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Drought assessment in the districts of Assam using standardized precipitation index

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This study assessed the drought characteristics in various districts of Assam using a standardized precipitation index (SPI). Assam has been traditionally affected by floods; however, in the last few decades, droughts have occurred due to erratic rainfall patterns. In this study, gridded rainfall data provided by India Meteorological Department for 70 years (1951–2020) was used. The SPI was calculated at a 3-month time scale (SPI03) using accumulated rainfall of a 3-month sliding window to reflect seasonal or, to some extent, agricultural drought. In Assam, the percentage of drought in August and September that represented monsoonal drought was about 15% during the course of 70 years. Additionally, Assam's overall percentage of drought was at 14.5%, indicating that dryness will occur throughout the year regardless of the season. The most hit district in terms of the number of times was Bishwanath Chariali, and the least affected was Karbi Anglong. Furthermore, the Sivasagar district was found to be experiencing the highest number of droughts in the most intense category. The average drought in Assam lasted for roughly 5.2 months. Dhubri district, which had the lowest inter-arrival time (IAT) of drought, experienced drought spells more frequently. It is concluded that drought mitigation planning should be implemented in areas with a higher frequency of droughts, longer drought spells, and shorter IATs. The findings of this study will aid the efforts being made by various departments in proper planning, action, and management of multiple entities with regard to the state's drought.

Keywords. Drought; Assam; standardized precipitation index (SPI); drought duration; inter-arrival time.

1. Introduction

Recent extreme weather occurrences, such as droughts and floods brought on by irregular rainfall, have resulted in losses in agricultural production. Hence, mitigation and adaptation measures have been called for. These actions can be implemented with a thorough characterization of the natural phenomenon of hazards. Numerous studies have shown that changes in climate variables, such as an increase in the frequency of heavy rainstorms, a decrease in the number of rainy days, and the occurrence of dry spells during the rainy season, are the foreseeable characteristics of changing rainfall patterns. An investigation in the Brahmaputra and Barak basins revealed that annual and

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monsoon rainfall has reduced since 2001, which is associated with an increase in the number of deficit years (Deka *et al.* 2013; Rathore *et al.* 2013). Contrary to other natural disasters, droughts take a long time to develop and frequently stretch a large area, making it difficult to predict when they will begin and to what degree they will be severe. It is a natural phenomenon caused by a persistent shortage of rainfall, causing hydrological, agricultural, and socio-economic impacts. Since the majority of Indian agriculture is rainfed, the roughly four-month monsoon season, from June to September, has a significant impact on the country's agricultural industry. This makes the monsoon's behaviour extremely important for the nation's agricultural production.

The occurrence of drought conditions is frequently sparked by an increase in the frequency of dry spells, which has detrimental effects on the economy and society. Longer dry spells may impair the availability of surface and groundwater resources, whereas shorter dry spells frequently impact agricultural operations. About 50 million people in India experience drought every year, and 16% of the country's total land area is drought-prone (Arumugam and Anbazhagan 2017). Drought has traditionally been a frequent occurrence in dry and semi-arid areas. This is no longer the case because many areas with considerable rainfall frequently experience severe water shortages. For instance, Cherrapunji in Meghalaya, which is the second rainiest place on earth and receives over 11,000 mm of rain annually, currently experiences meteorological drought (Ray *et al.* 2015) for approximately nine months in a year (NDMA 2010). Other instances of drought occurrences in high rainfall regions of North East India are Guwahati city of Assam (Jhajharia *et al.* 2007), North Lakhimpur district of Assam (Shrivastava *et al.* 2008), Tura town of Meghalaya (Ray *et al.* 2013), East Sikkim district (Kusre and Lalringliana 2014), and Nagaland (Nongbri *et al.* 2016). Parida and Oinam (2015) also reported drought occurrences in northeastern region of India. Thus, drought can occur at any place, irrespective of the climate, and is an issue related to water resource management (NDMA 2010).

Assam is situated in one of the areas with heavy rainfall, where floods occur virtually every year. However, it has recently experienced drought-like situations (Assam State Disaster Management Authority 2022) twice in 2010 and 2014, affecting large areas of Assam. According to a report from the Assam State Disaster Management Authority published in 2022 and also from the report published by the Department of Environment and Forests, Government of Assam in 2015 (Department of Environment and Forests 2015) on Assam State action plan on climate change, the number of drought weeks will increase by 75% from the baseline period of 1971–2000 to the future period of 2021–2050, having an impact on Assamese people's livelihood due to reduction in production in agriculture and allied sectors. It has also been reported that an increase in the frequency of dry spells has produced extensive damage to paddy cultivation in the North Brahmaputra Plain zone (Neog *et al.* 2020). In a report published by Assam State Disaster Management Authority (2015), several districts of Assam were severely impacted due to drought-like conditions in 2005 and 2006, which had an impact on more than 1.95 crore people whose livelihood depended on agriculture and allied sectors. A loss of over 100 crore rupees was also reported due to crop failure and other incidentals.

Thus, it becomes crucial to measure and quantify the extent of drought so that timely and effective measures can be made to mitigate its impact. Drought indices are used for quantifying droughts and help decision-makers to get quantitative data on the characteristics of drought (Dogan *et al.* 2012). Understanding a drought's features, such as its duration, severity, inter-arrival time, and frequency, is essential for coping with the misery it might cause. With these characteristics known, drought mitigation planning becomes quite simple and easy to implement (Pandey and Ramasastri 2001). The present study attempts to characterize drought occurrences in each district of Assam using the standardized precipitation index (SPI).

2. Study area and data

Assam is situated in the northeastern part of India and comprises 35 districts. It covers an area of 78,438 km^2, including both plains and hills. With an average annual rainfall of 2201 mm between 1951 and 2020, it received more precipitation than most regions in India. The Brahmaputra River, the Barak River, and their tributaries make up Assam's primary drainage system. The state has a tropical monsoon climate, which is characterized by persistent heavy rainfall and high humidity.

