Theoretical and Applied Climatology (2023) 151:1419–1433
https://doi.org/10.1007/s00704-022-04316-w

RESEARCH

Changing characteristics of meteorological drought and its impact on monsoon-rice production in sub-humid red and laterite zone of West Bengal, India

Sabita Roy[1] · **Sugata Hazra**[1] · **Abhra Chanda**[1]

Received: 6 August 2022 / Accepted: 2 December 2022 / Published online: 15 December 2022

Abstract
The incidence of droughts and their intensity in recent times are affected by climatic variability and change, consequently affecting the agro-based economy of red and laterite zone (RLZ) India. In the present study, changing characteristics of meteorological droughts have been investigated over the sub-humid RLZ of West Bengal, India, using the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). SPI and SPEI were computed over 1-, 3-, and 12-month time scales from monthly meteorological data from 1930 to 2019 to explore variations in drought frequency, intensity, duration, and spatial extent in the RLZ. It was observed that since the 1990s, the RLZ has been frequently affected by short-term extreme to severe drought, even in the wet-monsoon months. The frequency and intensity of droughts were observed to have increased in the recent period with a decrease in the duration. The Mann–Kendall test on the drought trend analysis of the region indicated a rising trend in monsoon months. The SPEI-monsoon was found to be more significantly correlated ($r^2 = 0.65$) with the rainfed Kharif (monsoon)-rice production anomaly than the SPI. SPEI appeared to have a more pronounced impact on drought incidences in the region over the recent decades. Field surveys were conducted to validate the two recent drought occurrences and associated crop failure. A total of 95% of the farmers in the survey reported crop failure during the short-term meteorological droughts in monsoon months. It is therefore suggested to monitor changing patterns and extent of droughts, particularly in water-scarce RLZs, to design appropriate drought preparedness planning.

1 Introduction

Globally, climate change has recently exacerbated drought risks and associated crop failure (Zhang et al. 2017; Lesk et al. 2016). In India, this risk is more significant due to various factors like the variability of monsoon rains (Sharma and Mujumdar 2017; Thomas and Prasannakumar 2016), dominantly rainfed agriculture (Vikramarjun et al. 2019; Ward and Makhija 2018), and livelihood of 75% people depend on agriculture (Rao et al. 2018) and the growing demand for food population (Kumar and Joshi 2016). In India, the occurrence of meteorological drought is reported to be linked to the shortage of monsoon rainfall, while rising temperatures can potentially increase the drought (Pandey and Srivastava 2019; Bhunia et al. 2020). Due to the erratic and uneven distribution of monsoon rainfall with increasing temperature, drought conditions are prevalent even in the sub-humid regions of India (Pathak and Dodamani 2019). Various studies (Zhai et al. 2020; Sam et al. 2020; Nath et al. 2017; Pai et al. 2017) on drought analysis in India indicated an increasing trend in drought severity and frequency over the agriculturally important sub-humid eastern part of the country in recent decades. Frequent droughts can threaten food security in this region (Sharma and Goyal 2020). A slight departure of average monthly rainfall from normal in the red and laterite zone (RLZ) significantly affects rainfed agricultural production considerably (Brahmachari et al. 2018; Mandal et al. 2018). Subash and Ram Mohan (2011) also found that the variability of Kharif rice yield has influenced the monthly monsoon rainfall. Hence, an intensive study of the drought of various categories in sub-humid RLZ is essential.

✉ Sabita Roy
sabita21.roy@gmail.com

Sugata Hazra
sugata_hazra@yahoo.com

Abhra Chanda
abhrachanda1985@gmail.com

[1] School of Oceanographic Studies, Jadavpur University, 188, Raja S.C. Mallick Road, Kolkata 700032, India

Even though the RLZ understudy receives an annual average rainfall of 1200 mm, it became more erratic and uneven during the 1990–2000 period compared to the early decades (Mukherjee and Huda 2018). An increasing temperature trend and uncertain rainfall projection over sub-humid RLZ emphasized high sensitivity to climate change (Shukla et al. 2017). In RLZ, monsoon rain has decreased (Ghosh 2018), while an increase in minimum temperature (0.5–1 °C) was recorded in recent decades (Mukherjee and Huda 2018). As a result, recurrent drought has affected RLZ (Bhunia et al. 2020; Patra 2020). Due to rainfed agriculture, low water holding capacity, excessive drainage, surface runoff, and high soil erosion make such red lateritic zones more vulnerable to drought (Roy et al. 2020; Asutosh 2019; Mukherjee and Banerjee 2009). The changed evapotranspiration pattern due to increased temperature and absence of rainfall is expected to increase incidences of drought during recent periods in RLZ (Mandal and Chakrabarty 2013). Recent studies (Bhunia et al. 2020; Banik et al. 2020) indicated that the increased drought frequency severely impacts crop production in the RLZ. In the context of climate change, frequent droughts are considered limiting factors for the growth of agriculture and socio-economic development in this area (Goswami et al. 2019). In recent times, with 43% draught frequency (Nath et al. 2017) over the sub-humid region in India, agricultural production is progressively getting affected (Kumar et al. 2019). A detailed study is thus necessary to identify changing spatiotemporal characteristics of drought occurrence at the regional level in the context of climate variability for better mitigation planning and preparedness.

Various indices for meteorological drought analysis have been formulated based on various parameters (Guhathakurta et al. 2017). A detailed description of the drought indices can be found in Heim (2002), Mishra and Singh (2011), and Sivakumar (2011). The Standardized Precipitation Index (SPI, Mckee et al. 1993) is one of the most widely used among various drought indices. SPI can interpret rainfall data in different time scales (1, 2, 3, 6, 9, 12, 24, … months) to assess drought duration, intensity, severity, magnitude, and frequency (Bhunia et al. 2020). Compared to other indices, the SPI has simple calculations and is decisively performed space independently (Bhunia et al. 2020). As a result, SPI has already been widely used to detect and characterize drought conditions in many countries and regions, such as Turkey (Dabanlı et al. 2017), Iran (Awchi and Kalyana 2017), China (Li et al. 2020; Zhang et al. 2019, 2017; Xia et al. 2018), Bangladesh (Rahman and Lateh 2016), Italy (Marini et al. 2019), and Ethiopia (Belayneh et al. 2016).

The main shortcoming of SPI is that it uses only rainfall data and does not consider other variables, especially temperature. Although rainfall is the leading causative factor for drought in sub-humid regions, recent studies have demonstrated the significance of temperature in affecting the recent trends in the region's water resources (Gupta et al. 2020; Nath et al. 2017, 2018). The proximal drought index must account for changes in moisture demand caused by increased surface temperature (Pathak and Dodamani 2019). Recently, a new drought index, the standardized precipitation–evapotranspiration index (SPEI), has become popular (Begueria et al. 2010; Vicente-Serrano et al. 2010a, b) to quantify the drought condition in the context of increasing surface warming (Monish and Rehana 2020). The SPEI considers both temperature and precipitation; hence, considered to be a better approach for studying the effects of climate change on drought occurrence (Shaik et al. 2020).

Every region has individual climatic characteristics that interact differently with the influence of anthropogenic activity and climate change. Thus, several recent studies (Li et al. 2020; Pei et al. 2020; Wang et al. 2019; Liu et al. 2018; Tirivarombo et al. 2018; Labudova et al. 2017; Xu et al. 2015; Vicente-Serrano et al. 2015) compared SPEI and SPI to identify drought occurrence at the regional level from various climatic regions.

Several studies analyzed the occurrence and distribution of meteorological droughts using SPI in India (Kundu et al. 2020; Panday et al. 2020; Adarsh et al. 2019; Aadhar and Mishra 2018; Guhathakurta et al. 2017; Joshi et al. 2016). However, in recent times, various researchers used both SPI and SPEI to evaluate the influence of climate change on drought occurrences in India (Singh et al. 2020; Singh and Shukla 2020; Singh et al. 2019; Pathak and Dodamani 2019; Gupta and Jain 2018; Aadhar and Mishra 2017; Alam et al. 2017; Mallya et al. 2016).

The Purulia, RLZ of West Bengal is a sub-humid drought-prone region; many researchers studied meteorological droughts only with the aid of SPI on a long-term time scale (Keskin et al. 2011; Mishra and Desai 2005). Mishra and Singh (2009) prognosticated that Purulia is likely to experience severe drought with more areal extent during 2001–2050. Analysis using SPI in annual and seasonal time scales also have been used to analyze meteorological drought incidences in Purulia for the period 1901–2017 (Patra 2020; Bhunia et al. 2020; Asutosh 2019).

Previous studies in Purulia only used a rainfall-based single index (SPI) to assess meteorological drought and mainly focused on its long-term (annual and seasonal) behavior. In the climate change context, however, temperature and evapotranspiration appear to have a greater influence (Shah et al. 2015) on meteorological drought, especially for sub-humid regions. Thus, evapotranspiration-based SPEI is considered a more suitable index for analyzing the effects of climate change on drought occurrence by various recent researchers (Monish and Rehana

2020; Alam et al. 2017; Das et al. 2016). Due to increasing temperature and monsoon rainfall variability, India's droughts are becoming more regional, and a spatial shift has been observed toward sub-humid regions (Mallya et al. 2016). RLZ has frequently witnessed short-term droughts in the previous decades (Jha et al. 2013). A comprehensive study of these changing characteristics and trends of meteorological drought is still relatively unavailable in Purulia of RLZ. The effect of the changing behavior of drought on crop production is also lacking in the previous studies in the RLZ of Purulia.

