

Hydro-climatic trend analysis in the Upper Kolab Command Area, India

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ABSTRACT

This study examines long-term trends in rainfall and temperature over the Upper Kolab Command Area (UKCA) in southern Odisha—a region heavily reliant on monsoon rainfall for agricultural and irrigation purposes. The primary objective of the study is to analyze climatic variability and identify seasonal and interannual patterns for climate-resilient water and agricultural management. Monthly rainfall and temperature data from the India Meteorological Department were analyzed using the non-parametric Mann–Kendall test for trend detection, while Sen’s Slope Estimator was applied to quantify the rate of change. The analysis revealed considerable fluctuations in annual rainfall, ranging from 936 mm in 2002 to 2,127 mm in 2006. The 60% and 75% dependable rainfall levels were calculated at 1505 mm and 1441 mm, respectively. More than 85% of the annual rainfall occurred during the monsoon season, with July and August emerging as the most dependable months for agricultural operations. In contrast, non-monsoon months experienced erratic and low rainfall, highlighting the necessity for adaptive water resource planning. The return period analysis revealed a strong logarithmic relationship ($R^2 = 0.8021$), indicating the infrequent occurrence of extremely wet years. Temperature data reflected a consistent seasonal pattern, with peak maximum temperatures recorded in May (average 37.32°C) and the lowest in January (average 16.35°C). Overall, the findings highlight the UKCA’s significant vulnerability to climatic fluctuations, especially rainfall variability. The study emphasizes the urgent need to incorporate dependable rainfall benchmarks, temperature trends, and the probability of extreme weather events into strategic irrigation and crop planning. These insights serve as essential baseline information for future hydrological modelling and contribute to the development of climate-adaptive policies for sustainable agriculture and water management in monsoon-dependent areas.

Keywords: Rainfall variability, Temperature trends, Mann–Kendall Test, Sen’s slope estimator, Monsoon dependency

INTRODUCTION

According to the India Meteorological Department (IMD), year 2024 was the warmest year on record in India since 1901. The annual average land surface air temperature was 0.65°C above the long-term normal, surpassing the previous record set in 2016. This trend has profound implications for a predominantly agrarian country like India, where agriculture supports the livelihoods of millions. In

this context, understanding and responding to long-term temperature changes is vital to safeguarding food security and rural incomes in the face of climate change (mausam.imd.gov.in). Similar temperature-linked effects on soil biological activity and nutrient behavior have been reported by Bhardwaj *et al.*, (2020), highlighting the sensitivity of agricultural soils to rising temperatures. Rainfall and temperature are the key climatic factors that influence water

availability, crop water demand, and the overall performance of irrigation systems. Analyzing long-term trends in these parameters is crucial for designing, managing, and adapting irrigation infrastructure to the increasing risks posed by climate variability and change. Bhardwaj *et al.*, (2019) similarly emphasized the influence of long-term climatic variability on soil carbon dynamics and ecosystem functioning. In recent years, climate change has manifested in shifting rainfall patterns and rising temperatures across India, with significant implications for agriculture and water resources management (Dash *et al.*, 2020; Maharana 2024; Singh *et al.*, 2024). Studies have demonstrated that rising temperatures and changing rainfall regimes can alter crop water requirements and irrigation needs, potentially leading to water stress or surplus conditions within irrigation command areas (Dash *et al.*, 2020; Rudraswamy and Umamahesh 2024). Related hydrological fluctuations driven by climatic variability were also identified by Singh *et al.*, (2014), particularly under shifting rainfall and temperature regimes. In Odisha, climate models project a 4-16% increase in rainfall, an extended rainy season, and more frequent extreme rainfall events, which could heighten the risk of both floods and droughts and threaten agricultural stability (Dash *et al.*, 2020; Maharana 2024). Comparable climate-induced water quality and availability risks were highlighted by Ashwin *et al.*, (2020) in monsoon-dominated agricultural regions. Many studies have been conducted in which statistical and modelling tools were used to analyse climatic trends in irrigation command areas. Radhakrishnan *et al.*, 2017 and Singh *et al.*, 2024 conducted a comprehensive trend analysis of temperature across multiple agro-climatic zones in India, revealing consistently increasing trends in monthly maximum and minimum temperatures in southern, western, and central regions. These temperature-driven shifts are consistent with the soil-environment responses documented by Thakur *et al.*, (2020) across Himalayan climatic gradients. In Odisha, the Mann-Kendall test and linear regression have detected long-term increases in annual and monsoon rainfall in several districts, alongside rising temperatures and reference evapotranspiration, which are likely to exacerbate soil erosion and alter irrigation water demands (Khare and Sahu, 2015; Dash *et al.*, 2020). Climate-linked water productivity challenges were also noted by Bhardwaj *et al.*, (2015), who

emphasized the role of irrigation scheduling under variable hydrological conditions. Moreover, investigations into the Bhadra and Tungabhadra command areas have highlighted the importance of forecasting future irrigated water requirements under changing climate scenarios, using outputs from CMIP-6-based global climate models and the CROPWAT software (Rudraswamy and Umamahesh 2024). Bhardwaj *et al.*, (2021) similarly stressed the importance of integrating climate-driven nutrient and water variability into long-term resource planning.

A nationwide assessment based on long-term meteorological data revealed a consistent warming trend across most regions of India. In contrast, rainfall patterns exhibited significant regional variability, with some areas experiencing increased precipitation while others recorded a decline (Mondal, Khare, and Kundu, 2015). The Mann-Kendall test is used to detect trends in rainfall and temperature across India's agro-climatic zones. Significant warming trends, stressing the implications of temperature rise was observed on water availability and agricultural productivity (Kumar and Jain, 2010). Such microclimate-driven shifts affecting crop and soil processes were also noted by Singh *et al.*, (2020). Their methodological approach validated the use of robust statistical tools in detecting climate change. In Odisha, several studies have provided insights into regional climate dynamics (Gouda *et al.*, 2023). Rainfall trends in the Mahanadi River basin were studied by using Sen's slope and the Mann-Kendall test. They reported a decline in monsoon rainfall in several sub-basins, underscoring the importance of basin-level assessments to design effective irrigation and water management responses (Pandey *et al.*, 2022). Rainfall-driven variability in soil and crop nutrient dynamics was further supported by Bhardwaj *et al.*, (2020b).