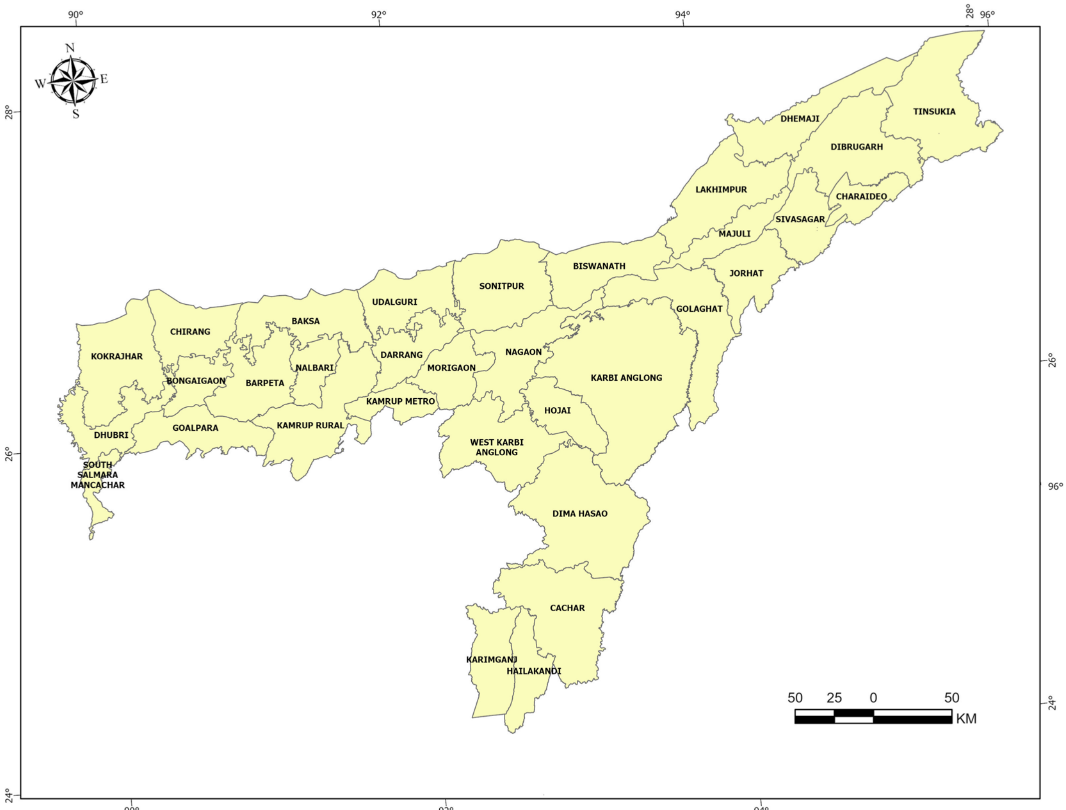


Figure 1. Study area: Assam and its districts.

Figure 1 shows the state of Assam and its 35 districts.

Gridded rainfall data with a spatial resolution of approximately 25 km at a daily scale has been obtained from the India Meteorological Department website (Pai *et al.* 2014) for a period of 70 years from 1951 to 2020. For this study, the daily data is retrieved from the binary raw files, converted to monthly data, and then extracted for each district in Assam through a series of preprocessing in Python and GIS operations. The yearly rainfall in Assam for the past 70 years has been about 2201 mm, with roughly 1438, 150, 56, and 558 mm falling during the monsoon, post-monsoon, winter, and pre-monsoon, respectively. It shows that the monsoon season (June–September) accounts for around 65% of the annual rainfall and that the pre-monsoon and monsoon seasons (from March to September) account for 91% of the total annual rainfall. This implies that any deviation from the normal during these two seasons will have a significant impact on the state's water resources. The long-term annual rainfall scenario in Assam and its districts is illustrated in figure 2. The data shows that the Hojai district experienced the least amount of rainfall, whereas Kokrajhar experienced the most. The coefficient of variation of rainfall among the districts was determined as 19.5%.

3. Methods

SPI was employed in the current study as an indicator for identifying drought. This index needed data on precipitation. Rainfall is the main indicator of drought and the foundation of most drought monitoring systems, even if it may not encompass the whole range of drought characteristics. SPI has a wide range of acceptability among various researchers on drought as it may be used to monitor droughts in relation to certain water resources at various time scales (Gurrapu *et al.* 2014). It is regarded as one of the top indicators for determining the severity of a drought (Keyantash and Dracup 2002; Dogan *et al.* 2012) and was suggested by Morid *et al.* (2006) for use in drought monitoring in Tehran, Iran, as it performed well in spotting the start of a drought. SPI may serve as a

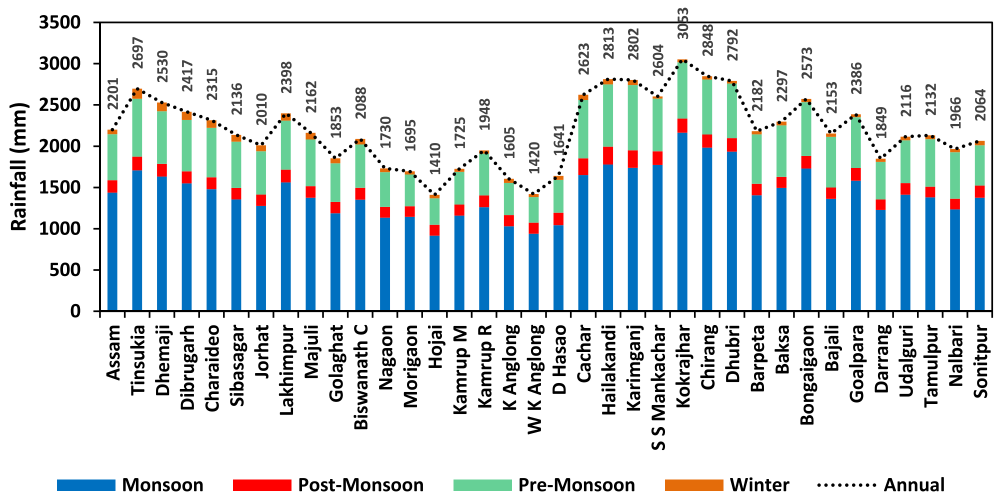


Figure 2. Rainfall scenario in Assam and its districts.

useful indicator for describing various aspects of agricultural drought because of its adaptability in adopting sliding time scales (White and Walcott 2009). If the rainfall deficit persists for a longer period, especially during the growing season of crops, agricultural drought may arise (Faiz *et al.* 2021) due to a shortage of soil moisture in the crop root zone. A shorter time period, such as 3- or 6-months, would be sufficient to describe a drought that affects agriculture, whereas a longer time scale, such as 12-, 24-, or longer months, would be significant from the perspective of water resources in reservoirs and groundwater. A 1-month time period for a drought analysis would frequently produce inaccurate conclusions in areas with considerable rainfall variability. Since the majority of crops grown in Assam have a growing period of 3–5 months, a timescale of 3 months is employed in this study to reflect the effects of drought on agriculture.

The SPI was developed by McKee *et al.* (1993) and extensively described by Edwards and McKee (1997). The Gamma probability distribution function is used to calculate the SPI as follows:

$$G(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\int_0^x x^{\alpha-1}e^{-x/\beta}\,dx, \quad (1)$$

where α and β are the shape and scale parameters, respectively. To determine these parameters, maximum likelihood solutions are used (Thom 1966) as follows:

$$\alpha = \frac{1}{4A}\left[1+\sqrt{\frac{4A}{3}}\right], \quad (2)$$

$$\beta = \frac{\overline{X}}{\alpha}, \quad (3)$$

$$A = \ln(\overline{x}) - \frac{\sum \ln(x)}{n}, \quad (4)$$

where n is the number of rainfall observations and $\overline{x}$ is the mean rainfall. When $x = 0$, the Gamma function is undefined, thus for rainfall $= 0$, the cumulative probability is:

$$H(x) = q + (1-q)\times G(x), \quad (5)$$

where q is the probability of zero events. If m is the number of zeros in the series of rainfall, then q becomes m/n (Thom 1966). Further in SPI calculation, the cumulative probability, $H(x)$ is normalized to become SPI as follows:

$$SPI = -\left[t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \quad (6)$$

for $0 < H(x) \le 0.5$,

$$SPI = +\left[t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \quad (7)$$

for $0.5 < H(x) \le 1$,

$$t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)} \quad \text{for } 0 < H(x) \le 0.5, \quad (8)$$

$$t = \sqrt{\ln\left(\frac{1}{[1-H(x)]^2}\right)} \quad \text{for } 0.5 < H(x) \le 1, \quad (9)$$

$$c_0 = 2515517;\ c_1 = 0.802853;\ c_2 = 0.010328;$$
$$d_1 = 1.432788;\ d_2 = 0.189269;\ \text{and}\ d_3 = 0.001308. \quad (10)$$

