P-ISSN: 2618-0723
E-ISSN: 2618-0731

NAAS Rating (2025): 5.04
www.extensionjournal.com

International Journal of Agriculture Extension and Social Development

Volume 8; Issue 10; October 2025; Page No. 16-21

Received: 14-07-2025
Accepted: 17-08-2025

Indexed Journal
Peer Reviewed Journal

Probability distribution of rainfall and climate variability in Karnataka's dry zones: Agricultural implications

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DOI: https://www.doi.org/10.33545/26180723.2025.v8.i10a.2503

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Abstract

Climate change and climatic variability pose significant challenges to rain-fed agriculture in Karnataka, particularly in its dry zones. These regions are characterized by erratic rainfall, recurrent droughts, and high dependence on climate-sensitive crops. Understanding rainfall variability and its probability distribution is essential for developing adaptive strategies. This study analyzed annual rainfall data (1979-2023) across five major dry zones North Eastern Dry Zone (NEDZ), Northern Dry Zone (NDZ), Central Dry Zone (CDZ), Eastern Dry Zone (EDZ), and Southern Dry Zone (SDZ) using probability distribution models to identify variability patterns and assess climatic risks. Rainfall data were sourced from the Karnataka State Natural Disaster Monitoring Cell (KSNDMC) and NASA POWER datasets. Probability distribution fitting was carried out using parameters such as shape, scale, and location to capture the central tendency and variability of rainfall across zones. The results revealed distinct rainfall characteristics across the zones. The NEDZ and NDZ are the most drought-prone, with Weibull and Gamma distributions capturing their high variability. The CDZ shows moderate stability, with rainfall clustering around 500-600 mm, though extreme wet years occur. The EDZ is marked by high inter-annual variability, best explained by a lognormal distribution, while the SDZ displays relatively stable rainfall following a normal distribution but remains vulnerable to both droughts and surpluses. Overall, the findings highlight the critical need for zone-specific adaptive measures such as drought-tolerant crops, efficient irrigation systems, water harvesting, and climate-informed crop planning. Integrating rainfall probability models into agricultural decision-making can significantly enhance resilience and sustainability in Karnataka's dryland agriculture.

Keywords: Rainfall variability, Probability distribution, dry zones, climate resilience

Introduction

Climate change and its variability have emerged as critical challenges for Indian agriculture, exerting a profound influence on weather patterns and crop productivity. Recent projections indicate an increase in extreme events such as heat waves, prolonged dry spells, erratic rainfall, and droughts, along with rising atmospheric carbon dioxide and ground-level ozone concentrations. These changes have notably altered weather parameters, particularly rainfall distribution and temperature anomalies, which directly affect rain-fed farming systems across the country (Reddy *et al*., 2022) [9].

Karnataka, with diverse agro-climatic conditions, is particularly vulnerable to such climatic variability. While the coastal and hilly regions receive heavy monsoon rainfall, the dry zones comprising the Northern dry zone, North Eastern dry Zone, Central Dry Zone, and Eastern dry zone, Southern Dry zone are characterized by low and highly erratic rainfall. Agriculture in these regions is predominantly rain-fed, with major crops including sorghum, pearl millet, pulses, groundnut, and oilseeds. Even small deviations in rainfall critically impact yields, groundwater recharge, and farm livelihoods, making these areas highly sensitive to climate-induced risks (Sridhar *et al*., 2019) [12].

In the case of Karnataka's dry zones, projections for the coming decades indicate greater rainfall variability, with a likely increase in extreme rainfall events during the southwest monsoon and longer dry spells during pre-and post-monsoon periods (Anonymous, 2010) [1]. Given that these regions already experience frequent droughts, limited groundwater resources, and high dependence on rain-fed crops, such variability poses serious risks to agricultural productivity. Studies suggest that yields of major dryland crops such as sorghum, pearl millet, pigeon pea, and groundnut may decline by 8-15 percent under future climate scenarios, primarily due to moisture stress and heat extremes (Gangwar, 2013) [4]. This highlights the critical importance of analyzing rainfall variability in the dry zones, where even small changes in distribution and frequency can translate into significant impacts on farming systems and rural livelihoods.

Materials and Methods

Understanding the probability distribution of rainfall is essential for assessing climatic risks and guiding adaptive strategies. This study analyzes annual and seasonal rainfall patterns in Karnataka's dry zones using probability models to quantify variability and provide insights for crop planning, water management, and climate resilience.

