Open Access
Volume 5 Issue 3
Research Article

Journal of Water Engineering and Management
ISSN: 2582-6298

Frequency Analysis of Rainfall Data for Roorkee, Uttarakhand, India

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Article Info

Article History:
Received on: September 5, 2024
Revised on: November 15,2024
Accepted on: November 25, 2024
Published on: December 31, 2024

Published by Academic Hope

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How to Cite:
Pal, A., M., Kumar, S., Mishra, G. S. and Singh V. 2024. Frequency Analysis of Rainfall Data for Roorkee, Uttarakhand, India, Journal of Water Engineering and Management 5(3):19-25. DOI: https://doi.org/10.47884/jweam.v5i3pp19-25

Abstract

Daily rainfall data for 20 years (2005–2024) were obtained from the Global Weather Data portal for SWAT modelling applications. The dataset was processed to determine the annual maximum and minimum daily rainfall values, as well as to examine monthly rainfall variability. In addition, the standard deviation and coefficient of variation (CV) were computed to evaluate the consistency and variability of rainfall during the study period. The analysis revealed that the maximum daily rainfall during the 20-year period ranged from 18.8 mm to 632.5 mm, indicating a substantial inter-annual fluctuation in extreme rainfall events. Monthly rainfall assessment showed that October consistently received the lowest rainfall among the monsoon-related months, whereas July and August recorded the highest rainfall across all years. The lowest coefficient of variation was observed in July (50.3%), followed by September (53.6%), signifying relatively stable rainfall during peak monsoon months. Conversely, the highest CV was recorded in June (77.4%), reflecting significant variability in early-monsoon rainfall. Frequency analysis was carried out using Normal, Log-Normal, and Gumbel extreme value distributions to estimate rainfall magnitudes at a 20% probability of exceedance (return period ≈ 5 years) for the months of July to October. The results indicate that the Gumbel distribution produced comparatively higher design rainfall estimates, followed by Log-Normal and Normal distributions, making it more suitable for extreme event analysis in the study region.

Keywords: Frequency analysis: Rainfall variation: Rainfall: Probability distribution: California formula.

Introduction

Water is precious for survival of human and life and for the growth and development of plants. The term precipitation denotes all forms of water that reach the earth from the atmosphere. Rainfall is the predominant form of precipitation that has a direct or indirect effect on agriculture. Most of the farmers have to deal with the problem of uncertain and variable rainfall and the effect it has on agriculture production. Around 70% of the irrigated area of the country is under rain fed agriculture. Average annual rainfall of the country is about 1200 mm and 80% of this occurs only in monsoon season. The knowledge of rainfall and its distribution throughout the year is also important for better crop planning, irrigation and drainage of crops. Intensity and distribution of rainfall may be used for design of hydrological structures, planning of soil conservation and flood programs (Singh et al., 2007).

Probability analysis can be used for prediction of occurrence of future events from available records of rainfall with the help of statistical methods. Based on theoretical probability distributions, it would be possible to forecast the rainfall of various magnitudes of different return periods. analysis of consecutive days and monthly return period is the basic tools for safe and economic planning and design of structural and non-structural measures, small and medium hydraulic structure such as small dams, bridges, culverts, spillways, check dams, ponds, irrigation and drainage work in the watershed.

Uttarakhand, a Himalayan state located in the northern part of India, exhibits considerable topographical and climatic diversity. This diversity results in significant spatial and temporal variability in rainfall. The state comprises mountainous regions, foothills, and plains, each with unique microclimatic conditions. Roorkee, situated in the Haridwar district at the base of the Shivalik hills, is an area that is frequently impacted by the extremes of rainfall — ranging from intense downpours to prolonged dry spells. Such variability complicates agricultural planning, water resource management, and infrastructure development in the region.

The document reviews various studies focusing on the trends and variability of rainfall across different regions in India, particularly emphasizing the differences in distribution, intensity, and frequency of rainfall over time. Patel and Shete (2018) compare statistical distributions using goodness-of-fit tests and observe that the best-fit distribution is influenced by geographical conditions. Tiwari and Jha (2020) advocate using modern techniques like L-moments for the Ganga basin, while Kaur et al. (2021) analyze annual maximum rainfall in Roorkee, focusing on extreme events relevant to infrastructure planning. Venkata Sai and Joseph (2018) utilize the effective drought index to highlight increasing drought frequency in Uttarakhand, prompting calls for efficient water management strategies. Chauhan et al. (2022) report variations in rainfall across seasons and detect decreasing trends in monsoon rainfall despite increases in post-monsoon periods.

