mean sea level as shown in Fig. 1. In Udham Singh Nagar, Haridwar, the Gangetic plain, Pauri Garhwal and some parts of Nainital were called the *Tarai* region. Its width is from 20 to 30 km. The geographical area of the town is 3055 km^2 and it ranks 9th in Uttarakhand state.

Ranichauri is a town and a university campus, Veer Chandra Singh Garhwali Uttarakhand University of Horticulture & Forestry, formerly Uttarakhand University of Horticulture and Forestry, is a state agricultural university located in Tehri Garhwal district. It is situated about 15 km from New Tehri, 71 km from Rishikesh and 110 km from Dehradun on Rishikesh - New Tehri Road. It is 30.3^{0}N latitude, 78.4^{0}E longitude and at an altitude of 1864 meters above the mean sea level as shown in Fig. 2. The geographical and climatic conditions of the region are considered to be suitable for different forest species, wild fruits, horticultural crops, off season vegetables, medicinal, aromatic plants, minor millets and pulses.

2. MATERIALS AND METHODOLOGY

The daily rainfall data are collected from the Agrometeorological observatory located at N. E. Borlaug Crop Research Centre, G B Pant Univ of Ag & Tech, Pantnagar (29.02^{0}N & 79.48^{0}E and altitude of 244 m) and VCSG Uttarakhand University of Horticulture & Forestry, Ranichauri (30.3^{0}N latitude, 78.4^{0}E longitude and altitude of 1864 meters) from 1981-2020 and 1985-2020 as per availability of data from 1981-2020 and 1985-2020. The statistical analysis was carried out with the following parameters using MS EXCEL and WeatherCock. Weathercock software is developed by AICRPAM Unit of CRIDA, Hyderabad for the agroclimatic analysis of an area. This particular software is based on Visual Basic (VB) and easy to operate even by beginners. Moreover, batch processing a special provision was made in the Weathercock to facilitate to run the analysis for hundreds of stations at a moment if input files are prepared in the said format as doing agro-climatic analysis at localized scale have hundreds / thousands of stations (Sikdar et al*.,* 2020).

2.1 Trend Analysis

The trend analysis was done to detect the presence of increasing or decreasing trend using the graphical method. The trend analysis is done on the annual and seasonal basis. For calculation of average annual rainfall is done by taking weekly data from 1981-2020 for the plain region and from 1985-2020 for the hill region (sum of the daily rainfall of a year)

a. Pentads (i.e., 1981-85, 1986-90……….2016-20) for the plain region

b. Pentads (i.e., 1985-90, 1991-95……….2016-20) for the hill region

Then graph is plotted and regression equation is computed on the graph and positive or negative slope shows positive or negative trend of different parameters stated above both for annual and seasonal basis. The Mann-Kendall non-parametric test was used to evaluate the trend in temperature for each individual station (Mann, 1945; Kendall, 1975) which is represented by Z statistic. A very high positive value of Z is an indicator of an increasing trend, and a negative value indicates a decreasing trend, when Z value lies between +1.96 to -1.96 then null hypothesis is accepted, and when the value of $Z > +1.96$ or $Z < -1.96$ then null hypothesis (H_0) is rejected at 95% confidence level. P value can be thought of as a continuous measure of the data's compatibility with the entire model used to compute it, ranging from 0 for complete incompatibility to 1 for perfect compatibility, and can thus be thought of as a measure of whether the model is fits to the data or not. However, the p value is frequently deteriorated into a dichotomy, with findings labelled as "statistically significant." If p is equal to or less than a cut-off value (typically 0.05), it is declared ‘‘nonsignificant."

The trend magnitude is calculated by slope estimator methods. The slope (Qi) between two data points is given by the Sen’s equation (1968):

$$Qi = X_j - X_k / j - k, \text{ for } i = 1,2,3 \ldots N$$

Where,

X_j and X_k are data points at time j and k ($j > k$), respectively. When there is only a single datum in each time then, N = n(n−1)/2; n is several periods. However, if the amount of data in each year are many then N < n(n−1)/2; n is the total number of observations. The N values of the slope estimator are arranged from smallest to biggest.

Then, the median of slope (β) is computed as:

$\beta = 1/2\ (Q_{N+1})$ if n is Odd
$\beta = ½\ \{(Q_N/2) + (Q_{N+2}/2)\}$ if n is Even

The positive sign shows increasing trend whereas the negative sign shows a decreasing trend.

The mean is the average or the most common value in a collection of numbers.

Mean = ∑ Xi / n

Where,

Xi is the ith data value (rainfall)
n is the total number of data

Rainfall deviation is analyzed to understand fluctuations from the normal rainfall pattern, identifying extreme years with drought or excess rainfall.

The percentage deviation from the mean is calculated using:

$D_i=[(R_i-R_{mean})/R_{mean}]\times100$

where:

D_i = Rainfall deviation (%) for year i
R_i = Annual rainfall for year i (mm)
R_{mean} = Mean annual rainfall (mm)

Positive deviation ($D_i > 0$) → Higher than average rainfall (wet/excess rainfall years).
Negative deviation ($D_i < 0$) → Lower than average rainfall (dry/drought years).

The mean seasonal rainfall for winter, summer, southwest monsoon, and northeast monsoon is computed similarly by considering only seasonal totals over the years. The statistical analysis like pentadal annual and seasonal rainfall changes from the average (1981-2020 for Pantnagar and 1985-2020 for Ranichauri) for these two zones has been calculated and trend can be observed by plotting the graph.