The present study is confined to the Northern Dry Zone, North Eastern Dry Zone, Central Dry Zone, and Eastern Dry Zone, Southern Dry zone of Karnataka, which together constitute the state's largest dryland belt. These regions are characterized by low and erratic rainfall ranging between 500-900 mm annually, high temperatures, and frequent droughts (Table 2). Such climatic constraints contribute to low and unstable agricultural productivity, particularly in rain-fed crops such as sorghum, pearl millet, groundnut, and pulses. The zones were purposefully selected as they represent the core of Karnataka's dryland farming systems and highlight the vulnerability of agriculture to rainfall variability. Data on key climatic variables rainfall, maximum temperature, and minimum temperature, were collected from the Karnataka State Natural Disaster Monitoring Cell (KSNDMC), Bengaluru, and NASA POWER data sets for the period 1979-2023.The study analyzed rainfall patterns in the dry zones of Karnataka using probability distribution analysis. This method was employed to identify the best-fitting statistical distributions that capture variability and trends in rainfall data. Key parameters such as shape, scale, and location were estimated to describe the characteristics of rainfall patterns. The properties and parameters of the probability distributions used are detailed in Table 1.

Table 1: Properties and Parameters of Probability Distributions

Distribution	Properties	Parameters
Normal Distribution	1. Symmetry: Perfectly symmetric around the mean.	• Mean (μ): Central location. • Standard Deviation (σ): Determines spread.
	2. Bell-Shaped Curve: PDF follows a bell-shaped curve.	
	3. Mean, Median, Mode: All are equal and at the center.	
	4. Asymptotic: Tails approach but never touch the x-axis.	
	5. Defined by mean (μ) and standard deviation (σ).	
Gamma Distribution	1. Skewness: Positively skewed.	• Shape (α): Controls shape. • Scale (β): Controls spread.
	2. Defined by shape (α) and scale (β).	
	3. Special Case: α = 1 reduces to exponential distribution.	
Weibull Distribution	1. Flexibility: Models increasing, decreasing, or constant hazard rates.	• Shape (κ): Determines shape. • Scale (λ): Determines scale.
	2. Defined by scale (λ) and shape (κ).	
	3. Special Cases: (i) κ = 1 → exponential distribution; (ii) κ = 3.4 → approximates normal distribution.	
Lognormal Distribution	1. Right-Skewed: Positively skewed.	• μ: Mean of log(X), location parameter. • σ: Standard deviation of log(X), scale parameter.
	2. Multiplicative Property: The logarithm of the variable is normally distributed.	
	3. Defined by mean (μ) and standard deviation (σ) of log-normal.	
	4. Non-Negative: Values are positive.	

Table 2: Annual normal and actual rainfall statistics and probability distributions across Agro-climatic zones of Karnataka (1979-2023)

Sl. No	Agro-climatic zones	Normal Rainfall (mm)	Actual Rainfall (mm)	Coefficient of Variation (%)	Best-Fit Probability Distribution
1	North Eastern Dry Zone	635.3	513.3	23.8	Weibull
2	Northern Dry Zone	632.4	352.9	23.1	Gamma
3	Central Dry Zone	584.1	537.2	21.3	Weibull
4	Eastern Dry Zone	738.12	975.7	23.8	Lognormal
5	Southern Dry Zone	1355.4	917.7	18.9	Normal

Table 2 represents the summary of annual rainfall characteristics and the best-fit probability distributions for the five dry zones of Karnataka. The North Eastern Dry Zone has a normal rainfall of 635.3 mm, while the observed average rainfall is 513.3 mm, with a coefficient of variation (CV) of 23.8 percent. The Weibull distribution was identified as the best-fit model for this zone, reflecting moderate rainfall variability.

The Northern Dry Zone shows a normal rainfall of 632.4 mm, but the observed mean is much lower at 352.9 mm, with a CV of 23.1 percent. The rainfall distribution is best described by a Gamma distribution, indicating a right-skewed pattern and frequent drought-prone years.

For the Central Dry Zone, the normal and observed rainfall are 584.1 mm and 537.2 mm, respectively, with a CV of 21.3 percent. Weibull distribution again provides the best fit, capturing the moderate variability in annual rainfall.

The Eastern Dry Zone experiences higher rainfall, with a normal value of 738.12 mm and an observed mean of 975.7 mm, and a CV of 23.8 percent. The lognormal distribution is the best fit, indicating occasional extreme wet or dry years.