To address the aforementioned research gap in Purulia, the present study aimed to exemplify the changing characteristics of meteorological drought in terms of its duration, intensity, frequency, and spatial–temporal evolution using SPI and SPEI during the 1930–2019 period and their influences on Kharif rice yield in recent times. The present study also intends to analyze the meteorological drought trend and suggest an appropriate meteorological drought index for Purulia. Additionally, for the first time, results have been validated by rigorous field surveys. Such an integrated approach would help us to have a refined view of the region's spatiotemporal variability of drought, which is necessary for decision-makers and planners to formulate appropriate strategies to minimize the impacts of drought on the overall development of RLZ.

2 Study area

Purulia district, as representatives of RLZ (Roy et al. 2020), lies between latitude 22° 42′ 16.38″ and 23° 41′ 54.36″ N, and longitude 85° 49′ 10.89″ and 86° 54′ 20.64″ E (Fig. 1). The geographical area of the district is 6259 km^2. Purulia is registered under Drought Prone Areas Programme (DPAP) by the Department of Land Reforms, Ministry of Rural Development (Bhunia et al. 2020).

A subtropical monsoon climate dominates the area. The principal source of rainfall in the district is the southwest monsoon. The average annual and monsoon rainfall is 1300 and 950 mm, respectively. Due to its undulated topography and red and laterite soil, nearly 50% of the rain flows away as runoff. Temperature varies over a wide range from 7 °C in winter to 46.8 °C in the summer, causing a high evaporation rate. Purulia district primarily depends on surface water, which is highly susceptible to drought. Increasing drought frequency has been recorded in Purulia during the recent decade (Patra 2020).

Agriculture is the primary livelihood source for more than 75% of the district population. Paddy is the primary crop of the district. A total of 77% of the net-cropped area is under rain-fed Aman rice cultivation (Roy et al. 2022a, b, c). High dependency on monsoon rains for recharging most of its water resources directs towards severe water deficiency and drought in the state if monsoon failures occur. Also, high variability in crop production exists because of the uncertain climate in the state (Roy et al. 2022a, b, c).

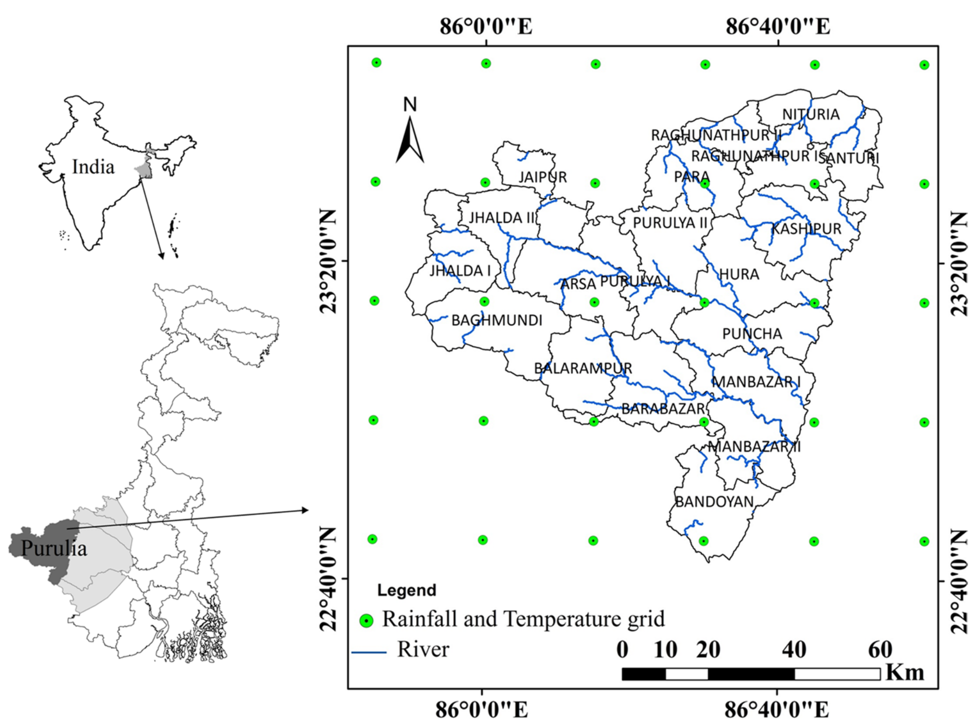

Fig. 1 Location map of the study area

3 Materials and methods

The Indian Meteorological Department (IMD) generated gridded daily rainfall (0.25° latitude × 0.25° longitude) (Pai et al. 2014) and daily temperature data (1° latitude × 1° longitude) (Srivastava et al. 2009) from 1930 to 2019 (90 years) were used as the input data in this study. Temperature data were re-gridded to the scale of rainfall using bilinear interpolation. The details of bilinear interpolation by the National Centre for Atmospheric Research (NCAR) are available at https://climatedataguide.ucar.edu/climate-data-tools-and-analysis/regridding-overview. District-level rice production data (from 1991 to 2015) was collected from the Directorate of Agriculture, West Bengal.

Monthly rainfall and mean temperature were used to examine monthly and seasonal drought intensity, duration, frequency, and spatial extent in Purulia during 1930–2019 by calculating the SPI and SPEI. Trends in the SPI/SPEI were detected by the nonparametric Mann–Kendall (M–K) test. Three equal climatic periods have been classified (1930–1959, 1960–1999, and 2000–2019) to determine the changing behavior of recent drought events compared to the past based on drought intensity, duration, and frequency. Based on the rainfall and temperature grid points (30 points), interpolation was employed at a 250 m resolution through inverse distance weighted (IDW) interpolation technique to generate the spatial drought distribution maps and proceed with the homogeneity test.

3.1 Computation of SPI

The SPI (McKee et al. 1993) calculation for a specific time scale and location requires a long-term monthly rainfall series. The first step is to find the probability density function that best describes the distribution of the rainfall data for a selected time scale. Here, the rainfall data (1930–2019) was fitted to a gamma distribution function (Liu et al. 2021). Detailed calculation procedures for gamma distribution and SPI are in the supplementary material. EasyFit 5.5 was employed in the current investigation for gamma distribution. It is a programmer for data analysis and simulation that enables users to fit probability distributions to data samples, choose the best model, and use the analysis's findings to improve their decision-making.

SPI is an index that was developed to quantify rainfall deficit at different time scales, and thus it enables the assessment of drought severity. It was computed using the monthly rainfall data as defined by (Abramowitz and Stegun 1965; Zarch et al. 2015). Positive SPI values signify greater than average rainfall (wet condition), and negative values imply less than average rainfall (dry condition). The current study evaluated drought using the SPI program (http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx) to compute SPI at various time scales from monthly rainfall data. The present research calculates SPI at 1-, 3-, and 12-month time scales representing monthly, seasonal, and annual droughts, respectively. Table 1 shows the different categories of drought intensity according to the SPI values given by Mckee et al. (1993).

3.2 Computation of SPEI

SPEI considers both rainfall and temperature components and presents the influence of evaporation variations, which is more responsive to drought occurrences caused by rising temperatures (Liu et al. 2021). Under the warming condition, SPEI can better exhibit dry and wet conditions owing to its combination of rainfall and temperature (Zhao et al. 2017). The Log-logistic distribution provided a better fit for SPEI (Hernandez and Uddameri 2014). The SPEI is obtained by normalizing the water balance into the Log-logistic probability distribution. In the present study, the procedure for calculating SPEI adopted by Vicente-Serrano et al. (2010a) has been used. The measures of the drought intensity classifications according to SPEI are the same as the SPI value (Table 1). The supplementary material includes step-by-step computation instructions for SPEI.

3.3 Analysis of drought characteristics

Drought characteristics, which include drought intensity, frequency, and duration, have been defined using the runs theory proposed by Yevjevich (1967). The following formula calculated the drought intensity:

$$S = \frac{\sum_{n=1}^{T} \left[S_{\mathrm{SPI/SPEI}} - K\right]}{T}$$

where S refers to drought intensity, $S_{\mathrm{SPI/SPEI}}$ is SPI or SPEI value below the threshold, K is a drought threshold value, set to be less than or equal to − 0.99 in the present study, means the drought level is mild, T refers the duration of the drought. The drought frequency calculation formula is as follows (Liu et al. 2021):

$$P = \frac{n}{N} * 100\%$$

where N denotes the time and n signifies the number of droughts during the time.

Table 1 Classification of drought category

SPI/SPEI values	Drought category
0 to − 0.99	Mild drought
− 1 to − 1.49	Moderate drought
− 1.5 to − 1.99	Severe drought
< − 2	Extreme drought

Source: McKee et al. (1993)

3.4 Method of trend analysis

The rank-based Mann–Kendall (M–K) trend test, a non-parametric statistical test, is used frequently to evaluate significance in a monotonic increasing or decreasing trend in hydro-meteorological time series (Sicard et al. 2010; Kumar et al. 2009) including a series of drought indices (Damberg and AghaKouchak 2014). The M–K test had high computational efficiency and was not sensitive to measurement error, missing values, and outlier data. Therefore, in this study, M–K test has been used to detect the significant trends in SPI and SPEI time series. In this study, the M–K trend test was performed in *R* at a significance level of 0.05 and was used to determine the drought characteristic trend on different time scales (1 month, 3 months, and 12 months). The supplemental material contains comprehensive computation methods for the M–K trend.

