

Rainfall Characteristics, Groundwater Recharge Estimation, and Meteorological Drought Analysis in the Tungabhadra River Basin, Kurnool District, India

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Abstract

The aim of this paper is analyzing the seasonal and annual rainfall characteristics viz., Mean rainfall, Rainfall intensity, Rainfall variability, Rainfall ratio, Rainfall recharge and meteorological drought of the Tungabhadra River basin. The daily rainfall data for the period of 30 years from 9 stations have been collected from Indian meteorological department (IMD), Converted and computed and tabulated to seasonal and annually. The mean seasonal rainfall is distrusted as follows: winter (6 mm), summer (76 mm), South west monsoon (452mm) and North east monsoon (133mm). The analysis of seasonal rainfall reveals that the basin experiences the highest rainfall received from South west monsoon season. The annual rainfall of the basin is 668mm Groundwater recharge through rainfall was estimated using Four different empirical equations proposed by Radhakrishna (1974), U. S. Geological Survey method (1963), Seghal (1973), and Krishna Rao method (1970). The average annual recharge calculated using these empirical equations were found to be 66.75mm, 100.13mm, 203.11mm and 66.88mm respectively. The mean annual recharge for the basin is calculated to be 109.23 mm. This accounts for 16.35% of the annual rainfall. Departure Analysis of Rainfall shows that the normal rainfall received for 15 years, while annual rainfall exceeded normal levels in seven years. On the other hand, deficit rainfall was experienced in 8 years. Rainfall anomaly Index was near average for five years, slightly wet for two years, and slightly dry for two years. Tungabhadra River basin's significant agricultural resource base, which frequently experiences droughts and prolonged dry spells, this study's spatial analysis of rainfall and recharge provides critical scientific insights to inform sustainable cropping systems and mitigate drought risks in the region.

Key words: Rainfall variability, Ground water recharge, Meteorological drought, Monsoon rainfall, Sustainable cropping

Rainfall data plays a vital role in the planning and implementation of regional initiatives, particularly those related to sustainable agriculture and food production systems. Moreover, it serves as a key factor influencing hydrological processes, climatic conditions, water resource management, soil erosion prediction, drought and flood forecasting and ecological modeling [2]. Precipitation serves as fundamental source for global agricultural practices. The agricultural productivity within a given year is contingent upon the volume of rainfall, its intensity, and the spatial distribution of this rainfall across a specific region, all of which are indicative of the state's economic development. The characteristics of precipitation within a specific region exhibit significant spatial variability. Analyzing the rainfall patterns at the sub-basin level is crucial for comprehending the micro-level fluctuations in precipitation, which is essential for effective planning in agricultural practices as well as land and water development initiatives [25]. It is a significant input in water balance studies. The output is evaporation and evapotranspiration. A study on water resource planning and development was conducted for

the river basins. It is crucial to systematically evaluate a region's surface water resources by studying the distribution of rainfall data collected from available rain gauge stations over time [13]. Rainfall is a critical factor influencing the total cropped area under rained conditions, and accurate rainfall timing is essential for crop growth. Any significant deviation from average rainfall can cause stress, making moisture crucial for crop production. Understanding surface water resources is vital for understanding vegetation and its variations for agricultural planning and development. [9] conducted a study analyzing rainfall data for crop planning in dry-land agriculture at Rajkot. The study assesses the impact of rainfall variability on crop production. The study also highlighted the importance of incorporating rainfall data into agricultural planning strategies. [26] conducted an analysis of rainfall characteristics in the North Saurashtra Agro-climatic Zone to inform crop planning strategies. The study emphasized the need for cultivating drought-resistant, low-water-requiring, and short-duration crop varieties, with a maximum crop growth period of 99 days, to adapt to the region's climatic constraints.

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Rainfall distribution in Ahmednagar District highlights significant spatial variability in precipitation, which affects local agriculture [4]. The research underscores the need for artificial water supply systems to counteract the adverse impacts of inconsistent rainfall on crop productivity. Rainfall distribution in Bhatapara, Chhattisgarh, reveals significant rainfall variability affecting agricultural sustainability, particularly for paddy cultivation [21]. The research highlights how fluctuations in rainfall both excessive and insufficient can disrupt crop cycles and impact productivity. Performed a spatial analysis of rainfall in the drought-prone area of Cuddapah district, Andhra Pradesh. Based on rainfall distribution, the study likely identified areas within the district that are more susceptible to drought [14]. Rainfall variability analysis and its impact on crop productivity, focusing on a case study in India. The research analyzed the relationship between rainfall patterns and regional crop productivity [10]. Rainfall variability and crop planning in the Sabour region of Bihar. It likely analyzed rainfall variability in the Sabour region of Bihar to develop crop planning strategies. The findings may include information on how farmers can adapt their planting schedules, crop selection, and other management practices to optimize yields in response to changing rainfall patterns [20]. Rainfall analysis in the humid southern plains of Rajasthan to assist in crop planning [23].

The authors assessed the rainfall patterns to determine the best crops to cultivate in the region. Using GIS, [6] conducted a study on the spatial analysis of rainfall variation in Coimbatore District, Tamil Nadu. He has mapped and interpreted spatial distribution and variability through different seasons, precipitation ratios, and Frequency occurrences. [3] attempted to study the spatial distribution of weekly rainfall characteristics like Average rainfall, rainfall variability, and rainfall ratio for 50 years in the chronically drought-prone district of Anantapur. [7] studied the spatial distribution of rainfall in the Salem and Namakkal districts. The main findings of this study include mapping rainfall patterns in the districts and identifying areas with high and low rainfall variability. The study also highlighted the importance of spatial analysis in understanding rainfall distribution. [8] studied rainfall analysis and recharge in the Papagni River basin in Andhra Pradesh. The main findings of this study include an analysis of rainfall patterns in the region and an assessment of groundwater recharge potential based on rainfall data.

The study provides valuable insights into the hydrological dynamics of the Papagni River basin. [17] studied the temperature, rainfall, and rainfall recharge of the Kakodonga River Basin in India. The study's main findings included the analysis of temperature trends, rainfall patterns, and the impact of rainfall on groundwater recharge in the basin. [19] studied the rainfall patterns in the Cuddalore district, focusing on the spatial distribution of rainfall, its variability, and the precipitation ratio. The research found that the combined contribution of southwest and northeast monsoons to the mean annual rainfall of the study area is about 87 percent, of which the Northeast monsoon alone contributes 57.85 percent.

