



A comprehensive statistical assessment of drought indices to monitor drought status in Bangladesh

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Abstract

In Bangladesh, drought has negative consequences on agriculture, environments, livelihood, and food security. However, a comprehensive statistical assessment of drought indices has rarely been found in the existing literature. To address this issue, firstly, this paper used daily temperature and precipitation data from the Bangladesh Meteorological Department (BMD) to calculate Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). After that, we performed a statistical assessment, for instance, Pearson correlation coefficient, cross-correlation, cross-wavelet transform, and root mean square error, to identify the strengths of SPI and SPEI. Our findings showed that though both indices had a strong correlation with each other, SPEI performed better than SPI because evaporative demand has a positive impact on defining drought conditions in Bangladesh. Temperature and rainfall indices, for example, warm spell duration indicator (WSDI) and maximum amount of rain (Rx5day) that falls in five consecutive days, have been applied to find out the relationship between climate extremes and drought indices using cross-wavelet transform. Our results suggested that climate extremes such as WSDI and Rx5day have an influence on droughts in Bangladesh. Our results recommended that multi indices of drought assessment should be required in order to draw a robust conclusion.

Keywords Drought · SPI · SPEI · WSDI · Rx5day · Cross-wavelet · Bangladesh

Introduction

Drought is a recurring extreme event which symbolizes as occurring lower precipitation over a long-time period reaching from several months to a year (Dai 2011), and it is one of the major concerns for local and regional management worldwide, particularly in water shortage areas (Van Loon and Van Lanen 2013). In Bangladesh, drought mainly encounters a dry period for 7 months, from November to May, when precipitation is regularly low (Umma et al. 2011). This country has experienced many extreme and severe drought events

in the 1980s, 1995–2001, and 2005–2010 (Miah et al. 2017). Therefore, it is necessary to investigate statistical analysis to find out the appropriate tool for drought assessment in Bangladesh.

To measure drought severity, many popular drought indices have been created globally: the Palmer Drought Severity Index (PDSI) (Palmer 1965), the Standardized Precipitation Index (SPI) (McKee 1993), and the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010). PDSI requires precipitation and temperature as information sources; however, in comparison with SPI, it cannot assess multi-scale drought characteristics (Belayneh and Adamowski 2013). To address this issue, McKee (1993) built up SPI that links to the multi-scalar nature of droughts. Although the World Meteorological Organization (WMO) perceived SPI as the chief reference drought index (Hayes et al. 1999), it can use only precipitation dataset, which does not uncover dry season conditions caused by climate variability (Wang et al. 2015). Considering the disadvantages of SPI, SPEI is just the straightforwardness of estimation, and it offers an extra advancement of the drought record by taking into consideration month to month climatic water adjusts (e.g.,

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the differences between Precipitation and Potential Evapotranspiration (PET)). SPEI comprises PET that is an essential factor of the hydrologic water cycle (Oki and Shinjiro 2006).

Globally, some studies have investigated robust statistical assessment to compare the strengths of various drought indices (Mavromatis 2010; Zhai et al. 2010; Potop 2011; Vicente-Serrano et al. 2012; Yang et al. 2017; Liu et al. 2018). Mavromatis (2010) compared different drought indices to see the ability to monitor soil moisture. Zhai et al. (2010) compared between PDSI and SPI and investigated their relationship to streamflow in 10 large regions of China. Potop (2011) investigated different drought indices to evaluate drought effects on corn yield in Moldova. Vicente-Serrano et al. (2012) performed a global study of the performance of different drought indices to monitor drought impacts on agricultural and ecological response variables. Yang et al. (2017) compared seven drought indices to determine regional applicability in China. Liu et al. (2018) compared the strengths of SPI, SPEI, and PDSI for agricultural drought in the North China Plain. They found small differences in the comparative performances of SPI and SPEI which were smaller at the long-term scale than those at the short-term scale.

In Bangladesh, some studies applied SPI to identify drought conditions in Bangladesh (Shahid and Behrawan 2008; Alamgir et al. 2015; Rahman and Lateh 2016). These studies have concentrated on defining droughts and their spatiotemporal variability. Shahid and Behrawan (2008) found that droughts had the highest risk to the northern and northwestern districts of Bangladesh. Alamgir et al. (2015) showed that while pre-monsoon droughts are more often in the northwest, monsoon droughts mainly happen in the west and northwest, and winter droughts are more frequent in the west of Bangladesh. Rahman and Lateh (2016) identified the worst drought years in 1971, 1972, 1978, 1982, 1995, 1999, and 2006. However, the abovementioned studies did not compare drought indices for drought assessment in Bangladesh.