A study analysed 120 years (1901-2020) of rainfall data in Odisha to assess drought trends using the Standardized Precipitation Index (SPI). The findings revealed a geographic shift in drought-prone areas-from the eastern and southern parts of the state towards the western regions over time. The study also established strong correlations between drought occurrences and global climate drivers such as El Niño (Oceanic Niño Index), the Indian Ocean Dipole (IOD), and the Atlantic Multidecadal Oscillation (AMO), particularly during major

drought years like 1965-66 and 2009-10 (Guria *et al.*, 2025). In Keonjhar district, this study examined recent climate changes in rainfall, temperature, and humidity. It found a decrease in June rainfall and rising trends in temperature and humidity. These changes can impact crop schedules and farming patterns, particularly for marginal farmers and communities that rely on forests. The study recommends further research on the impact of these shifts on local agriculture (Das *et al.*, 2024). In South Singhbhum, rainfall trends from 2008 to 2022 were studied by using Mann-Kendall tests and found changes in annual and seasonal rainfall. This highlights the need for improved water management plans to safeguard agriculture and local ecosystems (Mohanta and Pathy, 2024). In Karnataka, rainfall patterns changed drastically due to climate change and regular monitoring is recommended to manage water and farming systems effectively (Vivekanandan, 2024). Similarly, approximately 40 years of temperature data (1979-2019) were analysed across different zones in Karnataka (Behera *et al.*, 2025). It showed a general rise in both minimum and maximum temperatures, except in hilly regions where temperatures declined. The study recommends climate-resilient crops and farming

strategies to adopt to these temperature changes (Rani *et al.*, 2024).

In this paper, study was conducted for one of the oldest river basins of Odisha i.e. Upper Kolab command area, which faces high rainfall variability, with frequent droughts and extreme wet years affecting agriculture and water security. The objective of this paper is to identify the intra-annual and interannual rainfall variability within the basin and to evaluate rainfall extremes and probabilities, which would guide sustainable water management and support adaptive strategies for the region's vulnerable farming communities.

Study area

The study was conducted for Upper Kolab Command Area, situated in the Koraput district of southern Odisha, India (Fig. 1). The region falls under the Eastern Ghats Highland agro-climatic zone and is predominantly tribal and agrarian. The Upper Kolab irrigation project, located on the Kolab River (a tributary of the Godavari River), plays a crucial role in sustaining agricultural activities in the region by providing an assured irrigation supply. Geographically, the command area lies between