The importance of precipitation in climate and hydrological cycles, the role of rainfall in recharging groundwater systems, the significance of analyzing rainfall data for understanding micro-level variability and planning of agriculture, land, and water development, the impact of geological formations on water quality, and the presence of various mineral resources in the Cuddapah Basin [24]. Understanding rainfall variability is essential to optimally managing scarce water resources under continuous stress due to increasing water demands, population increases, and economic

development. [5] conducted a study analyzing rainfall patterns in the Gariyaband District of Chhattisgarh. The study aimed to develop effective crop planning and water management strategies based on the region's rainfall patterns. The study likely includes insights into the distribution of rainfall, its variability, and ways to optimize crop planning and water management practices in the area.

Amount of Ground water recharge estimated by Indian researchers by using empirical methods at Regional and Basin or watershed level by [15], [12], [1], [11]. [21-22] of rainfall data for Mungeli, Chhattisgarh, based on a 16-year dataset, highlights the recurrent nature of drought, particularly during the non-monsoon period. Researchers used empirical recharge-estimation methods applied at two spatial scales—regional (district/administrative) and basin or watershed level—relying on a 16-year rainfall record for Mungeli, Chhattisgarh. Their analysis produced estimates of the amount of groundwater recharge and, importantly, showed a recurrent drought signal, especially pronounced during the non-monsoon months. The study underscores the need for effective water harvesting strategies to capture excess runoff during the monsoon season, enabling supplemental irrigation to mitigate moisture deficits in post-monsoon and summer. [16] Analyzed 31 years of rainfall data for Chintapalle in the High Altitude and Tribal Zone of Andhra Pradesh. Estimating groundwater recharge for Mungeli using empirical methods on a 16-year rainfall dataset provides a practical, actionable picture: the aquifer is recharged mainly during monsoon months, but the system experiences recurrent seasonal drought stress in non-monsoon periods. While empirical methods give useful first approximations for planning and identifying vulnerable zones, addressing the recurrent non-monsoon drought will require better monitoring, targeted recharge interventions at the watershed scale, demand management, and combining empirical approaches with more detailed hydrological and socio-economic analyses. The study revealed both positive and negative rainfall trends across different months using the Mann-Kendall test and linear regression. Drought assessment through DAR (Departure analysis of rainfall), RAI, and SPI indicated predominantly normal rainfall with fewer drought years. The findings highlight the region's favorable kharif conditions and provide insights for effective crop planning and drought management.

MATERIALS AND METHODS

Study area

The Tungabhadra River has its source in the Western Ghats, a mountain range stretching along India's western coastline. It is fed by two primary tributaries: the Tunga River and the Bhadra River. The Tunga River originates in the Chikmagalur district of Karnataka, while the Bhadra River originates in the Shimoga district of Karnataka, also within the Western Ghats. These two rivers converge near Kudli, located in the Shimoga district, giving rise to the Tunga Bhadra River. Maliganur village, Kowthalam (Mandal), which is the entry point of Tungabhadra in the Kurnool district of Andhra Pradesh. The Tungabhadra River basin covers an area of about 6,934 sq. km. It measures a maximum length of 260 km in the district. The study area is geographically located in the northern part of the district: it lies between 15° 15' 00" to 16° 00' 00" North Latitude and 77° 00' 00" to 78° 15' 00" East longitudes (Fig 1). It is falling in the Survey of India (SOI) toposheet no 57E/1 to 57 E/16 and 57I/1 to 57I/5. The altitude of the basin varies from a maximum of 246 mts to a maximum of 674 mts above mean sea level. The average annual rainfall of the Tungabhadra River basin is 668 mm and the average minimum temperature is 26

°C to a maximum of 46 °C. The basin enjoys the semi-arid and dry sub-humid type of climate. The main occupation and source

of livelihood for this basin is Agriculture. More than 70% of the people are engaged in farming.