For calculation of average seasonal rainfall mainly 4 seasons were considered:

a. Southwest monsoon season (June to September month)
b. Northeast monsoon season (October & November)
c. Winter season (December to February)
d. Summer season (March to May)

2.2 Statistical Measures for Variability

Standard Deviation (σ\sigma): Measures the spread of rainfall values around the mean:

$$\sigma = \sqrt{\frac{\sum(R_i - R_{mean})^2}{N}}$$

Coefficient of Variation (CV%): Expresses rainfall variability relative to the mean:

$$CV = \left(\frac{\sigma}{R_{mean}}\right) \times 100$$

A higher CV% suggests erratic or unreliable rainfall, impacting agriculture and water resource planning. WeatherCock software is developed by AICRPAM Unit of CRIDA, Hyderabad for the agroclimatic analysis of an area. Different agro-climatic analysis viz., converting daily rainfall data on to weekly, monthly, seasonal and annual data, rainy days analysis, meteorological and agricultural drought analysis. This particular software is based on Visual Basic (VB) and easy to operate even by beginners. Doing agro-climatic analysis with MS EXCEL for individual stations is drudgery and may lead to wrong results. The weathercock software reduces this drudgery and eliminates any mistakes associated with MS-EXCEL. Moreover, batch processing a special provision was made in the weathercock to facilitate to run the analysis for hundreds of stations at a moment if input files are prepared in the said format as doing agro-climatic analysis at localized scale have hundreds / thousands of stations (Sikdar et al., 2020).

2.2.1 Number of rainy days

The number of rainy day analysis gives an idea on rainy days in a week / month / season / annual. Information of rainy days of a place over a period of time determine the need and design both for rainwater harvesting and structure to recharge groundwater aquifers. With the help of number of rainy days planners may plan cropping pattern/cropping systems. Rainy day: A day with rainfall amount equal or more than 2.5

mm considered as a rainy day according to India Meteorological Department for Indian region.

2.2.2 Drought analysis

Drought is a normal, recurrent climatic feature that occurs in virtually around the world causing huge loss for the farming community. Drought is universally acknowledged as a phenomenon associated with deficiency of rainfall. There is no single definition, which is acceptable universally. Droughts occur at random and there is no periodicity in its occurrence and cannot be predicted in advance. In semiarid stations, the occurrence of rainfall is seasonal and is known more for its variability with respect to space and time. Drought is characterized by moisture deficit resulting either from i) Below normal rainfall ii) erratic rainfall distribution iii) higher water need iv) a combination of all the three factors.

2.2.3 Meteorological drought

A period of prolonged dry weather condition due to below normal rainfall. According to India Meteorological Department 2 types: based on rainfall deficit from normal (Table 1).

Table 1. Criteria of meteorological drought condition (IMD)

Deviation (%)	Drought Condition
-25 and above	No Drought
-25 to -50	Moderate Drought
< -50	Severe Drought

Based on the daily rainfall data as input file in the Weathercock software it gives the output in % deviation of rainfall of the particular year.

Agricultural drought: Agricultural impacts caused due to short-term precipitation shortages, temperature anomaly that causes increased evapotranspiration and soil water deficits that could adversely affect crop production. According to National Commission on Agriculture, 1976, at least four consecutive weeks receiving less than half of the normal rainfall during Kharif season and six such consecutive weeks during Rabi season is considered as agricultural drought period and based on weekly rainfall as input file. Normal rainfall: Average rainfall for a location/region over a period of years (preferable 30years) (https://www.ipcc.ch/report/ar6/syr/resources/spm-headline-statements/).

In agroclimatic analysis, meteorological and agricultural drought study is important. The frequencies of occurrence of different type of meteorological droughts (moderate and severe) over a period of year would give insight for vulnerability of a particular location/region to drought on annual basis. Agricultural drought analysis would give idea about susceptibility of a region to drought on seasonal basis, i.e., main crop growing season.

Heavy Rainfall events: It calculates the frequency and amount of rainfall for the categories 25-50, 50-75, 75-100 mm and more than 100 mm occurred during annual and seasons (winter, summer, Southwest and Northeast). It also calculates highest rainfall event in a year with date (on which date) and amount of rainfall based on the daily rainfall as input file.

3. RESULTS AND DISCUSSION

The pentadal rainfall analysis for Uttarakhand, covering 1981-2020 for the plain zone (Pantnagar) and 1985-2020 for the hill zone (Ranichauri), provides crucial insights into the temporal variability and trends of annual and seasonal rainfall. The analysis highlights contrasting trends between the two zones, with Fig. 2 showing a declining trend in annual rainfall in the plain zone and an increasing trend in the hill zone. This difference arises due to the high concentration of rainfall in the monsoon season in the plains, often leading to waterlogging, while the hill zone experiences a more uniform distribution of rainfall. The coefficient of variation (CV) in percentage is an indicative of dependability of rainfall. The threshold levels for CV for any interpretation are < 25, < 50, < 100 and < 150 per cent for annual, seasonal, monthly and weekly rainfall respectively.