3.5 Sampling method and data collection for field verification

Fieldwork followed in September 2015 and 2019 to develop a more comprehensive understanding of short-term droughts and their impacts on crop production in the study site. A multiple-stage sampling approach was applied. Kashipur block was chosen because the block experiences irregular monthly rainfall and is highly vulnerable to drought (Roy et al. 2022a, b, c). Ten villages of Kashipur (Fig. 2) were recognized and selected based on the percentage of the tribal population, who are primarily small and marginal farmers. The farmers were selected for the study using the probability proportional to size sampling method among the ten villages, and individual farmers were selected using the stratified random sampling method (Delfiyan et al. 2021). The

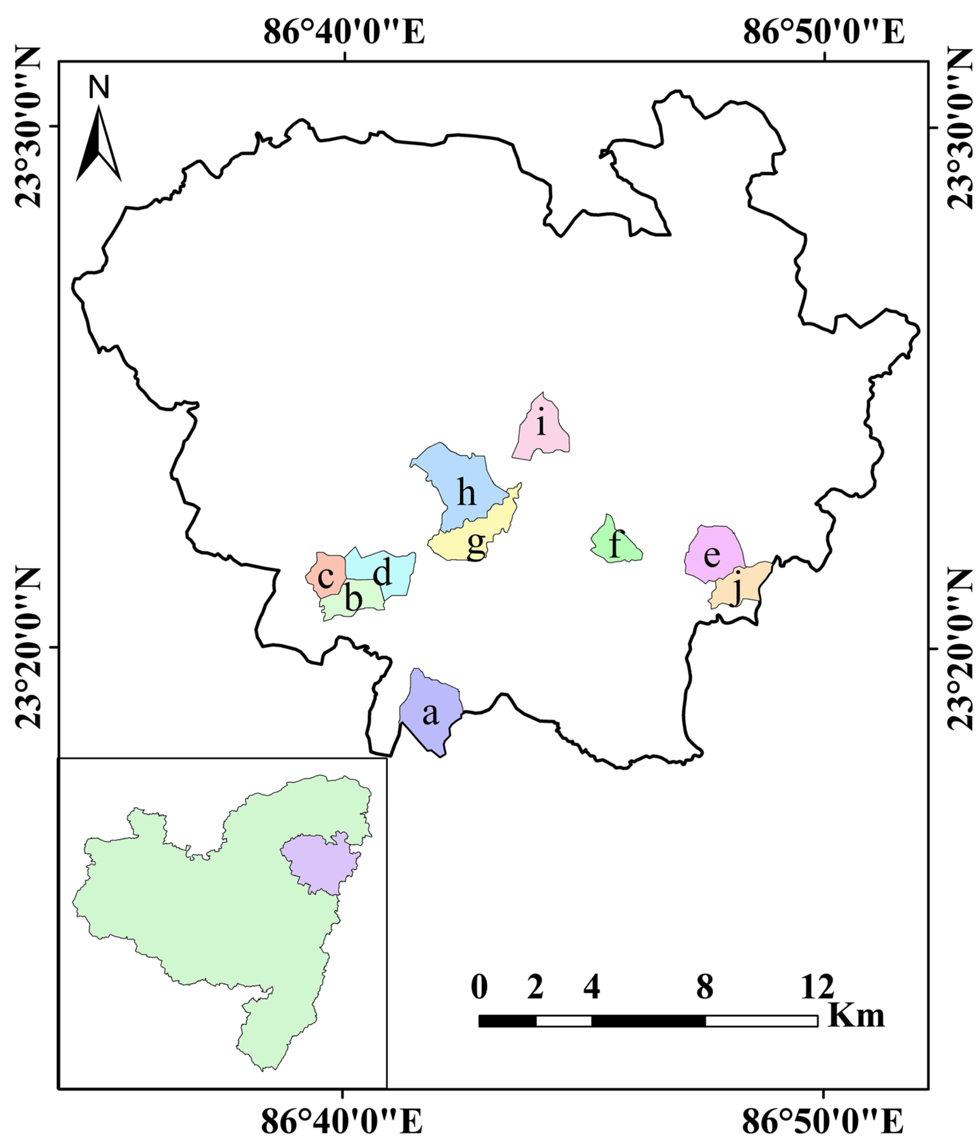

Fig. 2 The villages in the Kashipur block used for field Survey: **a**: Pabra Pahari **b**: Kashidi **c**: Sura **d**: Seja **e**: Jagannathdi **f**: Jibanpur **g**: Bhatin **h**: Ranjandi **i**: Bodma **j**: Lari

sample size of the farmer unit was determined by the following equation (Sathaiah and Chandrasekaran 2020):

$$n = \frac{Nz^2 p(1-p)}{Nd^2 + z^2 p(1-p)}$$

where n is the sample size, N is the total number of small and marginal farmers (21,245), z denotes confidence level (at 95% level z is 1.96), d signifies error limit (0.05), and p refers to estimated population proportion (0.5 maximizes the sample size). A total of 375 small and marginal farmers were selected for the study and interviewed to quantify the impact of the drought on crop production in 2015 and 2019 (Tables 2 and 4).

A pre-tested questionnaire consisting of open-ended questions, multiple choice, and focus group discussions (FGD) was used to explore farmers' experiences with droughts. A structured questionnaire was designed for the present study (Mare et al. 2018; Keshavarz et al. 2013; Udmale et al. 2014) to quantify the impact of the drought in 2015 and 2019. Face-to-face interviews were conducted in the local language, mostly with heads of households but sometimes with other family members. Interest in drought-related issues was high in the area, and the response rate was almost 100%. The checklist-guided discussions with focus group members, both men and women, concentrated on the effects of drought on Kharif crop production.

Table 2 Basic socio-economic outlines of the respondents' farmers in villages of Kashipur

Household socio-economic characteristics			Kashipur (%) $n = 375$
Cast structure	Scheduled tribes (ST)		75
	Scheduled casts (SC)		15
	Other backward casts (OBC)		9
	General category(GEN)		1
Age composition	< 20 yrs	M	12
		F	11
	21–35 yrs	M	20
		F	19
	35– 59 yrs	M	14
		F	15
	> 60 yrs	M	4
		F	5
Educational status (%)	Primary	M	7
		F	6
	Upper primary	M	20
		F	15
	Secondary	M	14
		F	13
	Higher secondary	M	10
		F	7
	Under graduate	M	5
		F	4
Average land holding size (hectare)	Pediment (Tnar)		0.16
	Upper mid terrace (Baid)		0.30
	Lower mid terrace (Kanali)		0.20
	Lower terrace (Bohal)		0.11
Source of drinking water (%)	Tube well		84
	Dug well		15
	Tap water		1
Main source of lighting (%)	Electricity		93
	Kerosene		7
Number of households having latrine facility (%)			60
Total number of households availing banking services (%)			86

4 Results

The 1-month SPI provides a monthly estimation of rainfall (Ji and Peters 2003), while the 3-month SPI reflects medium-term (seasonal) trends in rainfall patterns (Potop et al. 2012), and the 12-month estimate provides an annual estimation of water condition. Therefore, this study used the SPI/SPEI values at 1-, 3- and 12-month scales to explore the drought variability and their duration, intensity, and frequency at short and long-term (monthly, seasonal, and annual time scales), respectively. The time series of all drought indicators were examined from 1930 to 2019, which were split into three intervals of 30-year (1930 – 1959, 1960–1989, and 1990–2019) duration to identify recent changes in meteorological drought events. The present study also focused on the impact of drought on rainfed agriculture of such low permeability RLZs.

4.1 Temporal variation in the SPI and SPEI

Usually, the SPI/SPEI values at the 12-month time scale indicate the status of annual drought (Wang et al. 2014), and the SPI/SPEI values at a 3-month scale are appropriate indicators of the status of seasonal drought. The pre-monsoon, monsoon, and post-monsoon values were denoted by the May, September, and January SPI/SPEI values, respectively. Figure 3 shows the annual and seasonal SPI/SPEI series of the entire Purulia during 1930–2019.

Out of 90 years (1930 to 2019), an annual drought occurred in 47 years (52%). Severe to extreme annual drought (− 1.5 to > − 2) occurred in 1962, 1966, 1979, 1992, 2000, 2001, 2010, and 2015. The maximum number of severe to extreme annual drought years (63%) have been identified by the SPI/SPEI in the recent period (1990–2019) compared to the first (1930 – 1959) and second (1960–1989) periods.

Pre-monsoon, monsoon, and post-monsoon drought events occurred 44, 49, and 41 times respectively from 1930 to 2019. In pre-monsoon and post-monsoon seasons, the maximum number of moderate to severe droughts (− 1.0 to − 1.5) have been identified by the SPI/SPEI in the first (1930 – 1959) and second (1960–1989) periods. But in monsoon season, the maximum number of severe to extreme droughts (− 1.5 to − 2.0) has been found by the SPI/SPEI in the recent period (1990–2019) only.