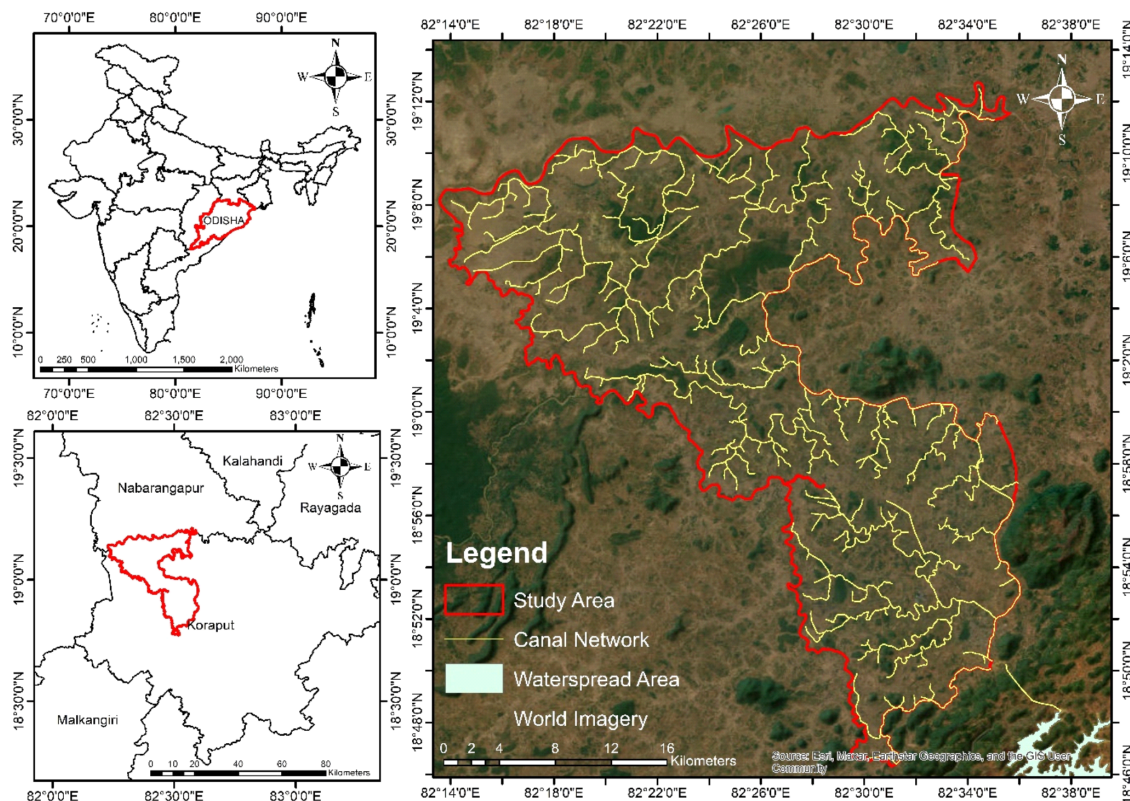


Fig. 1. Study area of Upper Kolab, Koraput, Odisha

latitudes 18°15' N to 19°10' N and longitudes 82°15' E to 83°25' E, with an average elevation ranging from 850 m to 1,200 m above mean sea level. The terrain is mostly undulating to hilly, with interspersed valleys that support intensive cultivation. Climatically, the area experiences a sub-humid to humid climate, characterized by distinct seasons. The average annual rainfall ranges from 1,300 mm to 1,700 mm, with the majority received during the southwest monsoon (June–September). The mean annual temperature ranges from 17°C to 28°C, with the summer months reaching up to 34°C and winter temperatures dropping to around 10°C. Soil types in the command area are predominantly red and lateritic soils, rich in iron and aluminium oxides but low in nitrogen and organic matter. These soils are generally well-drained but require proper fertility management for sustainable crop production. Agriculturally, the region supports a mixed cropping system with a dominance of kharif paddy. Other major crops include maize, millets, pulses (particularly arhar and green gram), oilseeds (like groundnut and niger), and vegetables. Due to irrigation from the Upper Kolab reservoir, double cropping is practiced in several parts of the command area.

MATERIALS AND METHODS

Data source

Long-term rainfall and temperature data for the period from 1991 to 2024 were downloaded from the India Meteorological Department (IMD) web portal to analyse climatic trends in the Upper Kolab Command Area, Koraput, Odisha. The dataset included monthly rainfall, maximum, minimum, and mean temperatures, providing a comprehensive view of the region's hydro-climatic behaviour over three decades. Data quality checks and interpolation methods were applied to ensure continuity and accuracy. These high-resolution records were then analysed using the Mann-Kendall trend test and Sen's slope estimator to detect significant temporal

trends. This robust dataset forms the foundation for assessing climate variability and supports the development of irrigation and agricultural planning in the command area (Table 1).

Methodology

Robust statistical techniques were used to analyse the long-term trends in rainfall and temperature within the Command Area of the Upper Kolab Irrigation Project. The methodology adopted involves a structured approach that includes data preparation, trend detection, and slope estimation.

Data Preparation

Monthly rainfall and temperature data (maximum, minimum, and mean) from 1991 to 2024 were aggregated to annual and seasonal time scales to understand both short-term and long-term variability. Standard interpolation techniques were used to check the quality of data set and missing data.

Trend Detection Using Mann-Kendall Test

The Mann–Kendall (MK) test, a non-parametric statistical test was used to detect monotonic trends (increasing or decreasing) in climatic time-series data without requiring the data to be normally distributed. The test compared the relative magnitudes of sample data rather than the actual values.

For a time, series a_1, a_2, \dots, a_n the MK statistic S is calculated as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(a_j - a_k) \quad \dots(1)$$

Where the sign function, $\text{sgn}(\cdot)$, is defined as:

$$\text{sgn} = \begin{cases} -1 & \text{if } a < 1 \\ 0 & \text{if } a = 0 \\ +1 & \text{if } a > 1 \end{cases}$$

Under the null hypothesis of no trend, the test statistic S is approximately normally distributed with mean:

Table 1. Data used and software details

Study/ Analysis	Data Used and Type	Data Source
Metrological data (Precipitation and Temperature)	Daily precipitation(0.25°×0.25°) dataset from the year 1991 to 2024 Temp max, and temp min (1° × 1°) data from the year 1991 to 2024	The Indian Meteorological Department (IMD) Rainfall Source: https://imd pune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html Temp source: https://imdweb.lwcc.in/

$$E(S) = 0$$

and variance:

$$var(S) = \frac{n(n-1)(2n+5)}{18} \dots(2)$$

The standardized test statistic Z is calculated as:

$$z = \begin{cases} \frac{S - 1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S + 1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases}$$

A positive Z indicates an increasing trend, and a negative Z indicates a decreasing trend. The trend is considered statistically significant at the 95% confidence level if $|Z| > 1.96$.

Magnitude estimation using sen’s slope estimator

To quantify the magnitude of the trend, Sen’s Slope Estimator was used. This non-parametric method calculates the median of all possible pairwise slope in the time series.

For a dataset of ‘N’ data points, the slope Q between all pairs of points is given by:

$$Q_i = \frac{a_j - a_k}{j - k} \text{ for all } j > k \dots(3)$$

The Sen’s slope (Qmed) is the median of all such slopes: $Q_{med} = \text{Median}(Q_1, Q_2, \dots, Q_N)$

This value represents the rate of change per time unit, offering a reliable measure of trend magnitude even in the presence of outliers or non-linear fluctuations.

Software used

All statistical analyses were performed using Python and R programming languages, utilizing

packages such as trend, Kendall, and open air for computing MK and Sen’s slope. Data visualization and interpretation were supported using GIS tools for spatial context.

RESULTS

Rainfall variability and dependability analysis

The annual rainfall trend in the Upper Kolab Command Area over the 34 years (1991–2024) exhibits pronounced inter-annual variability, with rainfall ranging from a low of 936 mm (2002) to a high of 2,127 mm (2006). Dependability analysis reveals that 60% dependable rainfall is 1505.16 mm, while 75% dependable rainfall is 1441.22 mm, representing critical thresholds for irrigation planning and crop management (Fig. 2). Several years, including 1998, 1999, 2002, and 2009, recorded rainfall well below the 75% dependability level, indicating potential drought conditions. Conversely, years such as 2006, 2010, 2013, and 2019 experienced significantly higher rainfall.

This pattern highlights the highly variable and unpredictable nature of monsoon rainfall in the region. The frequent deviation from dependable thresholds underscores the urgent need for adaptive water resource management and improved irrigation scheduling to ensure sustainable agricultural productivity in the command area.