If the CV is within the threshold limit of variability, it is considered that the rainfall is highly dependable and vice-versa (Manikandan et al., 2017). As seen in Table 2, rainfall variability is more pronounced in the northeast monsoon season (CV% = 118.3%) in Ranichauri, making irrigation essential. In Pantnagar, rainfall outside the southwest monsoon season is erratic, with CV% exceeding 50%, indicating low rainfall reliability in these periods. If we observe the Fig. 2 closely, there is a steep decreasing slope in the rainfall during 1991-95, as India experienced drought during 1992-93 (Zhang et al., 2017) so there was less rainfall comparatively. Similar steep slope could be observed in the Figs. 3, 4 and 5 which depicts the rainfall during summer, southwest monsoon and northeast monsoon season respectively.

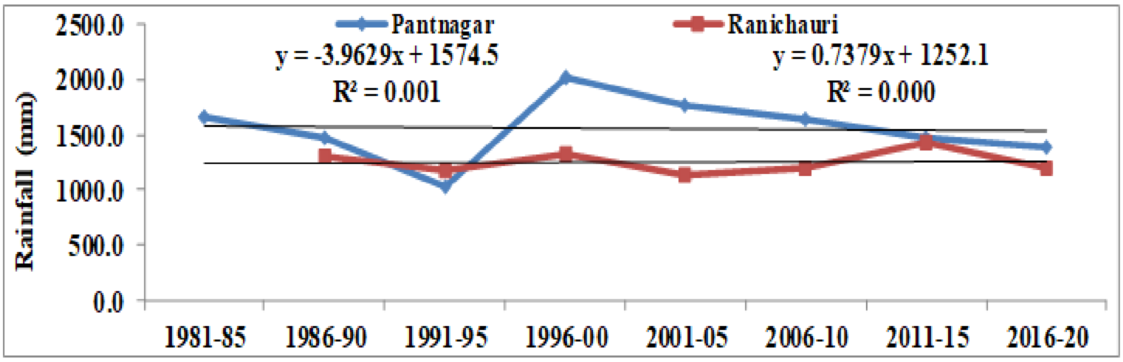

Fig. 2. Pentadal trend analysis of rainfall for both the plain and hill zones of Uttarakhand annually

Table 2. Descriptive seasonal and annual statistical analysis of rainfall for the plain and hill zones of Uttarakhand

	Pantnagar		Ranichauri	
Annual/ Seasons	**Mean Rainfall (mm)**	**CV (%)**	**Mean Rainfall (mm)**	**CV (%)**
Winter season	69.3	86.2	153.1	54.1
Summer season	91.5	73.1	190.9	41.4
Southeast season	1336.3	36.2	837.1	30.6
Northeast season	59.5	149.4	76.3	118.3
Annual	1556.7	34.1	1257.3	23.3

 # CV% is Coefficient of Variation in percentage

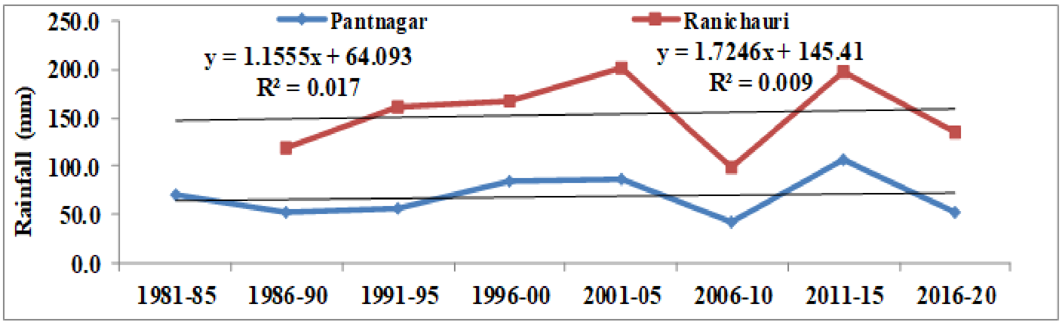

Fig. 3. Pentadal trend analysis of rainfall in the winter season for both the plain and hill zones of Uttarakhand

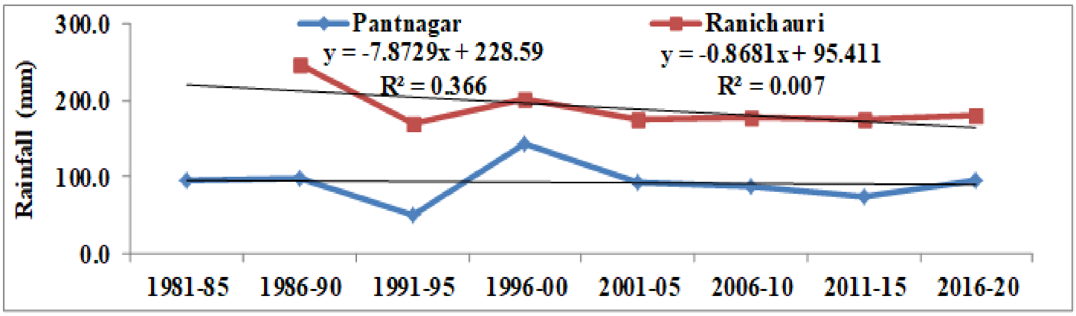

Fig. 4. Pentadal trend analysis of rainfall in the summer season for both the plain and hill zones of Uttarakhand