Taxak et al. (2014) uncover abrupt patterns in rainfall in Uttarakhand, emphasizing the unpredictability that complicates water resource management. Mehta et al. (2022) assess rainfall trends in Surat city, revealing a negative trend for several months while an increase in annual and pre-monsoon periods is notable, indicating climatic changes. Ahmed et al. (2022) analyze satellite data, showing heightened short-duration, high-intensity rainfall events in Northeast India, necessitating enhanced urban flood management strategies. The primary objectives of this study are to examine the spatial and temporal variation in rainfall using various statistical parameters, and to analyze the frequency distribution of long-term historical rainfall data. In addition, the study aims to estimate the return periods of extreme rainfall events for Roorkee by applying probability distribution methods, specifically calculating design rainfall values corresponding to 10-year, 25-year, 50-year, and 100-year return periods.

Materials and Methods

Study Area Description

Roorkee (29.8667° N, 77.8833° E) in the state of Uttarakhand is situated at an elevation of approximately 268 m above sea level (Fig. 1). It lies within a humid-subtropical climate zone. The average annual temperature is about 23.0 °C (73.4 °F). The city receives around **~1,000 mm** of precipitation per year. The monsoon period (July-September) accounts for the bulk of rainfall; for example, average monthly rainfall in July is about 148 mm and in August about 172 mm. Relative humidity is highest during the monsoon months (e.g., around 80 % in August) and lowest in the pre-monsoon summer months. The soils of Uttarakhand can broadly be divided into four main groups, viz. alluvial soils, piedmont soils, hill soils and lateritic soils. Roorkee is basically a city on the banks of Upper Ganges Canal with not much soil variations. The soil type around this region is none other than alluvial soils found in the Ganga plains along its course. Agriculture is a significant contributor to Uttarakhand’s Gross State Domestic Product (11% in 2011- 12). It is the chief source of livelihood for over 70% of its population.

Data Collection and Analysis

The annual rainfall data for a 20-year period (2005–2024) for Roorkee, Uttarakhand, were collected from the National Institute of Hydrology (NIH). The dataset was analyzed to assess extreme rainfall events and identify long-term rainfall behavior. The statistical characteristics of the hydrological series were examined using standard parameters. For frequency analysis, the Gumbel distribution, Log-Pearson Type III distribution, and Log-Normal distribution were applied to estimate annual maximum rainfall and predict design rainfall values for the study area. Daily rainfall data were used to evaluate trend variability and mean rainfall patterns. From the daily records, monthly rainfall series for the station were generated. Subsequently, monthly district-level rainfall was computed using the arithmetic mean of rainfall recorded at all stations within the district. State-level monthly rainfall was then derived through area-weighted averaging of rainfall values across all districts of Uttarakhand.

Methodology

Rainfall variability was assessed by calculating the mean, standard deviation, and coefficient of variation (CV). Hydrologic frequency analysis commonly employs several probability distributions to estimate the likelihood of extreme rainfall events. In this study, the California formula was first used to determine the