Very few studies have been performed based on SPEI in Bangladesh to monitor drought (Islam et al. 2017; Miah et al. 2017). Islam et al. (2017) showed that the southwestern region was more at risk to drought hazard than the north-western region of Bangladesh from 1984 to 2013. Miah et al. (2017) identified Rangpur, northwest region, as a hot spot to get an insight of drought assessment in Bangladesh. However, these studies did not concentrate on statistical assessment to identify the appropriate tool for drought assessment in Bangladesh.

It is necessary to compare between SPI and SPEI to obtain solid and objective criteria for selecting appropriate drought index in Bangladesh. Therefore, our main objective of this study is to analyse the performance of SPI and SPEI over Bangladesh. To attain this objective, we outline the steps that are performed. Firstly, we represent the data and method in the “**Material and methods**” section. Secondly, we compare SPI and SPEI in the

“**Comparison between SPI and SPEI**” section. After that, we discuss the correlation and performance of SPI and SPEI in the “**Correlation and performance analysis of SPI and SPEI**” section. Then, we discuss responses of SPI and SPEI to climate extreme in the “**Responses of SPI and SPEI to climate extreme**” section. Finally, we wrap up by “**Conclusion**”.

Material and methods

Study domain

Bangladesh is located in South Asia with the Bay of Bengal to the south, India to the north and west, and Myanmar to the east. Its summer gets hot and humid, and during this season, the maximum temperature increases up to 40 °C. However, the temperature goes lower in the pre-winter. The country was divided into western, eastern, and central regions based on its climatic zones (Banglapedia 2006). The western region is a dry drought-prone region and comprises three meteorological stations (Salam et al. 2019), while the eastern region is characterized by a tropical monsoon climate and contains seven meteorological stations. The central region represents ten stations with slide dry ecosystems. As different parts of Bangladesh have a distinct climatic pattern, we have carefully chosen 20 meteorological stations in this study (Fig. 1).

Data and quality control

We have used 38 years of data of rainfall and temperature that were collected from the Bangladesh Meteorological Department (BMD). Before we perform data analysis, we have carried out some quality control procedures. Firstly, the missing data did not count in data analysis, and all missing values coded as –99.9 with a standard format in R statistical software package. Secondly, we recognized outliers in the monthly maximum and minimum temperatures and also monthly precipitations. The outliers can be defined as values higher or lower than 3σ from the long-term average value for that month. After that, we used the RHtestsV4 software (<http://etccdi.pacificclimate.org/software.html>) to find multiple change points (shifts) that could exist in a dataset that may have first-order autoregressive errors.

Methods

The Standardized Precipitation Index (SPI) was calculated by using SPI_SL_6.exe software (<https://drought.unl.edu/droughtmonitoring/>), while the Standardized Precipitation Evapotranspiration Index (SPEI) was calculated by ClimPACT2 software in R programming (<https://github.com/ARCCSS-extremes/climpact2/>). Please note that SPI software requires monthly total rainfall whereas SPEI software requires