To evaluate rainfall trends, Table 3 presents the Mann-Kendall trend test and Sen's slope estimator (Yadav et al., 2014). The annual rainfall trend in Pantnagar is declining (Z = -0.87, β = -35.12 mm per pentad), whereas in Ranichauri, the trend is increasing (Z = 0.30, β = 2.81 mm per pentad). However, these trends lack statistical significance (p-values of 0.39 and 0.76, respectively), indicating that long-term changes are not yet definitive. At the seasonal level, the summer and northeast monsoon rainfall exhibit a declining trend, while winter and southwest monsoon rainfall show an increasing trend in both zones. Notably, the southwest monsoon trend is increasing, which is beneficial for Kharif crops, but the high variability in rainfall (Table 2) poses challenges in planning. The declining northeast monsoon rainfall in Ranichauri is particularly concerning, as it may affect post-monsoon water availability for Rabi crops.

The Figs. 3, 4, and 5 reveal steep declines in seasonal rainfall during specific periods, such as the winter season (Fig. 3) from 2006-10, which coincided with El Niño events in 2006-07 and 2009-10 (Golden Gate Weather Services, 2023). Fig. 5 further illustrates that southwest monsoon rainfall is significantly higher in the plain zone, whereas in other seasons, the hill zone generally receives more rainfall. Fig. 6 specifically analyzes northeast monsoon rainfall, confirming a declining trend in both Pantnagar and Ranichauri, reinforcing concerns about post-monsoon water availability.

The Fig. 7, which shows annual deviations from mean rainfall, further highlights rainfall variability. The 2009 rainfall deficit coincides with El Niño conditions, reinforcing the strong influence of extreme climatic events on rainfall patterns in Uttarakhand. Overall, rainfall trends indicate an increase in winter and southwest monsoon rainfall, while northeast monsoon and summer rainfall are declining. The role of western disturbances in enhancing winter rainfall is evident, as both the plain and hill zones experience significant winter showers. However, the erratic nature of rainfall (high CV%) and the absence of statistically significant trends (Table 3) suggest that while changes are occurring, they do not yet indicate strong long-term shifts.

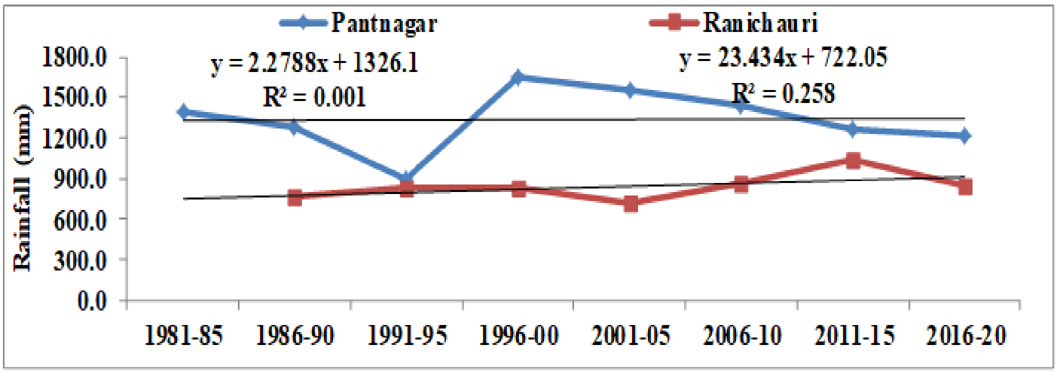

Fig. 5. Pentadal trend analysis of rainfall in the southwest monsoon season for both the plain and hill zones of Uttarakhand

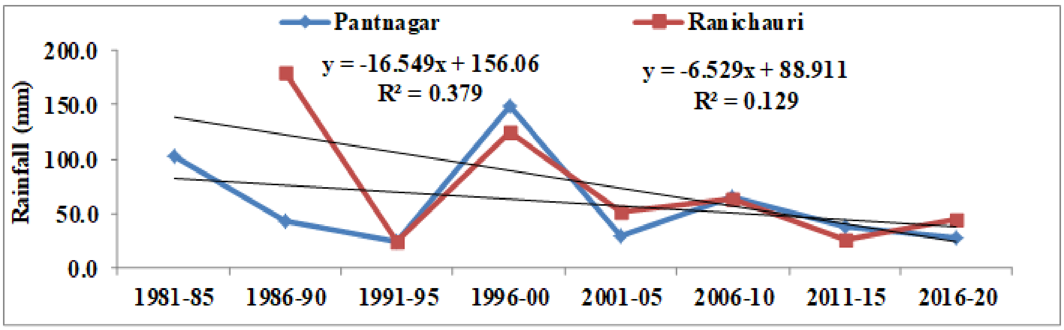

Fig. 6. Pentadal trend analysis of rainfall in the northeast monsoon season for both the plain and hill zones of Uttarakhand

Table 3. Pentadal descriptive Mann Kendall test analysis of Rainfall in plain and hill Zones of Uttarakhand

