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Meteorological Drought Trends and Patterns in the Gundar River Basin Using the Standardized Precipitation Index (SPI)

[1]Ilamathi.P.R. and [2]Dr. Emayavaramban. V
[1]Research scholar, School of Earth and Atmospheric Science, Department of Geography, Madurai Kamaraj University
[2]Professor, School of Earth and Atmospheric Science, Department of Geography, Madurai Kamaraj University

ABSTRACT
This study investigates the spatio-temporal patterns of meteorological drought in the Gundar River Basin, Tamil Nadu, using the Standardized Precipitation Index (SPI) at a 3-month scale (SPI-3). Monthly rainfall data from 1988 to 2023 were obtained from the CHIRPS dataset and analyzed across 20 monitoring stations. The SPI-3 was computed to identify seasonal drought events, and key drought metrics—onset, offset, duration, magnitude, intensity, and frequency—were derived. Results reveal frequent moderate droughts with significant spatial variability. Sub-basins such as Vembar and Therkkar experienced more prolonged and severe events, while others showed fewer occurrences. Although droughts were recurrent, their intensity remained within the moderate range across the basin. The study highlights the effectiveness of SPI-3 and geospatial tools for localized drought assessment and emphasizes the need for adaptive water resource management in semi-arid regions.

1. INTRODUCTION
Drought is one of the most complex and least understood natural hazards, causing widespread socio-economic and environmental impacts, particularly in arid and semi-arid regions like southern Tamil Nadu (Mishra & Singh, 2010; Wilhite, 1996). Among various types of droughts, meteorological drought, characterized by a prolonged deficit in precipitation, serves as the early warning for other drought types (Paulo & Pereira, 2006; AghaKouchak et al., 2015). The Standardized Precipitation Index (SPI), developed by McKee et al. (1993), is a widely accepted tool for characterizing meteorological drought due to its flexibility across multiple time scales and ease of calculation (Guttman, 1999; Svoboda et al., 2012). Recent advancements in geospatial analysis and remote sensing have enhanced drought monitoring capabilities by facilitating spatial and temporal mapping of drought severity (Kogan et al., 2013; AghaKouchak et al., 2015). Several studies have applied SPI in different geographic contexts to assess drought variability and trends using both ground and satellite-based rainfall data (Bonaccorso et al., 2003; Peters et al., 2002; Gidey et al., 2018). In India, district-level and gridded rainfall datasets provided by the India Meteorological Department (IMD) and other global products such as CHIRPS and SRTM DEM have made regional drought modeling more robust (Pai et al., 2014; Maidment et al., 2017).
Trend detection methods like the non-parametric Mann–Kendall test and Sen's slope estimator are commonly employed to quantify the direction and magnitude of drought trends over time (Mann, 1945; Sen, 1968; Tabari et al., 2015). Spatial interpolation techniques within GIS further support localized assessments of drought vulnerability (Farr et al., 2007; Rossi et al., 2007).
Small and medium-sized basins in southern India often lack detailed, long-term drought characterization studies despite their high vulnerability to climate variability. Understanding the meteorological drought patterns in such basins is critical for water resource management and agricultural planning. This study aims to model and analyze the spatio-temporal trends of meteorological drought in the Gundar River Basin using SPI derived from long-term rainfall records, supported by geospatial tools and trend detection techniques.

2. STUDY AREA
The Gundar River Basin is located in the southern part of Tamil Nadu, India, extending across parts of Madurai, Virudhunagar, Sivagangai, Ramanathapuram, and Thoothukudi districts. (Fig:1)The river originates from the Saptur Reserve Forest in the Varushanadu Hills of the Eastern slopes of the Western Ghats and flows eastward to join the Gulf of Mannar near the coastal plains of Ramanathapuram (TNWRD, 2014; PWD Tamil Nadu, 2018). The basin covers a total area of approximately 5,690 km^2 and is divided into nine administrative sub-basins: Upper Gundar, Lower Gundar, Therkkar, Paralaiyar, Kanal Odai, Palar, Vembar, Gridhumal, and Uthirakosamangaiyar (TNWRD, 2014). The region lies in the rain-