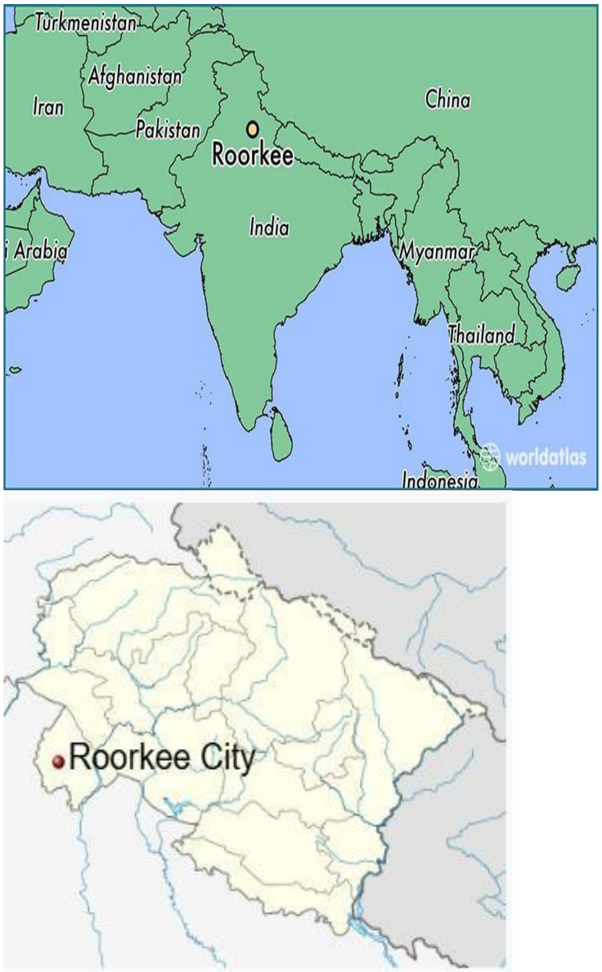

Fig.1 Location of Roorkee, Uttarakhand

plotting position, expressed as:

$$P=M/n \tag{1}$$

where

P = probability of occurrence,

M= rank of the rainfall value (largest value assigned rank 1), and

n = total number of years of record.

The recurrence interval (return period) of a given rainfall event represents the average time interval within which a rainfall magnitude is expected to be equaled or exceeded. Selection of the probability of exceedance (PX) or return period (TX) for hydrologic design depends on the acceptable level of risk, the potential consequences of excess or deficit rainfall, and the design life of the concerned project or system. For classification of rainfall conditions, the guidelines given by FAO (Smith, 1992) were adopted. According to these, a period is considered:

- Dry when rainfall is exceeded in 4 out of 5 years (probability of exceedance = 80%)
- Normal when rainfall is exceeded in 1 out of 2 years (probability of exceedance = 50%)
- Humid when rainfall is exceeded in 1 out of 5 years (probability of exceedance = 20%)

A probability plot was constructed by plotting rainfall values against their calculated probability of exceedance. A straight-line fit through the plotted points enabled estimation of rainfall depths corresponding to selected probabilities. The goodness of fit was evaluated using the coefficient of determination R^2. For analytical estimation, the Normal distribution was applied, as it is fully defined by its mean and standard deviation. Rainfall depths corresponding to selected probabilities of exceedance were computed using:

$$X_p = \bar{X} \pm ks \tag{2}$$

where

X_p = rainfall depth at a specified probability of exceedance,

$\bar{X}$ = sample mean rainfall,

s = standard deviation, and

k = frequency factor determined from statistical tables for the chosen probability level.

The sign and magnitude of k vary depending on the exceedance probability.

Normal distribution: Normal Distribution is the most common or normal form of distribution of Random Variables, hence the name "normal distribution." It is also called Gaussian distribution in Statistics or Probability. We use this distribution to represent a large number of random variables. It serves as a foundation for statistics and probability theory.

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \tag{3}$$

where,

σ = standard deviation, x = variate, μ = mean.

Log-normal distribution: The log-normal distribution is a right skewed continuous probability distribution, meaning it has a long tail towards the right. It is used for modeling various natural phenomena such as income distributions, the length of chess games or the time to repair a maintainable system and more.

$$P(x) = \frac{1}{\sigma_y e^y \sqrt{2\pi}} e^{-\left(y/\mu_y\right)^2/2\sigma_y^2} \tag{4}$$

where,

$y = \ln x,\ x\ is\ a\ variable,\ \sigma_y$ is mean of y and σ_y is standard deviation of y.

Gumbel's extreme value distribution: Gumbel's extreme value distribution was proposed by Gumbel (1941). This distribution is one of the most widely used probability distribution functions for extreme value in hydrology and meteorological studies for prediction of maximum rainfall, maximum wind velocity and maximum flood discharge.