Annual/ Seasonal (mm)	Pantnagar				Ranichauri			
	Mann Kendall's statistic (Z)	Sen's Slope (β)	p value	Trend Significance at 95% confidence level	Mann Kendall's statistic (Z)	Sen's Slope (β)	p value	Trend Significance at 95% confidence level
Annual	-0.87	-35.12	0.39	NS Decreasing	0.30	2.81	0.76	NS Increasing
Winter	0.12	3.71	0.90	NS Increasing	0.30	5.94	0.76	NS Increasing
Summer	-0.62	-1.20	0.54	NS Decreasing	-0.30	-3.18	0.76	NS Decreasing
Southwest monsoon	0.62	23.91	0.52	NS Increasing	1.50	12.91	0.13	NS Increasing
Northeast monsoon	-0.87	-5.89	0.39	NS Decreasing	-0.90	-20.29	0.37	NS Decreasing

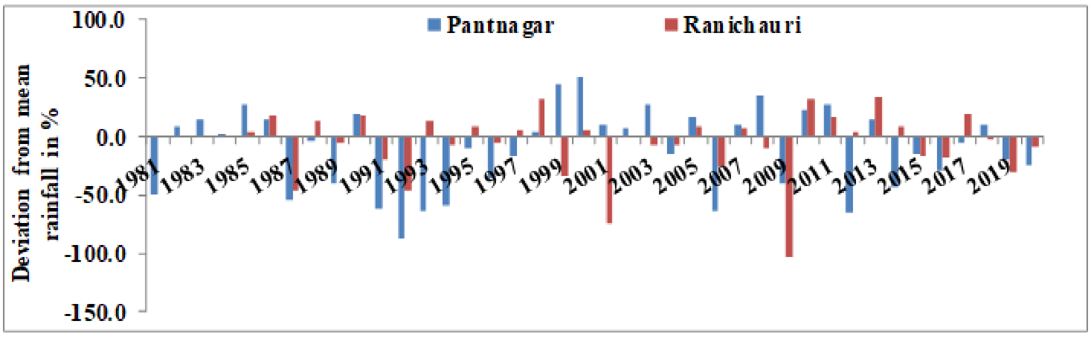

Fig. 7. Annual percent deviation from mean rainfall for both the plain and hill zones of Uttarakhand

The findings emphasize the need for effective water management strategies, especially in the summer and post-monsoon seasons, where rainfall is declining. The high CV% in the northeast monsoon season (Table 2) highlights the necessity of irrigation in Ranichauri. Similarly, the erratic southwest monsoon rainfall in Pantnagar underscores the importance of improved flood control and drainage infrastructure. Additionally, the lack of statistically significant trends in Table 3 suggests that long-term monitoring and adaptive climate strategies are essential to mitigate risks associated with rainfall variability and extreme climatic events.

The consolidated rainfall event was also calculated to find the frequency and no. of rainy days for the amount of rainfall in the range of 10-25, 25-50, 50-75, 75-100 mm and more than 100 mm that occurred during annual and different seasons. The frequency of rainy days within the rainfall limit of 10 < 25 mm is less in the hill region as compared to plain region (Fig. 8). If we go on increasing the rainfall limit as shown in the Figs. 9, 10, 11 & 12, then no. and frequency of rainy days decreases in the hill region and becomes almost nil for the rainfall limit of > 100 mm (https://mausam.imd.gov.in/Forecast/marquee_data/Statement_climate_of_india_2022_final.pdf).

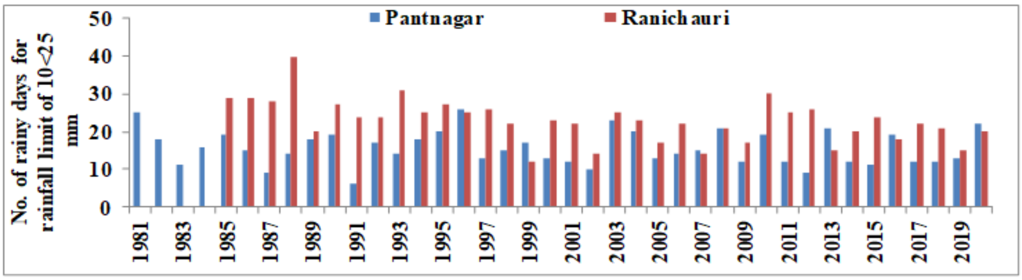

Fig. 8. Annual no. of rainy days for rainfall limit of 10 < 25 mm for both the plain and hill zones of Uttarakhand

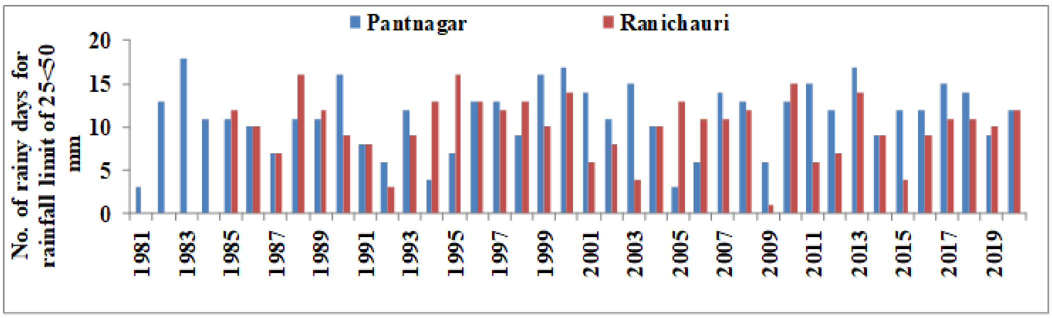

Fig. 9. Annual no. of rainy days for rainfall limit of 25 < 50 mm for both the plain and