Ghosh (2010) compared four probability distributions, Weibull, normal, lognormal, and Gamma, to fit the monthly monsoon (June–September) rainfall in AM (Assam and Meghalaya) and NMMT (Nagaland, Manipur, Mizoram and Tripura) regions. The study found that Gamma distribution fits the best in both regions. The study period they chose (1951–2000) is also within the study period in the current research. Therefore, the source code of the SPI generator, which is based on Gamma distribution fitting, was not modified in this study. Because SPI values are normalized, they represent both wet and dry conditions equally. Table 1 shows how McKee *et al.* (1993) classified drought situations based on SPI values. In this study, a drought event begins when the SPI reaches –1.0 or lower and ends when the SPI becomes positive. In this study, an SPI generator program developed by the National Drought Mitigation Centre has been employed. This program can calculate SPI at multiple time scales and drought durations for multiple drought severity levels.

Jain *et al.* (2015), Merabti *et al.* (2018), Kumar *et al.* (2019), Surmaini *et al.* (2019), Ekwezuo and Ezeh (2020), Oikonomou *et al.* (2020), Adisa *et al.* (2021), Mianabadi *et al.* (2022), Razmi *et al.* (2022), Saini *et al.* (2022), and Jafarpour *et al.* (2023) are some recent applications of SPI in different parts of the world. Applications of drought indices such as the SPI in the northeastern region of India are very limited. Few recent applications can be found in Pai *et al.* (2010), Guhathakurta *et al.* (2017), Taggu and Shrivastava (2018), Hangshing and Dabral (2018a, b), Sharma *et al.* (2022), and Lairenjam and Hangshing (2023). The ability of SPI to characterize drought in a multitude of time scales makes it a perfect tool for monitoring different variations of drought (Zargar *et al.* 2011; Faiz *et al.* 2021). World Meteorological Organization also recommended using SPI for hydro-meteorological services at the national level (World Meteorological Organization 2012). A seasonal estimation of precipitation, given by a 3-month SPI (SPI03), represents short- and medium-term moisture conditions and could be more useful in illustrating moisture conditions in agricultural areas (World Meteorological Organization 2012). One of the features of drought is how frequently a drought spell resurfaces. In this study, the average inter-arrival time of drought (IAT), which is the average months between two consecutive onsets of drought, was determined.

Table 1. *Classification of drought based on SPI range.*

Drought category	Range of SPI
Moderate drought	–1.49 to –1.00
Severe drought	–1.99 to –1.50
Extreme drought	–2.00 and less

4. Results and discussion

SPI03 of all the districts was averaged each month and displayed in figure 3 to depict the general drought state in Assam. In terms of time coverage, the positive SPI03 (shown by blue colour) was found to be slightly more dominant than the negative SPI03 (represented by orange colour). However, the wettest magnitude of SPI = 2.25, reported in February 1993, was less severe than the driest magnitude of SPI = –3.09, which was observed in February 1999. This plot has shown that there have been occasional droughts in addition to occasional floods in Assam.

When computing a 3-month SPI (SPI03) for a given month, the sum of that month's rainfall and the rainfall from the preceding two months are considered. For instance, SPI03 of May 2000 used the total amount of precipitation in March, April, and May 2000. As a result, it will be helpful to first estimate the SPI03 for August and September of each year since these two series will cover the entire four months of the monsoon season. These values will be crucial for Kharif crops. Likewise, with knowledge of the growing period of a crop, it can be studied for any type of crop. In the present study, out of 70 years (1951–2020), 54 years were affected by drought in the month of August in at least one of the 35 total districts in Assam (figure 4a). Similarly, 53 years of the total 70 years were affected by drought in the month of September in minimum one of the 35 total districts in Assam (figure 4b). Again, in the 70 years period, every district had witnessed at least seven or five drought years in the month of August (figure 5a) and September (figure 5b), respectively. August drought ranged between 7 and 14 years, while September drought ranged between 5 and 14 years

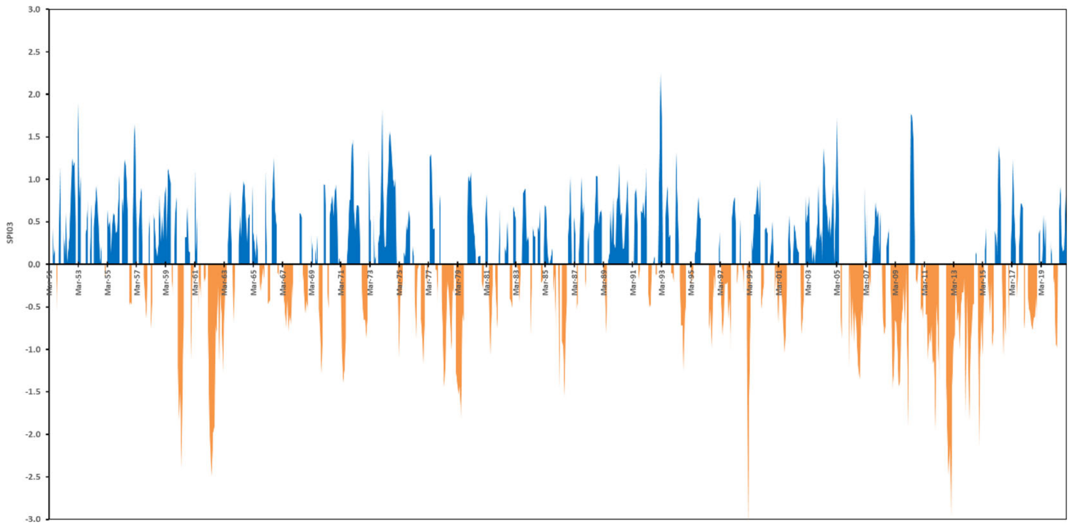


Figure 3. Three-month SPI in Assam.