Monthly rainfall patterns and variability

The rainfall distribution in the Upper Kolab Command Area demonstrates a distinct seasonal pattern, with the monsoon months (June to September) contributing the bulk of annual rainfall. August (443.68 mm) and July (423.42 mm) are the wettest months, marked by relatively low variability,

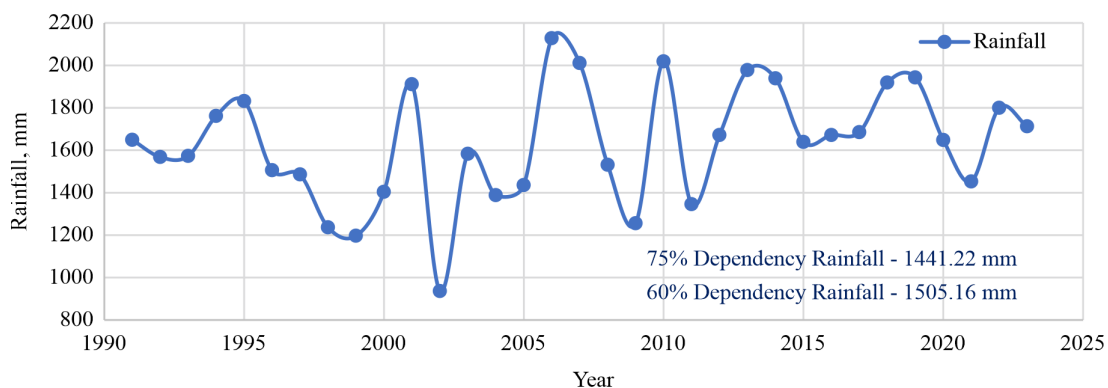


Fig. 2. Rainfall Variability and Dependability Analysis (1991-2024)

Table 2. Monthly Statistical Summary of Rainfall (1991–2024) in the Upper Kolab Command Area

Months	Maximum	Minimum	Mean	Standard deviation	CV (%)	Skewness	Kurtosis
Jan	47.91703	0	5.712317	11.02542	193.0113	2.776623	7.913061
Feb	24.14423	0	4.740555	7.018824	148.0591	1.747088	2.167921
Mar	100.5596	0	17.06247	22.07449	129.3745	1.994658	5.109406
Apr	116.0648	0.889867	42.84371	31.1844	72.78641	0.702162	-0.36569
May	282.8158	0.17391	77.30588	54.47476	70.46651	1.720478	5.185388
Jun	657.6086	63.17248	240.3316	129.1106	53.72186	2.14865	5.445639
Jul	700.9989	174.1976	423.4274	143.7878	33.95809	-0.01459	-0.88925
Aug	734.3947	176.6635	443.6803	122.856	27.69021	0.303704	-0.01272
Sep	581.2605	90.69472	299.0655	113.6208	37.99195	0.454018	0.080368
Oct	213.8797	9.808269	98.00574	55.90067	57.03816	0.202055	-0.8675
Nov	109.0853	0	21.18358	25.4717	120.2426	1.911766	3.814608
Dec	64.08917	0	9.330134	17.80587	190.8426	1.958282	2.70992

making them highly dependable for agricultural and irrigation activities. In contrast, pre-monsoon (March–May) and post-monsoon (October–November) months exhibit higher rainfall fluctuations, with elevated coefficients of variation, as indicated in Table 2. The winter months (December to February) record the lowest rainfall, accompanied by extremely high variability and positive skewness, suggesting rare but intense rainfall events. High skewness and kurtosis values in months like January and December highlight the presence of occasional extreme rainfall in dry conditions.

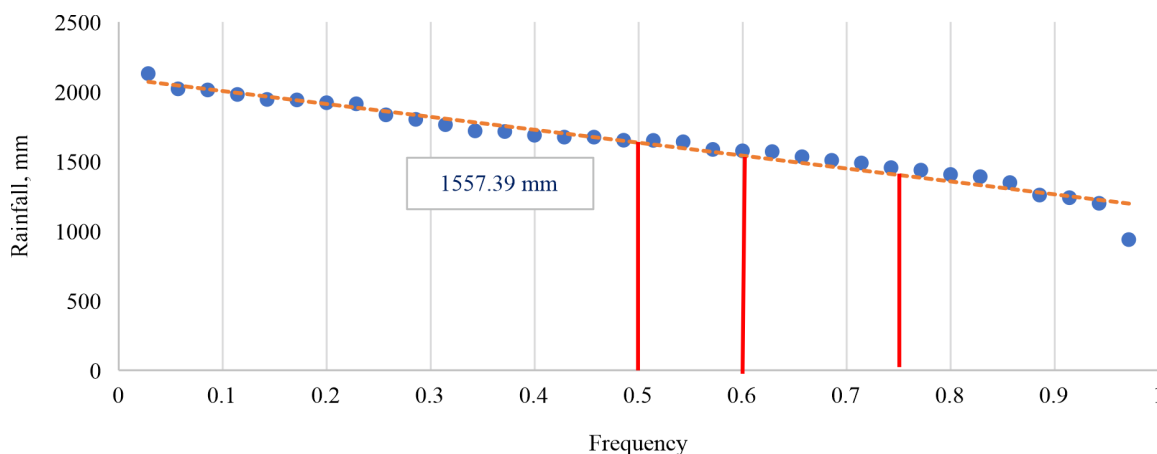
Rainfall probability analysis

The rainfall probability analysis for the Upper Kolab Command Area shows that the 50% probability (median) rainfall is approximately 1557.39 mm, meaning this amount can be expected in half of the years (Fig. 3). The curve indicates a clear decline in rainfall with increasing probability, highlighting the variability and uncertainty of annual

rainfall. High rainfall years (low probability) exceed 2000 mm, while frequent low rainfall years (high probability) drop below 1400 mm. This analysis is crucial for planning dependable irrigation supply, managing water resources, and preparing for drought-prone years in the command area.

Rainfall return period analysis

The rainfall return period analysis for the Upper Kolab Command Area reveals a strong logarithmic relationship between rainfall and frequency, with an R^2 value of 0.8021, indicating a good model fit (Fig. 4). The analysis showed that higher rainfall events occur less frequently, while moderate rainfall is more common. This information is crucial for predicting extreme events and aids in designing flood control structures, irrigation systems, and reservoir management plans. It supports the development of climate-resilient strategies by helping planners prepare for both drought and excess rainfall conditions.