hill zones of Uttarakhand

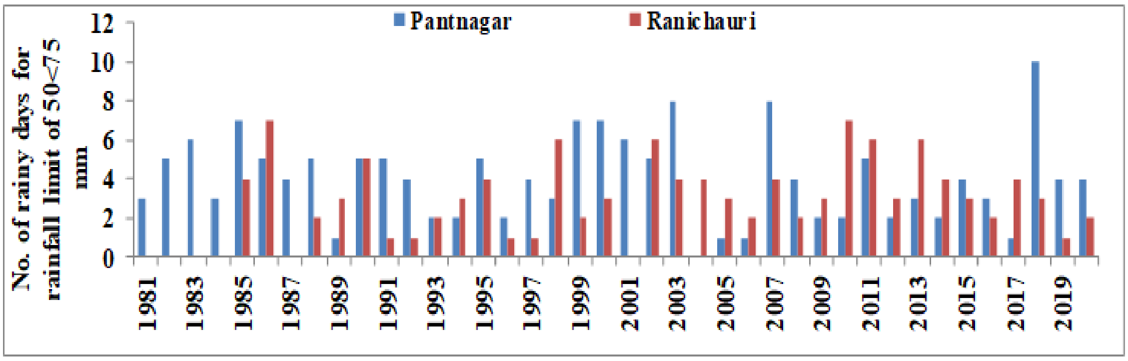

Fig. 10. Annual no. of rainy days for rainfall limit of 50 < 75 mm for both the plain and hill zones of Uttarakhand

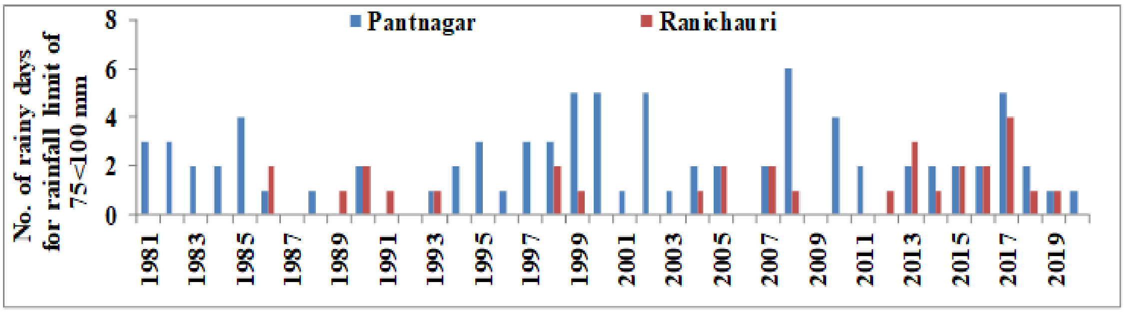

Fig. 11. Annual no. of rainy days for rainfall limit of 75 <100 mm for both the plain and hill zones of Uttarakhand

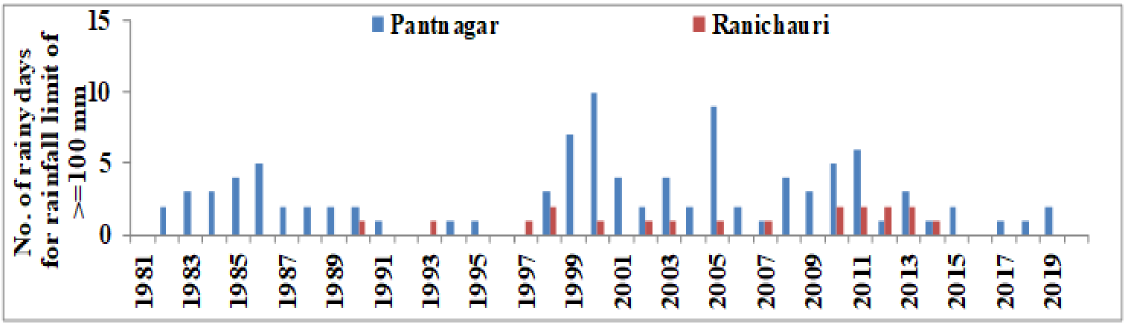

Fig. 12. Annual no. of rainy days for rainfall limit of < 100 mm for both the plain and hill zones of Uttarakhand

Similar results could be observed on the seasonal basis *i.e.,* no. of rainy days during all the seasons for the rainfall limit of 10 < 25 mm is more for the hill region as per Fig. 13 but if we observe Figs. 14 & 15 closely then it has been found that most of the rainfall was experienced in the southwest monsoon season in the plain region while in the hill region, rainfall was not only limited to southwest monsoon season but it was experienced in other seasons also at limit of 50 to < 75 mm of rainfall. It can be concluded from the above discussion that the rainfall distribution is more erratic and intense during southwest monsoon season in the plain region (Figs. 16 & 17) as compared to hill region, which is detrimental for the soil health and may get eroded. So the crops can be grown throughout the year in the hill region with minimal irrigation or water harnessed from natural springs while subsequent irrigation has to be provided for crops growth and productivity in the plain region (https://ggweather.com/enso/oni.htm).