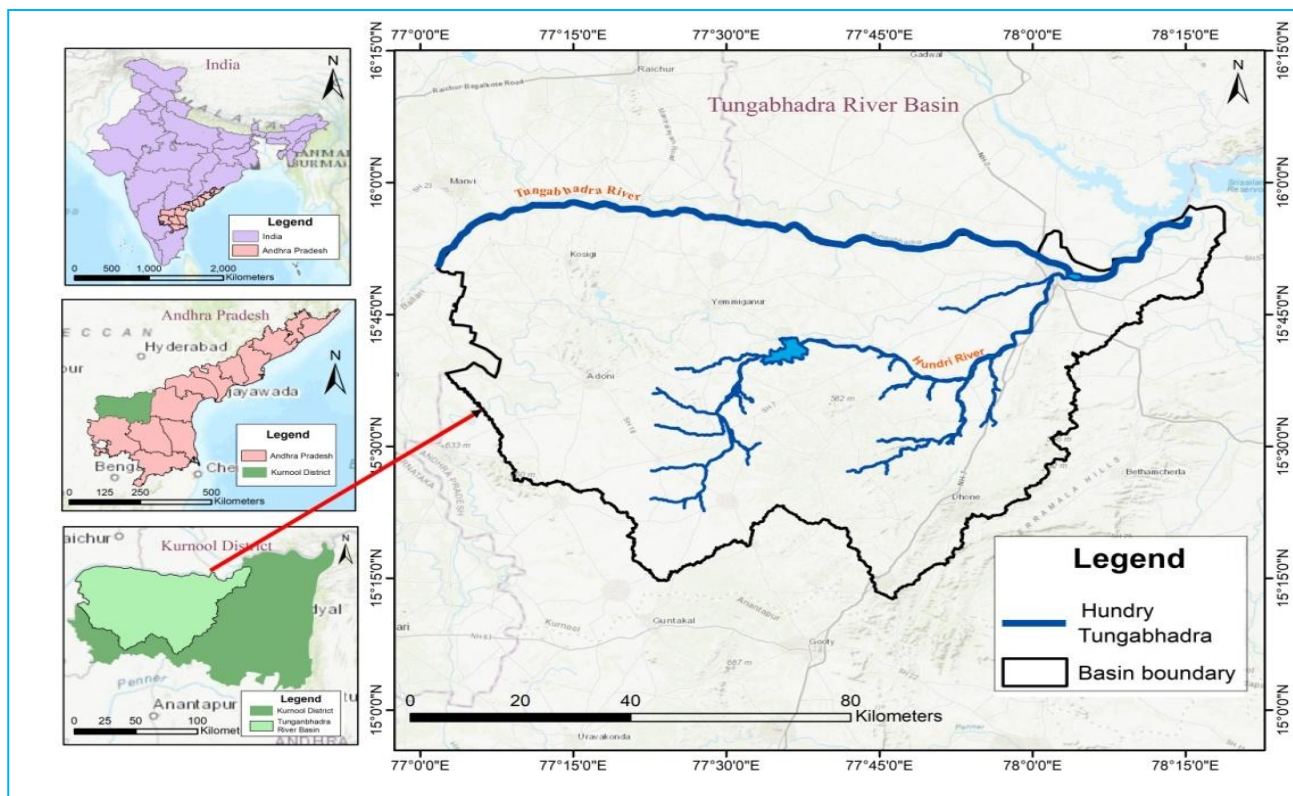


Fig 1 Location map of the Tungabhadra River basin

Rainfall data has been collected over 30 years (1991-2020) from nine different rain-gauge stations. These stations have been carefully selected in and around the Tungabhadra River basin to analyze the monthly, seasonal, and annual rainfall data. In addition, the surface water resources of the basin have also been studied based on the mean annual rainfall and the geographical area of the basin. The statistical methods used to analyze annual mean rainfall; rainfall intensity, rainfall variability, and rainfall ratio are based on the approach adopted by Bhargava (1977). The formulas mentioned in below:

$$\text{Mean rainfall} = \frac{\sum X}{N} \quad \text{Where X variates,} \\ \text{N number of variates}$$

$$\text{Rainfall intensity} = \frac{\text{Average rainfall}}{\text{Average number of rainy days}} \times 100$$

$$\text{Rainfall variability} = \frac{\text{Standard deviation (S.D)}}{\text{Mean}} \times 100$$

$$\text{Rainfall ratio} = \frac{P_{\text{Maximum}} - M_{\text{Minimum}}}{P_{\text{Average}}} \times 100$$

The groundwater recharge of the basin has been studied by various researchers using different methods. Radhakrishna *et al.* (1974) method suggests that the recharge is 10% of the annual rainfall, while the U.S. Geological Method (1962) indicates that it is 15%. On the other hand, Seghals (1973) has developed a formula for groundwater recharge, represented as $G = 2.5 (P-16)^{0.5}$, where P represents precipitation in inches. Additionally, Krishna Rao (1970) has proposed a method that calculates the annual groundwater recharge based on different precipitation ranges. According to this method, when precipitation is between 400mm and 600mm, the recharge is

estimated as $R = 0.20 (P-400)$. When precipitation is between 600mm to 1000mm, the recharge is estimated as $R = 0.25 (P-400)$. Finally, when precipitation is above 1000mm, the recharge is estimated as $R = 0.35 (P-600)$. These different methods have been used to estimate the basin's groundwater resources, considering the recharge and the geographical area.

RESULTS AND DISCUSSION

Winter season

During the winter, the average precipitation in the basin area exhibits variation, with a minimum of 5.15 mm recorded at Kuppagal station and a maximum of 7.33 mm at Kammarachedu station (Table 1). The mean precipitation value for the basin is 6 mm. Spatial Analysis reveals that rainfall values increase from 5.8 mm in the western and northeastern regions of the basin to 6.6 mm in the southern part of the basin. The intensity of rainfall ranges from 2.92 mm/a rainy day at Laxmipuram station to a maximum of 4.78 mm/a rainy day at Kammarachedu station. The average rainfall intensity for the basin is 4 mm/a rainy day. Spatial Analysis indicates that the intensity is higher in the southwestern and southern regions of the basin.

The rainfall variability in the basin area ranges from a minimum of 123.54% at Mutukur station to a maximum of 159.49% at Veldurthi station, with an average value of 139.78%. Spatial Analysis reveals that rainfall variability during this period is approximately 135% in the southern parts of the basin, exceeding 147% in the northwestern, northern, and southeastern regions. The rainfall ratio in the study area ranges from a minimum of 353.63% at Peapully station to a maximum of 710.23% at Kuppagalu station, with a mean value of 506.88%. Spatial Analysis indicates that the value is less than 472% in the basin's southern part, while it exceeds 591% in the northwestern and southwestern regions.

Table 1 Seasonal rainfall characteristics of the Tungabhadra River basin of Kurnool district (1991-2020)

(Winter)					
S. No.	Station	Mean rainfall (in mm)	Rainfall intensity (in mm)	Rainfall variability (in %)	Rainfall ratio (in %)
1.	Peapully	7.26	4.74	123.54	353.31
2.	Kammarachedu	7.33	4.78	136.56	459.78
3.	Mutukur	7.31	4.30	123.88	365.68
4.	Erragudi	6.36	3.67	128.02	411.91
5.	Veldurthi	6.99	4.37	153.90	666.24
6.	Kuppagalu	5.15	3.51	159.49	710.23
7.	Chiraladoddi	6.01	4.00	141.46	492.96
8.	Erranelakanapuram	6.24	3.60	154.66	619.37
9.	Laxmipuram	5.45	2.92	136.48	469.49

Source: Indian Meteorological Department (Rainfall)

Summer

The average rainfall during the summer season in the basin exhibits a range of values, with the lowest recorded at 67.71 mm in the Kammarachedu station and the highest at 84.25 mm in the Erranelakanapuram station (Table 2). The overall mean precipitation value for the basin is 76 mm. Regarding spatial distribution, the western part of the basin experiences rainfall below 73 mm, while the eastern and southern parts range from 73 mm to 78 mm. The northern part of the basin, on the other hand, receives rainfall exceeding 78 mm. The intensity of rainfall also varies across different stations within the basin. The Kammarachedu station records the lowest intensity at 5.26 mm per rainy day, while the Erranelakanapuram station reports the highest intensity at 7.18 mm per rainy day. On average, the rainfall intensity is 6 mm per rainy day. Spatially, the intensity distribution ranges from 6 mm per rainy day to 6.5 mm in the

northwestern and northeastern parts of the basin. Rainfall variability, which indicates the degree of fluctuation in rainfall patterns, exhibits a range of values across different stations. The Kammarachedu station demonstrates the lowest variability at 41.96%, while the Kuppagalu station reports the highest variability at 64.77%, with a mean value of 53.24%. Regarding spatial distribution, the southwestern part of the basin experiences a rainfall variability of approximately 49% during this season. The rainfall ratio, which compares the current season's rainfall with the average rainfall, also displays variation across different stations. The Kammarachedu station exhibits a ratio of 177.37%, while the Laxmipuram station reports the highest ratio at 226.70%, with an average value of 201.73%. Spatially, the rainfall ratio ranges from 193.6% in the southwestern and southern parts to a maximum of 210% in the northeastern and northwestern parts of the basin.