$X_T = X_m(1 + C_v K_T)$
(5)

X_m = mean of the observed rainfall,
C_v = coefficient of variation,
K_T = frequency factor which is calculated by the formula given by Gumbel

Results and Discussion

Statistical analysis of the rainfall data for the selected region was carried out using measures of central tendency, while variability in the dataset was assessed using standard deviation and the coefficient of variation (CV). Table 1 presents the monthly rainfall characteristics for the 20-year period considered. The results indicate that the minimum mean monthly rainfall occurred in October (18.8 mm), followed by September (23.9 mm) and June (29.5 mm). In contrast, the highest mean monthly rainfall was recorded during August (632.5 mm), highlighting the peak monsoon influence. Analysis of the complete rainfall series further revealed that the average annual rainfall for Roorkee was 226.73 mm, with a maximum annual rainfall of 305.9 mm and a minimum of 144.1 mm during the study period. Corresponding values of standard deviation and coefficient of variation were also computed to quantify the variability and dispersion in annual rainfall.

Table 1 Statistical analysis of rainfall data.

Year	Jun	Jul	Aug	Sep	Oct
2005	74.0	400.1	249.2	337.9	292.6
2006	104.2	345.6	294.7	79.1	18.8
2007	139.9	522.9	502.8	325.6	25.1
2008	332.4	313.3	245.8	190.8	33.1
2009	41.9	157.5	632.5	206.6	164.3
2010	72.7	455.8	335.7	389.7	89.3
2011	223.1	433.3	523.7	148.4	184.7
2012	46.0	387.1	419.5	220.6	113.3
2013	488.9	413.4	359.4	111.3	139.0
2014	62.9	462.7	264.2	107.9	40.8
2015	186.6	337.0	305.3	52.6	66.4
2016	174.4	508.4	308.5	111.4	98.3
2017	175.6	460.9	349.0	213.4	152.0
2018	29.5	94.2	70.9	106.9	235.7
2019	58.4	93.9	142.8	211.4	196.3
2020	114.8	158.3	75.9	300.0	204.3
2021	91.1	203.3	98.3	188.5	366.3
2022	255.5	136.7	378.7	353.0	296.5
2023	72.3	141.5	12.6	248.4	126.8
2024	204.7	92.8	230.2	23.9	38.7
Min	29.5	92.8	89.7	23.9	18.8
Max	488.9	522.9	632.5	389.7	366.3
Average	147.4	305.9	290.0	196.4	144.1
SD	114.2	153.9	160.6	105.2	99.4
CV	77.4	50.3	55.4	53.6	69.0

Frequency Analysis

Storms of high intensity and varying durations occur from time to time. However, the probability of these heavy rainfalls varies with locality. The first step in designing engineering projects dealing with flood control, gully control etc. is to determine the probability of occurrence of a particular extreme rainfall. This information is determined by the frequency analysis of point rainfall data. Return period of various rainfall amount for the month of June, July, August, September and October from year 2005 to 2024 were calculated. The rainfall data for the month of June were subjected to frequency analysis to estimate the return periods of extreme precipitation events.

A probability plot was constructed by ranking the rainfall amounts and determining their corresponding probabilities of exceedance. The natural logarithm of the return period was plotted on the x-axis, and the observed rainfall values were plotted on the y-axis. A trendline was fitted to the data points to predict rainfall depths associated with various return periods (Fig. 2). The plot indicates a progressive increase in rainfall magnitude with increasing return period. Lower return periods (e.g., 2–5 years) correspond to moderate rainfall events, while higher return periods (50–100 years) are associated with significantly larger rainfall events. The line of best fit demonstrates a strong correlation, indicating that the selected distribution method provides a reliable estimate of rainfall frequency for the month of June.