**Fig. 3.** Rainfall Probability Analysis (1991-2024) in the Upper Kolab Command Area

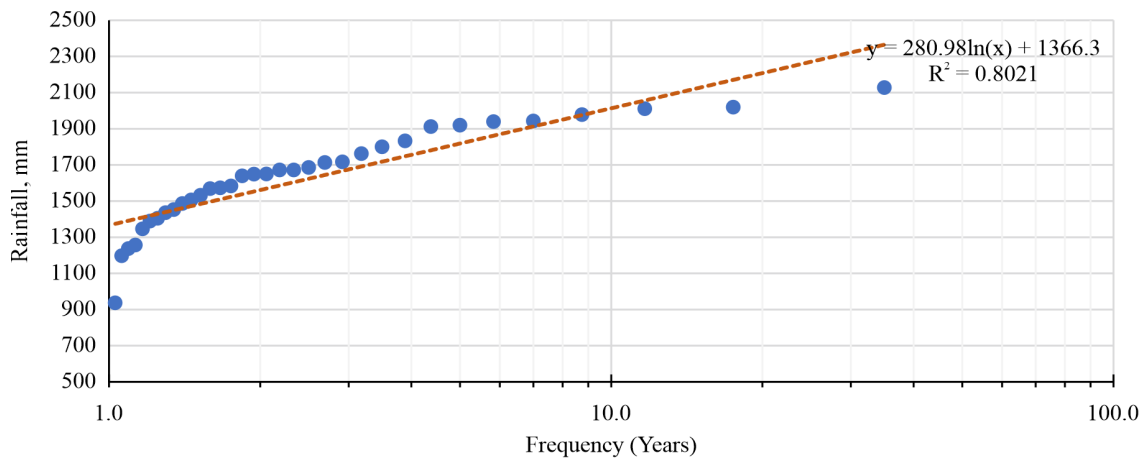


Fig. 4. Rainfall Return Period Analysis in the Upper Kolab Command Area

Monthly rainfall analysis using boxplot (1991-2024)

The rainfall analysis from 1991 to 2024 reveals a distinctly seasonal pattern dominated by the southwest monsoon, with the majority of precipitation occurring between June and September. July and August consistently record the highest rainfall, often exceeding 500 mm, making them the peak monsoon months, while June and September also contribute significantly, marking the onset and withdrawal phases, respectively. In contrast, the months from November to March exhibit minimal rainfall, often near zero, highlighting a prolonged dry season. April and May serve as transitional months, with gradually increasing rainfall signalling the approach of the monsoon. October, representing the retreating monsoon, shows moderate but variable rainfall. Over the years, significant interannual variability has been observed, with exceptionally wet years like 2006, 2007, 2010, and 2014, and dry spells in years like 2002 and 2005 (Fig. 5), indicating occurrences of both extreme rainfall and drought. Outliers in the data, especially in monsoon months, suggest the influence of cyclonic activity or intense low-pressure systems. This rainfall behaviour has critical implications for drought and flood management, agricultural planning, and climate impact assessments, emphasizing the need for robust water resource strategies aligned with the highly seasonal and variable rainfall regime.

Seasonal rainfall distribution and interannual variability (1991-2024)

Fig. 6 presents the annual rainfall distribution from 1991 to 2024, distinguishing between monsoon

(June–September) and non-monsoon (October–May) contributions. It highlights the dominance of the monsoon season, which consistently accounts for the bulk of the total rainfall, often contributing over 85% of the total each year. The non-monsoon rainfall remains comparatively minimal but occasionally shows noticeable contributions in select years such as 1995, 2010, and 2023, likely due to pre- or post-monsoon systems (Fig. 6). The overall pattern reveals significant interannual variability, with notably low rainfall in years such as 2001, 2002, 2009, and 2020, indicating possible drought conditions. In contrast, years like 2005, 2006, and 2010 recorded exceptionally high totals, exceeding 2000 mm, reflecting intense monsoon activity. Although no clear long-term trend of increasing or decreasing rainfall intensity is observed, decadal shifts in rainfall intensity are evident, particularly during the wetter period of the mid-2000s. The chart underscores the region's strong dependency on monsoonal rainfall and the importance of monitoring its variability for effective water resource management and climate-resilient planning.

Seasonal variation in monthly maximum temperatures

The boxplot illustrates the monthly variation in maximum temperatures, capturing a clear seasonal trend throughout the year. The coolest months are December, January, and February, with maximum temperatures ranging between 26°C and 31°C, reflecting the mild winter period (Fig. 7). As the year progresses, temperatures begin to rise in March and peak during April and May, where the median values