Table 2 Seasonal rainfall characteristics of the Tungabhadra River basin of Kurnool district (1991-2020)

(Summer)					
S. No.	Station	Mean rainfall (in mm)	Rainfall intensity (in mm)	Rainfall variability (in %)	Rainfall ratio (in %)
1.	Peapully	74.43	5.45	52.89	186.42
2.	Kammarachedu	67.71	5.26	41.96	177.37
3.	Mutukur	79.34	5.91	45.92	193.30
4.	Erragudi	76.02	5.74	56.78	200.17
5.	Veldurthi	71.25	5.34	56.88	200.04
6.	Kuppagalu	71.20	6.26	64.77	224.70
7.	Chiraladoddi	82.33	7.12	49.61	212.36
8.	Erranelakanapuram	84.25	7.18	50.90	194.93
9.	Laxmipuram	74.46	6.20	59.47	226.30

Source: Indian Meteorological Department (Rainfall)

South west monsoon

The mean seasonal rainfall during the Southwest monsoon exhibits significant variation across different regional stations. Specifically, the Kammarachedu station experiences the lowest mean seasonal rainfall of 409.94 mm, while the Laxmi Puram station records the highest mean seasonal rainfall of 497.44 mm (Table 3). On average, the precipitation in the region amounts to 452 mm. The spatial distribution of rainfall reveals a gradual increase in values from the western and southwestern parts of the basin, where the rainfall measures 439 mm, to the northeastern part, where it reaches 468 mm. This indicates a clear pattern of increasing rainfall intensity towards the northeastern region. The rainfall intensity shows that the Kammarachedu station has the lowest intensity, with 7.36 mm of rainfall per a rainy day. The Laxmipuram station exhibits the highest intensity at 8.32 mm per a rainy day. The mean rainfall intensity for the entire basin is calculated to be 8 mm/a rainy

day. Furthermore, the spatial distribution of rainfall intensity during the southwest monsoon period indicates that the western part of the basin experiences an intensity of 7.5 mm/a rainy day, while the northeastern part records an intensity of 8 mm/a rainy day.

The rainfall variability ranges from 32.98% at the Kammarachedu station to a maximum of 43.00% at the Peapully station, with a mean value of 37.15%. The spatial distribution of rainfall variability indicates a value of approximately 36% in the western and northeastern parts of the basin, while it exceeds 39% in the southern part. Analyzing the rainfall ratio, it is observed that the Kuppagalu station exhibits the lowest value of 130.05%, while the Erragudi station records the highest value of 220.81%. The average rainfall ratio for the basin is 180.75%. The spatial distribution of rainfall ratio reveals that values are below 180% in the western part of the basin but exceed 190% in the southeastern part.

Table 3 Seasonal rainfall characteristics of the Tungabhadra River basin of Kurnool district (1991-2020)

(South West Monsoon)

S. No.	Station	Mean rainfall (in mm)	Rainfall intensity (in mm)	Rainfall variability (in %)	Rainfall ratio (in %)
1.	Peapully	428.03	7.78	43.00	219.72
2.	Kammarachedu	409.94	7.36	32.98	145.83
3.	Mutukur	433.68	7.74	37.54	188.10
4.	Erragudi	433.33	7.74	42.35	220.81
5.	Veldurthi	486.33	7.93	38.51	200.90
6.	Kuppagalu	438.01	7.60	34.21	130.05
7.	Chiraladoddi	455.27	8.33	35.61	159.97
8.	Erranelakanapuram	485.68	8.24	37.27	186.00
9.	Laxmipuram	497.44	8.32	32.87	178.39

Source: Indian Meteorological Department (Rainfall)

North-east monsoon

During the northeast monsoon, the mean precipitation values exhibit a range of variability across different stations within the basin. Specifically, Chiraladodi station experiences a mean rainfall value of 125.46 mm, while Veldurthi station records the highest mean rainfall value of 151.03 mm (Table 4). The average precipitation value for the basin as a whole is 133 mm. Spatial Analysis of the rainfall distribution reveals that the basin's western, northern, and southern regions receive less than 134 mm of rainfall. Conversely, the North Eastern and Eastern parts receive rainfall ranging from 134 mm to 142 mm. The rainfall intensity varies across the basin, with Kuppagal station recording the highest intensity of 9.96mm/a rainy day and a minimum intensity of 7.39 mm/a rainy day. The average rainfall intensity value is 8 mm/a rainy day. Spatial Analysis of the rainfall intensity indicates that the southern and southeastern

regions of the basin experience an intensity of approximately 8 mm/a rainy day.

In comparison, the northwestern region records an intensity of 9 mm/a rainy day. The rainfall variability across the study area ranges from 53.22% in Peapully station to a maximum of 80.07% in Kuppagalu station. The average rainfall variability for the basin is 63.24%. Spatial Analysis of the rainfall variability reveals that the southern and southeastern regions of the basin exhibit a variability of approximately 62%. In comparison, the northwestern region records a variability exceeding 71%. The rainfall ratio values range from 225.53% in Erragudi station to a maximum of 361.31% in Kuppagal station, with an average value of 257.14%. Spatial Analysis of the rainfall ratio values indicates that the eastern and southern regions of the basin record a ratio of 270%, while the northwestern region exhibits a ratio of 316%.

