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Research Article

Spatiotemporal Variation in Agricultural Drought Conditions in Northwestern Bangladesh under a Changing Climate

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ABSTRACT

Drought threatens agriculture and water security in northwestern Bangladesh, yet its multi-scale seasonal characteristics remain insufficiently understood. This study assessed SPEI-based drought variability at six meteorological stations across 1-, 3-, 6-, 9-, 12-, and 24-month scales. Monthly precipitation and temperature records from 1976–2022 were used to calculate SPEI. Seasonal drought was evaluated for Rabi (November–February), Kharif-I (March–June), and Kharif-II (July–October) using the four-month SPEI ending in February, June, and October, respectively. Trends were examined using the Mann–Kendall test and Sen's slope estimator, with magnitude expressed as SPEI units yr^{-1}. Drought conditions were classified using SPEI values as mild (-0.99 to 0.00), moderate (-1.49 to -1.00), severe (-1.99 to -1.50), and extreme drought (≤ -2.00). Drought frequency in each drought category was compared between earlier and recent periods. Drought calculated from SPEI values increased across most stations and time scales, with stronger intensification at longer scales. Among stations considered, Rajshahi showed the steepest long-term decline at SPEI-24 (Sen's slope = -0.0538 SPEI units yr^{-1}), followed by Syedpur, Bogura, Rangpur, Ishwardi, and Dinajpur. Extreme drought at SPEI-24 became more frequent during 2006–2022, reaching 19.1% of valid months in Bogura, 23.0% in Rajshahi, and 20.6% in Rangpur. Kharif-II drought increased at Bogura and Dinajpur (-0.04 SPEI units yr^{-1}) and at Rajshahi and Rangpur (-0.03 SPEI units yr^{-1}), suggesting increasing water stress during the late-monsoon to post-monsoon transition. Rangpur and Dinajpur (-0.03 and -0.05 SPEI units yr^{-1}, respectively) also experienced significant drought stress during Rabi season, while Kharif-I drought trends were weak and mostly non-significant. Overall, drought conditions in northwestern Bangladesh are becoming more persistent and seasonally consequential, supporting multi-scale SPEI monitoring for irrigation scheduling, seasonal preparedness, and climate-resilient agricultural planning.

Introduction

Bangladesh is exposed to a wide range of hydroclimatic hazards, but drought poses a distinctive challenge because it develops gradually, can persist across seasons, and affects both water supply and agricultural production (Mahmud et al., 2021). The northwestern part of Bangladesh, including the Barind region and adjacent districts, is particularly vulnerable to drought because rainfall is comparatively variable and dry-season evaporative demand is high (Shahid and Behrawan, 2008; Habiba et al., 2011; Rahman and Lateh, 2016). Drought-prone climate conditions create water stress and consequently make irrigated agriculture more vulnerable to drought. Repeated rainfall and soil-moisture deficits in this region can reduce soil-water availability, delay crop establishment, increase groundwater abstraction for irrigation, and raise production risks for farming households.

Drought is commonly described as meteorological, agricultural, hydrological, or socioeconomic, depending on the part of the water–human system being affected (Heim, 2002). These forms are related but do not necessarily begin or end at the same time. A precipitation deficit may first appear as meteorological drought, then develop into agricultural drought as root-zone moisture declines, and later affect streamflow, reservoir storage, and groundwater. Consequently, drought monitoring requires indices that can represent both short-lived moisture deficits and longer cumulative

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anomalies relevant to seasonal crops and water resources.

The Standardized Precipitation Index (SPI) has been widely used in Bangladesh because it is simple and can be calculated at different accumulation periods (Shahid and Behrawan, 2008; Alamgir et al., 2015; Mortuza et al., 2019). Its exclusive reliance on precipitation, however, limits its ability to capture the effect of warming and associated changes in atmospheric water demand. The Standardized Precipitation Evapotranspiration Index (SPEI) addresses this limitation by standardizing the climatic water balance between precipitation and potential evapotranspiration (Vicente-Serrano et al., 2010). The SPEI retains the multi-scalar structure of precipitation-based indices while incorporating temperature-sensitive evaporative demand, making it particularly useful for drought assessment under a changing climate (Beguería et al., 2014; Miah et al., 2017).

Previous studies have documented substantial drought exposure in western and northwestern Bangladesh and have examined meteorological or agricultural drought using several indices (Akter and Rahman, 2012; Kamruzzaman et al., 2019; Rahman et al., 2021). Nevertheless, three issues require further attention for multiple reasons. First, a single accumulation period cannot represent both short agricultural moisture stress and prolonged water-resource deficits. Second, comparisons between earlier and recent periods are needed to show whether the distribution of drought categories is changing. Third, season-specific analysis is important because the same annual drought signal may have different consequences during the irrigated Rabi season and the two Kharif seasons. This study therefore examines drought conditions at six meteorological stations in northwestern Bangladesh using SPEI at accumulation periods from 1 to 24 months. The objectives were to determine the direction and magnitude of long-term SPEI trends, compare the frequency of drought categories between earlier and recent periods, and evaluate changes in agricultural drought conditions during Rabi, Kharif-I, and Kharif-II crop seasons. The analysis is intended to provide a transparent, station-based assessment that can inform drought monitoring and agricultural water-management decisions.

Materials and Methods

Study area and data

The analysis covered six meteorological stations in northwestern Bangladesh: Bogura, Rajshahi, Rangpur, Dinajpur, Ishwardi, and Syedpur (Figure 1). These stations represent a broad range of climatic conditions within a region where crop production is highly sensitive to rainfall variability and dry-season water availability. The water-scarce Barind Tract is also located within this region, where irrigated agriculture depends predominantly on groundwater. Monthly precipitation and temperature records were compiled for the period 1976–2022, subject to data availability at each station. A few stations, including Rangpur, Dinajpur, and Syedpur, had shorter historical records. These differences in record length were taken into account when comparing various drought conditions between the earlier and more recent periods. Before analysis, the monthly series were screened for internal consistency and missing observations. Missing observations were treated before calculating the climatic water balance and SPEI. For isolated short gaps, missing daily values were estimated by averaging the immediately preceding and following observations. For moderate gaps, values were estimated using the average of the corresponding period in the previous and following years. For longer gaps, the long-term mean for the corresponding month was used. The completed daily records were then aggregated to monthly precipitation and temperature series, which were used to calculate PET, climatic water balance, and SPEI. Thus, SPEI fitting was performed using the completed monthly time series for each station, while station-specific record lengths were retained according to data availability.