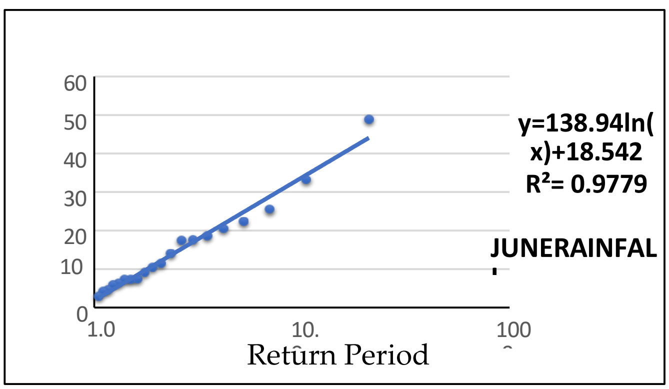

Fig. 2 Return period of various rainfall amount for month June

For the 20-year record (2005–2024), plotting-position frequency analysis indicates that the maximum monthly rainfalls correspond to an approximate 21-year return period (top rank in a 20-year sample), while the minimum monthly rainfalls correspond to about 1.1-year return period (lowest rank). Specifically, July's maximum is 522.9 mm and minimum 92.8 mm; August's maximum 632.5 mm and minimum 89.7 mm; September's maximum 389.7 mm and minimum 23.9 mm; and October's maximum 366.3 mm and minimum 18.8 mm.

Predication of Rainfall for Return Period

The rainfall was predicted for return period of 10, 25, 50, 100 years using graphical regression equation. The highest rainfall occurs in the month of July for return period as compared to June, August and September. Frequency analysis of monthly maxima shows a consistent increase in design rainfall with return period across all monsoon months. August has the highest design depths at every return period (e.g., 10-year: 582.0 mm; 100-year: 979.7 mm), followed by July. Relative growth from 10- to 100-year events is largest in June (~95%) and October (~90%), reflecting higher variability at the monsoon onset and withdrawal, and smallest in August (~68%), indicating comparatively more stable peak-monsoon behavior (Table 2). These values can be used as monthly design depths for planning and reliability assessments, with probability of exceedance approximately P=1/T (10-year ≈ 10%, 100-year ≈ 1%).

Table 2 Rainfall for Return Period of 10, 25, 50 and 100 Year

Years	10-years	25-Years	50-years	100-years
Months	Predicted rainfall (mm)			
June	338.46	465.77	562.08	658.38
July	536.11	689.50	805.54	921.58
August	582.02	719.67	849.66	979.65
September	365.74	478.62	564.01	649.39
October	309.54	419.78	503.18	586.58

Table 3 presents observed monthly rainfall totals corresponding to exceedance probabilities and return periods. As expected, rarer events (≈21-year) show the highest rainfall, with August and July recording the largest extremes, followed by June, September, and October. Rainfall decreases steadily as the return period shortens, indicating a consistent monsoon pattern where high-intensity events are infrequent. For example, the 10-year rainfall is around 332 mm (June), 508 mm (July), 524 mm (August), 353 mm (September),

Table 3 Probabilities of exceedance for June-October

and 297 mm (October), while near-annual values are much lower. One outlier appears: August at 95.24% probability = 12.6 mm, which likely requires correction. Overall, the table shows a logical declining trend with probability and serves as a reliable empirical basis for monsoon design rainfall estimates.

S. No.	Probability Percentage	Return Period	Observed Rainfall June (mm)	Observed Rainfall July (mm)	Observed Rainfall August (mm)	Observed Rainfall September (mm)	Observed Rainfall October (mm)
1	4.76	21.0	488.9	522.9	632.5	389.7	366.3
2	9.52	10.5	332.4	508.4	523.7	353	296.5
3	14.29	7.0	255.5	462.7	502.8	337.9	204.3
4	19.05	5.3	223.1	460.9	419.5	325.6	196.3
5	23.81	4.2	204.7	455.8	378.7	300	96.0
6	28.57	3.5	186.6	433.3	359.4	248.4	89.3
7	33.33	3.0	175.6	413.4	349	220.6	81.3
8	38.10	2.6	174.4	400.1	335.7	213.4	63.3
9	42.86	2.3	139.9	387.1	308.5	211.4	40.8
10	47.62	2.1	114.8	345.6	305.3	206.6	38.7
11	52.38	1.9	104.2	337	294.7	190.8	29.1
12	57.14	1.8	91.1	313.3	264.2	188.5	25.1
13	61.90	1.6	74	203.3	249.2	148.4	23.1
14	66.67	1.5	72.7	158.3	245.8	111.4	19.8
15	71.43	1.4	72.3	157.5	230.2	111.3	18.8
16	76.19	1.3	62.9	141.5	142.8	107.9	16.8
17	80.95	1.2	58.4	136.7	98.3	106.9	15.7
18	85.71	1.2	46	94.2	75.9	79.1	14.1
19	90.48	1.1	41.9	93.9	70.9	52.6	12.8
20	95.24	1.1	29.5	92.8	12.6	23.9	12.7