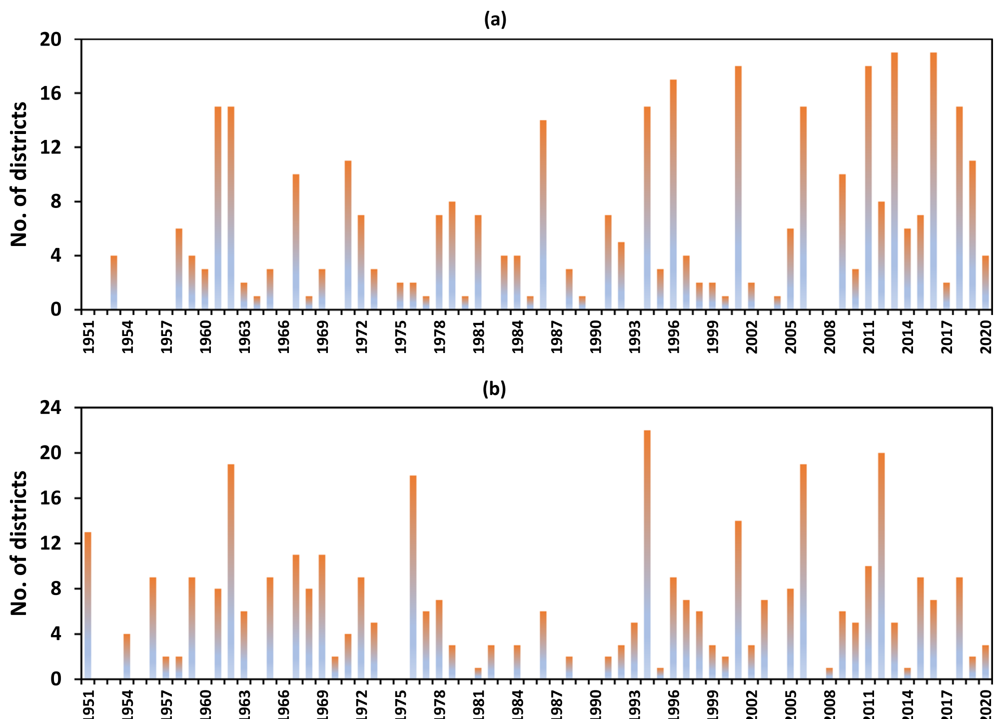


Figure 4. Number of districts affected by (**a**) August drought and (**b**) September drought during the 70 years period.

of the total 70 years. The Charaideo district witnessed the highest number of August droughts (14 years), while Lakhimpur, Bishwanath Chariali, and Bongaigaon districts had the highest number of September droughts with 14 years in total. On average, the percentage of August and September drought for the districts of Assam is approximately 15%.

The years having ten or more drought-affected districts in the month of August are 1961 (15), 1962 (15), 1967 (10), 1971 (11), 1986 (14), 1994 (15), 1996 (17), 2001 (18), 2006 (15), 2009 (10), 2011 (11), 2013 (19), 2016 (19), 2018 (15), and 2019 (11). Similarly, for September drought, they were in the years 1951 (13), 1962 (19), 1967 (11), 1969 (11), 1976 (18), 1994 (22), 2001 (14), 2006 (19), 2011 (10), and 2012 (20). This nature of spatial variability indicates that droughts have been more frequent in the last 35 years of the study period. Also, the periods of 1960s, 2000s, and 2010s have

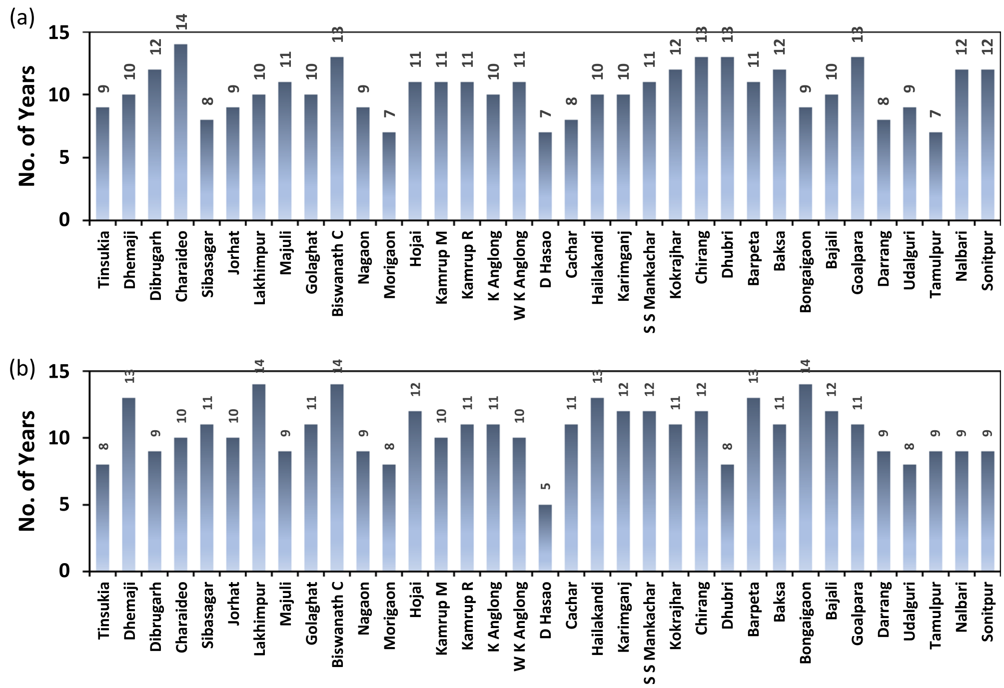
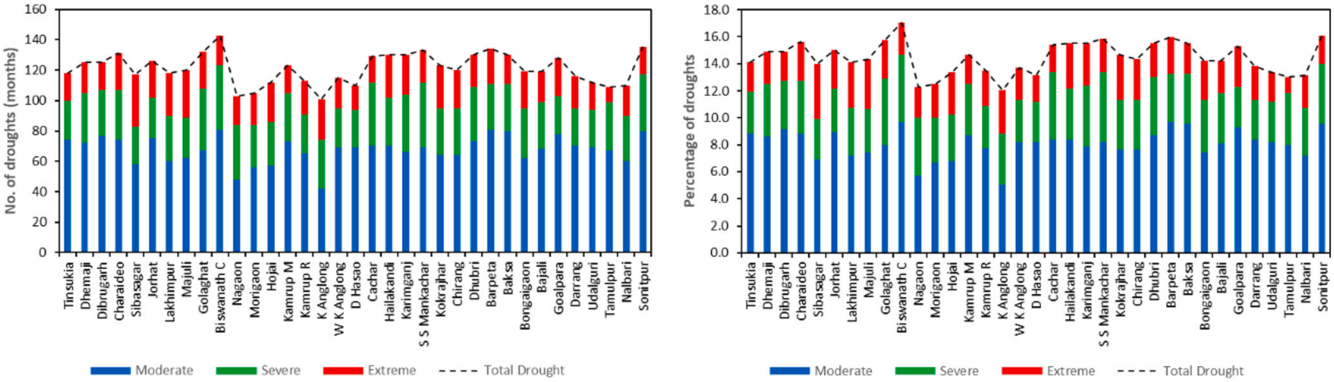


Figure 5. Number of years affected by (**a**) August drought and (**b**) September drought across the 35 districts of Assam.

been more affected by drought. In August 2013, 19 districts, viz., Tinsukia, Dhemaji, Hojai, Kamrup Rural, West Karbi Anglong, Dima Hasao, Cachar, Hailakandi, Karimganj, South Salmara Mankachar, Kokrajhar, Chirang, Dhubri, Barpeta, Baksa, Bongaigaon, Bajali, Goalpara, and Nalbari, were affected by at least moderate drought. Similarly, in August 2016, 19 districts, viz., Dhemaji, Dibrugarh, Charaideo, Jorhat, Majuli, Kamrup Metro, Kamrup Rural, D Hasao, Cachar, Hailakandi, Karimganj, Barpeta, Baksa, Bajali, Darrang, Udalguri, Tamulpur, Nalbari, and Sonitpur were affected by drought. For September, the maximum number of drought-affected districts were seen in 1994 with the 22 drought-affected districts were Tinsukia, Dhemaji, Sivasagar, Jorhat, Lakhimpur, Majuli, Bishwanath Chariali, Nagaon, Hojai, Kamrup Rural, West Karbi Anglong, Cachar, South Salmara Mankachar, Kokrajhar, Chirang, Dhubri, Baksa, Bongaigaon, Goalpara, Darrang, Udalguri, and Tamulpur.