Finally, the Southern Dry Zone receives the highest rainfall, with a normal value of 1355.4 mm and an observed mean of 917.7 mm, and a relatively low CV of 18.9 percent. The rainfall in this zone is approximately normally distributed, suggesting fairly stable and symmetrical variability around the mean.

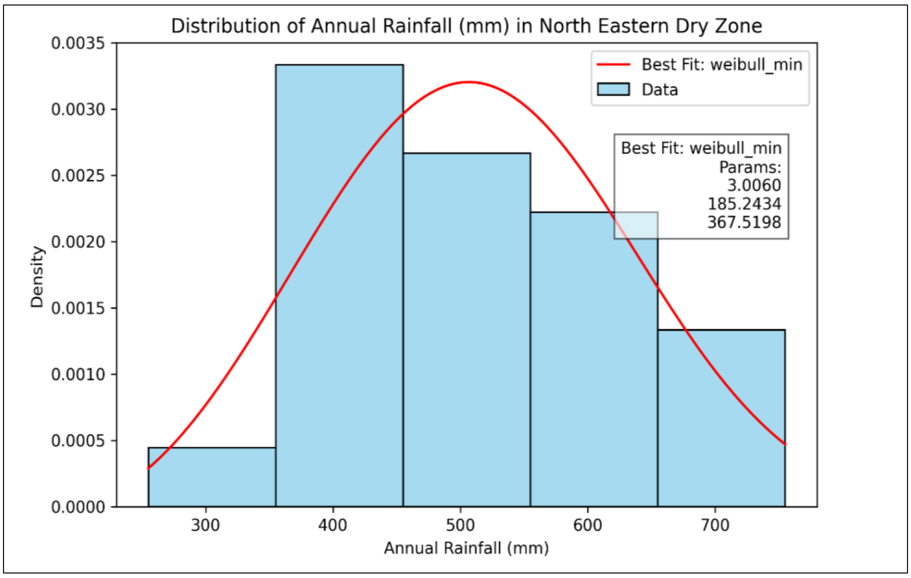

Fig 1: Probability Distribution of Rainfall in the North Eastern Dry Zone (1979-2023)

Figure 3 shows the probability distribution of annual rainfall in the North Eastern Dry Zone (NEDZ) of Karnataka during 1979-2023. The histogram represents observed rainfall values, while the red line depicts the best-fit Weibull minimum distribution. Most rainfall observations lie between 400-600 mm, with a peak around 500 mm, while extremely low (<300 mm) or high (>700 mm) rainfall years are rare. The fitted Weibull parameters (shape = 3.00, location = 185.24, scale = 367.51) indicate a moderately symmetric distribution with limited skewness. These results are in line with earlier studies of Siddaram *et al*. (2020) + and Rani *et al*. (2021) [8] highlighted the region's recurrent droughts and moderate rainfall clustering**;** Samanth *et al*. (2022) [10] and Chowdari *et al*. (2023) [3] noted high inter-annual variability in semi-arid districts like Kalaburgi, Raichur, and Yadgir, Madolli *et al*. (2014) [5], observed a rising trend in precipitation in some years despite overall dry conditions; and Mann and Gupta (2022) [6] reported links between rainfall fluctuations and large-scale climate drivers such as El Niño, affecting rainfall reliability. Collectively, these findings reinforce the NEDZ's vulnerability and underscore the importance of understanding rainfall distributions for planning adaptive strategies in agriculture and water management.