Table 4 Seasonal rainfall characteristics of the Tungabhadra River Basin of Kurnool district (1991-2020)

(South East Monsoon)

S. No.	Station	Mean rainfall (in mm)	Rainfall intensity (in mm)	Rainfall variability (in %)	Rainfall ratio (in %)
1.	Peapully	138.70	7.39	53.22	225.71
2.	Kammarachedu	129.31	8.18	61.62	249.14
3.	Mutukur	127.39	8.05	58.43	227.22
4.	Erragudi	129.34	7.92	58.05	225.53
5.	Veldurthi	151.03	7.94	56.23	232.41
6.	Kuppagalu	131.42	9.96	80.07	361.31
7.	Chiraladoddi	125.46	8.53	73.12	324.21
8.	Erranelakanapuram	129.47	8.81	63.69	325.82
9.	Laxmipuram	138.64	8.81	64.72	232.95

Source: Indian Meteorological Department (Rainfall)

Table 5 Annual rainfall characteristics of the Tungabhadra River Basin of Kurnool district (1991-2020)

(Annual)

S. No.	Station	Mean rainfall (in mm)	Rainfall intensity (in mm)	Rainfall variability (in %)	Rainfall ratio (in %)
1.	Peapully	648.42	7.34	32.18	139.56
2.	Kammarachedu	614.29	7.15	26.26	99.15
3.	Mutukur	647.71	7.44	27.68	120.45
4.	Erragudi	645.05	7.39	31.55	144.59
5.	Veldurthi	715.61	7.51	30.11	131.75
6.	Kuppagalu	645.80	7.72	28.42	109.88
7.	Chiraladoddi	669.06	8.05	27.99	113.49
8.	Erranelakanapuram	705.64	8.10	27.99	121.64
9.	Laxmipuram	715.99	8.01	24.93	124.64

Source: Indian Meteorological Department (Rainfall)

Annual

The study area exhibits a range of mean annual rainfall values, with Kammarachedu station recording the lowest value

of 615 mm and Laxmipuram station recording the highest value of 716.00 mm while the average annual rainfall for the basin is 667.15 mm (Table 5). Spatial Analysis reveals that rainfall

values increase from 648.5 mm in the western part of the basin to 682.3 mm in the northeastern part. Rainfall intensity also varies across the study area, with Kammarachedu station recording a minimum intensity of 7.16 mm/a rainy day and Erranelakanapuram station recording a maximum intensity of 8.10 mm/a rainy day. The average rainfall intensity for the basin is 8 mm/a rainy day. Spatial Analysis shows that rainfall intensity is higher in the northern and northeastern parts of the basin, gradually decreasing towards the western and southern parts. Rainfall variability in the basin area ranges from 24.93% in Laxmipuram station to a maximum of 32.18% in Peapully

station, with a mean value of 29%. The average rainfall variability for the basin is 29 %. Spatial Analysis reveals that variability is less than 27.00% in the northeastern and southwestern parts of the basin, while it exceeds 29.00% in the southeastern part. The rainfall ratio also varies across the study area, with Kammarachedu station recording a ratio of 99.03% and Erragudi station recording the highest ratio of 144.59%. The average rainfall ratio of the basin is 123 %. Spatial Analysis shows that the ratio ranges from 114% in the western and southwestern parts to a maximum of 129% in the southeastern part of the basin.

Table 6 Annual recharge of the Tungabhadra River basin (1991-2020) (All Values in mm)

S. No	Station	Average annual rainfall in mm	Radhakrishna Method (1974)	U.S. Geological method 1962	Seghal method (1970)	Krishna Rao method	Average recharge in mm
1	Peapully	648.42	64.84	97.26	196.01	62.11	105.06
2	Kammarachedu	614.29	61.43	92.14	181.66	53.57	97.20
3	Mutukur	647.71	64.77	97.16	195.72	61.93	104.89
4	Erragudi	645.05	64.51	96.76	194.64	61.26	104.29
5	Veldurthi	715.61	71.56	107.34	221.55	78.90	119.84
6	Kuppagalu	645.80	64.58	96.87	194.95	61.45	104.46
7	Chiraladoddi	669.06	66.91	100.36	204.20	67.27	109.68
8	Erranelakanapuram	705.64	70.56	105.85	217.96	76.41	117.69
9	Laxmi puram	715.99	71.60	107.40	221.69	79.00	119.92

Annual rainfall recharge of the Tungabhadra River basin

The annual rainfall recharge of the Tungabhadra River basin has been worked out using the Radha Krishna *et al.* (1974) method, U.S. Geological Survey (1963), Seghal (1973) and Krishna Rao (1970) method. Groundwater recharge from the four methods has been used to determine the annual recharge of nine rain gauge stations in the basin. The first method, as Radha Krishna *et al.* (1974) proposed, involves taking 10% of the annual rainfall as recharge. This method yields an annual recharge ranging from 61.43mm to 71.60 mm, with a mean value of 66.75mm (Table 6). Six stations, namely Peapully, Kamarachedu, Mutuku, Erragudi, Kuppagalu, and Chiraladodi, have an annual recharge of less than 70 mm, while Erranelakanapuram, Veldurthi, and Laxmipuram stations have a recharge depth exceeding 70 mm.

The second method, adopted by the U.S. Geological Survey, involves taking 15% of the annual rainfall as recharge. This method yields an annual recharge ranging from 92.14 mm to 107.40 mm, with an average depth of 100.13 mm. Kammarachedu, Erragudi, and Kupagalu stations have a recharge depth of less than 97 mm, while Mutukur, Peapully, and Chiraladodi stations have a recharge depth ranging from 97 mm to 102 mm. Erranelakanapiuram, Veldurthi, and Laxmipuram stations have a recharge exceeding 102 mm.

The third method, proposed by Seghal (1973), involves using the formula $G=2.5 (P-16)^{0.5}$ to determine the annual recharge. This method yields an annual recharge ranging from 181.66 mm to 221.69 mm, with an average depth of 203.16 mm. Kammarachedu, Erragudi, and Kuppagalu stations have a recharge depth of less than 195 mm, while Peapully, Mutukur, and Chiraladodi stations have a recharge ranging from 195 mm to 208 mm. Veldurthi, Erranelakanapuram, and Laxmipuram stations have a recharge exceeding 208 mm.