Calculation of SPEI

SPEI was selected because it incorporates both precipitation supply and temperature-related atmospheric demand (Vicente-Serrano et al., 2010). For month i, the climatic water balance was calculated as:

$D_i = P_i - PET_i$

where D_i is the climatic water balance, P_i is monthly precipitation, and PET_i is monthly potential evapotranspiration. Potential evapotranspiration (PET) was estimated using the Hargreaves method implemented in the SPEI package in R. This method was selected because the available long-term monthly station records mainly included precipitation and temperature, whereas the additional meteorological variables required for the FAO-56 Penman–Monteith method, particularly wind speed, relative humidity, and solar radiation or sunshine duration, were not consistently available for all stations and years. Therefore, FAO-56 Penman–Monteith PET estimation was not feasible for maintaining a consistent multi-station time series. The Hargreaves method is commonly used under such data-limited conditions and is suitable for SPEI calculation at the monthly scale (Droogers and Allen, 2002; Hargreaves and Allen, 2003)

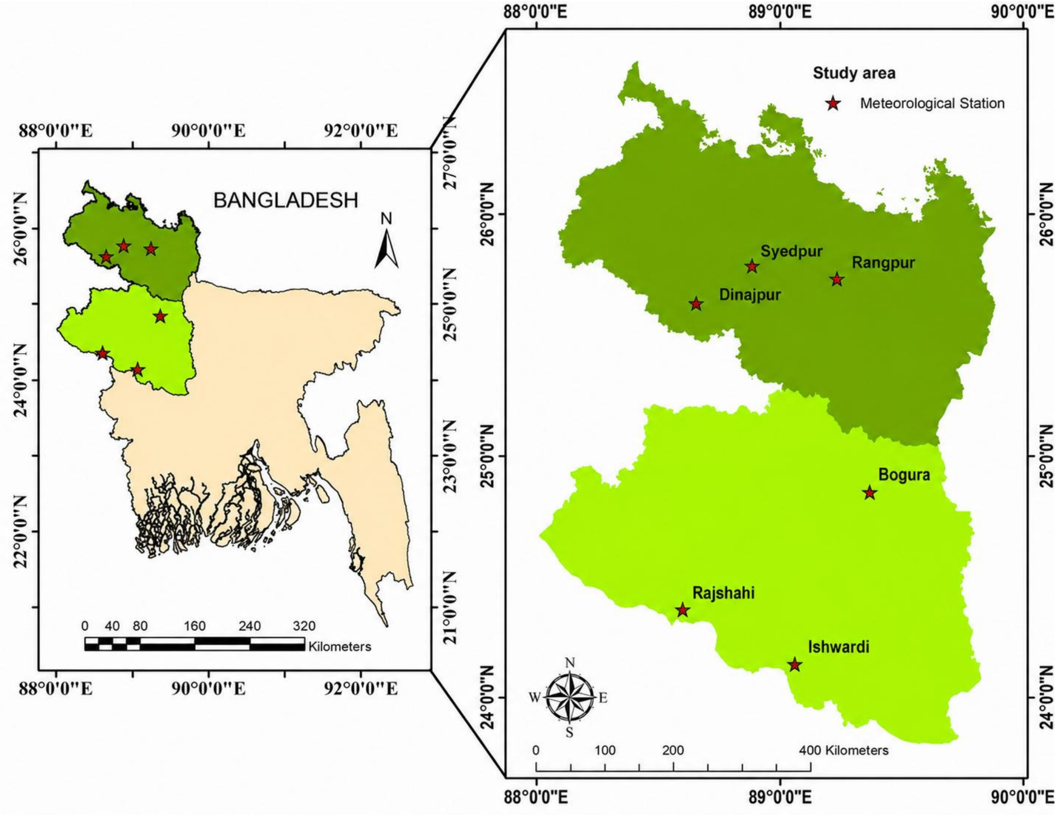

Figure 1. Location of the six meteorological stations in northwestern Bangladesh

The water-balance series was accumulated over 1, 3, 6, 9, 12, and 24 months to represent drought processes operating over different time horizons. The accumulated values were fitted to a log-logistic distribution and transformed to standardized SPEI values following Vicente-Serrano et al. (2010) and Beguería et al. (2014). SPEI values were standardized using 1981–2000 as the reference period, so negative and positive SPEI values represent departures from this baseline climate rather than deviations from the full 1976–2022 record. For stations with shorter records, the available observations within the reference period were used for standardization.

Drought classification and frequency

Drought severity was classified using commonly applied standardized drought-index thresholds proposed by McKee et al. (1993), recommended by the World Meteorological Organization (2012), and recently applied in SPEI-based drought assessment by Samim et al. (2025). Because SPEI is a standardized and dimensionless index, these thresholds represent standardized departures from the reference-period climatic water balance. Accordingly, drought categories were defined as mild drought (-0.99 ≤ SPEI < 0.00), moderate drought (-1.49 ≤ SPEI ≤ -1.00), severe drought (-1.99 ≤ SPEI ≤ -1.50), and extreme drought (SPEI ≤ -2.00) (Table 1). Values at or above zero were treated as non-drought conditions.

The percentage of months in each drought category was calculated as:

$$DF_i = (n_i/N) \times 100$$

where DF_i is the frequency of drought category i, n_i is the number of months with SPEI values falling within drought category i, and N is the total number of valid months in the comparison period. Thus, frequency refers to the percentage of months belonging to each drought-severity category rather than the number of independent drought episodes.

Table 1. Classification of drought severity based on SPEI values

SPEI value	Drought category
≥ 0.00	Non drought
-0.99 to 0.00	Mild drought
-1.49 to -1.00	Moderate drought
-1.99 to -1.50	Severe drought
≤ -2.00	Extreme drought

Note: The SPEI thresholds follow commonly used standardized drought-index classification ranges proposed by McKee et al. (1993) and recommended by the World Meteorological Organization (2012). SPEI is dimensionless; values represent standardized departures from the reference-period climatic water balance.