The monthly meteorological drought assessment found that 56% of the monthly drought was concentrated from June

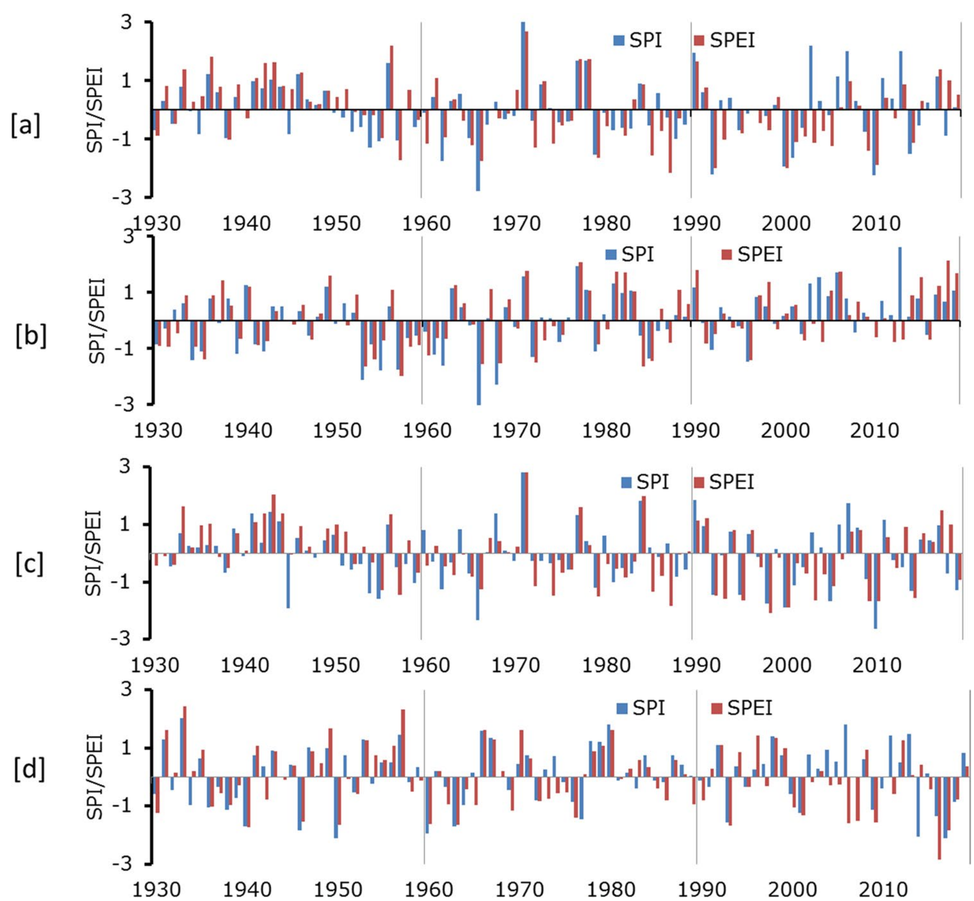

Fig. 3 Variation in annual **a**, pre-monsoon **b**, monsoon **c**, and post-monsoon (d) SPI and SPEI values at the 3-month time scale in Purulia during the years 1930–2019

to August, while other months experienced 42% of monthly droughts. Extreme droughts were prevalent from May to October, whereas severe droughts were found between February and April. Above 50% of the years, extreme to severe meteorological droughts occurred from June to October. Around 80% of the year, mild droughts are concentrated in November and December.

4.2 Drought duration, intensity, and frequency

The drought duration identified by the SPI is generally consistent with that by the SPEI. Annual drought duration identified by both SPI and SPEI was 6–8 months during the years 1930–1990, but after 1990, drought duration was 5–7 months. Both SPI and SPEI identified a maximum annual drought duration (37 months continuous) from Sep 2000 to Aug 2006. For seasonal drought analysis, a 5–7-month duration has been found in the recent period (1990–2019), and a 3–5-month duration has been identified in 1930–1990 years.

Drought intensity evaluated from the SPI for most years was greater than those from the SPEI in Purulia. For the 12-month time scale, extreme drought intensity (> − 2) was found to occur for times during the years 1990–2019 (1992, 2000, and 2010). In the 12-month timescale, mild drought (i.e., − 0.99 to 0) intensity was observed in 73% of the years, while 20% of the years were under moderate to severe drought conditions (i.e., − 1.49 to − 1.0) and 7% of the years exhibited extreme condition (> − 2), 80% of them occurring after 1990.

For seasonal drought conditions, 65%, 24%, and 11% years belonged to mild, moderate to severe, and extreme intensity, respectively, in the post-monsoon. While 58% and 41% years under moderate to severe and mild intensity in the pre-monsoon and 53% and 45% years under moderate to severe and mild intensity in monsoon.

Most extreme to severe droughts have been found in the monsoon season, 85% of them occurring during recent years (1990–2019). Moderate drought years occurred mainly in the monsoon and pre-monsoon seasons, concentrating in the first (1930 − 1959) and second (1960–1989) part of the century. In the second part, around 60% of the years experienced mild droughts in all seasons.

The frequency of drought events in the area has been estimated in 1-, 3-, and 12-month time scales by SPI and SPEI. Annual and monsoon extreme drought frequency increased in Purulia for the 1990–2019 period compared to the period of 1930–1990. For pre-monsoon, monsoon, post-monsoon, and annual time scales, moderate and severe drought frequency gradually increased for 1990–2019 compared to the period of 1930–1959 and 1960–1989. But mild drought frequency gradually decreased from 1990–2019 compared to 1960–1989.

4.3 Spatial variability of drought

The spatial distribution of drought maps has been generated by Inverse Distance Weighting (IDW) interpolation method in the ArcGIS platform. A spatial extent with the intensity of seasonal drought was analyzed in 3 recent drought years (2010, 2015, and 2019) by SPI and SPEI to understand the spatial variation during the current decade (Fig. 4). Drought in the area seems to affect the area first in the west and progresses further to the east and south.

In the pre-monsoon of 2010, the district was under mild to no drought conditions. Due to the deficit of monsoon rainfall, the scenario changed considerably in the monsoon, with 91.45% of the area found to be under extreme to severe drought as identified by SPI. In comparison, 55% area could be identified under severe drought by SPEI. However, post-monsoon rainfall drought conditions recovered significantly with the prevalence of mild-moderate drought over 85% of the area in 2010.

In 2015, during the monsoon season, 85% of the area came under severe drought and the other 10% was under moderate drought conditions. In pre-monsoon and post-monsoon, the area experienced mild drought to no drought at all.

In 2019, a severe drought was observed in the monsoon months in 80% of the district. Drought beginning in western areas extended to east and southwards. In pre-monsoon, mild drought conditions prevailed in 90% area of the district. But in the post-monsoon, wet condition prevailed all over the area due to good post-monsoon rainfall.

Spatial analysis of propensity of drought incidence identified the western, eastern, and southern blocks (Jaldhi, Joypur, Baghmundi, Arsa, Purulia II, Balarampur, Kashipur, HuraBandoyan, Barabazar, etc.) to be prone to severe drought. The blocks of the northern part like Para, Raghunathpur, Nituria, and Santuri of the study area were prone to mild or no drought.

4.4 Effect on crop

Rainfed paddy cultivation is a major livelihood for this region. The rain-dependent nature of Kharif agricultural practices in the district makes it vulnerable to soil moisture fluctuations, which is a function of precipitation and temperature during the monsoon season. The Pearson correlation coefficient of monsoon-SPI and SPEI with Kharif rice production anomaly was performed to understand whether the recent meteorological drought affected the agricultural production in the area (Madadgar et al. 2017). The analysis of correlation coefficients displays that the monsoon SPEI exhibits a stronger association with Kharif rice production ($r^2 = 0.6542$) than does SPI ($r^2 = 0.6144$; Fig. 5). Figure 5 demonstrates that the negative SPI and SPEI indices (< − 1) indicating meteorological droughts recorded in the years