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shadow zone and is characterized by semi-arid climatic conditions with frequent rainfall variability and prolonged dry spells, making it vulnerable to recurring meteorological droughts (IMD, 2020; Mishra & Singh, 2010). Agriculture is the primary livelihood, and the basin depends heavily on the northeast monsoon (October–December) for water availability. The topography ranges from undulating hill slopes in the west to flat plains in the east, with elevation gradually declining toward the coastal region (Farr et al., 2007; SRTM DEM Data, USGS, 2022). This physiographic setting and climate sensitivity make the Gundar River Basin an ideal case for assessing drought trends using geospatial and climatic indices like the Standardized Precipitation Index (SPI).

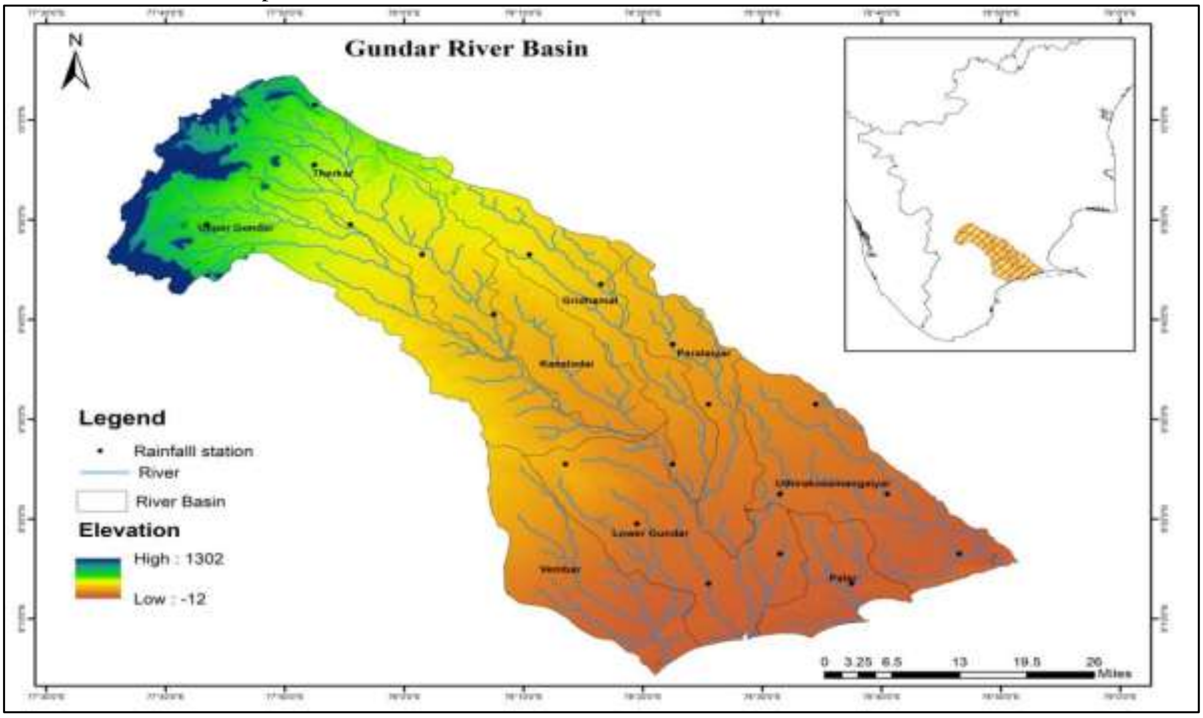

Fig 1: Map of the Study area

3. DATA COLLECTION

This study utilizes monthly precipitation data obtained from the Climate Hazards Group InfraRed Precipitation with Station data (**CHIRPS**) for the period spanning **1988 to 2023**. CHIRPS is a high-resolution gridded rainfall dataset developed by the Climate Hazards Group at the University of California, Santa Barbara, combining satellite imagery with in-situ station data to provide reliable precipitation estimates (Funk et al., 2015). The dataset offers a spatial resolution of **0.05° (~5 km)** and has been extensively validated for drought monitoring and climate variability studies in semi-arid regions. For the present analysis, CHIRPS monthly precipitation data were extracted for **20 rainfall monitoring stations** distributed across the **Gundar River Basin** in Tamil Nadu. The data were retrieved in raster format and spatially processed in a Geographic Information System (GIS) environment using ArcGIS software. Point-based rainfall values were extracted for each station location using spatial analyst tools to ensure consistency and accuracy in capturing localized precipitation variations. The compiled dataset served as the primary input for calculating the **Standardized Precipitation Index (SPI)** to assess the temporal and spatial patterns of meteorological drought within the study area.