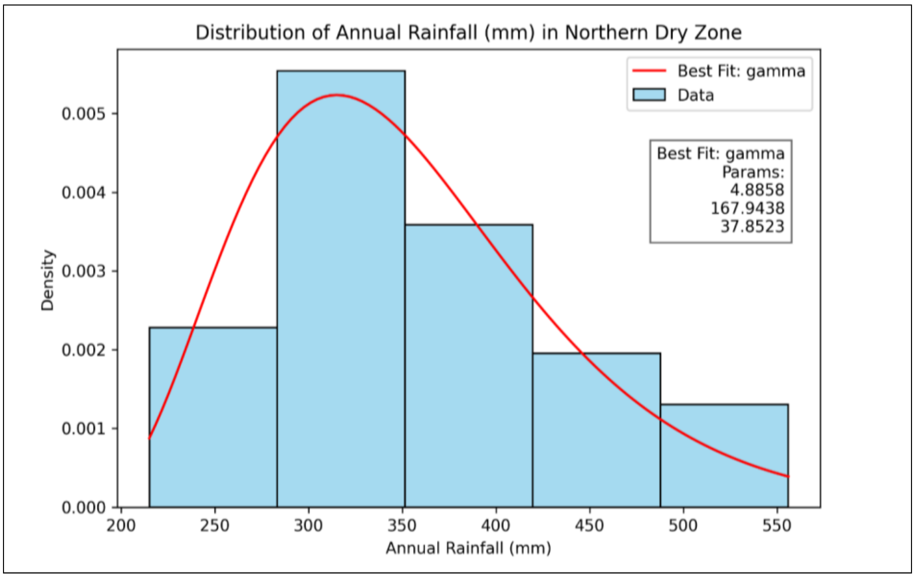

Fig 2: Probability Distribution of Rainfall in Northern Dry Zone (1979-2023)

Figure 4 presents the probability distribution of annual rainfall in the Northern Dry Zone (NDZ) of Karnataka for the period 1979-2023. The histogram depicts observed rainfall frequencies, while the red line represents the fitted Gamma distribution. Most rainfall values fall between 280-400 mm, with a peak around 320-330 mm. The fitted Gamma parameters (shape = 4.88, location = 167.94, scale = 37.85) reflect the spread and central tendency, indicating a moderately right-skewed distribution with most rainfall concentrated in the lower range.

The NDZ is among the driest regions of Karnataka, with rainfall rarely exceeding 500 mm and occasional extreme drought years (<250 mm). These results are consistent with previous studies reporting high rainfall variability and climatic vulnerability in the region. Madolli *et al*. (2014) [5] observed frequent droughts, while Samanth *et al*. (2022) [10] highlighted periods of excess rainfall and oscillations during the southwest monsoon. Yogananda *et al*. (2015) [13] and Badekhan & Nayak (2023) [2] reported fluctuations in rainfall alongside rising minimum temperatures, emphasizing the growing impact of climate variability on agriculture.

These findings underscore the NDZ's dependence on low and variable rainfall, making adaptive measures such as drought-tolerant crops, efficient water use, and irrigation support crucial for reducing risks to livelihoods.

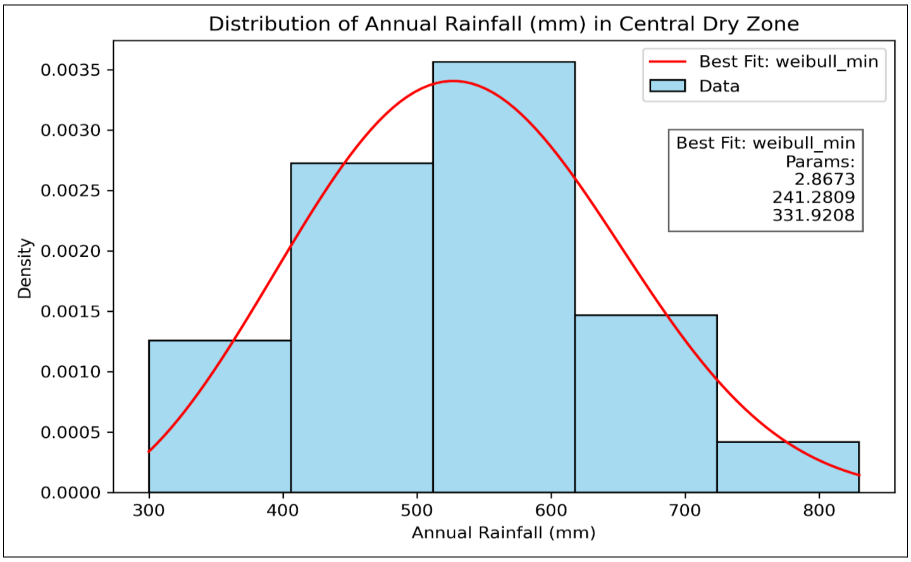

Fig 3: Probability Distribution of Rainfall in Central Dry Zone (1979-2023)

Figure 3 shows the probability distribution of annual rainfall in the Central Dry Zone (CDZ) of Karnataka during 1979-2023. The histogram displays observed frequencies, while the red curve represents the fitted Weibull minimum distribution. Most rainfall values are concentrated between 400-700 mm, with a peak around 550-600 mm. The fitted Weibull parameters (shape = 2.86, location = 241.28, scale = 331.92 explain the distribution's spread and central tendency.