The fourth technique is presented by the Krishna Rao (1970) method. According to Krishna Rao method the annual recharge $R_r = K(P-X)$. $R=0.20(P-400)$, where annual rainfall between 400-600 mm, $R= R=0.25(P-400)$, where annual rainfall between 600-1000 mm, $R=0.20(P-600)$, where annual rainfall above 2000 mm. As per the Krishna Rao method, the annual recharge ranges from 53.57 mm to 79 mm, with an average recharge of 66.88 mm. The recharge is below 62 mm in Kammarachedu, Mutukur, Erragudi, and Kuppagal stations, while it varies from 62 mm to 70 mm at Peapully and Chiraladodi stations. It exceeded 70 mm in Erranelakanapuram, Veldurthi, and Laxmi Puram stations. The average annual recharge of the basin was determined by taking the average of the four methods, which ranged from 97.20 mm to 119.92 mm, with an average of 109.23 mm. This accounts for 16.35% of the annual rainfall. The average recharge is less than 105 mm in Kmmarachedu, Mutukur, and Erragudi and Kuppagalu stations, while it only varies from 105 mm to 113 mm in Peapully Station. It exceeded 113 mm in Erranelakanapuram, Veldurthi, and Laxmipuram stations.

Drought analysis of Tungabhadra River basin

Departure analysis of rainfall (DAR)

According to the India Meteorological Department's classification, an area is classified as drought-affected if it receives seasonal rainfall less than 75% of its average value [16]. DAR measures the deviation from the mean annual rainfall of a specific year. It can be calculated using the following formula:

$$DAR (\%) = \frac{X_i - X_m}{X_m} \times 100$$

Where, xi is the annual rainfall of the year 1, xm is the mean annual rainfall from the annual rainfall.

Table 7 Statistical analysis of departure analysis of rainfall from 1991-2020

S. No.	Year	Actual rainfall	DAR (%)	S. No.	Year	Actual rainfall	DAR (%)
1	1991	563.58	-15.57	16	2006	696.01	4.27
2	1992	522.89	-21.66	17	2007	1097.08	64.36
3	1993	640.81	-4	18	2008	669.7	0.33
4	1994	531.09	-20.44	19	2009	803.81	20.42
5	1995	708.51	6.14	20	2010	762.34	14.21

6	1996	970.81	45.44	21	2011	429.44	-35.67
7	1997	634.98	-4.87	22	2012	537.15	-19.53
8	1998	904.9	35.56	23	2013	742.12	11.18
9	1999	491.58	-26.36	24	2014	640.24	-4.09
10	2000	841.74	26.1	25	2015	467.92	-29.9
11	2001	701.66	5.12	26	2016	574.02	-14.01
12	2002	562.31	-15.76	27	2017	697.13	4.44
13	2003	507.98	-23.9	28	2018	319.19	-52.18
14	2004	577.21	-13.53	29	2019	628.19	-5.89
15	2005	875.4	31.14	30	2020	925.46	38.64

Table 8 Departure analysis of rainfall (DAR) of Tungabhadra River basin from 1991-2020

DAR categories (%)	Rainfall regime	Years (1991-2020)	Percentage of total years (%)
>20	Excess	7	23
19 to -19	Normal	15	50
-20 to -59	Deficit	8	27
-60 to -99	Scanty	0	0
<-100	No Rain	0	0
Total		30	100

An analysis of the rainfall departure revealed that the annual rainfall and maximum annual rainfall deficiency during drought was -52.18% in 2018 (Table 7, Fig 2). The computed values from 1991-2020 (Table 8, Fig 3) showed that normal rainfall was received for 15 years, while annual rainfall exceeded normal levels in 1996, 1998, 2000, 2005, 2007, 2009, and 2020. On the other hand, deficit rainfall was experienced in 1992, 1994, 1999, 2003, 2011, 2012, 2015, and 2018. The frequency of years with regular rainfall in this period suggests a higher likelihood of average rainfall. The normal onset of

southwest monsoons dramatically influences the average rainfall in the study region. Drought conditions resulted from the deficit of southwest monsoons during drought years, leading to water stress in the area and negatively impacting major agricultural activities. Overall, the rainfall analysis indicates that while the region generally experiences normal rainfall due to the timely onset of the southwest monsoon, periodic monsoon failures such as the severe deficit of -52.18% in 2018 cause recurrent droughts that lead to significant water stress and adversely affect agricultural productivity.