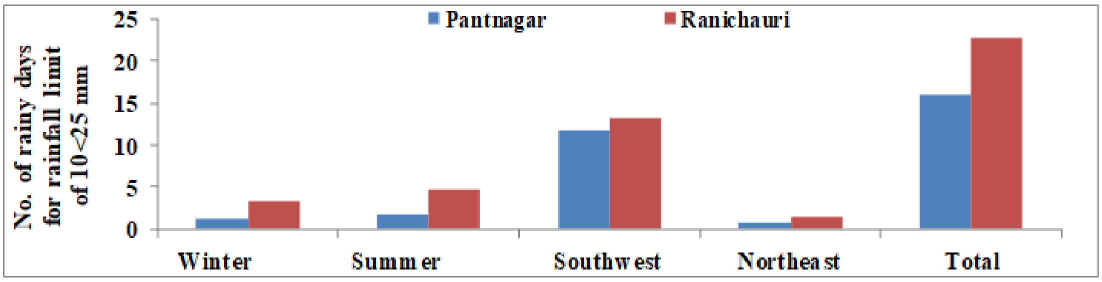

Fig. 13. Seasonal no. of rainy days for rainfall limit of 10 < 25 mm for both the plain and hill zones of Uttarakhand

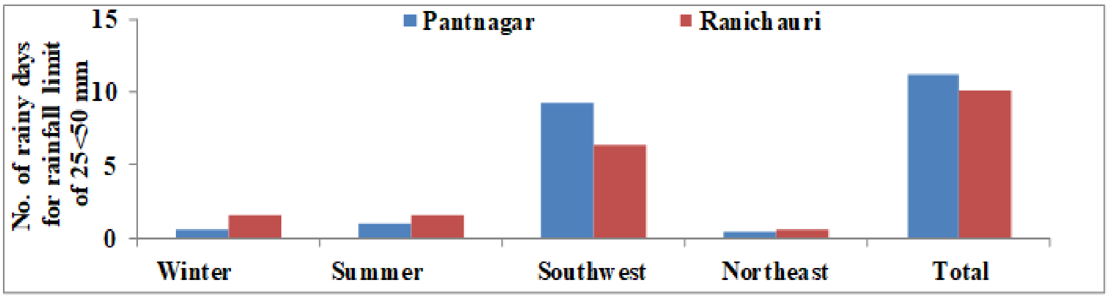

Fig. 14. Seasonal no. of rainy days for rainfall limit of 25 < 50 mm for both the plain and hill zones of Uttarakhand

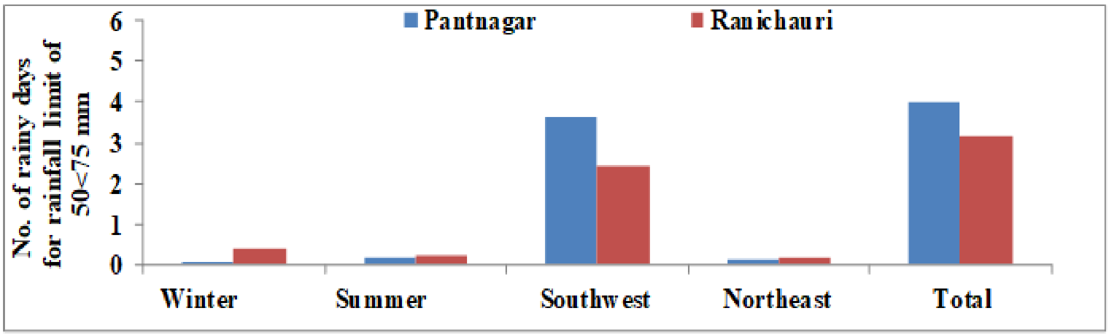

Fig. 15. Seasonal no. of rainy days for rainfall limit of 50 < 75 mm for both the plain and hill zones of Uttarakhand

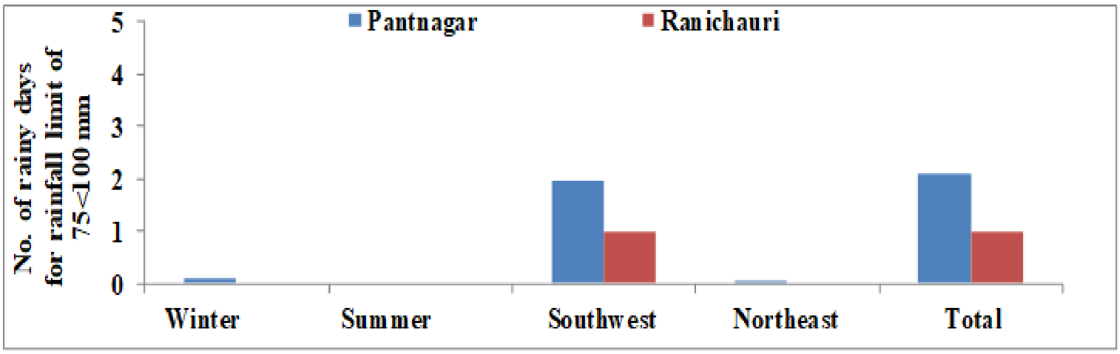

Fig. 16. Seasonal no. of rainy days for rainfall limit of 75 <100 mm for both the plain and hill zones of Uttarakhand

Table 3. Meteorological drought condition for both plain and hill zones of Uttarakhand

Drought Condition	Pantnagar		Ranichauri	
	No. of years	Drought (%)	No. of years	Drought (%)
No Drought	28	70	32	89
Moderate Drought	12	30	3	8
Severe Drought	0	0	1	3
Total	40	-	36	-