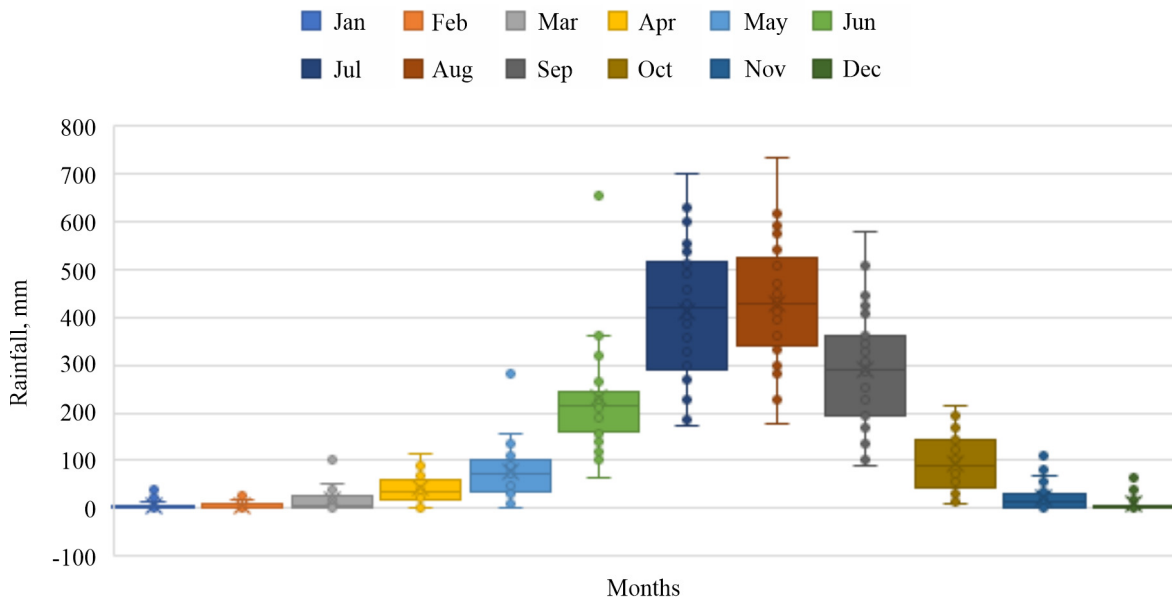


Fig. 5. Boxplot of Monthly Rainfall (1991-2024) Showing Seasonal and Interannual Variation

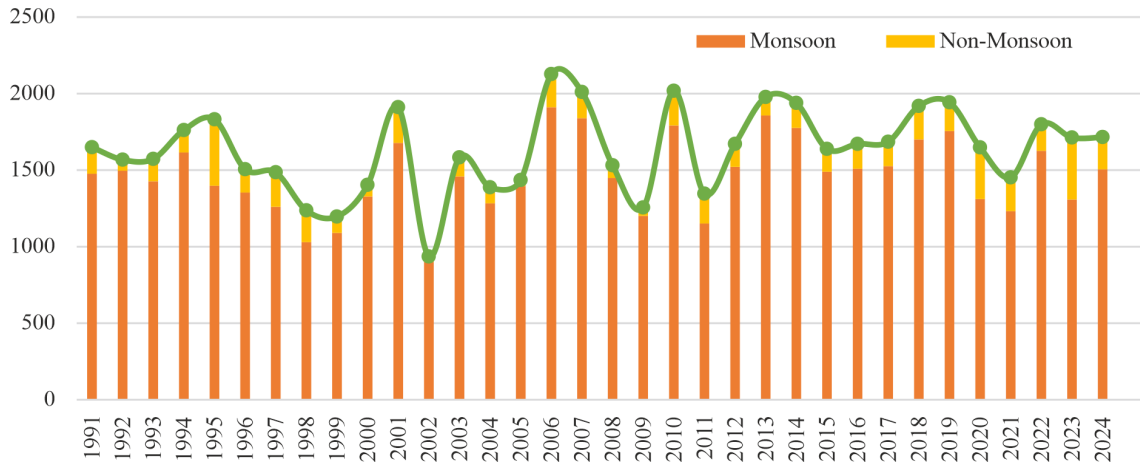


Fig. 6. Year-wise Monsoon and Non-Monsoon Rainfall Contribution (1991-2024)

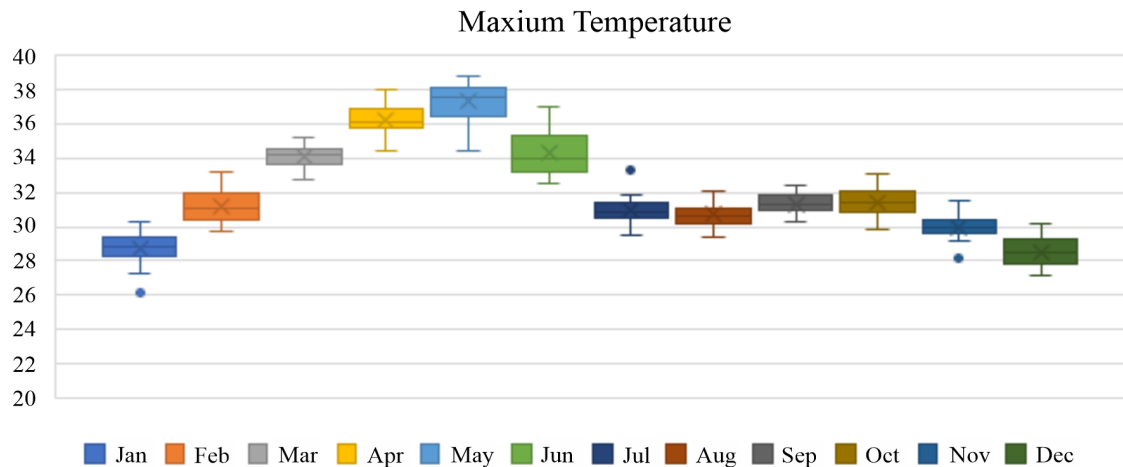


Fig. 7. Monthly Distribution of Maximum Temperatures Using Boxplots

surpass 37°C, indicating the intense summer heat typical of the pre-monsoon season. June remains hot but begins to show a slight dip as the monsoon approaches. During the monsoon months of July, August, and September, maximum temperatures stabilize around 30°C to 33°C, with reduced variability owing to cloud cover and rainfall. A transitional rise is observed in October, followed by a steady decline through November, signalling the return of cooler conditions.

Statistical overview of monthly maximum temperature patterns

The monthly maximum temperatures exhibit a clear seasonal pattern, with the highest mean temperature in May (37.32°C) and April (36.21°C), indicating the peak summer (Table 3). The lowest temperatures occur in December (28.52°C) and January (28.75°C), marking winter. Temperature variability is relatively low throughout the year, with standard deviations ranging from 0.58°C (Sep) to 1.31°C (Jun). The coefficient of variation (CV%)

remains under 4%, suggesting consistent temperature trends. Positive skewness in months like July (1.26) and June (0.48) indicates occasional higher temperature spikes, while negative skewness in winter and summer months (e.g., May, Jan) points to more frequent cooler extremes. Kurtosis is mostly negative, indicating flatter distributions, except in July (3.08) and January (1.66), where peak values are more concentrated.