Trend analysis

Temporal trends in the Standardized Precipitation Evapotranspiration Index (SPEI) were evaluated using the non-parametric seasonal Mann–Kendall (SMK) test and the seasonal Sen's slope estimator (Mann, 1945; Kendall, 1975; Sen, 1968; Hirsch et al., 1982). The SMK test was selected because it detects monotonic trends without requiring normally distributed data and accounts for recurring seasonal differences by comparing observations from the same calendar month across years. For each station, SPEI series at the 1-, 3-, 6-, 9-, 12-, and 24-month accumulation scales were analysed separately. A negative test statistic or Sen's slope indicates declining SPEI and increasing drought tendency, whereas a positive value indicates increasing SPEI and wetter conditions. Statistical significance was assessed using a two-sided test at $p < 0.05$, and Sen's slope was reported in SPEI units yr^{-1}. Trend calculations were performed in R using the smk.test() function of the trend package and related functions from the Kendall package.

The smk.test() procedure accounts for seasonality and tied values but does not apply an explicit serial-correlation correction. This limitation is relevant for longer accumulation periods, particularly SPEI-12 and SPEI-24, because overlapping monthly water-balance totals can introduce autocorrelation and may inflate Mann–Kendall significance. Therefore, statistical significance at longer SPEI scales was interpreted cautiously, with greater emphasis placed on the direction, consistency, and magnitude of Sen's slope. The potential influence of serial dependence was considered following Hirsch and Slack (1984).

Seasonal Mann–Kendall test

Let x(i,g) denote the SPEI observation in year i and season g, where g = 1, 2, …, p and p = 12 for monthly data. For any difference u, the sign function is defined as:

$$\operatorname{sgn}(u) = \begin{cases} 1, & u > 0 \\ 0, & u = 0 \\ -1, & u < 0 \end{cases} \tag{1}$$

The Mann–Kendall score for season g is calculated from all chronologically ordered pairs within that season:

$$S_g = \sum_{i=1}^{n_g - 1} \sum_{i=i+1}^{n_g} \operatorname{sgn}(x_{jg} - x_{ig} 0, \;\; g = 1,2,\ldots p \tag{2}$$

where n(g) is the number of observations available in season g. The overall seasonal Mann–Kendall statistic is the sum of the season-specific scores:

$$s = \sum_{g=1}^{p} s_g \tag{3}$$

Under the null hypothesis, E[S(g)] = 0. When tied values occur within a season, the variance of S(g) is corrected as follows:

$$\operatorname{var}(s_g) = \frac{n_g(n_g - 1)(zn_g + 5) - \sum_{r=1}^{q_g} t_{rg}(t_{rg} - 1)(2t_{rg} + 5)}{18} \tag{4}$$

where q(g) is the number of tied groups in season g and t(r,g) is the number of observations in the rth tied group. In the general form, the variance of the overall statistic may include covariance among seasonal scores:

$$Var(S) = \sum_{g=1}^{p} Var(S_g) + 2 \sum_{g=1}^{p-1} \sum_{h=g+1}^{p} Cov(S_g, S_n) \tag{5}$$

For the standard seasonal Mann–Kendall implementation, the seasonal scores are assumed to be independent and the covariance terms are zero; therefore:

$$Var(S) = \sum_{g=1}^{p} Var(S_g) \tag{6}$$

The standardised statistic, with continuity correction, is:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, & S > 0 \\ 0, & S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, & S < 0 \end{cases} \tag{7}$$

For a two-sided test, the probability value is obtained from the standard normal distribution:

$$P = 2\left[1 - \Phi\left|Z\right|\right] \tag{8}$$

where Φ(·) is the cumulative distribution function of the standard normal distribution. A statistically significant negative Z value indicates a drying trend, whereas a statistically significant positive Z value indicates a wetting trend.

Seasonal Sen's slope estimator

The magnitude of change was quantified using the seasonal Sen's slope estimator. This estimator is resistant to extreme observations because it is based on the median of pairwise slopes rather than a least-squares fit. Pairwise slopes were calculated only between observations belonging to the same season:

$$d_{gij} = \frac{x_{jg} - x_{ig}}{t_j - t_i}, \quad 1 \le i < j \le n_g,\ g = 1,2,\ldots\ldots, p \tag{9}$$

where t_i and t_j are the observation times expressed in years. For regularly spaced annual observations within each calendar month, $t_j - t_i$ is equivalent to j − i. After all within-season pairwise slopes were arranged in ascending order, the seasonal Sen's slope was estimated as their median:

$$\hat{\beta} = \text{median}\ \left\{d_{gij}\right\} \tag{10}$$

If N pairwise slopes are available and d(1) ≤ d(2) ≤ … ≤ d(N) are the ordered slopes, the median is given by:

$$\hat{\beta} = \begin{cases} d_{\left(\frac{N+1}{2}\right)}, & N\ odd \\ \dfrac{d_{\left(\frac{N}{2}\right)} + d_{\left(\frac{N}{2}+1\right)}}{2}, & N\ even \end{cases} \tag{11}$$

The estimated slope is reported in SPEI units per year. A negative slope indicates that SPEI decreased through time, corresponding to increasing drought tendency, whereas a positive slope indicates a wetting tendency.

Trend analysis of cropping-season droughts

Drought conditions of different cropping seasons were represented using SPEI at a four-month accumulation scale (SPEI-4). The February, June, and October SPEI-4 values were extracted to represent the droughts of Rabi (November–February), Kharif-I (March–June), and Kharif-II (July–October) seasons, respectively. Each resulting series contained one observation per year. Therefore, the Mann–Kendall test and Sen's slope estimator were applied separately to the annual series for each cropping season and station. This is equivalent to the above formulation with a single season (p = 1).