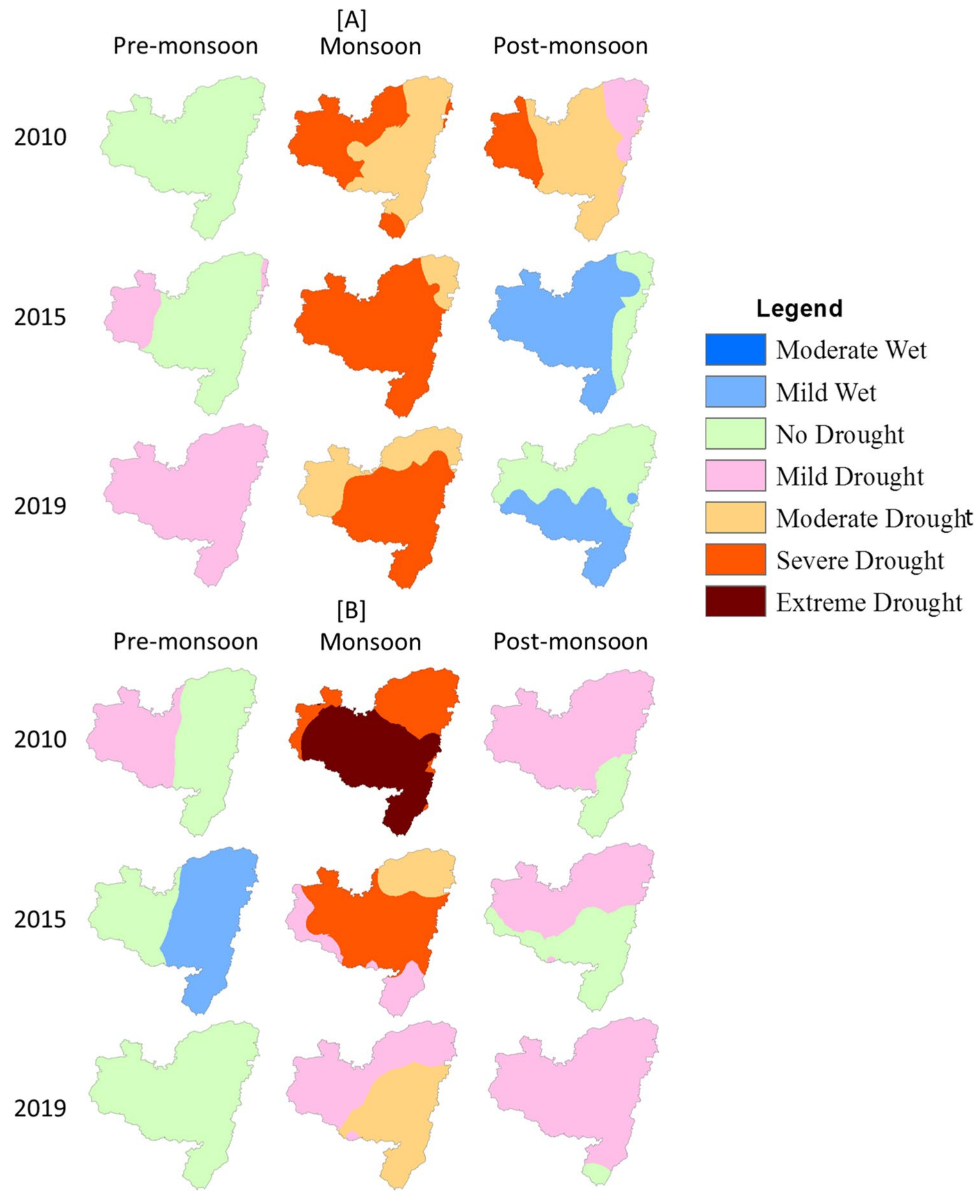

Fig. 4 Spatial variation of drought indices SPEI (A) and SPI (B) for the pre-monsoon, monsoon, and post-monsoon seasons in the drought years 2010, 2015, and 2019

1998, 2000, 2005, 2010, and 2015 were associated with Kharif crop failures in Purulia district leading to agricultural drought.

4.5 Trend analysis

M–K trends and Sen's slope were calculated from the SPI/SPEI values at the 1-, 3-, and 12-month time scale during the years 1930–2019 in Purulia. On a monthly scale, droughts identified by the SPI increased in August and decreased in May and no trends were found in other months. While, those calculated by the SPEI increased in February, July, and August (Table 3). At the seasonal scale, drought analyzed from the SPEI has increasing trends in monsoon seasons, but for that calculated from the SPI, no trends were detected in all seasons. At the annual scale, the increasing annual droughts were identified by the SPEI while the SPI revealed no trend.

5 Discussions

Analysis of monthly and seasonal drought characteristics over the last 90 years in the RLZ indicates that the most extreme to severe droughts were found in monsoon seasons in the recent century (1990–2019) while maximum moderate droughts were identified in monsoon and pre-monsoon seasons during the first (1930–1960) and second parts (1960–1990). The area was affected by long-term (8–10 month duration) droughts during the years

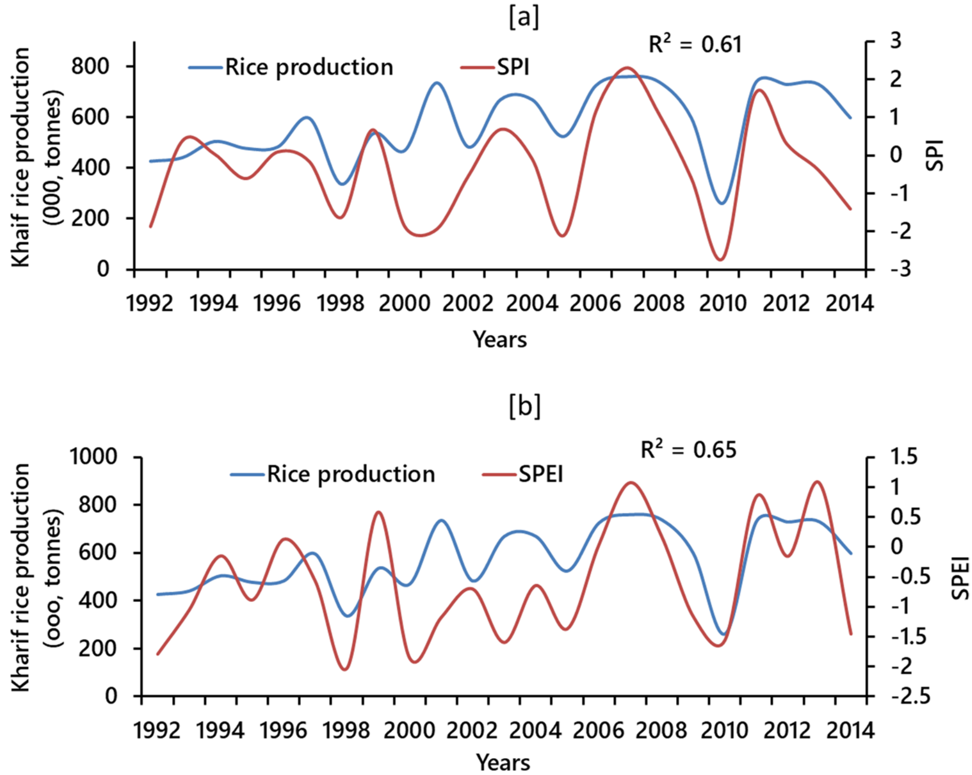

Fig. 5 Pearson's correlation coefficient functions of the Kharif rice production with monsoon **a** SPI and **b** SPEI from 1991 to 2015

Table 3 M–K trends calculated from the SPI/SPEI at the1-, 3-, 12-month time scale during years 1930–2019 in Purulia

	SPI		SPEI				
Month/season	May	August	February	July	August	Monsoon	Annual
S	917	−1149	−555	−754	−591	−903	−850
VAR (*S*)	99,771	99,787.66	71,875.66	69,416.66	71,879.66	71,881.66	71,880.66
z	2.9	−3.63	−2.07	−2.86	−2.2	−3.36	−3.17
Sen's slope	0.11	−0.014	−0.009	−0.016	−0.011	−0.016	−0.016

Trends statistically significant at $P<0.05$, S Kendall's S, VAR(S) variance of S, z Mann–Kendall test

1960–1990, which were less frequent. But after 1990, the area experienced more frequent short-term (4–5-month duration) droughts. Since 1990, frequent occurrences of extreme to severe droughts for a short duration in monsoon months over the sub-humid district could be attributed to rainfall variability and rising temperature due to climate change at a regional scale. Climatic variability and occurrence of extreme events during monsoon season in the sub-humid region of India have been attributed to climatic change by various researchers (Sam et al. 2020; Parida and Oinam 2015; Udmale et al. 2014). An increase in evapotranspiration due to global warming would likely play a major role in affecting drought dynamics in the sub-humid region of India (Gupta and Jain 2018) in the future.

Trend analysis of monthly drought also denotes the increasing intensity and frequency of drought in July and August when maximum monsoon rainfall is expected. A statistically significant rising trend in monsoon and annual drought at a 95% confidence level have been observed by the analysis of the SPEI in Purulia. Kumar et al. (2013) had similar findings from Central India where drought frequency increased during the period 1990–2010. Similarly, an increasing trend of frequency and magnitude of the monsoonal drought was observed in the Eastern regions of India (Das et al. 2016). Drought events have increased also in South Asia in recent decades (Aadhar and Mishra 2017).

From monthly and seasonal SPI/SPEI analysis, non-uniform spatiotemporal characteristics (duration, intensity, and frequency) were observed in drought occurrences. In 1998, 2005, and 2015, severe monsoon drought leading to crop failure in the Kharif season could be detected but annually no drought condition was shown because annual rainfall was the same as the long-term annual mean. On the other hand, in 1993, 1996, 2004, 2007, 2011, and 2012, annual rainfall was greater than the long-term annual mean, yet drought conditions prevailed for pre and post-monsoon periods. The analysis indicates that the onset and monthly quantum of monsoon rainfall is the driver of drought notwithstanding whether the annual rainfall is greater or less than the normal rainfall. Thus, monthly or seasonal SPI/SPEI estimation can be taken up as a more appropriate indicator of drought assessment and preparedness planning. Similarly, Guhathakurta et al. (2017) and Joshi et al. (2016) concluded that the Eastern regions of India showed an increasing incidence of monthly drought during the second half of the twentieth century.