Table 3 presents observed monthly rainfall totals corresponding to exceedance probabilities and return periods. As expected, rarer events (≈21-year) show the highest rainfall, with August and July recording the largest extremes, followed by June, September, and October. Rainfall decreases steadily as the return period shortens, indicating a consistent monsoon pattern where high-intensity events are infrequent. For example, the 10-year rainfall is around 332 mm (June), 508 mm (July), 524 mm (August), 353 mm (September), and 297 mm (October), while near-annual values are much lower. One outlier appears: August at 95.24% probability = 12.6 mm, which likely requires correction. Overall, the table shows a logical declining trend with probability and serves as a reliable empirical basis for monsoon design rainfall estimates.

The Figure 3 compares predicted June rainfall depths obtained from three statistical distributions—Normal, Lognormal, and Gumbel across different return periods. In general, rainfall increases as the return period increases, reflecting the expected behaviour that rarer events are associated with higher rainfall. The Lognormal distribution consistently produces the highest values for extreme return periods, indicating that it is more sensitive to peak rainfall events. The Normal distribution gives intermediate estimates, falling between the Lognormal and Gumbel curves for most return periods. The Gumbel distribution yields the lowest predicted values, particularly for higher return periods, suggesting a more conservative representation of extreme rainfall. Overall, the comparison highlights the variation in rainfall magnitude depending on the chosen distribution, with Lognormal tending to estimate higher extremes, Normal offering moderate values, and Gumbel producing comparatively lower estimates. This was also calculated for July, August, September and October.

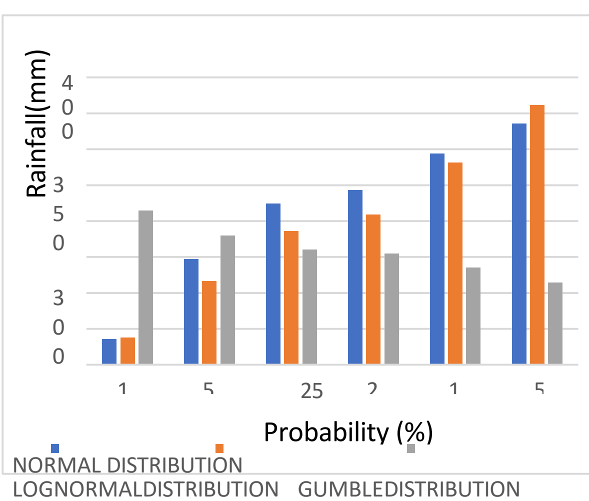

Fig. 3 Comparison of observed and predicted rainfall for various distribution levels for June

Conclusions

This study investigates rainfall frequency and trend characteristics for Roorkee District using Normal, Log-Normal, and Gumbel distribution methods. Daily rainfall records were processed to generate monthly and annual totals, and key statistical parameters such as mean, standard deviation, and coefficient of variation (CV) were computed. Frequency and probability analyses were conducted using the three distributions to estimate rainfall depths corresponding to different return periods. The monsoon months—June, July, August, and September—contribute the highest rainfall, with observed peak values of approximately 488.9 mm, 522.9 mm, 632.5 mm, and 389.7 mm, respectively. Among the months, July exhibits the lowest CV (50.3), followed by September (53.6), indicating relatively stable rainfall patterns, while November shows the highest CV (69), reflecting greater variability. Rainfall estimates were derived for return periods of 10, 25, 50, and 100 years, and results indicate that August receives the highest extreme rainfall, followed by July, June, and September. The analysis also shows that maximum predicted rainfall values are generally associated with lower exceedance probabilities (e.g., 20%), consistent with extreme event behavior. A comparison of observed and predicted rainfall for June to October demonstrates that distribution-based estimates closely follow observed trends, with Log-Normal typically predicting higher extremes and Gumbel providing more conservative estimates.

Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research received no external funding.

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