Results

Temporal trends in SPEI

SPEI trends were predominantly negative across the six meteorological stations and all six-time scales, namely 1, 3, 6, 9, 12, and 24 months (Table 2). This widespread pattern indicates an overall shift toward drier climatic conditions across northwestern Bangladesh. In general, the magnitude of the negative Sen's slopes increased with the accumulation period, showing that long-term moisture deficits intensified more strongly than short-term fluctuations.

At shorter accumulation periods, the strength and statistical significance of the trends varied among stations. For SPEI-1, Dinajpur showed a small, non-significant positive trend, while Syedpur exhibited a negative but non-significant trend. At SPEI-3 and SPEI-6, Dinajpur continued to show weak and statistically non-significant drying, whereas the remaining stations generally displayed significant negative trends. These short-term variations suggest that monthly and seasonal moisture conditions were still strongly affected by interannual climatic variability.

A more spatially consistent pattern emerged at longer accumulation periods. From SPEI-9 onward, all six stations showed negative trends, and many of these trends were statistically significant under the seasonal Mann–Kendall test. However, because SPEI-12 and SPEI-24 are based on overlapping accumulation windows, these longer-scale series may be serially autocorrelated. Therefore, the statistical significance of long-scale trends should be interpreted cautiously in the absence of an explicit serial-correlation correction. The strongest long-term decline was observed at Rajshahi, where the SPEI-24 Sen's slope reached -0.0538 SPEI units yr^{-1}. This was followed by Syedpur (-0.0430 SPEI units yr^{-1}), Bogura (-0.0420 SPEI units yr^{-1}), Rangpur (-0.0406 SPEI units yr^{-1}), Ishwardi (-0.0336 SPEI units yr^{-1}), and Dinajpur (-0.0328 SPEI units yr^{-1}). Thus, the longer-scale results are interpreted mainly in terms of the consistent negative direction and larger Sen's slope magnitudes, rather than statistical significance alone.

Table 2. Sen's slope of SPEI at multiple time scales for selected meteorological stations in northwestern Bangladesh. Values are expressed in SPEI units yr^{-1}.

SPEI time scale	Bogura	Rajshahi	Rangpur	Dinajpur	Ishwardi	Syedpur
SPEI-1	-0.009**	-0.0068*	-0.0124***	0.0015 (NS)	-0.0125***	-0.00795 (NS)
SPEI-3	-0.013***	-0.0165***	-0.0133***	-0.002 (NS)	-0.00925**	-0.0139*
SPEI-6	-0.021***	-0.0244***	-0.0148***	-0.0072 (NS)	-0.01725***	-0.017**
SPEI-9	-0.026***	-0.0299***	-0.0202***	-0.0138***	-0.0234***	-0.0236***
SPEI-12	-0.028***	-0.0344***	-0.024***	-0.0179***	-0.0248***	-0.028***
SPEI-24	-0.042***	-0.0538***	-0.0406***	-0.0328***	-0.0336***	-0.043***

Note: All Sen's slope values are expressed in SPEI units yr^{-1}. NS = not significant; *p *p ≤ 0.05; **p ≤ 0.01; ***p ≤ 0.001. Negative slopes indicate declining SPEI and increasing drought tendency, whereas positive slopes indicate increasing SPEI and wetter conditions.

The temporal patterns shown in the station-level SPEI series were consistent with the trend statistics. Short accumulation periods frequently alternated between positive and negative SPEI values, reflecting rapid transitions between wet and dry conditions. In contrast, the longer accumulation periods showed extended phases of negative SPEI, indicating greater drought persistence. Negative values became particularly prolonged after 2000 at several stations, including Bogura, Rajshahi, and Rangpur. This pattern is consistent with the negative Sen's slope estimates and suggests increasing persistence of medium- to long-term drought conditions during the more recent period (Figures 2–4).

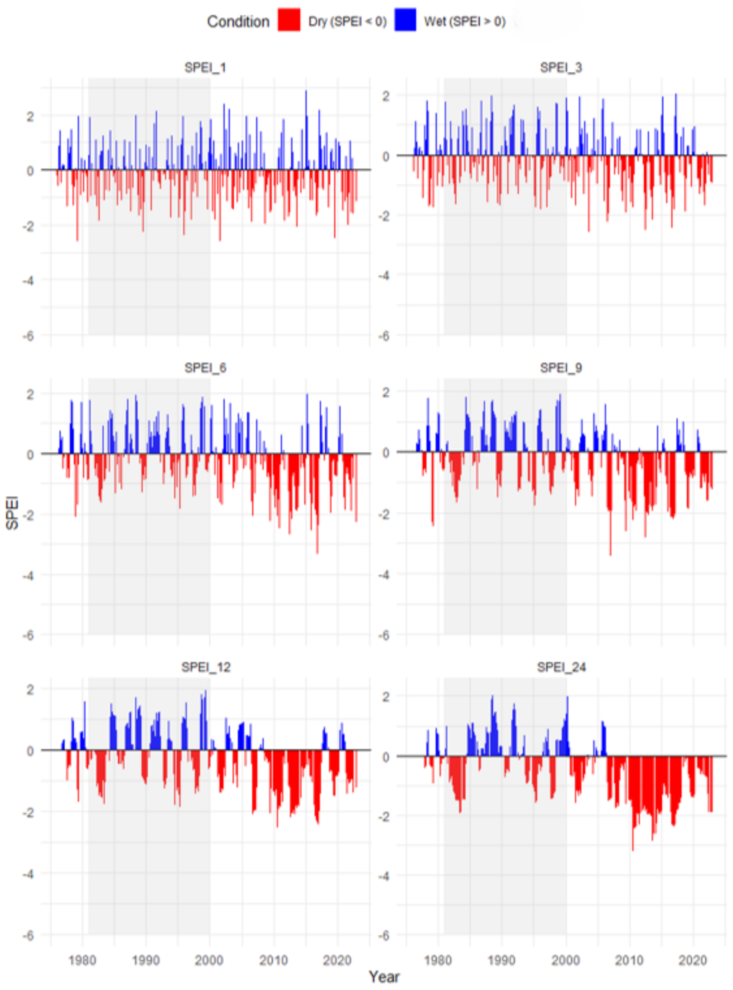

Figure 2. Temporal variation in SPEI at 1-, 3-, 6-, 9-, 12-, and 24-month scales at Bogura