In terms of drought severity, for August, Sivasagar witnessed the most severe drought in 1978, with an extreme SPI value of –3.42. The next severe August drought occurred in Lakhimpur in 2001 (SPI = –3.02), followed by Udalguri in 1971 with an extreme SPI value of –2.75. Similarly, for the September drought, the most extreme drought event occurred in the same district – Sivasagar, in the same year (1978) with an extreme SPI value of –3.84. This was followed by the Kamrup Rural district in 2006 (SPI = –3.27) and then by Bishwanath Chariali district in 2012 (SPI = –3.06). In general, drought events have been more severe in the years – 1994, 1996, 2001, and 2006. Other districts such as Majuli, Hojai, Kokrajhar, Bajali and Bongaigaon were more affected than the rest of the districts in terms of drought magnitude spanning the 70 years period.

In the previous sections, drought events in various districts of Assam in the month of August and September were discussed. Figure 6(a, b) illustrates the number of droughts (moderate, severe, extreme and total drought) and their percentages in the 70 years period considering all the months. It is found that the total number of drought events ranged between 101 and 143 months, indicating that every district in Assam had been affected by drought at least 12.1% of the entire period. On average, the districts in Assam are affected by drought in 121 months (14.5%) of the total 838 months. It comprises 68 months of moderate drought (8.1%), 31 months of severe drought (3.8%), and 22 months of extreme drought (2.6%). The maximum occurred in Bishwanath Chariali with 143 months out of 838 months, with 81 months of moderate nature, 42 months of severe nature, and 20 months of extreme nature. On the other hand, the minimum number of droughts that occurred in the Karbi Anglong district was



(a) (b)

Figure 6. (**a**) Number of droughts and (**b**) percentage of drought in the various districts of Assam for moderate, severe, and extreme drought conditions.

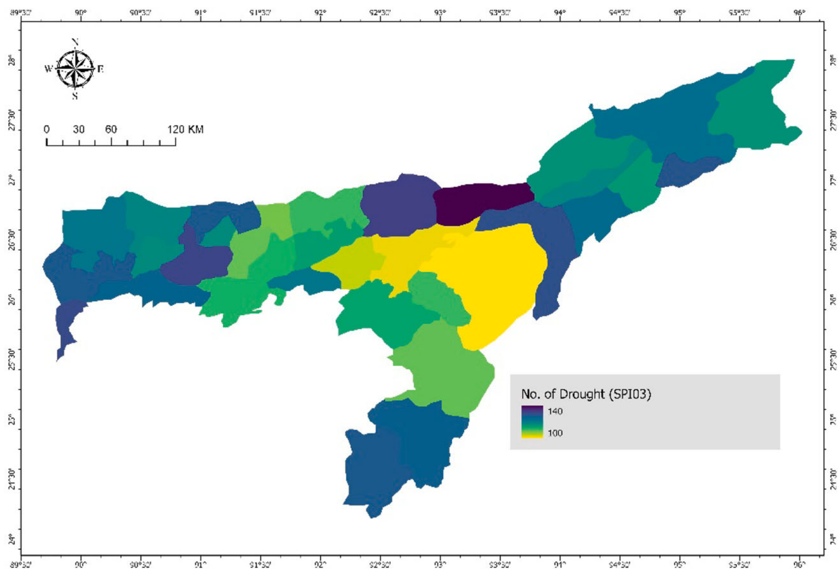


Figure 7. Spatial distribution of total number of droughts in Assam.

101 months. However, 27 months of this is extreme in nature, which is more than Bishwanath Chariali.

The highest number of moderate, severe, and extreme droughts occurred in Bishwanath Chariali (81 months), South Salmara Mankachar (43 months), and Sivasagar (34 months). Tamulpur district was found to be affected by least number of extreme droughts (10 months only). The spatial distribution of the total number of droughts in Assam is shown in figure 7. It shows that droughts are more frequent in the northern (northeastern), western and southern parts of the state. The average number of droughts that occurred in each month of the year is also checked and found that there is little variation, indicating that droughts in Assam occurred in all seasons. Analyzing the time series of SPI values, it is observed that positive SPIs (wet conditions) occurred in the state just a little more than negative SPIs. This shows that there is potential to make up the dry condition, however, the problem arises due to the fact that most of the flood water is not able to enter the soil profile and recharge the groundwater resources of the state. Hence, interventions to increase water entry are required to be taken up as a watershed management practice.

Maximum and average durations of drought occurred in each district of Assam were computed and is shown in figure 8. Average duration of drought due to deficit in rainfall in a cumulative 3-months basis ranges between 4 and 7 months with highest average month in the Tamulpur district. Furthermore, the maximum duration of drought occurred in the state ranges between 14

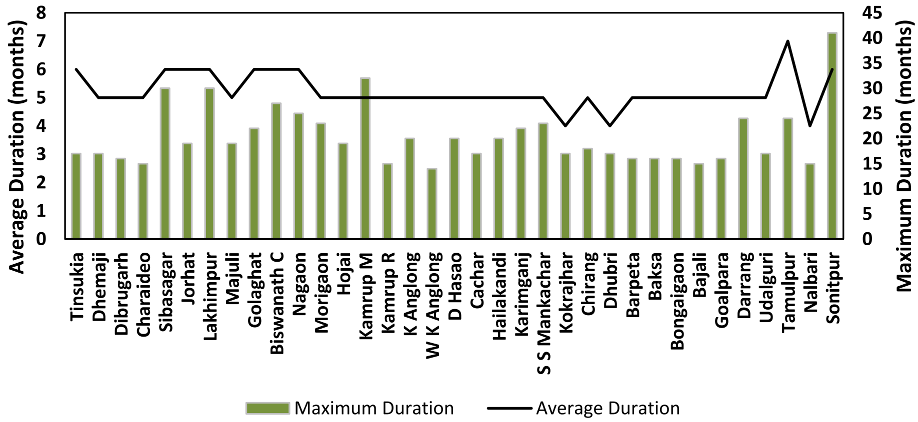


Figure 8. Maximum and average duration of drought in various districts of Assam.

and 41 months. The ranges were observed for districts – West Karbi Anglong (lowest) and Sonitpur (highest). The results showed that the average duration of drought in various districts of Assam is approximately 5.2 months, while the maximum duration is about 20.4 months. Other districts such as Kamrup Metro, Lakhimpur, Sivasagar, and Bishwanath Chariali also had high average duration of droughts.