Seasonal variation in monthly minimum temperatures

The boxplot illustrates monthly minimum temperature variations throughout the year, showing a clear seasonal trend. Temperatures gradually rise from January, peaking in May and June with consistently high minimums around 24-27°C, indicating warm summer nights (Fig. 8). From July onwards, temperatures begin to decline, with notable outliers in July possibly due to monsoon-related cooling. October marks the start of a sharper drop, leading to the coldest months-December and

Table 3. Statistical Parameters of Monthly Maximum Temperatures (1991–2024)

	St Dev	Max	Min	Mean	CV%	Skew	Kuto
Jan	0.8232	30.33871	26.20935	28.75359	2.862947	-0.84492	1.658289
Feb	0.937673	33.20964	29.72103	31.19808	3.005546	0.388448	-0.62238
Mar	0.616685	35.18323	32.74677	34.0863	1.809188	-0.25858	-0.67652
Apr	0.794672	37.92632	34.35667	36.20569	2.194882	-0.13974	0.213424
May	0.979525	38.81097	34.45935	37.31707	2.624872	-0.87846	0.729401
Jun	1.305133	36.94467	32.46328	34.34667	3.799884	0.475396	-0.93324
Jul	0.81446	33.52032	29.45421	30.99494	2.627719	1.260615	3.084458
Aug	0.691602	32.06049	29.33839	30.67477	2.254627	0.233681	-0.28608
Sep	0.584365	32.43033	30.26433	31.32458	1.865517	0.104066	-0.86052
Oct	0.864839	33.11809	29.81355	31.43287	2.751384	0.20147	-0.83271
Nov	0.695555	31.49564	28.17	29.96902	2.320915	-0.4205	1.086225
Dec	0.798361	30.11662	27.14194	28.51845	2.799456	0.173759	-0.9801

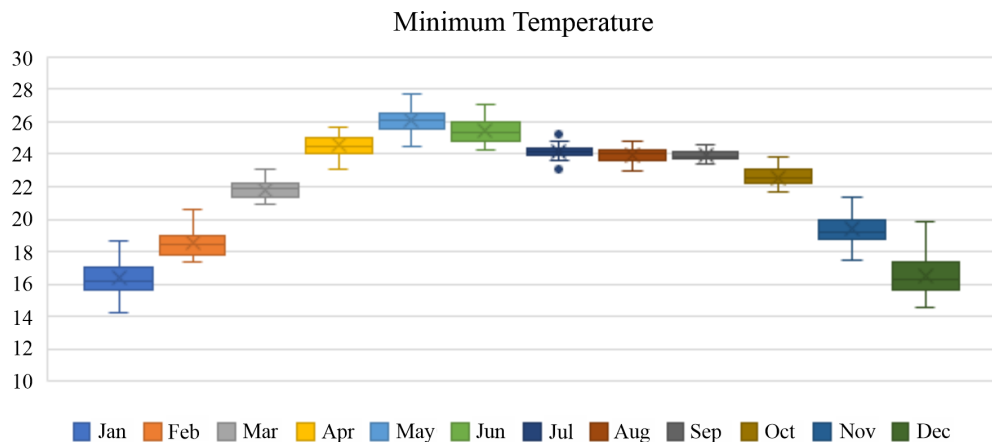


Fig. 8. Monthly Distribution of Minimum Temperatures Using Boxplots

January-where minimum temperatures range from around 14-19°C. The plot highlights symmetrical warming and cooling patterns across the year, with transitional shifts in March, October, and November.

Statistical overview of monthly minimum temperature patterns

The monthly minimum temperature data shows a smooth seasonal transition, with the lowest averages in January (16.35°C) and December (16.54°C), reflecting the winter months. In contrast, May (26.08°C) and June (25.44°C) exhibit the highest minimum temperatures, indicating peak summer warmth (Table 4). Standard deviation (SD) ranges from 0.30°C (September) to 1.30°C (December), indicating relatively stable nighttime temperatures, particularly during the monsoon months. The coefficient of variation (CV%) remains low across all months, with the highest variability in winter (December: 7.85%), and least in September (1.25%), indicating greater stability during the monsoon (Table 4). Skewness is generally positive in most months, indicating a tendency for occasional warmer nights, especially in December (0.84) and September (0.72). Kurtosis values are mostly negative, suggesting flatter distributions, except for July (1.79) and May (0.22), which show more peaked temperature distributions. Overall, the analysis reveals a consistent seasonal pattern, characterized by cooler winters, warmer summer nights, and relatively stable temperatures during the monsoon.

DISCUSSION

The analysis of rainfall and temperature data for the Upper Kolab Command Area (UKCA) from 1991 to 2024 revealed crucial insights into the

region's climatic behaviour, which held significant implications for water resource management, agricultural planning, and climate resilience.

Rainfall variability and agricultural dependability

The annual rainfall trends exhibit substantial inter-annual variability, ranging from a minimum of 936 mm (2002) to a maximum of 2,127 mm (2006). The calculated 60% and 75% dependable rainfall thresholds-1505.16 mm and 1441.22 mm, respectively-are critical reference points for irrigation planning. Notably, several years fell below the 75% dependable level, highlighting a recurrence of potential drought events, especially in 1998, 1999, 2002, and 2009. Conversely, high rainfall years, such as 2006 and 2010, while favourable for water availability, may have increased surface runoff, raising flood risks and erosion.

Monthly and seasonal rainfall characteristics

The seasonal distribution reinforces the dominance of the southwest monsoon (June to September), with August and July contributing the highest average rainfall, 443.68 mm and 423.42 mm, respectively. These months exhibit low variability, making them dependable for agricultural operations. In contrast, transitional periods (pre- and post-monsoon months) are characterized by high coefficients of variation, indicating uncertainty in rainfall occurrence. The winter months exhibit sparse and erratic precipitation, as indicated by high CV%, skewness, and kurtosis values.