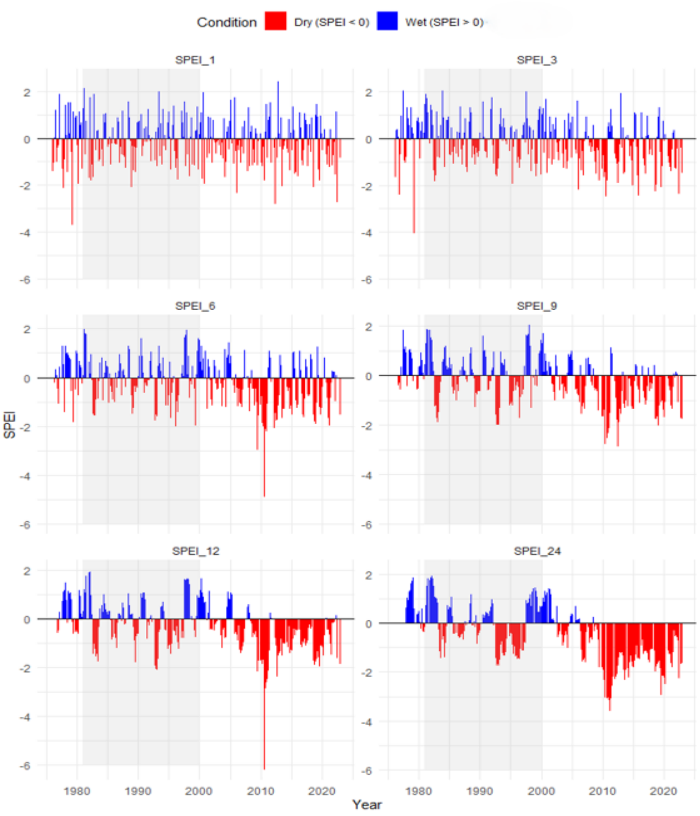

Figure 3 Temporal variation in SPEI at 1-, 3-, 6-, 9-, 12-, and 24-month scales at Rajshahi.

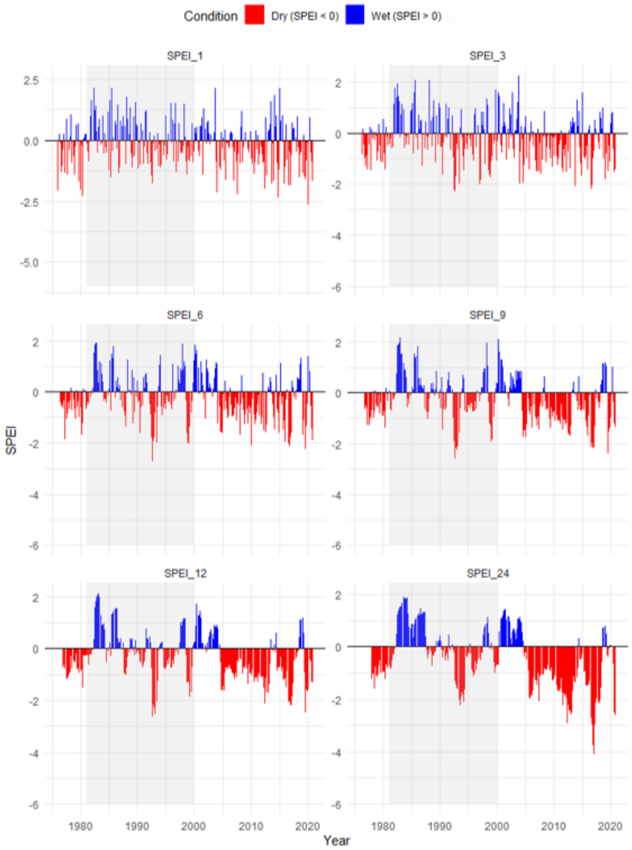

Figure 4. Temporal variation in SPEI at 1-, 3-, 6-, 9-, 12-, and 24-month scales at Rangpur.

Note for Figures 2–4: Shaded sections indicate the reference period (1981–2000) used to standardize SPEI values.

Changes in drought frequency

The category-frequency analysis showed that the percentage of months classified as moderate, severe, or extreme drought was generally higher in the recent period than in the earlier period (Figures 5–7; Figures S1–S3). Because SPEI was standardized using the 1981–2000 reference period, these percentages represent the share of months falling below drought-category thresholds relative to the baseline climate. The frequency analysis therefore provides a categorical summary of how the SPEI distribution shifted between the earlier and recent periods, while the Mann–Kendall and Sen's slope results provide the primary statistical evidence of long-term trends.

Bogura's extreme-drought frequency at SPEI-24 increased from 0.3% in 1976–2005, equivalent to approximately 1 month out of 360 valid months, to 19.1% in 2006–2022, equivalent to approximately 39 months out of 204 valid months (Figure 5). Rajshahi showed an even larger change, from 0% in 1976–2005, or 0 months out of 360 valid months, to 23.0% in 2006–2022, equivalent to approximately 47 months out of 204 valid months (Figure 6). At Rangpur, the extreme-drought category at SPEI-24 increased from 0.6% in 1978–2005, equivalent to approximately 2 months out of 336 valid months, to 20.6% in 2006–2022, equivalent to approximately 42 months out of 204 valid months (Figure 7). Dinajpur also recorded marked increases in severe and extreme drought at SPEI-24 (Figure S2), while Ishwardi showed a substantial rise in moderate drought but a smaller rise in the two most severe categories (Figure S1).