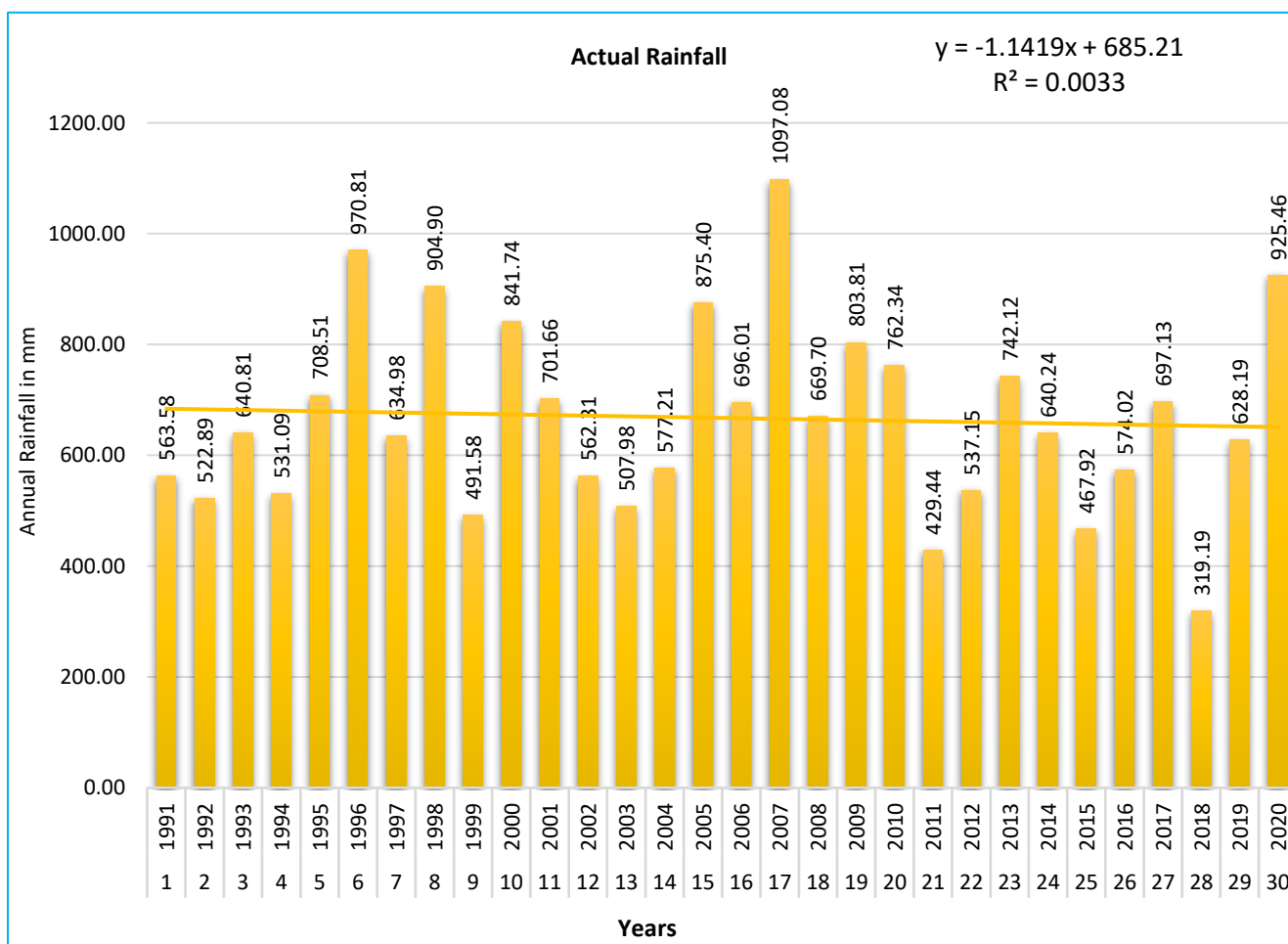


Fig 2 Annual rainfall particulars of the Tungabhadra River basin (1991-2020)

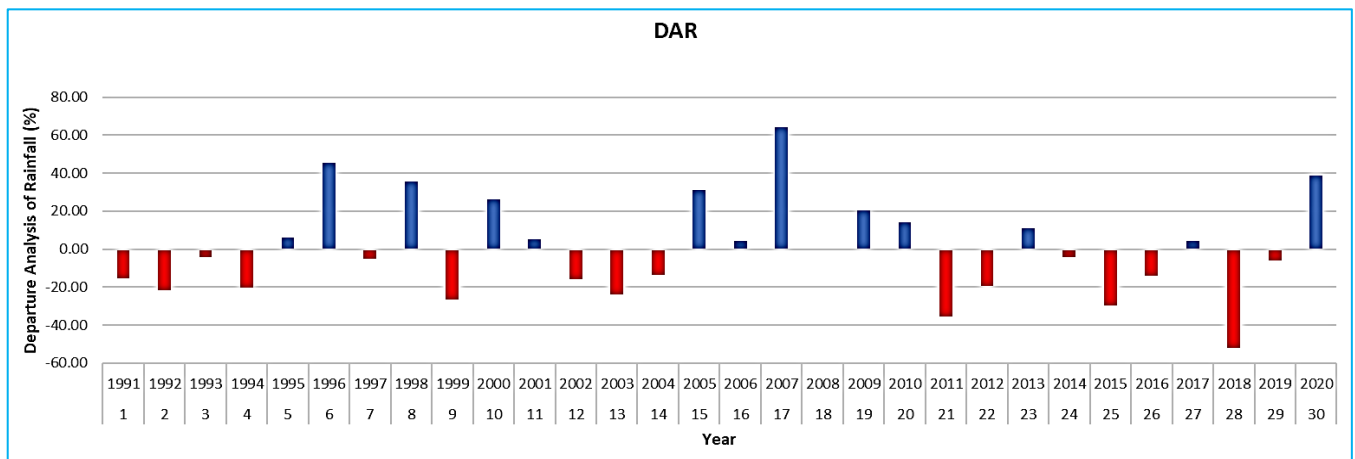


Fig 3 Departure analysis of rainfall for the time series 1991-2020

Rainfall anomaly indexes

It is the simplest and most effective index for measuring rainfall deficit for long-term data. We collected the average monthly rainfall of the Tungabhadra River Basin for 30 years (1991-2020) and the rainfall anomaly of each year using long-term monthly rainfall data of the study area. Years with low rainfall values indicate a negative anomaly. The following Formula was used to calculate the Rainfall Anomaly Index:

$$RAI = +3 \times \left[\frac{N - \bar{N}}{\bar{M} - \bar{N}} \right], \text{ For Positive Anomalies Eq 1}$$

$$RAI = -3 \times \left[\frac{N - \bar{N}}{\bar{X} - \bar{N}} \right], \text{ For Negative Anomalies Eq 2}$$

Where N = Current year rainfall, \bar{N} = Yearly Average Rainfall of the Historical series (mm);
 \bar{M} = Average of the ten highest yearly precipitations of the historical series (mm); \bar{X} = Average of the ten lowest yearly

precipitations of the historical series (mm): Positive anomalies have their Values above average, and negative anomalies have their values below average.

The Rainfall Anomaly Index (RAI) was analyzed over 30 years (1991-2020) to identify meteorological drought years. Based on the fig.4 and table.9 and fig.9 shows that Rainfall Anomaly Index (RAI) was near average for five years, slightly wet for two years, and slightly dry for two years. Compared to the Drought Area Ratio (DAR), Rainfall Anomaly Index (RAI) provides a more comprehensive representation of drought severity, categorizing it into four classes ranging from slightly to extremely dry. 2018 experienced the most significant rainfall deficit, followed by 1999, 2011, and 2015, which are notable for their dry drought occurrences. It is worth noting that there were very few years with a positive RAI. 2007 had the highest magnitude of rainfall, followed by 1996, 1998, 2005, and 2020 (Table 10). The Rainfall Anomaly Index (RAI) results align entirely with the Drought Area Ratio (DAR) trend in this study.