3.1 SPI Computation

The Standardized Precipitation Index (SPI) was computed to assess drought intensity and variability in the Gundar River Basin using monthly CHIRPS rainfall data from 1988 to 2023. The methodology proposed by McKee et al. (1993) [2] was followed, involving multiple statistical steps to transform raw precipitation data into a standard normal index.

3.1.1 Fitting the Gamma Distribution

Since rainfall data are positively skewed and do not follow a normal distribution, they must first be fitted to a two-parameter gamma probability distribution, defined as:

$g(x) = (1 / (\beta^\alpha \Gamma(\alpha))) * x^{(\alpha - 1)} * e^{(-x/\beta)}$, for $x > 0$

Where:

- x = observed monthly rainfall
- α = shape parameter

- β = scale parameter
- $\Gamma(\alpha)$ = gamma function

The mean $\bar{x}$ and standard deviation σ of the precipitation time series were computed as:

$\bar{x} = (1/n) * \Sigma\ xi$

$\sigma = sqrt((1/(n-1)) * \Sigma\ (xi - \bar{x})^2)$

These were used to estimate the gamma distribution parameters:

$\alpha = (\bar{x} / \sigma)^2, \quad \beta = \sigma^2 / \bar{x}$

3.1.2 Cumulative Probability Function

The cumulative probability of observing rainfall less than or equal to a certain value x is given by the incomplete gamma function:

$G(x) = (1 / \Gamma(\alpha)) * \int[0 \text{ to } x] (t^{(\alpha - 1)} * e^{(-t/\beta)} / \beta^{\alpha})\ dt$

To account for zero rainfall values:

$H(x) = q + (1 - q) * G(x)$

Where q is the proportion of zero rainfall months [3]

3.1.3 Standard Normal Transformation

The value H(x) was transformed into the standard normal distribution using the Abramowitz and Stegun (1965) approximation:

$SPI = \Phi^{-1}(H(x))$

Where Φ^{-1} is the inverse of the standard normal cumulative distribution function [4].

3.1.4 Interpretation of SPI Values

SPI values were classified into drought severity categories as recommended by McKee et al. (1993) [2]:

Table 1 Classification of meteorological drought by SPI (source: McKee et al. 1993; Paulo and Pereira 2006; Rossi et al. 2007)

SPI Range	Drought Severity
≥ 2.00	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.00 to −1.49	Moderate drought
−1.50 to −1.99	Severe drought
≤ −2.00	Extreme drought

3.1.5 Seasonal SPI (SPI 3) Aggregation

To assess agricultural droughts, the SPI was calculated at a 3-month timescale (SPI-3). This was done by computing moving 3-month rainfall totals:

$P_3,i = xi + xi\text{-}1 + xi\text{-}2$

Where P_3,i is the total rainfall over 3 months ending at month i. These values were used in theSPI algorithm, representing short-term drought conditions relevant to crop production [5].

3.2 Drought Event Analysis

To understand the dynamics and characteristics of meteorological droughts in the Gundar River Basin, each drought event was evaluated using the following parameters derived from SPI values:

3.2.1. Duration

The total number of consecutive months in which the SPI value remains less than zero (SPI < 0). It indicates how long a drought event persisted.

3.2.2. Magnitude

The cumulative severity of a drought event, calculated as the sum of all SPI values during the drought months:

$M = - \sum[j=1 \text{ to } x]\ SPI\_ij$

Where:

- x = number of months in a drought event
- SPI_ij = SPI value in the j-th drought month

The negative sign ensures that magnitude is reported as a positive value.