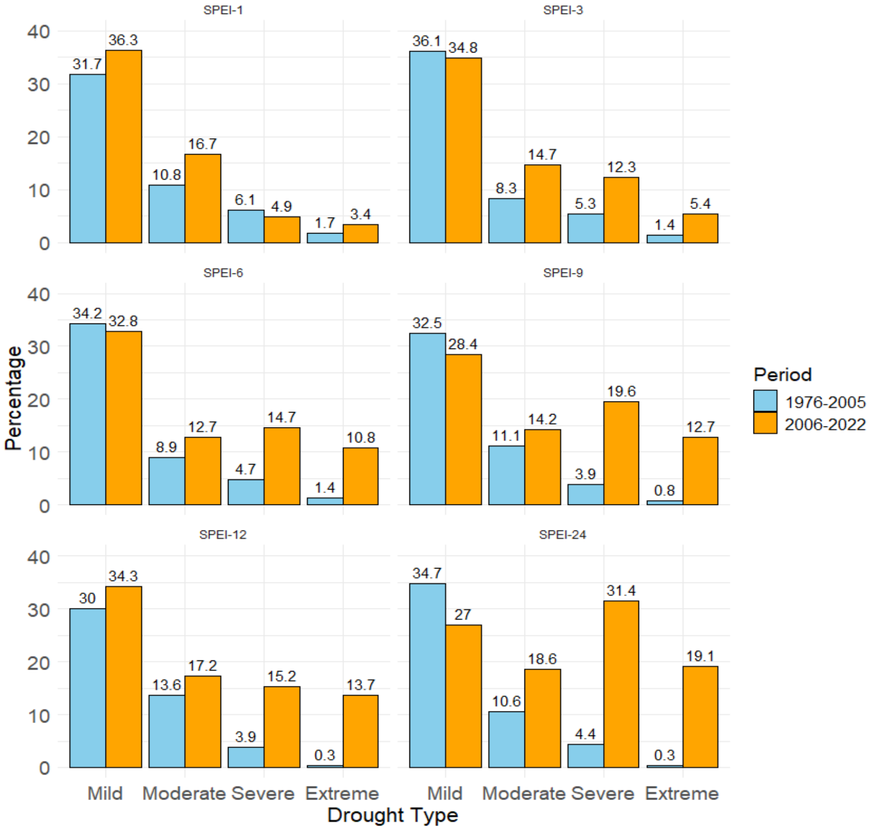

Figure 5. Frequency (%) of mild, moderate, severe, and extreme drought events across different SPEI time scales for Bogura, comparing 1976–2005 with 2006–2022

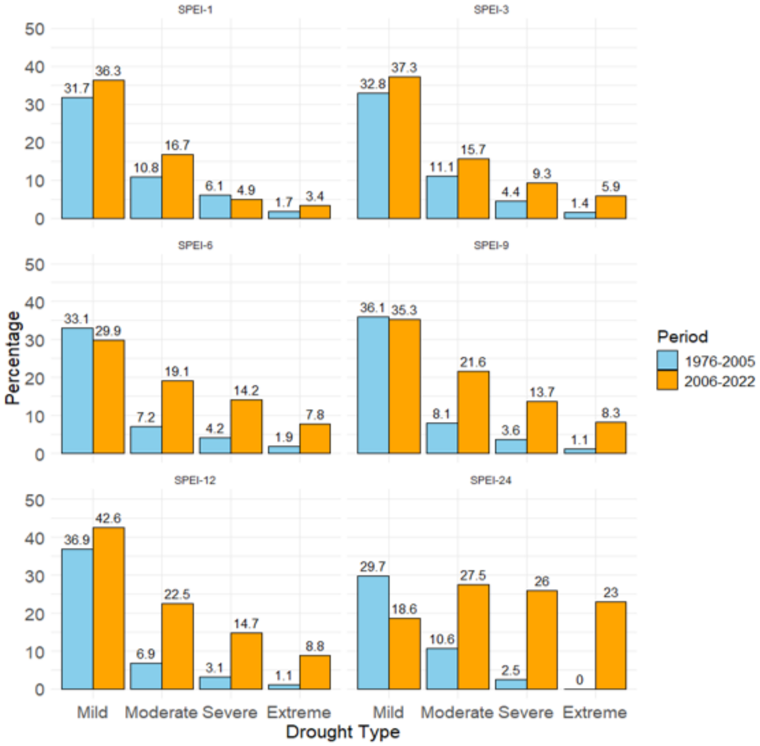

Figure 6. Frequency (%) of mild, moderate, severe, and extreme drought events across different SPEI time scales for Rajshahi, comparing 1976–2005 with 2006–2022.

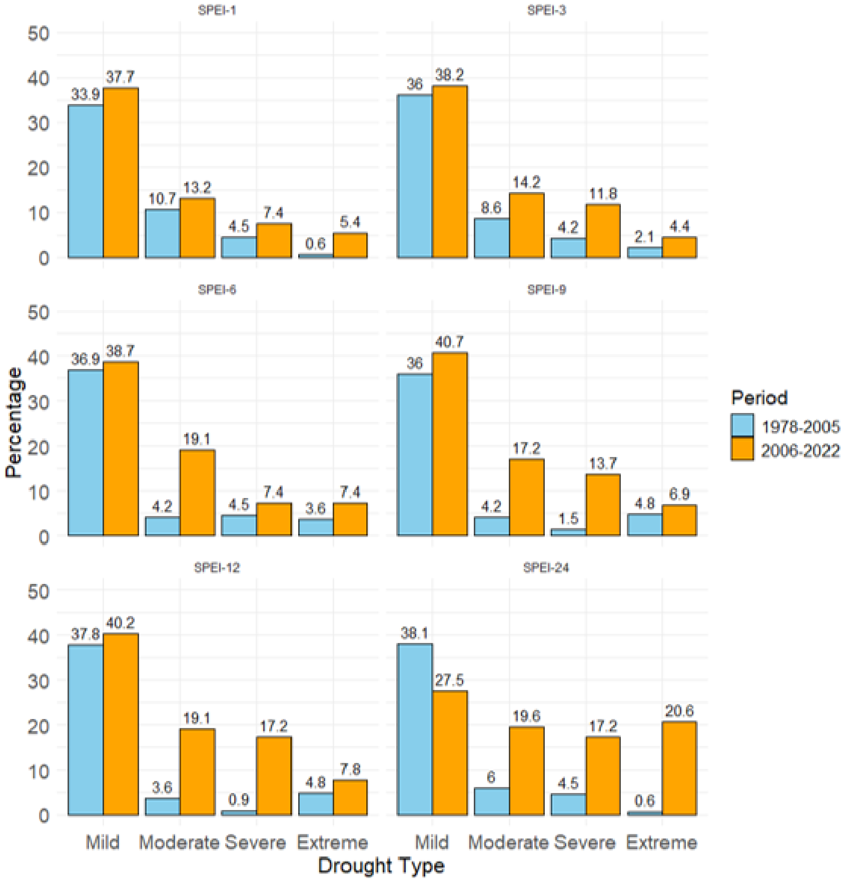

Figure 7. Frequency (%) of mild, moderate, severe, and extreme drought events across different SPEI time scales for Rangpur, comparing 1978–2005 with 2006–2022.