The SPI generator used in this study can also compute the start and end date of drought spells. For the sake of space in this manuscript, only the onset and end of 3-month droughts for the district with the highest number of droughts (Bishwanath Chariali) is presented in table 2. For all the other districts, it is provided as supplementary material. As seen in the table, there are 41 drought spells in Bishwanath Chariali during the span of 70 years from 1951 to 2020, of which 18 are moderate, 15 are severe, and 8 are extreme drought spells. The most extreme drought spell spans 15 months from July 2012 to October 2013 (peak SPI = –3.83). The drought of August 1959 to July 1960 (peak SPI = –3.43) spanning 11 months and the drought of November 1998 to May 1999 (peak SPI = –2.85) spanning six months are the second and third extreme droughts, respectively, in terms of severity. With respect to duration, the drought of January 2000 to April 2002, spanning more than two years (27 months), was the longest spell, which also happened to be a severe drought. The second and the third longest drought spells occurred in the drought of June 1961 to June 1963 (24 months) and September 2008 to March 2010 (18 months), in which both spells were of the severe drought category. The results indicate that there is no direct relationship between drought severity and its duration. Both of these characteristics are crucial in monitoring drought. A less severe drought with a very long spell would inflict socio-economic damages slowly but would aggregate to huge ones. On the other hand, shorter spell droughts with extreme severity could also cause irreversible damage to crops, thereby affecting the socio-economic conditions. In all the districts, the drought of spells in less than a year comprised more than 80% of all drought spells. In Bishwanath Chariali, of the 41 drought spells, 37 spells had been for less than a year, two spells were between 1 and 2 years, and the other two spells had been for two years and more. The drought spells shown at sl. no. 30–33 given in table 2 are compliant with the report published in Assam State Disaster Management Plan (Assam State Disaster Management Authority 2022).

In this study, the average inter-arrival time (IAT) of drought, or the average interval between the onset of consecutive droughts, was also determined. This parameter indicates how quickly and frequently a drought spell will occur at a particular place. The average IATs for the various districts of Assam are shown in figure 9(a) and their spatial variability is shown in figure 9(b). The average IATs of the districts of Assam range between 15 and 25 months. Smaller IATs indicate the tendency of frequent drought spells and vice-versa. Thus, the Dhubri district, with the smallest average IAT of 15 months, is likely to be affected by frequent drought spells, while Lakhimpur, with the highest average IAT of 25 months, was less affected by frequent drought spells. In a drought vulnerability analysis conducted by IIT Mandi and IIT Guwahati (2020), Dhubri was found to be the most vulnerable district. On analysis, it was

Table 2. *Onset, end, duration, severity, and drought category of 3-month drought (SPI03) in Bishwanath Chariali.*

Sl. no.	Onset	End	Duration (months)	Severity	Drought category
1	Mar-51	Apr-51	1	–1.98	Severe
2	Sep-51	Dec-51	3	–1.51	Severe
3	Feb-52	Sep-52	7	–1.74	Severe
4	Aug-53	Oct-53	2	–1.6	Severe
5	Apr-58	May-58	1	–1.02	Moderate
6	Aug-59	Jul-60	11	–3.43	Extreme
7	Dec-60	Mar-61	3	–1.5	Severe
8	Jun-61	Jun-63	24	–1.63	Severe
9	Oct-66	Feb-67	4	–1.12	Moderate
10	Dec-68	Mar-69	3	–1.58	Severe
11	Dec-69	Jan-70	1	–1.1	Moderate
12	Sep-77	Dec-77	3	–1.32	Moderate
13	Apr-78	Jul-78	3	–1.48	Moderate
14	Feb-79	Nov-79	9	–2.16	Extreme
15	Dec-80	Sep-81	9	–2.79	Extreme
16	Dec-82	Jan-83	1	–1.2	Moderate
17	Mar-84	May-84	2	–1.05	Moderate
18	Mar-86	Apr-86	1	–1.39	Moderate
19	Jun-87	Aug-87	2	–1.09	Moderate
20	Jun-88	Sep-88	3	–1.04	Moderate
21	May-89	Aug-89	3	–1.86	Severe
22	May-92	Dec-92	7	–1.08	Moderate
23	Sep-94	Nov-94	2	–1.36	Moderate
24	Aug-96	Oct-96	2	–1.01	Moderate
25	Apr-97	Jul-97	3	–1.27	Moderate
26	Nov-98	May-99	6	–2.85	Extreme
27	Jan-00	Apr-02	27	–1.9	Severe
28	Jul-02	Jan-03	6	–1.56	Severe
29	Aug-04	Oct-04	2	–1.08	Moderate
30	Jun-05	Feb-06	8	–1.88	Severe
31	May-06	Feb-07	9	–2.74	Extreme
32	Jul-07	Jan-08	6	–1.53	Severe
33	Sep-08	Mar-10	18	–1.98	Severe
34	Feb-11	Mar-11	1	–1.32	Moderate
35	Jun-11	Apr-12	10	–2.43	Extreme
36	Jul-12	Oct-13	15	–3.83	Extreme
37	Jan-14	Jul-14	6	–2.59	Extreme
38	Dec-14	Apr-15	4	–1.93	Severe
39	Nov-15	Jan-16	2	–1.11	Moderate
40	Jan-17	Feb-17	1	–1.21	Moderate
41	Apr-20	Jun-20	2	–1.76	Severe

determined that in most of the districts in Assam, a drought spell (whether it was of only one month or more) occurred every 20 months. A point to be considered is that the above figures are the outcomes of the SPI series computed using 3-month cumulative rainfall. Since SPI03 is effective in monitoring seasonal drought or, to some extent, agricultural drought, in which soil moisture deficit in the last three months is replicated, this study has also suggested that, after every 20 months, at least a month of agricultural/seasonal drought had occurred in most of the districts in Assam. To understand the importance of time scale selection, average IATs for SPI12 and SPI24 were also determined. These two SPIs signify the deficit in rainfall accumulated over 12 and 24 months, respectively. It is found that the average inter-arrival time of drought for deficit rainfall over

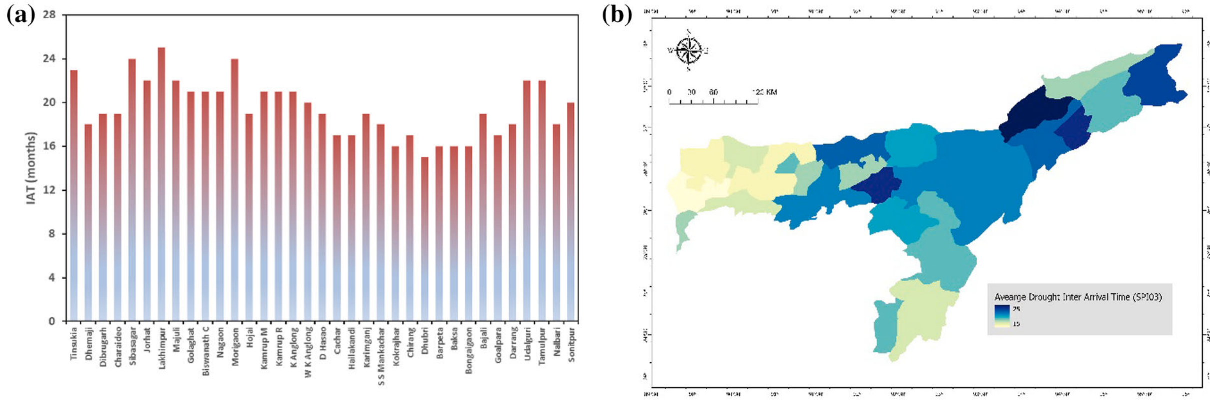


Figure 9. Average inter-arrival time of drought in various districts of Assam.