3.2.3. Intensity

The average severity of a drought event, calculated as:

$I = M / L$

Where:

- M = magnitude
- L = duration (in months)

It reflects how intense the drought was on average during its span.

3.2.4. Frequency

The percentage of years in which drought events occurred during the 36-year period:

$$F = (N / T) \times 100$$

Where:

- N = number of drought events
- T = total years of study (i.e., 36)

This metric shows how recurrent droughts were over the study period.

4. RESULTS AND DISCUSSIONS

4.1 Meteorological Drought Conditions in the Study Area

The spatial distribution of SPI-3 across the Gundar River Basin from 1988 to 2023 reveals considerable interannual variability in meteorological drought conditions.(Fig:2) During several years, negative SPI values (< 0) indicated mild to moderate drought events, particularly concentrated in the southern and eastern sub-basins.

In 1988, widespread negative SPI values were evident across Lower Gundar and Palar, suggesting a basin-wide dry spell. The intensity slightly decreased in 1989 and 1990, yet the Lower Gundar region persistently exhibited mild drought conditions. From 1991 to 1994, spatial variability increased with alternating dry and near-normal conditions across different sub-basins.

The years 1999, 2002, and 2004 showed more favorable moisture conditions with SPI values nearing or exceeding zero. However, 2006 and 2013 marked severe dry phases across much of the basin, with Lower Gundar and Uthirakosamangaiyar showing consistent drought signals. The 2016 El Niño effect likely contributed to drier conditions seen in that year’s SPI map.

Recent years (2018–2021) continued to show alternating patterns, where northern regions like Upper Gundar received slightly better moisture (positive SPI), while southern and coastal areas often displayed negative SPI values. The year 2022 marked a relative recovery, with above-normal SPI values (positive) dominating the eastern basin. Conversely, in 2023, widespread mild drought reappeared, particularly in Palar and Uthirakosamangaiyar. These spatial dynamics underline the localized nature of meteorological drought within the basin and highlight the utility of SPI-3 as a robust indicator for monitoring seasonal moisture variability at the sub-basin level.

To further understand these temporal patterns, sub-basin-wise SPI-3 trends have been visualized through line graphs.(Fig:3) These graphical representations provide deeper insight into the annual drought fluctuations experienced within each sub-region.