Probability and return period insights

The rainfall probability curve confirms a declining rainfall trend with increasing probability,

Table 4. Statistical Parameters of Monthly Minimum Temperatures (1991-2024)

	St Dev	Max	Min	Mean	CV%	Skew	Kuto
Jan	1.061453	18.60449	14.27839	16.34886	6.492519	0.324278	-0.17939
Feb	0.905178	20.5475	17.36855	18.50586	4.891303	0.717731	-0.17231
Mar	0.56663	23.09129	20.91595	21.83744	2.594766	0.365031	-0.5342
Apr	0.623517	25.646	23.037	24.58569	2.536099	-0.12042	-0.15711
May	0.692467	27.68226	24.46226	26.07712	2.655457	-0.20695	0.220142
Jun	0.739147	27.05467	24.30367	25.44143	2.905291	0.600461	-0.52435
Jul	0.38607	25.25079	23.12009	24.17374	1.597063	0.011173	1.795049
Aug	0.428514	24.78516	23.02151	23.97776	1.78713	-0.32151	-0.09713
Sep	0.297553	24.60067	23.432	23.89495	1.245253	0.718995	-0.34822
Oct	0.542918	23.83062	21.69709	22.5624	2.406293	0.46383	-0.38921
Nov	0.957016	21.30233	17.42196	19.36514	4.941953	0.425312	-0.2729
Dec	1.298126	19.78903	14.59129	16.53807	7.84932	0.839172	0.121893

with median rainfall at 1557.39 mm. This highlights the need for conservative water planning to account for years of rainfall deficiency. The return period analysis further emphasizes the rarity of extreme rainfall events and the relative frequency of moderate rainfall, which is vital for the design of hydraulic structures and long-term agricultural policies.

Interannual rainfall trends and monsoonal influence

Boxplot and seasonal trend analyses reinforce the strong control of the monsoon over annual rainfall distribution. While July and August remain consistently wet, the interannual variability, including wet spells (2006, 2010, 2013) and dry years (2002, 2005), indicates the role of broader climatic anomalies such as El Niño-Southern Oscillation (ENSO). Occasional outliers in monsoon months also suggest cyclonic or low-pressure system influences, demanding real-time monitoring and early warning systems for disaster mitigation.

Temperature patterns and climatic extremes

The temperature regime displays a distinct seasonal trend. Maximum temperatures peak in May (37.32°C), confirming the harsh pre-monsoon summer, while the coolest months are December and January (below 29°C). Minimum temperatures mirror this pattern, with winter lows averaging around 16.35°C (January). The relatively low standard deviations and CV% across months suggest stable thermal conditions, though occasional spikes in skewness (e.g., July) indicate the potential for brief heatwaves or anomalously warm nights.

CONCLUSION

Rainfall and temperature trend analysis is essential for understanding the long-term climatic behaviour and its impact on water availability and agricultural planning in a command area. By examining historical data over several decades, trends in annual and seasonal rainfall help identify periods of deficit or surplus, interannual variability, and changes in the onset and distribution of monsoon. Similarly, analyzing temperature trends—both maximum and minimum—provides insights into warming patterns, heat stress risks, and shifts in crop-growing conditions. Such analyses support informed decision-making for irrigation scheduling, crop diversification, and climate-resilient agricultural practices.

The 34-year (1991–2024) hydro-climatic assessment of the Upper Kolab Command Area reveals a highly variable and monsoon-dependent rainfall regime, coupled with consistent seasonal temperature patterns. Annual rainfall fluctuated significantly, from a low of 936 mm (2002) to a high of 2,127 mm (2006). The 60% and 75% dependable rainfall levels—1505.16 mm and 1441.22 mm, respectively—serve as critical benchmarks for irrigation and crop planning. Several drought-prone years fell below these dependable thresholds, while others exceeded 2000 mm, raising concerns about flood risks. Monsoonal rainfall (June–September) accounts for over 85% of annual precipitation, with July and August emerging as the wettest and most reliable months. Conversely, the pre- and post-monsoon periods exhibit erratic and uncertain rainfall, characterized by high coefficients of variation. In contrast, the winter months record sparse but occasionally extreme rainfall events, as indicated by high skewness and kurtosis values. Probability and return period analyses emphasize the unpredictability of annual rainfall, with a median of 1557.39 mm and a strong logarithmic return trend ($R^2 = 0.8021$). These insights are crucial for developing drought and flood management plans, designing irrigation systems, and ensuring water security.

The temperature profile exhibits a clear seasonal cycle. May (37.32°C) is the hottest month, and January (16.35°C) the coldest. Temperature variability remains low, with CV% < 4%, suggesting stable thermal conditions across seasons. Minimum temperatures peak in May–June (26–25°C) and dip in December–January (16–17°C), with monsoon months offering thermal stability. In the future, the Kolab command area should adopt climate-smart practices to mitigate the effect of rainfall variability. During low rainfall years, farmers can switch to short-duration, drought-tolerant crops, such as millets and pulses, and practice water-saving techniques. In moderate rainfall years, medium-duration paddy crops with pulses or vegetables in rotation can be promoted, along with improvements in soil fertility. In high rainfall years, flood-tolerant paddy and water-loving vegetables should be prioritized, along with proper drainage to prevent waterlogging. Strengthening drainage systems, building check dams and ponds, and providing early warning systems will help manage floods. Farmer training and timely weather updates will further

support sustainable, resilient agriculture in the region. The rainfall and temperature during certain years (e.g., 2002, 2006, 2010) suggest influences of cyclonic activity or large-scale climatic anomalies. These extremes, alongside the recurring variability, underline the urgent need for climate-smart agricultural practices, efficient irrigation scheduling based on dependable rainfall, flood and drought mitigation infrastructure, and data-driven water resource management policies. This study reveals the vital role of long-term climatic analysis in shaping sustainable, resilient, and adaptive strategies for agriculture and water management in the Upper Kolab Command Area.

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DATA AVAILABILITY STATEMENT

Data relevant to this study will be made available by the corresponding author upon reasonable request.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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