Note for Figures 5–7: Percentages were calculated as the number of valid months in each drought category divided by the total number of valid months in the corresponding comparison period.

Syedpur differed from the other stations because its earlier comparison period began in 1991 (Figure S3). The recent period nevertheless showed a higher share of mild and moderate drought months at several scales and a small emergence of extreme drought at SPEI-24. Across the region, changes in mild drought were less consistent than changes in the moderate-to-extreme categories.

Cropping-season based drought trends

Seasonal trend analysis based on SPEI-4 revealed distinct differences among the three major cropping seasons (Table 3). During the Rabi season, negative Sen's slopes were observed at five of the six stations, indicating a general tendency toward drier conditions. Statistically significant drying trends occurred at Rangpur (Z = −2.50, Sen's slope = −0.03, p = 0.01) and Dinajpur (Z = −2.57, Sen's slope = −0.05, p = 0.01). Bogura, Rajshahi, and Syedpur also showed negative trends, although these were not statistically significant. In contrast, Ishwardi exhibited a negligible positive trend (Z = 0.19, Sen's slope = 0.0014, p = 0.85).

Table 3. Mann–Kendall statistics and Sen's slopes for drought trends across cropping seasons at the six stations. Sen's slope values are expressed in SPEI units yr^{-1}.

Stations	Rabi (November to February) season drought (SPEI-4 of February)			Kharif-I (March to June) season drought (SPEI-4 of June)			Kharif-II (July to October) season drought (SPEI-4 of October)		
	Z-value	Sen's slope	p-value	Z-value	Sen's slope	p-value	Z-value	Sen's slope	p-value
Bogura	-1.46	-0.02	0.14	-0.13	-0.0013	0.89	-2.33	-0.04^{*}	0.02
Rajshahi	-1.65	-0.02	0.10	-1.15	-0.014	0.25	-3.07	-0.03^{**}	0.002
Ishwardi	+0.19	+0.0014	0.85	-1.78	-0.02	0.07	-1.23	-0.01	0.21
Rangpur	-2.50	-0.03^{**}	0.01	+0.09	0.001	0.93	-2.38	-0.03^{*}	0.02
Dinajpur	-2.57	-0.05^{**}	0.01	-0.01	~0.00	0.99	-2.41	-0.04^{**}	0.01
Syedpur	-1.16	-0.03	0.25	-0.17	-0.01	0.87	-1.19	-0.02	0.23

Note: Sen's slope values are expressed in SPEI units yr^{-1}. Z = Mann–Kendall test statistic; p = probability value; NS = not significant; *p ≤ 0.05; **p ≤ 0.01; ***p ≤ 0.001. Negative Sen's slope values indicate declining SPEI and increasing drought tendency, whereas positive values indicate increasing SPEI and wetter conditions

During the Kharif-I season, trends were generally weak and statistically non-significant across all stations. Sen's slopes ranged from -0.02 at Ishwardi to 0.001 at Rangpur, while Dinajpur showed almost no change. The absence of significant trends suggests that pre-monsoon drought conditions remained highly variable from year to year, without a consistent long-term drying or wetting tendency.

The Kharif-II season exhibited the most spatially consistent drying pattern, with negative Sen's slopes recorded at all six stations. Significant drying trends were detected at Bogura (Z = -2.33, Sen's slope = -0.04, p = 0.02), Rajshahi (Z = -3.07, Sen's slope = -0.03, p = 0.002), Rangpur (Z = -2.38, Sen's slope = -0.03, p = 0.02), and Dinajpur (Z = -2.41, Sen's slope = -0.04, p = 0.01). Ishwardi and Syedpur also showed negative trends, but these were not statistically significant. Overall, the results indicate that drought intensification was most evident during the Kharif-II season, followed by the Rabi season, whereas no consistent long-term change was observed during Kharif-I.

Discussion

The multi-scale analysis indicates that drought conditions in northwestern Bangladesh have generally shifted toward lower SPEI values, but the strength and interpretation of the signal depend on the accumulation period. Short-period SPEI responds rapidly to individual wet and dry months and therefore retains considerable variability. In contrast, SPEI-12 and SPEI-24 showed more consistent negative Sen's slopes, suggesting that climatic water deficits have become more persistent across seasons and years. However, because longer SPEI accumulation periods are based on overlapping monthly water-balance totals, their statistical significance may be affected by serial autocorrelation. Therefore, the long-scale results should be interpreted cautiously, with emphasis on the direction, consistency, and magnitude of Sen's slope rather than statistical significance alone. This distinction is important because prolonged climatic water deficits can affect irrigation demand, reservoir and groundwater recovery, and the capacity of farming systems to withstand a sequence of dry seasons.

The direction of change is consistent with earlier drought assessments of western and northwestern Bangladesh. Shahid and Behrawan (2008) and Rahman and Lateh (2016) identified the western part of the country as a major drought-risk zone, while SPEI-based studies have reported widespread drying and substantial spatial differences among climatic regions (Miah et al., 2017; Rahman et al., 2021). The present study extends that evidence by comparing six accumulation periods and by showing that the steepest declines occur in the longer-duration indices. The result supports the use of multi-scale monitoring rather than reliance on a single drought indicator.

SPEI combines precipitation anomalies with potential evapotranspiration, so a negative trend may reflect reduced precipitation, increased evaporative demand, or both. The present analysis did not decompose these contributions and should not be interpreted as a direct attribution study. Nevertheless, previous research has documented temperature-related increases in reference evapotranspiration and irrigation demand in northwestern Bangladesh (Shahid, 2011; Mojid et al., 2015), and climate projections indicate that meteorological drought characteristics may worsen under continued warming (Khan et al., 2020). The strong long-period SPEI decline is therefore consistent with a climate system in which episodic rainfall deficits are amplified by atmospheric demand.