Results show that SPI fared equally well as SPEI and successfully detected the most significant drought events before 2000. SPEI could identify a larger number of drought years after 2000 than SPI in Purulia. Moderate drought conditions could be placed in 5 specific years (1993, 2003, 2004, 2005, and 2012) in recent times (1990–2019) by SPEI, while SPI could pick up no such drought conditions. Similar findings were obtained in another investigation (Tefera et al. 2019; Labudova et al. 2017; Wang et al. 2015). According to the literature, both indices could detect major drought incidences in the first half of the twentieth century; however, SPI was unable to capture the degree of drought severity suggested by SPEI in the later part of the twentieth and early twenty-first centuries. Additionally, the SPI values seem higher than the corresponding SPEI values. Other investigations (Tefera et al. 2019; Labudova et al. 2017; Wang et al. 2015) have shown the similar differences between SPI and SPEI. When temperature changes are combined with precipitation, the findings may differ from when precipitation alone is used. SPI solely uses rainfall data as an input, but SPEI uses rainfall and temperature data as input, allowing it to account for the effects of temperature variation on drought assessment. However, variances between SPI and SPEI values do not imply that they provide wholly different results. SPI can be equally effective as SPEI in locations with low-temperature changes. The correlation of Kharif rice production with SPEI is much more significant than the SPI's. The above differences between the SPEI and the SPI are mainly attributed to the rising temperature in Purulia. Several other researchers have found similar results (Pathak and Dodamani 2019; Aadhar and Mishra 2018; Tirivarombo et al. 2018). SPEI performs well in capturing drought occurrences in sub-humid RLZ in a climate change context.

Spatial analysis of recent droughts could identify community blocks (Jaldhi, Baghmundi, Balarampur, Bandoyan, Manbazar-II, Barabazar, Para, Raghunathpur, Nituria, Kashipur, Hura, etc.) of the districts to be prone to severe to extreme drought. The spatial analysis identified such blocks in need of special assistance at the time of drought and helps in preparedness planning by augmenting water and agricultural resources.

6 Field validation

The changing characteristics of meteorological drought and associated crop failure have been validated using field surveys in the recent 2 consecutive drought years (2015 and 2019) to assess the accuracy of the assessment. Ten villages of predominantly rural and tribal populations located in the Kashipur community development block of the Purulia district were surveyed. These communities have also experienced extreme to moderate droughts in the past years 2005 and 2010 and hence, make good targets for comparative case studies.

A total of 375 farmers' households in the selected villages were surveyed in 2015 and 2019 (Table 4). The interviews investigated their experience of drought occurrences in 2015 and 2019, the time and intensity of such droughts, and their impacts on crop production. The villagers informed us that they faced drought in June, from August to October 2015, and from June to August 2019. Farmers also mentioned the intensity of drought in 2015 was higher than in 2019. More than 95% of surveyed households reported that Kharif rice production was significantly reduced in these 2 drought years, however, lesser in 2019 (Table 4). The field validation thus could establish the relationship between the indices derived existence of short-term monsoon droughts with human experience and crop failure.

7 Conclusion

In the present study, multi-scalar meteorological drought indices, SPI, and SPEI have been used to identify the changing characteristics of drought conditions for 1-, 3-, 6-, and

Table 4 Village wise sample size and Kharif rice production failure in two drought years 2015 and 2019

		Sample house-hold	Average Kharif rice production (kg/ 2500 sq meter)	Loss of Kharif rice production (%)	
				2015	2019
Kashipur	Jagannathdi	25	520	85	12
	Lari	26	460	95	24
	Jibanpur	42	555	90	14
	Bodma	64	600	84	13
	Kashidi	27	575	92	16
	Sunra	35	500	89	20
	Seja	26	510	88	19
	Ranjandi	60	528	83	11
	Bhatin	25	437	95	15
	Pabra Pahari	45	465	93	14

12-month time scale in sub-humid RLZ (Purulia) over 90 years (1930 to 2019). The Mann-Kendell and Sen's slope tests were applied to evaluate trends in monthly drought and spatiotemporal drought characteristics obtained from SPI and SPEI during the recent decade. Further, the relationship between drought and Kharif (monsoon) rice production was analyzed to identify crop failures during identified droughts. Results indicate a minor change in the long-term droughts (12-monthly) condition while a major change is observed in short-term (1-, 3-monthly) droughts on a monthly time scale, extreme droughts were found from May to October, while severe droughts were found in the lean periods of February to April. Mild droughts could be found in the months of concentrated in November and December. Among the cases of drought incidences in the region, 50% were found to be of extreme to severe (−2 to −1.5) nature, which occurred from June to October between 1990 and 2019. A majority (53%) of mild droughts could be identified to have occurred before the 1960s. The long-duration drought of 8 to 10 months, more prevalent during 1930–1960, appeared to have been replaced in recent times by frequent short-duration droughts in the region. Both drought frequency and intensity appeared to have increased in recent decades. At a seasonal scale, extreme to severe droughts is observed to be more prevalent in the monsoon season of the post-1990 period. Frequent meteorological droughts in monsoon months consequently imparted the loss of the Kharif crop production of the RLZ. From the perspective of the persistent rise of temperature and variability in the monsoon rainfall the changing characteristics of meteorological droughts over the RLZ need immediate intervention to initiate drought preparedness and management planning. The relation between drought and Kharif rice production indicates that SPEI functioned as a better index compared to SPI, especially in recent years, when the temperature is significantly higher, promoting more evapotranspiration and dryness. Trend analysis of meteorological drought through the SPEI index revealed a significant increasing trend in July, and August in the monsoon season, which indicates that the sub-humid RLZs may undergo frequent droughts during monsoon months in the future due to increasing temperature. The close correspondence of monsoon meteorological droughts in the Kharif season in the lateritic terrain of poor percolation capability is significant for the region's water resource and agriculture management. The findings of our study can be helpful for policymakers, planners, and all the other stakeholders to obtain an initial idea into better preparedness for droughts, to be monitored monthly for identification in higher resolution. The study also suggested suitable drought indices for RLZ in the context of rising temperatures having a more pronounced effect on drought incidences of recent times. This understanding of the changing nature of meteorological droughts and increased incidences of short-term droughts in the monsoon season is expected to enhance our ability to plan, manage, and implement sustainable water use and agricultural practices in the face of climate change.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00704-022-04316-w.

Acknowledgements The authors are grateful for the financial and logistic support. The authors also express their gratitude to the Department of Planning & Statistics, Government of West Bengal for providing the block-level crop data. The author (S. Roy) is thankful to Jadavpur University, India, for providing her with the State Fellowship.

Author contribution This work forms a part of the doctoral thesis of Sabita Roy who performed the analysis and wrote the paper. Sugata Hazra and Abhra Chanda executed a critical and constructive review to improve the quality of the manuscript. Sabita Roy and Sugata Hazra collected the data during fieldwork.

Funding The study was sponsored by the National Bank for Agriculture and Rural Development, India (NABARD) through the Development Research Communication and Services Centre (DRCSC), Kolkata from the Climate Adaptation Fund (AFB/PPRC15/12).

Data Availability The secondary data has been collected from Indian Meteorological Department (IMD), Pune (https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html) and the Directorate of Agriculture, West Bengal. The primary data has been collected through field surveys.

Code availability Not applicable.

Declarations

Ethical approval The authors are committed to maintaining the integrity of the scientific record.

Consent to participate Not applicable.

Consent for publication All individuals listed as authors have agreed to be listed and approved the submitted version of the manuscript.

Conflict of interest The authors declare no competing interests.

References

Aadhar S, Mishra V (2018) Impact of climate change on drought frequency over India. Book Climate Change and Water Resources in India Publisher: Ministry of Environment, Forest and Climate Change (MoEF&CC), Government of India
Aadhar S, Mishra V (2017) High-resolution near real-time drought monitoring in South Asia. Sci Data 4:170145. https://doi.org/10.1038/sdata.2017.145
Abramowitz M, Stegun A (1965) Handbook of Mathematical Functions: with Formulas, Graphs, and Mathematical Tables. Dover Publications Inc., New York
Adarsh S, Kumar DN, Deepthi B, Gayathri G, Aswathy SS, Bhagyasree S (2019) Multifractal characterization of meteorological drought in India using detrended fluctuation analysis. Int J Climatol 39(11):4234–4255
Alam NM, Sharma GC, Moreira E, Jana C, Mishra PK, Sharma NK, Mandal D (2017) Evaluation of drought using SPEI drought class