12- and 24-month periods is approximately 6 and 10.5 years. The spatial distribution in figure 9(b) shows that drought spells repeated quicker in the western Assam (Dhubri district lies in this region) and also in the southern region of Assam. Central and northern parts of Assam were comparatively less affected by frequent drought spells.

Sahana *et al.* (2021) mentioned that Assam is one of the states in India that is affected by moderate to severe drought and is also put in the moderate to severe drought risk category. The Disaster Management Authority of Assam (Assam State Disaster Management Authority 2022) has also reported that the majority of the districts in Assam, except southern districts, would be more vulnerable to drought in the future, with a potential increase in the number of drought weeks. The above drought occurrences do not necessarily translate to the worst conditions. A district well-equipped with irrigation systems and water resources could cope with the drought situation easily. So, a vulnerability analysis would add value to the preparation of a framework for drought mitigation planning in the state, which is currently taking place with consideration of both the physical and socio-economic status of the state. Districts with a greater number of droughts, greater duration of drought spells, and smaller IATs between two consecutive drought spells are recommended to fasten mitigation and adaptation planning. The results of this study, which used the recommended drought indicator – SPI at a 3-month time scale, would benefit the efforts being made by the Disaster Management Authority, Agriculture Department, Irrigation Department, and Water Resources Department of Assam in proper planning, action, and management of several entities with regards to drought in the state.

5. Conclusions

This study found that 91% of the average annual rainfall occurred during pre-monsoon and monsoon seasons, suggesting great dependency on these two seasons for the growth of agriculture sectors. This also led to the suggestion that there is an urgent need to turn to irrigation-based systems from the traditional rainfed ecosystems. The dominant positive SPI series also suggested that there is enough potential for developing an irrigation system and recharging groundwater resources. The percentage of August and September droughts representing monsoonal drought in Assam was approximately 15% in the 70 years (1951–2020) period. Also, the total percentage of drought in Assam was about 14.5% of the entire period, suggesting that irrespective of the season, drought will occur. Based on the number of droughts, Bishwanath Chariali was the most affected district, while Karbi Anglong was the least affected one. In terms of severity, Sivasagar district was found to be affected by the greatest number of droughts of extreme nature. The average duration of drought in Assam was found to be about 5.2 months, in which Sonitpur, Kamrup Metro, Lakhimpur, Sivasagar, and Bishwanath Chariali districts had high drought durations. This study also found that droughts occur faster in the western region of Assam, including Dhubri district, which had the lowest IAT of SPI03 drought. It is concluded that districts with a greater number of droughts, greater duration of drought spells and smaller IATs between two consecutive drought spells are required to set up drought mitigation planning.

Author statement

All authors contributed to the preparation of the manuscript. Waikhom Rahul Singh and Swapnali Barman contributed to the conception, analysis, and interpretation of the results of the study. Annu Taggu contributed to the analysis of drought duration. Nilutpal Hazarika and Biman Kalita contributed to the preprocessing of input data. SV VijayaKumar contributed to the final structuring of the manuscript.

References

Adisa O M, Masinde M and Botai J O 2021 Assessment of the dissimilarities of EDI and SPI measures for drought determination in South Africa; *Water* **13(1)** 82, https://doi.org/10.3390/w13010082.

Arumugam J and Anbazhagan S 2017 Drought hazard assessment in Ponnaiyar River Basin, India using remote sensing and geographic information system; *Int. J. Earth Sci. Eng.* **10(02)** 247–256.

Assam State Disaster Management Authority 2015 *Assam State Disaster Management Plan*, Government of Assam, 195p, https://smartnet.niua.org/sites/default/files/resources/asdmp.pdf.

Assam State Disaster Management Authority 2022 *Assam State Disaster Management Plan*, Vol. 1 (Perspective Plan), Government of Assam, 170p, https://asdma.assam.gov.in/sites/default/files/swf_utility_folder/departments/asdma_revenue_uneecopscloud_com_oid_70/this_comm/asdmp_vol-_i.pdf.

Deka R L, Mahanta C, Pathak H, Nath K K and Das S 2013 Trends and fluctuations of rainfall regime in the Brahmaputra and Barak basins of Assam, India; *Theor. Appl. Climatol.* **114** 61–71, https://doi.org/10.1007/s00704-012-0820-x.

Department of Environment and Forests 2015 *Assam State Action Plan on Climate Change (2015–2020)*, Government of Assam, 127p, http://moef.gov.in/wp-content/uploads/2017/08/ASSAM-SAPCC.pdf.

Dogan S, Berktay A and Singh V P 2012 Comparison of multi-monthly rainfall-based drought severity indices, with application to semi-arid Konya closed basin, Turkey; *J. Hydrol.* **470–471** 255–268, https://doi.org/10.1016/j.jhydrol.2012.09.003.

Edwards D C and McKee T B 1997 Characteristics of 20th Century drought in the United States at multiple time scales; In: *Climatology Report Number 97-2*, Colorado State University, Fort Collins.

Ekwezuo C S and Ezeh C U 2020 Regional characterisation of meteorological drought and floods over west Africa; *Sustain. Water Resour. Manag.* **6** 80, https://doi.org/10.1007/s40899-020-00439-y.

Faiz M A, Zhang Y, Ma N, Baig F, Naz F and Niaz Y 2021 Drought indices: Aggregation is necessary or is it only the researcher's choice?; *Water Supply* **21(8)** 3987–4002, https://doi.org/10.2166/ws.2021.163.

Ghosh S 2010 Modelling bivariate rainfall distribution and generating bivariate correlated rainfall data in neighbouring meteorological subdivisions using copula; *Hydrol. Process.* **24** 3558–3567, https://doi.org/10.1002/hyp.7785.

Guhathakurta P, Menon P, Inkane P M, Krishnan U and Sable S T 2017 Trends and variability of meteorological drought over the districts of India using standardized precipitation index; *J. Earth Syst. Sci.* **126** 120, https://doi.org/10.1007/s12040-017-0896-x.

Gurrapu S, Chipanshi A, Sauchyn D and Howard A 2014 Comparison of the SPI and SPEI on predicting drought conditions and streamflow in the Canadian prairies; In: Proceedings of the 28th Conference on Hydrology. American Meteorological Society Atlanta, USA, 5p.

Hangshing L and Dabral P P 2018a Characterisation, trend assessment and copula based bivariate modelling of meteorological drought for central Brahmaputra valley – an agro climatic zone of Assam; *J. Indian Water Resour. Soc.* **38(1)**.

Hangshing L and Dabral P P 2018b Multivariate frequency analysis of meteorological drought using copula; *Water Resour. Manage.* **32** 1741–1758, https://doi.org/10.1007/s11269-018-1901-0.

IIT Mandi and IIT Guwahati 2020 Climate vulnerability assessment for adaptation planning in India using a common framework, in collaboration with Indian Institute of Science, Bengaluru under the project Climate vulnerability and risk assessment at the national level using a common framework, 184p.

Jafarpour M, Adib A, Lotfirad M and Kisi O 2023 Spatial evaluation of climate change-induced drought characteristics in different climates based on De Martonne Aridity Index in Iran; *Appl. Water Sci.* **13** 133, https://doi.org/10.1007/s13201-023-01939-w.