The comparison of drought-category frequencies provides a categorical interpretation of the SPEI changes relative to the 1981–2000 reference climate. Since SPEI was not standardized over the full 1976–2022 record, the increase in recent drought-month percentages is not a mechanical consequence of full-record standardization. However, because both the trend and frequency analyses are derived from the same SPEI series, the frequency results should be interpreted as supporting and illustrating the trend results rather than as fully independent evidence. The larger recent share of moderate, severe, and extreme drought months indicates that negative water-balance conditions, relative to the 1981–2000 baseline, occupied a greater proportion of the recent record, particularly at SPEI-12 and SPEI-24.

The seasonal results have direct agricultural relevance because drought impacts depend strongly on crop calendars and seasonal water demand. Significant negative SPEI-4 trends during the Rabi season at Rangpur and Dinajpur indicate increasing drought tendency during a period when crop production relies heavily on irrigation and stored water. The more widespread negative SPEI-4 trends during Kharif-II at Bogura, Rajshahi, Rangpur, and Dinajpur are particularly important because this season overlaps with the latter part of the monsoon and the transition toward the post-monsoon period. A plausible mechanism is that weakened or earlier withdrawal of late-monsoon rainfall may reduce water supply during September–October, while warmer post-monsoon conditions may increase PET and further lower the climatic water balance. However, this interpretation should be considered a plausible mechanism rather than direct attribution, because rainfall and PET contributions were not decomposed separately in this study. Earlier studies have reported pronounced seasonal variation in Bangladesh drought conditions and emphasized the value of linking drought indices with cropping calendars (Alamgir et al., 2015; Mohsenipour et al., 2018; Kamruzzaman et al., 2019). Recent work on seasonal drought prediction further highlights the potential of climate-based indicators to support anticipatory agricultural decisions (Al Mamun et al., 2024).

The findings support several practical actions. Drought monitoring systems should report SPEI at more than one accumulation period so that short agricultural stress and prolonged water-resource deficits can be distinguished. Seasonal advisories could combine SPEI-4 with crop calendars, irrigation schedules, and local water-storage information. In locations showing strong long-period drying, water managers may also need to review dry-season abstraction, promote efficient irrigation, and strengthen contingency planning for consecutive drought years.

Several limitations should be considered when interpreting the findings. First, the analysis was based on six meteorological stations and therefore represents drought variability at selected monitoring locations rather than the full spatial pattern across northwestern Bangladesh. Future studies could improve spatial representation using gridded climate datasets, remote-sensing products, or spatial interpolation methods. Second, station-specific record lengths, particularly for Rangpur, Dinajpur, and Syedpur, may affect direct comparison of long-term trends among stations. Although missing observations were filled using standard temporal averaging and long-term monthly means before SPEI calculation, station-wise percentages of missing data were not reported; this should be addressed in future assessments to improve data transparency. Third, the seasonal Mann–Kendall test was applied without an explicit serial-correlation correction; therefore, the significance of SPEI-12 and SPEI-24 trends should be interpreted cautiously because longer accumulation scales may be autocorrelated by construction. Finally, SPEI represents climatic water balance based on precipitation and potential evapotranspiration, but it does not directly measure soil moisture, crop stress, streamflow, or groundwater response. Future research should integrate SPEI with root-zone soil moisture, crop-yield records, groundwater levels, streamflow observations, and remote-sensing indicators, and should identify independent drought events to evaluate duration, peak intensity, severity, and recovery more explicitly.

Despite these limitations, the consistent negative direction and magnitude of SPEI trends suggest a shift toward more persistent drought conditions at several northwestern stations. The drought-frequency results should be interpreted as a categorical representation of this SPEI shift rather than as independent confirmation. Overall, the findings show that seasonal and multi-scale

SPEI analyses can reveal drought patterns that may be overlooked in annual or single-scale assessments.

Conclusion

This study assessed temporal, between-station, and cropping-season variation in drought conditions across northwestern Bangladesh using SPEI at six accumulation periods: 1, 3, 6, 9, 12, and 24 months. SPEI declined at most stations, indicating a shift toward greater climatic water deficit. The clearest declines occurred at SPEI-12 and SPEI-24, which represent longer-term moisture conditions accumulated over one to two years. Among the study locations, Rajshahi showed the steepest long-term decline at SPEI-24, with a Sen's slope of −0.0538 SPEI units yr^{-1}. The recent period also showed a higher share of moderate, severe, and extreme drought-category months at several stations. At SPEI-24, extreme drought reached 19.1% of valid months in Bogura, 23.0% in Rajshahi, and 20.6% in Rangpur during 2006–2022.

The cropping-season analysis showed that drought tendency is not increasing equally across the year. Significant Rabi-season SPEI declines were found at Rangpur and Dinajpur, indicating greater water stress during a season that depends strongly on irrigation and stored water. Significant Kharif-II declines were observed at Bogura, Rajshahi, Rangpur, and Dinajpur, suggesting increasing drought tendency during the late-monsoon to post-monsoon transition. In contrast, Kharif-I trends were weak and mostly non-significant. These results show that drought monitoring and adaptation planning should be linked with crop calendars and seasonal water requirements.

Overall, multi-scale SPEI analysis provides a useful basis for drought surveillance, irrigation scheduling, and seasonal preparedness in northwestern Bangladesh. Its practical value would be improved by combining SPEI with soil-moisture observations, crop-response data, groundwater and surface-water records, and event-based drought analysis. Such integration would support stronger early warning systems and more targeted climate-resilient agricultural planning.

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Conflict of interest

The authors declare that they have no conflict of interest related to this study.

Ethics approval

This study used secondary meteorological records and did not involve human participants or animals; therefore, ethical approval was not required.

Data availability

The meteorological data and analysis code used in this study are available from the corresponding author upon reasonable request, subject to any restrictions imposed by the original data provider.

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