transitions and log-linear models for different agro-ecological regions of India. Phys Chem Earth, Parts A/B/C 100:31–43
Asutosh G (2019) Identifying the trend of meteorological drought in Purulia district of West Bengal, India. Environ Ecol 37(1B):387–92
Awchi TA, Kalyana MM (2017) Meteorological drought analysis in northern Iraq using SPI and GIS. Sustain Water Resour Manag 3(4):451–463
Banik P, Mandal A, Rahman MS (2020) Markov chain analysis of weekly rainfall data in determining drought-proneness. Discret Dyn Nat Soc 7. https://doi.org/10.1155/S1026022602000262
Begueria S, Vicente-Serrano SM, Angulo-Martínez M (2010) A multiscalar global drought dataset: the SPEI-base: a new gridded product for the analysis of drought variability and impacts. Bull Am Meteor Soc 91(10):1351–1356
Belayneh A, Adamowski J, Khalil B (2016) Short-term SPI drought forecasting in the Awash River Basin in Ethiopia using wavelet transforms and machine learning methods. Sustain Water Resour Manag 2(1):87–101
Bhunia P, Das P, Maiti R (2020) Meteorological drought study through SPI in three drought prone districts of West Bengal, India. Earth Syst Environ 4(1):43–55
Brahmachari K, Sarkar S, Santra DK, Maitra S (2018) Millet for food and nutritional security in drought prone and red laterite region of eastern India. Int J Plant Soil Sci 26(6):01–07
Dabanlı I, Mishra AK, Şen Z (2017) Long-term spatio-temporal drought variability in Turkey. J Hydrol 552:779–792
Damberg L, AghaKouchak A (2014) Global trends and patterns of drought from space. Theor Appl Climato 117(3–4):441–448
Das PK, Dutta D, Sharma JR, Dadhwal VK (2016) Trends and behaviour of meteorological drought (1901–2008) over Indian region using standardized precipitation–evapotranspiration index. Int J Climatol 36(2):909–916
Delfiyan F, Yazdanpanah M, Forouzani M, Yaghoubi J (2021) Farmers' adaptation to drought risk through farm–level decisions: the case of farmers in Dehloran County, Southwest of Iran. Clim Dev 13(2):152–163
Ghosh KG (2018) Analysis of rainfall trends and its spatial patterns during the last century over the Gangetic West Bengal, Eastern India. J Geovisualization Spat Anal 2(2):15
Goswami BN, Venugopal V, Chattopadhyay R (2019) South Asian monsoon extremes. In: Tropical Extremes. Elsevier, pp 15–49
Guhathakurta P, Menon P, Inkane PM, Krishnan U, Sable ST (2017) Trends and variability of meteorological drought over the districts of India using standardized precipitation index. J Earth Syst Sci 126(8):120
Gupta V, Jain MK (2018) Investigation of multi-model spatiotemporal mesoscale drought projections over India under climate change scenario. J Hydrol 567:489–509
Gupta V, Kumar Jain M, Singh VP (2020) Multivariate modeling of projected drought frequency and hazard over India. J Hydrol Eng 25(4):04020003
Heim RR Jr (2002) A review of twentieth-century drought indices used in the United States. Bull Am Meteor Soc 83(8):1149–1166
Hernandez EA, Uddameri V (2014) Standardized precipitation evaporation index (SPEI)-based drought assessment in semi-arid South Texas. Environ Earth Sci 71(6):2491–2501
Jha S, Sehgal VK, Raghava R, Sinha M (2013) Trend of standardized precipitation index during Indian summer monsoon season in agroclimatic zones of India. Earth Syst Dyn Discuss 4:429–449. https://doi.org/10.5194/esdd-4-429-2013
Ji L, Peters AJ (2003) Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. Remote Sens Environ 87(1):85–98
Joshi N, Gupta D, Suryavanshi S, Adamowski J, Madramootoo CA (2016) Analysis of trends and dominant periodicities in drought variables in India: a wavelet transform based approach. Atmos Res 182:200–220
Keshavarz M, Karami E, Vanclay F (2013) The social experience of drought in rural Iran. Land Use Policy 30(1):120–129
Keskin ME, Taylan ED, Kuuml D (2011) Meteorological drought analysis using artificial neural networks. Sci Res Essays 6(21):4469–4477
Kumar S, Merwade V, Kam J, Thurner K (2009) Streamflow trends in Indiana: effects of long term persistence, precipitation and subsurface drains. J Hydrol 374(1–2):171–183
Kumar RA, Mishra JS, Upadhyay PK, Hans HA (2019) Rice fallows in the Eastern India: problems and prospects. Indian J Agric Sci 89:567–577
Kumar P, Joshi PK (2016) Food demand and supply projections to 2030: India. International Trade and Food Security: The Future Indian Agric 29–63
Kumar KN, Rajeevan M, Pai DS, Srivastava AK, Preethi B (2013) On the observed variability of monsoon droughts over India. 1:42–50. https://doi.org/10.1016/j.wace.2013.07.006
Kundu A, Patel NR, Denis DM, Dutta D (2020) An estimation of hdro-meteorological drought stress over the central part of India using geo-information technology. J Indian Soc Remote Sens 48(1):1–9
Labudova L, Labuda M, Takac J (2017) Comparison of SPI and SPEI applicability for drought impact assessment on crop production in the Danubian Lowland and the East Slovakian Lowland. Theor Appl Climato 128(1–2):491–506
Lesk C, Rowhani P, Ramankutty N (2016) Influence of extreme weather disasters on global crop production. Nature 529(7584):84–87
Li J, Wang Z, Lai C (2020) Severe drought events inducing large decrease of net primary productivity in mainland China during 1982–2015. Sci Total Environ 703:135541. https://doi.org/10.1016/j.scitotenv.2019.135541
Liu X, Pan Y, Zhu X, Yang T, Bai J, Sun Z (2018) Drought evolution and its impact on the crop yield in the North China Plain. J Hydrol 564:984–996
Liu C, Yang C, Yang Q, Wang J (2021) Spatiotemporal drought analysis by the standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI) in Sichuan Province, China. Sci Rep 11(1):1–14
Madadgar S, AghaKouchak A, Farahmand A, Davis SJ (2017) Probabilistic estimates of drought impacts on agricultural production. Geophysical Res Lett 44(15):7799–7807
Mallya G, Mishra V, Niyogi D, Tripathi S, Govindaraju RS (2016) Trends and variability of droughts over the Indian monsoon region. Weather Clim Extrem 12:43–68
Mandal R, Jana K, Ghosh S, Biswas A, Bhadra KK, Mallick GK (2018) Production oriented survey (POS) on different aspects of rice cultivation and farmers practices under red and lateritic zone of West Bengal, India. Arch Agric Environ Sci 3(4):378–381
Mandal SP, Chakrabarty A (2013) A comparative analysis of seasonal drought condition measured from evapotranspiration based on thermal remote sensing and field survey-a case study of Manbazar-I and Puncha Block of Purulia District, West Bengal, India. Indian Cartographer XXXIII:438–444
Mare F, Bahta YT, Van Niekerk W (2018) The impact of drought on commercial livestock farmers in South Africa. Dev Pract 28(7):884–898
Marini G, Fontana N, Mishra AK (2019) Investigating drought in Apulia region, Italy using SPI and RDI. Theor Appl Climato 137(1–2):383–397
McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology (Vol. 17, No. 22, pp. 179–183)
Mishra AK, Singh VP (2009) Analysis of drought severity-area-frequency curves using a general circulation model and scenario