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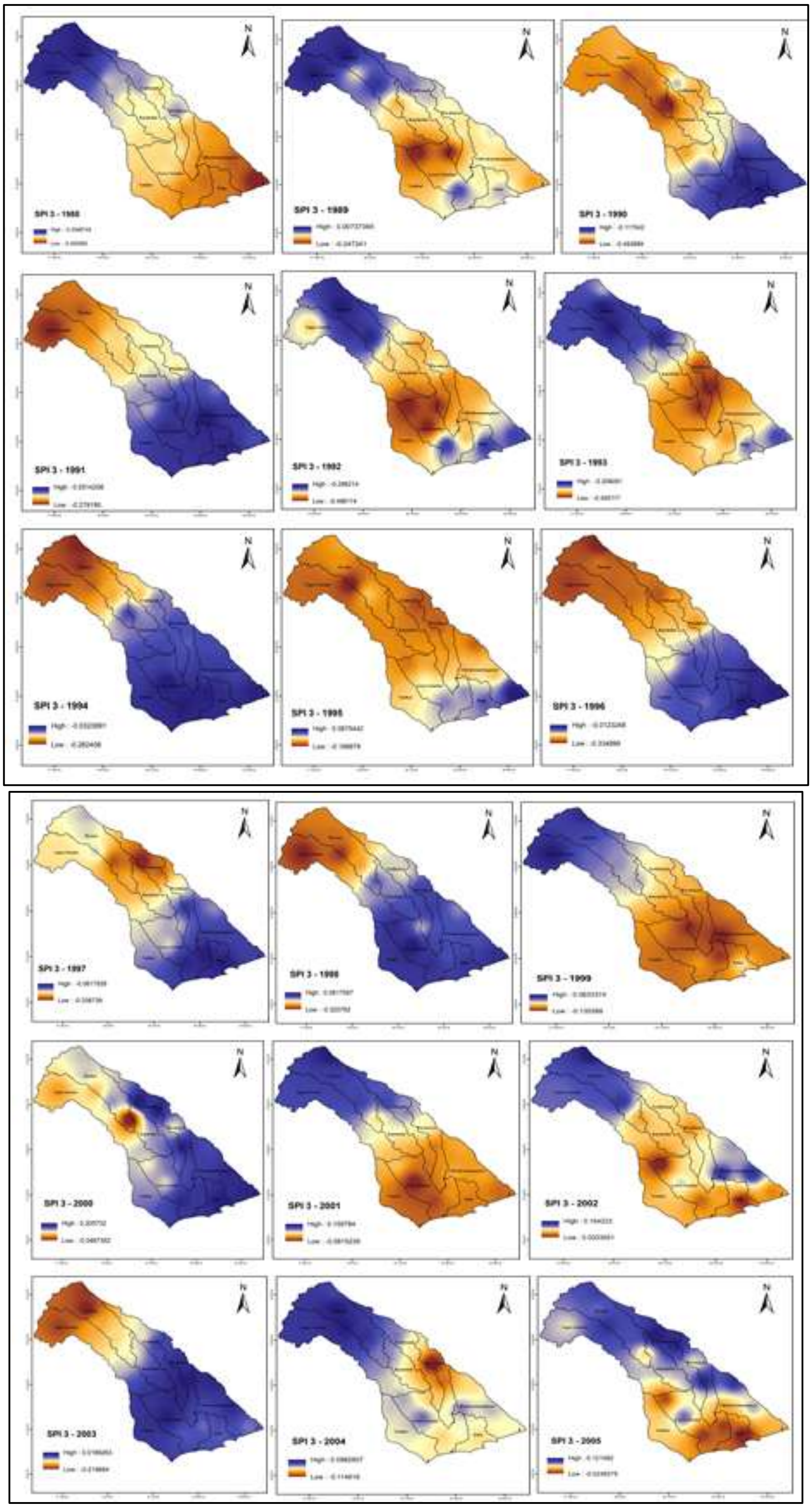