Jain V K, Pandey R P, Jain M K and Byun H R 2015 Comparison of drought indices for appraisal of drought characteristics in the Ken River Basin; *Wea. Clim. Extreme* **8** 11, https://doi.org/10.1016/j.wace.2015.05.002.

Jhajharia D, Shrivastava S K, Tulla P S and Sen R 2007 Rainfall analysis for drought proneness at Guwahati; *Indian J. Soil Cons.* **35(2)** 163–165.

Keyantash J and Dracup J A 2002 The quantification of drought: An evaluation of drought indices; *Bull. Am. Meteorol. Soc.* **83** 1167–1180.

Kumar A, Mishra S K, Pandey R P, Himanshu S K and Singh S 2019 Standardized precipitation index-based approach to predict environmental flow condition; *Ecohydrology*, https://doi.org/10.1002/eco.2127.

Kusre B C and Lalringliana J 2014 Drought characterization and management in the East district of Sikkim, India; *Irrig. Drain.* **63** 698–708.

Lairenjam C and Hangshing L 2023 Drought assessment in Kohima, Nagaland, India, using the standardized precipitation index (SPI); In: *AIP Conference Proceedings* **2690** 020017, https://doi.org/10.1063/5.0119452.

McKee T B, Doesken N J and Kleist J 1993 The relationship of drought frequency and duration to time scale; In: *Proceedings of the Eighth Conference on Applied Climatology,* *Anaheim, California*, 17–22 January 1993, Boston, American Meteorological Society, pp. 179–84.

Merabti A, Meddi M, Martins D S and Pereira L S 2018 Comparing SPI and RDI applied at local scale as influenced by climate; *Water Resour. Manage.* **32** 1071–1085.

Mianabadi A, Salari K and Pourmohamad Y 2022 Drought monitoring using the long-term CHIRPS precipitation over Southeastern Iran; *Appl. Water Sci.* **12** 183, https://doi.org/10.1007/s13201-022-01705-4.

Morid S, Smakhtin V and Moghaddasi M 2006 Comparison of seven meteorological indices for drought monitoring in Iran; *Int. J. Climatol.* **26** 971–985.

NDMA 2010 National Disaster Management Guidelines, Management of Drought, National Disaster Management Authority, Government of India, 108p.

Neog P, Sarma P K, Saikia D, Borah P, Hazarika G N, Sarma M K, Sarma D, Chary G R and Rao C S 2020 Management of drought in sali rice under increasing rainfall variability in the North Bank Plains Zone of Assam, North East India; *Clim. Change* **158** 473–484, https://doi.org/10.1007/s10584-019-02605-4.

Nongbri B, Feroze S M, Ray L I P and Devarani L 2016 Assessment of risk due to exposure to drought: A study of farm households of Nagaland; *Indian J. Agric. Econ.* **71(3)** 325–334.

Oikonomou P D, Karavitis C A, Tsesmelis D E, Kolokytha E and Maia R 2020 Drought characteristics assessment in Europe over the past 50 years; *Water Resour. Manage.* **34** 4757–4772, https://doi.org/10.1007/s11269-020-02688-0.

Pai D S, Sridhar L, Guhathakurta P and Hatwar H R 2010 District-wise drought climatology of the southwest monsoon season over India based on Standardized Precipitation Index (SPI); Research Report No: 2/2010, National Climate Centre, India Meteorological Department.

Pai D S, Sridhar L, Rajeevan M, Sreejith O P, Satbhai N S and Mukhopadhyay B 2014 Development of a new high spatial resolution ($0.25° \times 0.25°$) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region; *Mausam* **65** 1–18.

Pandey R P and Ramasastri K S 2001 Relationship between the common climatic parameters and average drought frequency; *Hydrol. Process.* **15** 1019–1032, https://doi.org/10.1002/hyp.187.

Parida B R and Oinam B 2015 Unprecedented drought in North East India compared to Western India; *Curr. Sci.* **109(11)** 2121–2126.

Rathore L S, Attri A D and Jaswal A K 2013 State level climate change trends in India; In: *Meteorological Monograph* (ESSO/IMD/EMRC/02/2013), India Meteorological Department, Govt of India.

Ray L I P, Bora P K, Singh V, Singh A K, Singh R and Feroze S M 2013 Meteorological drought occurrences in Tura, Meghalaya, India; *E-planet* **10(2)** 07–11.

Ray L I P, Bora P K, Singh A K, Singh R, Feroze S M, Singh N J and Das T R 2015 Meteorological drought in Cherrapunjee, Meghalaya; *J. Indian Water Resour. Soc.* **35(4)** 1–6.

Corresponding editor: Parthasarathi Mukhopadhyay

Razmi R, Sotoudeh F, Ghane M and Ostad-Ali-Askari K 2022 Temporal-spatial analysis of drought and wet periods: Case study of a wet region in Northwestern Iran (East Azerbaijan, West Azerbaijan, Ardebil and Zanjan provinces); *Appl. Water Sci.* **12** 251, https://doi.org/10.1007/s13201-022-01765-6.

Sahana V, Mondal A and Sreekumar P 2021 Drought vulnerability and risk assessment in India: Sensitivity analysis and comparison of aggregation techniques; *J. Environ. Manage.* **299**, https://doi.org/10.1016/j.jenvman.2021.113689.

Saini D, Singh O and Bhardwaj P 2022 Standardized precipitation index based dry and wet conditions over a dryland ecosystem of northwestern India; *Geol. Ecol. Landsc.* **6(4)** 252–264, https://doi.org/10.1080/24749508.2020.1833614.

Sharma A P M, Jhajharia D, Gupta S and Yurembam G S 2022 Multiple indices based agricultural drought assessment in Tripura, northeast India; *Arab. J. Geosci.* **15**, https://doi.org/10.1007/s12517-022-09855-0.

Shrivastava S K, Rai R K and Pandey A 2008 Assessment of meteorological droughts in North Lakhimpur district of Assam; *J. Indian Water Resour. Soc.* **28(2)** 26–31.

Surmaini E, Susanti E, Syahputra M R and Hadi T W 2019 Exploring Standardized Precipitation Index for predicting drought on rice paddies in Indonesia; In: *IOP Conference Series: Earth and Environmental Science, Vol. 303, International Conference On Tropical Meteorology And Atmospheric Sciences*, 19–20 September 2018, Bandung, Indonesia, https://doi.org/10.1088/1755-1315/303/1/012027.

Taggu A and Shrivastava S K 2018 Meteorological drought characterization of stations of humid Northeast India using SPI; In: *International Seminar on Land and Water Issues in South East Asia: Status, Challenges and Opportunities at NERIWALM*, Tezpur (Assam), India, 18–20 January 2018.

Thom H C S 1966 Some methods of climatological analysis; WMO technical note number 81, Secretariat of the World Meteorological Organization, Geneva.

White D H and Walcott J J 2009 The role of seasonal indices in monitoring and assessing agricultural and other droughts: A review; *Crop Pasture Sci.* **60** 599–616.

World Meteorological Organization 2012 Standardized Precipitation Index User Guide, WMO-No. 1090, Geneva, ISBN 978-92-63-11091-6, 24p.

Zargar A, Sadiq R, Naser B and Khan F I 2011 A review of drought indices; *Environ. Rev.* **19** 333–349.