Table 4. Agricultural drought condition for both for both plain and hill zones of Uttarakhand in the Kharif season

Year	Drought week (SMW)	
	Pantnagar	Ranichauri
1981	35 - 38	N.A.
1982	25 - 28, 36 - 40	N.A.
1983	22 - 25	N.A.
1984	39 - 42	N.A.
1985	-	-
1986	-	-
1987	37 - 42	37 - 41
1988	39 - 42	24 - 27, 36-42
1989	39 - 42	-
1990	-	26 - 29, 38-42
1991	25 - 30, 38-42	22 - 27, 38-42
1992	-	-
1993	33 - 38	37 - 42
1994	34 - 42	38 - 42
1995	37 - 42	-
1996	-	-
1997	-	-
1998	35 - 38	-
1999	-	39 - 42
2000	39 - 42	30 - 42
2001	38 - 42	27 - 30
2002	38 - 42	22 - 25, 37-42
2003	-	-
2004	-	22 - 25, 32-36
2005	22 - 25	33 - 37
2006	24 - 27	22 - 25
2007	-	-
2008	-	23 - 28, 30-35
2009	-	39 - 42
2010	-	38 - 42
2011	38 - 42	22 - 25, 39-42
2012	22 - 27, 39-42	-
2013	-	23 - 26, 37-42
2014	32 - 39	33 - 37
2015	33 - 37, 39-42	36 - 42
2016	39 - 42	-
2017	22 - 25, 39-42	-
2018	-	34 - 38
2019	37 - 42	36 - 42
2020	38 - 42	-

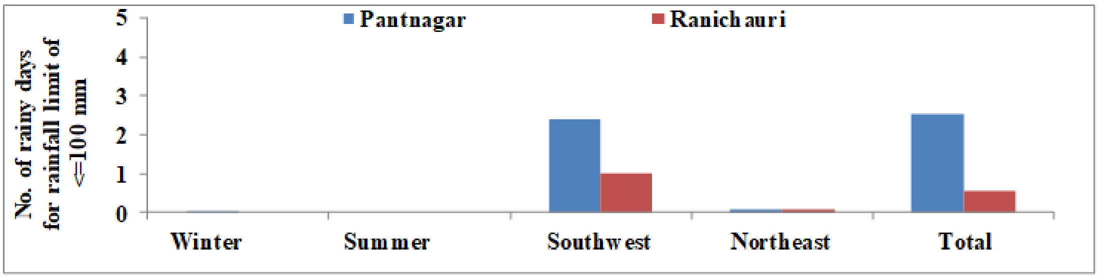

Fig. 17. Seasonal no. of rainy days for rainfall limit of < 100 mm for both the plain and hill zones of Uttarakhand

The meteorological drought condition was also analyzed for both plain and hill zones of Uttarakhand in terms of percentage of year having particular type of drought based on the deviation of rainfall as per criteria given by IMD discussed above in the Table 1. It had been found that no. of years having moderate drought condition is more in the plain region when compared with the hill region (Table 3). In the hill region one out of the study years *i.e.,* in the year 2009 the deviation in the rainfall is less than -50 % due to El Nino year as explained before, so there was severe drought of 3% in the hill region.

In the Table 4, Agricultural drought condition in the kharif season has been depicted and it had been observed that there is drought mostly occurs in the northeast monsoon and summer season as consecutively for four weeks (Kharif Drought) there is no or less rainfall which could not compensate the water requirement of the crops for both the plain and hill zones of Uttarakhand. The irrigation scheduling can be done *i.e.,* the decision of when and how much water to apply to a field. Its purpose is to maximize irrigation efficiencies by applying the exact amount of water needed to replenish the soil moisture to the desired level. Irrigation scheduling saves water and energy as well as shifting towards more suitable crop, time of sowing and varieties can be done. Agricultural operations are determined by the certain amount of rainfall received in a period. There are specific amounts of rainfall required for the activities like land preparation, sowing and for various agricultural activities.

4. CONCLUSION

This study indicated contrasting rainfall trends in both regions. While Pantnagar received higher total rainfall, most of it is concentrated in the southwest monsoon season, often leading to waterlogging. Conversely, Ranichauri experiences a more uniform distribution across seasons (Goel et al., 2024). The coefficient of variation (CV%) suggests higher rainfall variability in Pantnagar, particularly outside the monsoon season, making rain-fed agriculture less dependable. Analysis of rainy days shows that smaller rainfall events (10-25 mm) are more frequent in the plains, whereas heavier rainfall events (>100 mm) are rare in the hills. Seasonal analysis confirms that monsoonal rainfall dominates the plains, while the hills receive more evenly spread rainfall, supporting year-round cropping with minimal irrigation. Drought analysis indicated that, agricultural drought occurred during northeast monsoon and summer seasons for both the regions of Uttarakhand.

The findings highlight the need for region-specific water management strategies. In Pantnagar, excess monsoonal rainfall requires improved drainage and soil conservation, whereas Ranichauri relatively stable rainfall favoured diversified cropping with rainwater harvesting. Given the erratic rainfall trends, tailored advisories for irrigation scheduling, crop selection, and soil conservation are crucial to mitigate climate-induced risks in both agro-climatic zones.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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