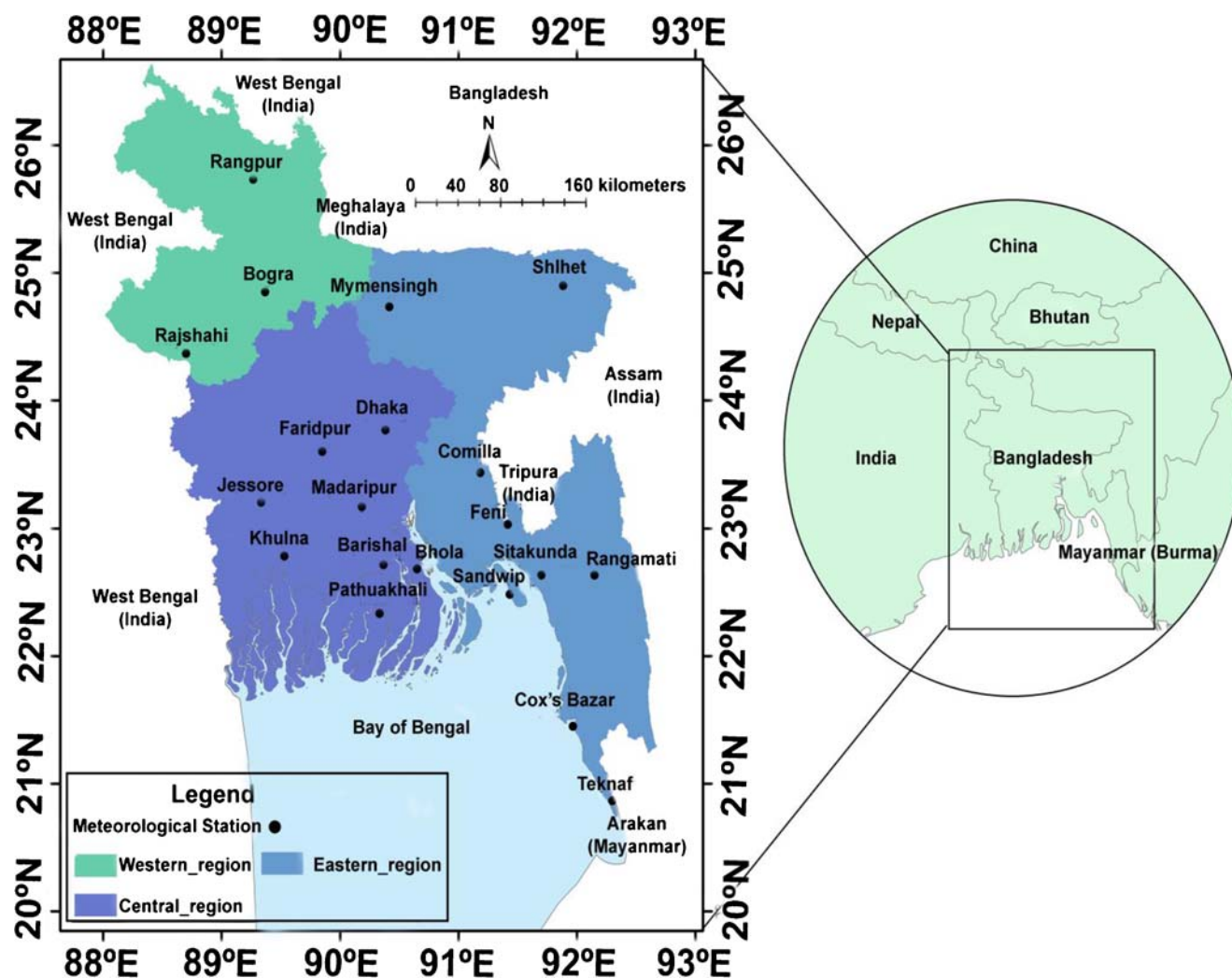


Fig. 1 Location map of the study area

a monthly minimum and maximum temperatures, total rainfall, and stations' latitude and longitude. Different values of SPI and SPEI have significant meanings (Table 1).

To find out the relation between SPI and SPEI, we used some statistical techniques such as the Pearson correlation coefficient, cross-correlation, and cross-wavelet transforms. The root mean square error (RMSE) has been used to

investigate the performance of SPI and SPEI. Finally, to see the influence of climate extreme on the variation between SPI and SPEI, we have calculated warm spell duration indicator (WSDI) and maximum amount of rain (Rx5day) that falls in five consecutive days by using RCLimDex V1.0 software. WSDI (maximum temperature > 99th percentile) can be defined as the number of days contributing to a warm period, where the period has to be at least 6 days long. The meanings of these indices are proposed by the Climate Commission of the World Meteorological Organization (WMO), the Global Climate Research Program (GCRP), and the Expert Team on Climate Change Detection and Indices (ETCCDI).

Table 1 Drought categories based on SPI and SPEI values (Alley 1984)

SPI	SPEI	Category
2 and above	2 and above	Extremely wet
1.50 to 1.99	1.50 to 1.99	Very wet
1.00 to 1.49	1.00 to 1.49	Moderately wet
−0.99 to 0.99	−0.99 to 0.99	Mild drought
−1.00 to −1.49	−1.00 to −1.49	Moderate drought
−1.50 to −1.99	−1.50 to −1.99	Severe drought
≤ −2.00	≤ −2.00	Extreme drought

Results and discussion

Comparison between SPI and SPEI

Figures 2, 3, 4, and 5 show the value of SPI and SPEI at 3-, 6-, 12-, and 24-month timescales over the western part, eastern