Table 9 Statistical analysis of rainfall anomaly indexes (1991-2020)

S. No.	Year	Rainfall anomaly index (RAI)	S. No.	Year	Rainfall anomaly index (RAI)
1.	1991	-1.79	16	2006	0.44
2	1992	-2.49	17	2007	6.58
3	1993	-0.46	18	2008	0.03
4	1994	-2.35	19	2009	2.09
5	1995	0.63	20	2010	1.45
6	1996	4.65	21	2011	-4.1
7	1997	-0.56	22	2012	-2.25
8	1998	3.64	23	2013	1.14
9	1999	-3.03	24	2014	-0.47
10	2000	2.67	25	2015	-3.44
11	2001	0.52	26	2016	-1.61
12	2002	-1.81	27	2017	0.45
13	2003	-2.75	28	2018	-6
14	2004	-1.56	29	2019	-0.68
15	2005	3.19	30	2020	3.95

Table 10 Rainfall anomaly index (RAI) of Tungabhadra River basin from 1991-2020

RAI categories	Rainfall regime	Years (1991-2020)
>3	Extremely wet	5
2 to 2.99	Very wet	2
1 to 1.99	Moderately wet	2
0.5 to 0.99	Slightly wet	2
-0.49 to 0.49	Near normal	5
-0.99 to -0.5	Slightly dry	2
-1.99 to -1	Moderately dry	4
-2.99 to -2	Very dry	4
<-3	Extremely dry	4

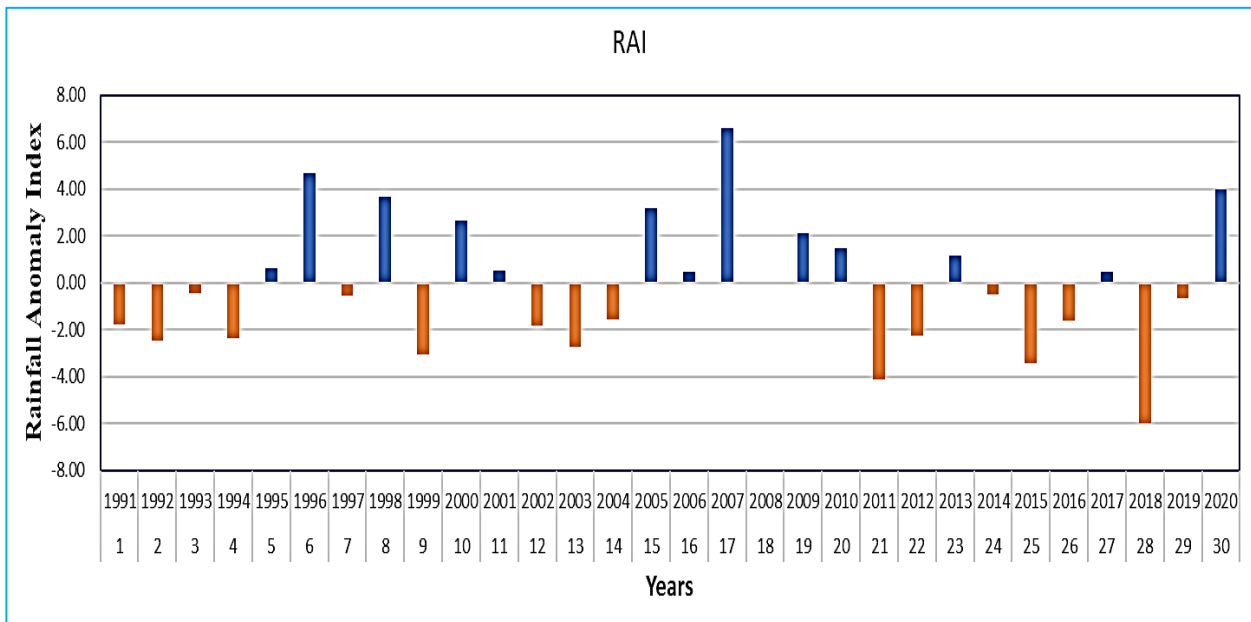


Fig 4 Rainfall anomaly index of annual rainfall 1991-2020

CONCLUSION

The Tungabhadra River basin exhibits a highly variable hydrological regime, characterized by an average annual rainfall of 668 mm, predominantly during the southwest monsoon (452 mm), with minimal contributions from other seasons. This erratic, insufficient, and uneven distribution of precipitation, coupled with an average annual recharge of 109.23 mm, has resulted in frequent droughts and occasional floods, as evidenced by rainfall departure analyses indicating normal conditions in 15 years, excesses in seven, and deficits in eight over the study period. Rainfall anomaly indices further underscore this variability, with near-average conditions prevailing in five years, slightly wet in two, and slightly dry in two. Agriculturally, the basin has transitioned toward water-efficient, rainfed crops such as Bengal gram, groundnut, sunflower, rice, sorghum, cotton, black gram, and onions, driven by low rainfall, labor shortages, rising wages, and limited irrigation infrastructure. Predominant "fallow-chickpea" systems reflect adaptations to these constraints, though productivity remains suboptimal. To mitigate drought impacts and enhance agricultural resilience, several evidence-based measures are recommended. Farmer education programs should emphasize the adoption of high-yielding crop varieties, optimal fertilizer and pesticide application, and bio fertilizers to maximize yields under resource-limited conditions. At the

village level within each mandal, the implementation of modern irrigation techniques such as sprinkler, drip, and trickle systems—can significantly improve water use efficiency. Structural interventions, including the construction of check dams and percolation pits, are essential to reduce surface runoff, augment groundwater recharge, and elevate water tables, thereby supporting domestic, irrigation, and industrial needs. Crop diversification toward drought-resistant species like green gram, black gram, maize, and minor millets, alongside intercropping (e.g., groundnut with red gram or maize with cowpea) and mixed cropping strategies, can optimize resource utilization on the region's loamy to clayey soils, which possess moderate to high water-holding capacities suitable for pulses, groundnut, sorghum, and cotton. Furthermore, practices such as mulching and summer green manure cultivation can enhance soil moisture retention and overall land productivity, fostering sustainable agriculture. In the basin's semi-arid conditions, marked by low rainfall, high evaporation, and scarce surface water, groundwater emerges as a critical resource to meet escalating demands. Accordingly, future research employing remote sensing, geographic information systems (GIS), and multi-influencing factor (MIF) techniques will delineate potential groundwater zones, informing targeted interventions for long-term water security and drought resilience in Tungabhadra River basin and beyond.

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