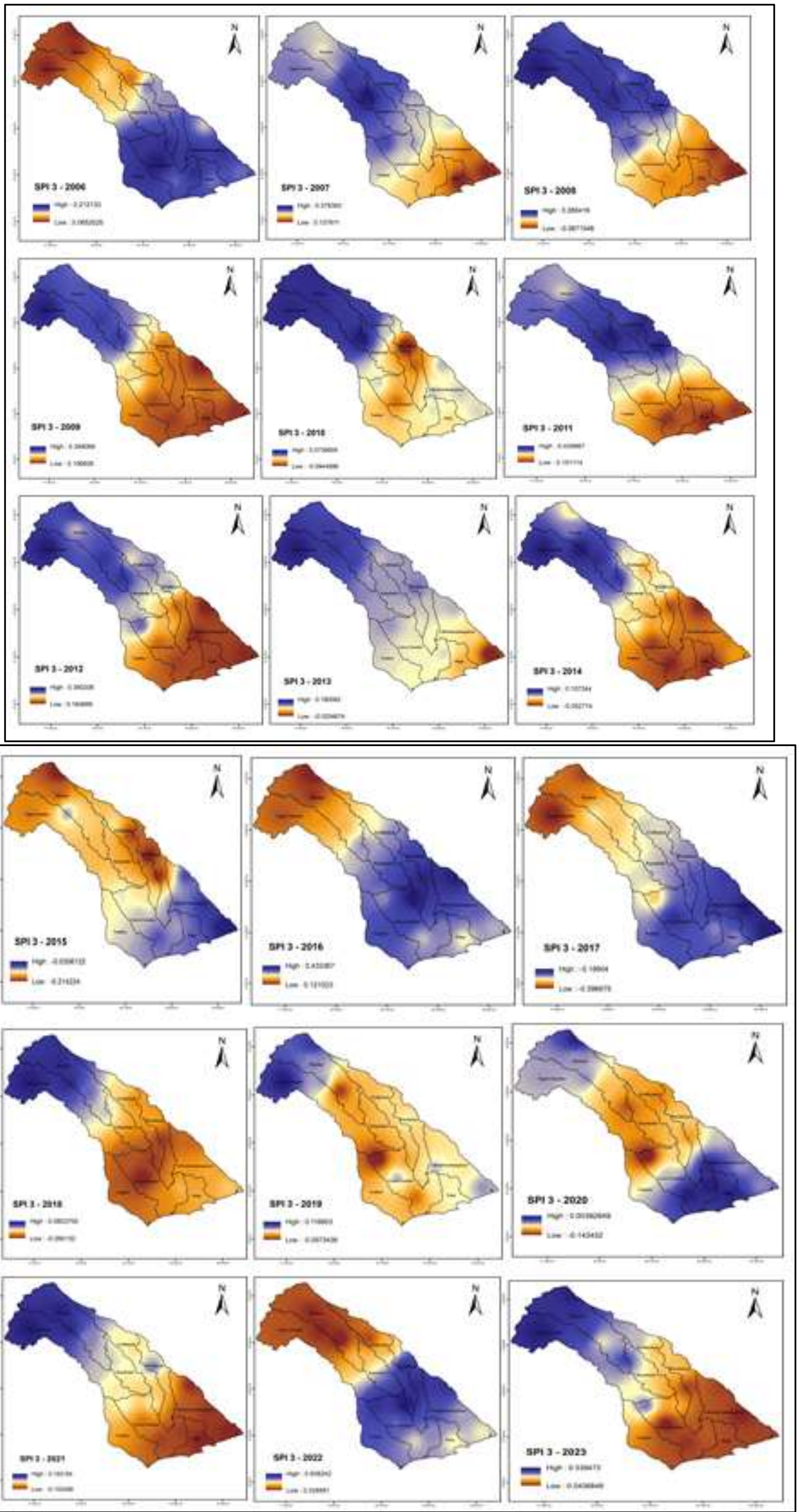

Fig 2: A spatio- temporal meteorological drought condition in the Gundar river basin over the period 1988 – 2023.

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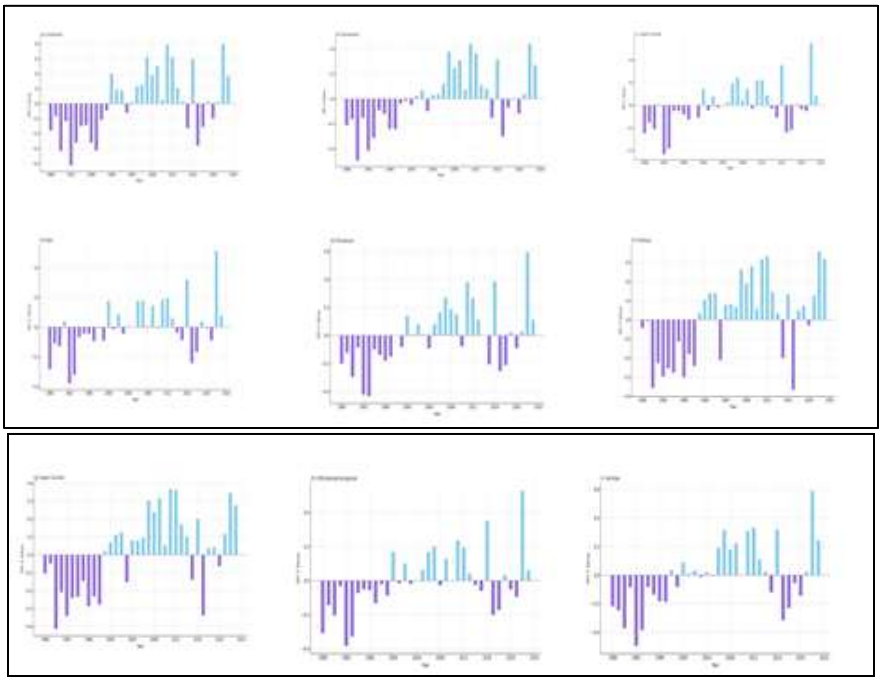

Fig 3 a-I Meteorological drought condition in the study area based on SPI – 3.