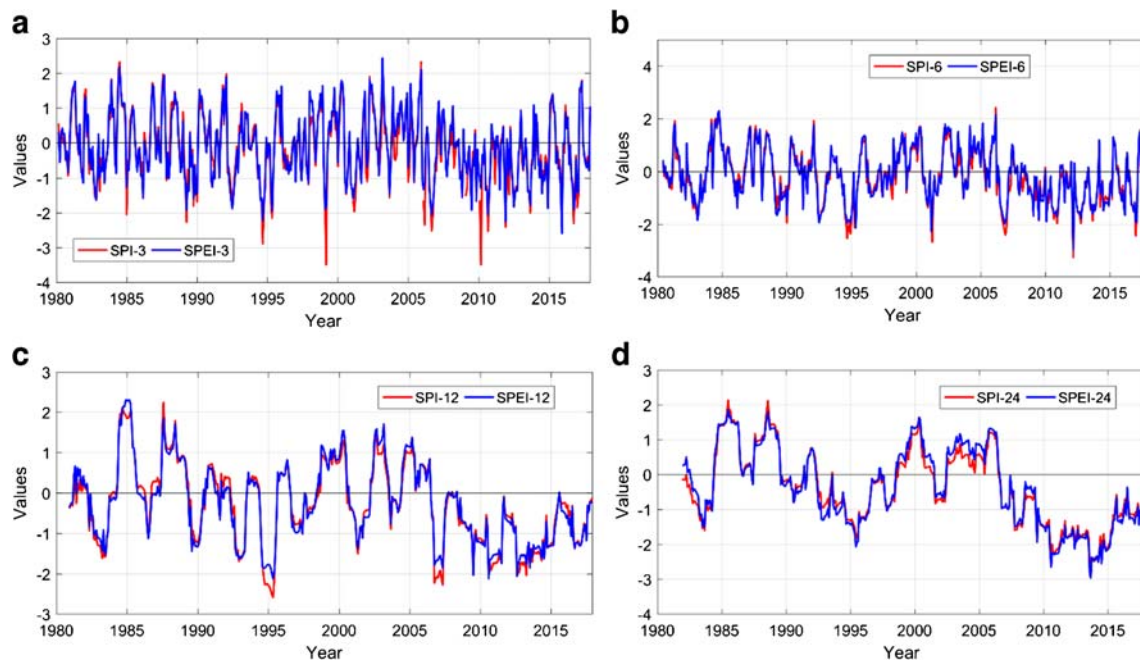


Fig. 2 SPI and SPEI values for Western part. **a** 3-, **b** 6-, **c** 12-, and **d** 24-month timescales

part, central part, and whole Bangladesh respectively from 1980 to 2017. In the western part, based on short-term drought, SPI did not detect extreme droughts in 1983, 1987, 1993, 2002, and 2012 while it could not recognize some long-term drought events (in 1984, 1993, 1995, 2007, 2011, and 2013). It is evident that SPEI was able to identify clearer drought events than SPI in this region. Please note that some years were overrating by SPI, for example, in 1994, 1995, 2002, 2007, and 2012 (Fig. 2). The eastern part faced extreme droughts in 1981, 1983, 1989, 1993, 1995, 1999, 2004, 2007,

2009, 2012, and 2014 (Fig. 3). In this region, SPI did not identify some severe drought events in 1987, 1989, 2002, 2004, and 2009. Both SPI and SPEI have identified short-term droughts very well over the central part. Severe and extensive drought episode faces over most parts of Southeast Asia are during the years (1999–2002) as mentioned by Malik et al. (2013), which is consistent with this research. However, SPI could not recognize long-term extreme droughts in 1993, 1995, 2014, and 2016 and showed these years as a mild drought (Fig. 4). For the entire Bangladesh,