uncertainty. J Geophys Res: Atmos 114(D6). https://doi.org/10.1029/2008JD010986
Mishra AK, Desai VR (2005) Spatial and temporal drought analysis in the Kansabati River basin, India. Intl J River Basin Manag 3(1):31–41
Mishra AK, Singh VP (2011) Drought modeling–a review. J Hydrol 403(1–2):157–175
Monish NT, Rehana S (2020) Suitability of distributions for standard precipitation and evapotranspiration index over meteorologically homogeneous zones of India. J Earth Syst Sci 129(1):25
Mukherjee AS, Banerjee S (2009) Rainfall and temperature trend analysis in the red and lateritic zone of West Bengal. J Agrometeorol 11(2):196–200
Mukherjee A, Huda AK (2018) Assessment of climate variability and trend on wheat productivity in West Bengal, India: crop growth simulation approach. Clim Change 147(1–2):235–252
Nath R, Nath D, Li Q, Chen W, Cui X (2017) Impact of drought on agriculture in the Indo-Gangetic Plain, India. Adv Atmos Sci 34(3):335–346
Nath R, Luo Y, Chen W, Cui X (2018) On the contribution of internal variability and external forcing factors to the cooling trend over the humid subtropical Indo-Gangetic Plain in India. Sci Rep 8(1):18047. https://doi.org/10.1038/s41598-018-36311-5
Pai DS, Rajeevan M, Sreejith OP, Mukhopadhyay B, Satbha NS (2014). Development of a new high spatial resolution (0.25× 0.25) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. Mausam 65(1):1–18
Pai DS, Guhathakurta P, Kulkarni A, Rajeevan MN (2017) Variability of meteorological droughts over India. In: Observed climate variability and change over the Indian Region. Springer, Singapore, pp 73–87
Panday SC, Kumar A, Meena VS, Joshi K, Stanley J, Pattanayak A (2020) Standardized precipitation index (SPI) for drought severity assessment of Almora, Uttarakhand, India. J Agrometeorol 22(2):203–206
Pandey V, Srivastava PK (2019) Integration of microwave and optical/infrared derived datasets for a drought hazard inventory in a subtropical region of India. Remote Sens 11(4):439
Parida BR, Oinam B (2015) Unprecedented drought in North East India compared to Western India. Current Sci 109:2121–2126
Pathak AA, Dodamani BM (2019) Comparison of meteorological drought indices for different climatic regions of an Indian River basin. Asia-Pac J Atmos Sci 56:563–576. https://doi.org/10.1007/s13143-019-00162-5
Patra P (2020) Comparative analysis of multi-temporal drought indices using monthly precipitation data: a study in the southwestern part of West Bengal, India. Geoecol Landsc Dyn. Springer, Singapore, pp 149–165
Pei Z, Fang S, Wang L, Yang W (2020) Comparative analysis of drought indicated by the SPI and SPEI at various timescales in inner Mongolia, China. Water 12(7):1925
Potop V, Mozny M, Soukup J (2012) Drought evolution at various time scales in the lowland regions and their impact on vegetable crops in the Czech Republic. Agric Forest Meteorol 156:121–133
Rahman MR, Lateh H (2016) Meteorological drought in Bangladesh: assessing, analysing and hazard mapping using SPI, GIS and monthly rainfall data. Environ Earth Sci 75(12):1026
Rao AN, Singh RG, Mahajan G, Wani SP (2018) Weed research issues, challenges, and opportunities in India. Crop Prot 104451. https://doi.org/10.1016/j.cropro.2018.02.003
Roy S, Hazra S, Chanda A, Das S (2020) Assessment of groundwater potential zones using multi-criteria decision-making technique: a micro-level case study from red and lateritic zone (RLZ) of West Bengal, India. Sustain Water Resour Manag 6(1):4
Roy S, Hazra S, Chanda A (2022a) Assessment of wet season agricultural droughts using monthly MODIS and SAR data in the red and lateritic zone of West Bengal, India. Spat Inf Res 1–6. https://doi.org/10.1007/s41324-022-00485-y
Roy S, Hazra S, Chanda A (2022b) Identifying rainwater harvesting structure sites using MCDM-based GIS approach: a mitigation measure for drought in sub-humid red and lateritic zones of West Bengal, India. Arab J Geosci 15(8):1–19
Roy S, Hazra S, Chanda A, Das S (2022c) Land suitability analysis using AHP-based multi-criteria decision model for sustainable agriculture in red and lateritic zones of West Bengal, India. J Earth Syst Sci 131(4):1–9
Sam AS, Padmaja SS, Kächele H, Kumar R, Müller K (2020) Climate change, drought and rural communities: understanding people's perceptions and adaptations in rural eastern India. Int J Disaster Risk Reduct 44:101436. https://doi.org/10.1016/j.ijdrr.2019.101436
Sathaiah M, Chandrasekaran M (2020) A bio-physical and socio-economic impact analysis of using industrial treated wastewater in agriculture in Tamil Nadu, India. Agric Water Manag 241:106394
Shah R, Bharadiya N, Manekar V (2015) Drought index computation using standardized precipitation index (SPI) method for Surat District, Gujarat. Aquat Proced 4:1243–1249
Shaik R, Monish NT, Naidu S (2020) Estimation of annual regional drought index considering the joint effects of climate and water budget for Krishna River basin, India. Environ Monit Assess 192(7):1–8
Sharma A, Goyal MK (2020) Assessment of drought trend and variability in India using wavelet transform. Hydrol Sci J 1–6. https://doi.org/10.1080/02626667.2020.1754422
Sharma S, Mujumdar P (2017) Increasing frequency and spatial extent of concurrent meteorological droughts and heatwaves in India. Sci Rep 7(1):1–9. https://doi.org/10.1038/s41598-017-15896-3
Shukla R, Chakraborty A, Joshi PK (2017) Vulnerability of agro-ecological zones in India under the earth system climate model scenarios. Mitig Adapt Strateg Glob Change 22(3):399–425
Sicard P, Mangin A, Hebel P, Malléa P (2010) Detection and estimation trends linked to air quality and mortality on French Riviera over the 1990–2005 period. Sci Total Environ 408(8):1943–1950
Singh RM, Shukla P (2020) Drought characterization using drought indices and El Nino effects. National Acad Sci Lett 43:339–342. https://doi.org/10.1007/s40009-019-00870-6
Singh GR, Jain MK, Gupta V (2019) Spatiotemporal assessment of drought hazard, vulnerability and risk in the Krishna River basin, India. Nat Hazards 99(2):611–635
Singh TP, Nandimath P, Kumbhar V, Das S, Barne P (2020) Drought risk assessment and prediction using artificial intelligence over the southern Maharashtra State of India. Model Earth Syst Environ 1–9. https://doi.org/10.1007/s40808-020-00947-y
Sivakumar B (2011) Global climate change and its impacts on water resources planning and management: assessment and challenges. Stoch Environ Res Risk Assess 25(4):583–600
Srivastava AK, Rajeevan M, Kshirsagar SR (2009) Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. Atmos Sci Lett 10(4):249–254
Subash N, Ram Mohan HS (2011) Trend detection in rainfall and evaluation of standardized precipitation index as a drought assessment index for rice–wheat productivity over IGR in India. Int J Climatol 31(11):1694–1709
Tefera AS, Ayoade JO, Bello NJ (2019) Comparative analyses of SPI and SPEI as drought assessment tools in Tigray Region, Northern Ethiopia. SN Appl Sci 1(10):1–4
Thomas J, Prasannakumar V (2016) Temporal analysis of rainfall (1871–2012) and drought characteristics over a

tropical monsoon-dominated state (Kerala) of India. J Hydrol 534:266–280
Tirivarombo S, Osupile D, Eliasson P (2018) Drought monitoring and analysis: standardised precipitation evapotranspiration index (SPEI) and standardised precipitation index (SPI). Phys Chem Earth, Parts a/b/c 106:1. https://doi.org/10.1016/j.pce.2018.07.001
Udmale P, Ichikawa Y, Manandhar S, Ishidaira H, Kiem AS (2014) Farmers' perception of drought impacts, local adaptation and administrative mitigation measures in Maharashtra State, India. Int J Disaster Risk Reduct 10:250–269
Vicente-Serrano SM, Beguería S, López-Moreno JI (2010a) A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23(7):1696–1718
Vicente-Serrano SM, Van der Schrier G, Beguería S, Azorin-Molina C, Lopez-Moreno JI (2015) Contribution of precipitation and reference evapotranspiration to Drought indices under different climates. J Hydrol 526:42–54
Vicente-Serrano SM, Beguería S, Lopez-Moreno JI, Angulo M, El Kenawy A (2010b) A new global 0.5 gridded dataset (1901–2006) of a multi-scalar drought index: comparison with current drought index datasets based on the Palmer Drought Severity Index. J Hydrometeorol 11(4):1033–43
Vikramarjun M, Seenappa C, Thimmegowda MN, Murthy KN (2019) Yield Performance of Different Contingent Crops under Delayed Sowings in Changed Climate in Rainfed Agriculture. Indian J Dryland Agric Res Dev 34(2):33–37
Wang Y, Liu PX, Cao LG, Gao Y, Yong GZ (2014) A study on spatial-temporal variation characteristics of drought based on Standardized Precipitation Index in Ningxia Autonomous Region during recent 53 years. Soil Water Conserv 34:296–302
Wang W, Zhu Y, Xu R, Liu J (2015) Drought severity change in China during 1961–2012 indicated by SPI and SPEI. Nat Hazard 75(3):2437–2451
Wang Y, Liu G, Guo E (2019) Spatial distribution and temporal variation of drought in inner Mongolia during 1901–2014 using Standardized Precipitation Evapotranspiration Index. Sci Total Environ 654:850–862
Ward PS, Makhija S (2018) New modalities for managing drought risk in rainfed agriculture: evidence from a discrete choice experiment in Odisha, India. World Dev 107:163–175
Xia L, Zhao F, Mao K, Yuan Z, Zuo Z, Xu T (2018) SPI-based analyses of drought changes over the past 60 years in China's major crop-growing areas. Remote Sens 10(2):171
Xu K, Yang D, Yang H, Li Z, Qin Y, Shen Y (2015) Spatio-temporal variation of drought in China during 1961–2012: a climatic perspective. J Hydrol 526:253–264
Yevjevich VM (1967) An objective approach to definitions and investigations of continental hydrologic droughts. Colorado State University, Denver
Zarch MAA, Sivakumar B, Sharma A (2015) Droughts in a warming climate: a global assessment of Standardized precipitation index (SPI) and Reconnaissance drought index (RDI). J Hydrol 526:183–195
Zhai J, Mondal SK, Fischer T, Wang Y, Su B, Huang J, Tao H, Wang G, Ullah W, Uddin MJ (2020) Future drought characteristics through a multi-model ensemble from CMIP6 over South Asia. Atmos Res 246:105111. https://doi.org/10.1016/j.atmosres.2020.105111
Zhang Q, Zhang J, Wang C (2017) Risk assessment of drought disaster in typical area of corn cultivation in China. Theor Appl Climato 128(3–4):533–540
Zhang S, Wu Y, Sivakumar B, Mu X, Zhao F, Sun P, Sun Y, Qiu L, Chen J, Meng X, Han J (2019) Climate change-induced drought evolution over the past 50 years in the southern Chinese Loess Plateau. Environ Model Softw 122:104519. https://doi.org/10.1016/j.envsoft.2019.104519
Zhao H, Gao G, An W, Zou X, Li H, Hou M (2017) Timescale differences between SC-PDSI and SPEI for drought monitoring in China. Phys Chem Earth, Parts a/b/c 102:48–58