The results indicate that the CDZ receives relatively moderate and stable rainfall compared to other dry zones, with fewer occurrences of extreme drought years (<350 mm) or excess rainfall (>750 mm). The shape parameter points to a moderately skewed distribution, with rainfall clustering around the central values. The location parameter reflects the minimum threshold, while the scale parameter highlights inter-annual variability. Overall, the probability of rainfall remaining in the 500-600 mm range is high, suggesting that agriculture in this zone is relatively more reliable.

On the other hand, wet years show significant surplus rainfall. The year 2010 recorded the highest annual rainfall in the study period, with 830 mm. Other wet years include 2015 (37.1% surplus), 2019 (34.5% surplus), and 2014 (30.9% surplus), which contributed to improved agricultural conditions and water availability. These surplus rainfall years align with the findings of Maraddi *et al*. (2023) [7], who highlighted high variability in areas like Chitradurga and Davanagere, where annual rainfall is often less than 700 mm.

Recent years have continued to show rainfall variability. In 2023, the CDZ experienced a dry year with 452.5 mm of rainfall, while 2022 marked a wet year with 664 mm. Similarly, 2020 and 2021 recorded moderate surpluses of 8.7 percent and 13.5 percent, respectively, reflecting relatively favorable rainfall conditions. These patterns of rainfall extremes and variability corroborate the findings of Samanth *et al*. (2022) [10], who observed periodic rainfall oscillations during the southwest monsoon, and Rani *et al*. (2021) [8], who documented the recurrence of frequent drought years (e.g., 1983, 1986), highlighting the CDZ's vulnerability to both excess and insufficient rainfall.

Figure 6 shows the probability distribution of annual rainfall in the Eastern Dry Zone (EDZ) for 1979-2023. Rainfall is mostly concentrated between 800-1100 mm, with the fitted lognormal curve closely matching the observed data. The distribution parameters (shape = 0.24, location = 67.15, scale = 881.01) indicate a moderately right-skewed distribution, reflecting occasional years of unusually high or low rainfall.

This pattern aligns with earlier studies on the EDZ. Madolli (2014) [5] highlighted that districts such as Kolar and Chikkaballapur experience recurring droughts, showing significant deficits in several years. Samanth *et al*. (2022) [10] observed increased pre-monsoon rainfall in the region, which can benefit crop productivity but also contributes to variability. Madaddi *et al*. (2023) [7] noted high inter-annual rainfall fluctuations across the EDZ, while increasing rainfall trends in certain districts like Kolar and Ramanagara. Rani *et al*. (2021) [8] emphasized that despite occasional surplus years, droughts continue to affect agriculture in the region.

The positive skewness of the distribution reflects this variability, indicating that while most years have moderate rainfall, extreme dry or wet years can occur. Such variability must be considered in agricultural planning, water management, and climate adaptation strategies to ensure drought resilience and sustainable resource use in the Eastern Dry Zone.

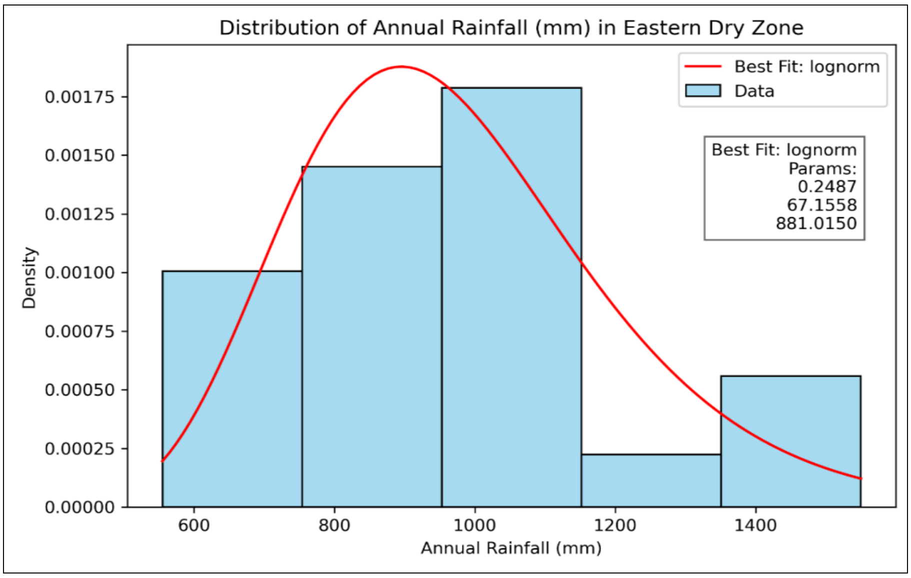

Fig 4: Probability Distribution of Rainfall in Eastern Dry Zone (1979-2023)