4.2 Historical Meteorological Drought Events

The results, summarized in Table 2, reveal distinct patterns of drought occurrence across stations. Most locations experienced notable drought spells during the early 1990s (1990–1994), early 2000s (2002–2003), and late 2000s (2008–2009), suggesting region-wide meteorological anomalies. Stations such as Therkkar, Upper Gundar, and Vembar recorded prolonged drought durations of up to five years during the 1990–1994 period, with cumulative magnitudes exceeding -2.0. Although shorter in duration, droughts in Kanalodai, Lower Gundar, and Paralaiyar during 2002–2003 and 2008–2009 exhibited high intensity values (up to -0.59), indicating severe dryness within a short timeframe. While some stations like Gridhamal and Uthirakosamangaiyar experienced relatively fewer and less intense droughts, others such as Vembar and Therkkar were more frequently and severely affected, highlighting spatial heterogeneity in drought vulnerability.

Table: 2 Historical meteorological drought onset, offset, duration, magnitude and intensity in the study area.

Station	Onset Year	Offset Year	Duration	Magnitude	Intensity
Gridhamal	1991	1994	4	-1.26	-0.32
	2002	2003	2	-1.22	-0.61
	2008	2009	2	-1.16	-0.58
Kanalodai	1990	1994	5	-2.06	-0.41
	2002	2003	2	-1.13	-0.57
	2008	2009	2	-1.11	-0.56
Lower Gundar	1991	1994	4	-1.28	-0.32
	2002	2003	2	-1.14	-0.57
	2008	2009	2	-1.16	-0.58
Palar	1991	1994	4	-1.25	-0.31
	2002	2003	2	-1.13	-0.57
	2008	2009	2	-1.15	-0.58
Paralaiyar	1991	1994	4	-1.31	-0.33
	2002	2003	2	-1.17	-0.59
	2008	2009	2	-1.18	-0.59
Therkkar	1990	1994	5	-2.03	-0.41
	2002	2003	2	-1.16	-0.58
	2008	2009	2	-1.14	-0.57
Upper Gundar	1990	1994	5	-2.01	-0.40
	2002	2003	2	-1.15	-0.58
	2008	2009	2	-1.13	-0.57
Uthirakosamangaiyar	1991	1994	4	-1.27	-0.32
	2002	2003	2	-1.14	-0.57
	2008	2009	2	-1.15	-0.58
Vembar	1990	1994	5	-2.08	-0.42
	2002	2003	2	-1.18	-0.59
	2008	2009	2	-1.17	-0.59

4.3 Frequency and Severity of Meteorological Droughts

The frequency and severity of meteorological droughts were assessed using SPI3 values across multiple stations. Drought events were identified based on a threshold of SPI3 < -1.0, following the classification standards proposed by McKee et al. (1993), and each event was evaluated for its duration and cumulative magnitude. The analysis revealed that all stations experienced three distinct drought events during the study period, indicating a consistent recurrence of moderate dryness across the region. Despite this regularity, the severity of these events—measured as the average magnitude per drought—remained relatively low, with intensity values ranging from -0.31 to -0.61. This places all identified events within the category of **moderate drought**, as none of the events met the criteria for severe (SPI3 ≤ -1.5) or extreme drought (SPI3 ≤ -2.0). These findings suggest that while droughts have been frequent and persistent, they have not reached critical intensity levels. The region appears to be more prone to sustained moderate droughts rather than short-term extreme events, underscoring the need for long-term water resource planning and adaptive management strategies.

5. CONCLUSION

This study assessed meteorological drought trends in the Gundar River Basin using SPI-3 derived from CHIRPS rainfall data (1988–2023). The results show recurring moderate drought events, especially during the early 1990s, 2000s, and late 2000s. Sub-basins like Vembar and Therkkar experienced longer and more severe droughts, while others were less affected, highlighting spatial variability.

Overall, droughts were frequent but moderate in intensity, emphasizing the need for long-term water resource planning. The SPI-3 and GIS-based approach proved effective in identifying drought-prone zones. These findings can support targeted mitigation strategies and improve drought preparedness in the region.

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