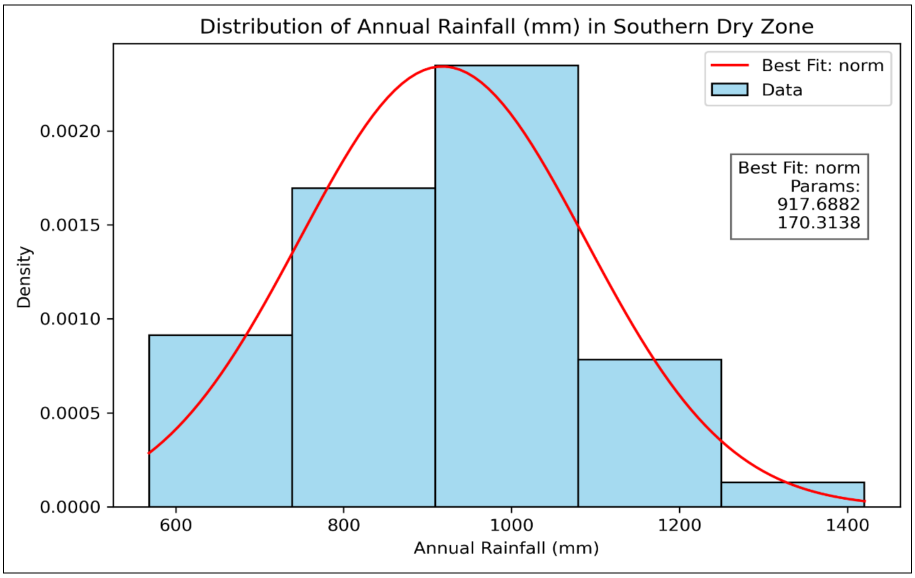

Fig 5: Probability Distribution of Rainfall in Southern Dry Zone (1979-2023)

The histogram of annual rainfall in the Southern Dry Zone, overlaid with a normal distribution curve, shows that most rainfall values cluster around a mean of 917.7 mm, with a standard deviation of 170.3 mm. The data are approximately normally distributed, indicating fairly stable annual rainfall with symmetrical variability.

Several years, however, experienced significant rainfall surpluses. The wettest year, 2005, recorded 1420.32 mm, while other wet years like 2017 and 2010 had surpluses of 32.15 percent and 21.85 percent, respectively. These surplus years benefit groundwater recharge and agriculture but can also cause flooding and soil erosion, as observed in previous studies. Conversely, dry years such as 2023 and historical events like 1985 highlight the region's susceptibility to drought.

The continuing variability in rainfall underscores the need for adaptive strategies, including efficient irrigation systems and climate-resilient farming. These observations are consistent with earlier studies, which documented both droughts and rainfall surpluses in the SDZ. Yogananda *et al.* (2015) [13] highlighted increasing rainfall variability and dual risks of deficit and surplus, Madaddi *et al.* (2023) [7] noted high rainfall with moderate variability in Kodagu, and Samanth *et al.* (2022) [10] reported increasing pre-monsoon rainfall trends. Rani *et al.* (2021) [8] also emphasized persistent drought conditions in the region.

Overall, the Southern Dry Zone experiences moderately stable rainfall around 917.7 mm but remains vulnerable to both extremes, highlighting the importance of climate-resilient agricultural and water management strategies.

Conclusion

The probability distribution analysis highlights significant variability in rainfall across the dry zones of Karnataka. The North Eastern and Northern Dry Zones are highly drought-prone, with rainfall concentrated in lower ranges, indicating high climatic vulnerability. The Central Dry Zone shows moderate rainfall stability but still experiences occasional dry and wet extremes. The Eastern Dry Zone exhibits high inter-annual variability, with occasional surplus and deficit years affecting agricultural productivity. The Southern Dry Zone has relatively stable rainfall around the mean but remains susceptible to both droughts and excessive rainfall. These patterns underscore the need for adaptive measures tailored to each zone. Suggested strategies include promoting drought-tolerant and resilient crop varieties, improving irrigation efficiency, and adopting water harvesting and storage systems. Early warning systems and climate-informed crop planning can help mitigate risks. Integrating local rainfall variability into agricultural decision-making is essential to enhance climate resilience. Overall, understanding rainfall probability distributions supports sustainable agriculture and resource management in Karnataka's dry zones.

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