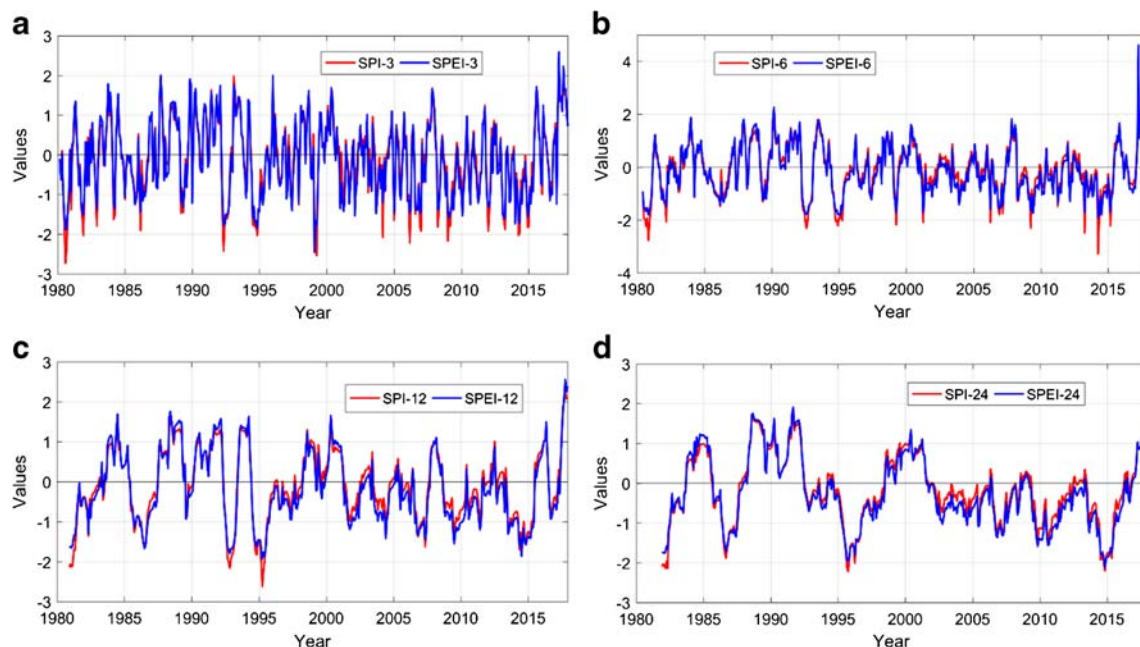


Fig. 3 SPI and SPEI values for the Eastern part. **a** 3-, **b** 6-, **c** 12-, and **d** 24-month timescales

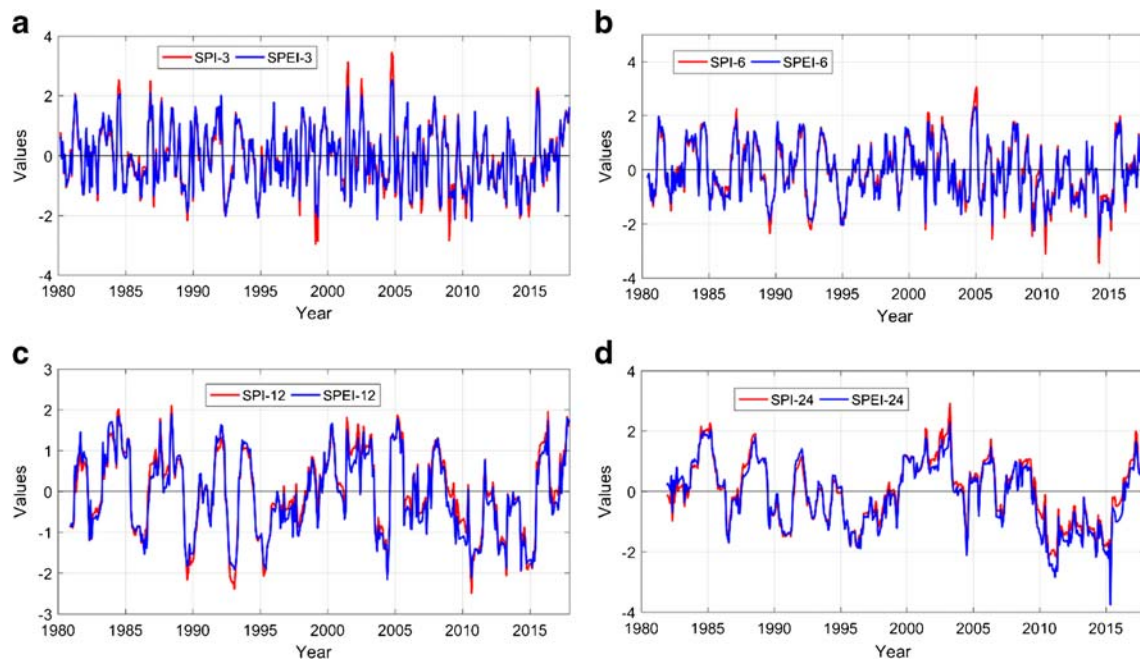


Fig. 4 SPI and SPEI values for the Central part. **a** 3-, **b** 6-, **c** 12-, and **d** 24-month timescales

extreme droughts occurred in 1989, 1993, 1994, 1995, 1996, 1998, 2004, 2009, 2011, 2014, 2015, and 2016 (Fig. 5). SPEI was able to detect these years as extreme drought, but SPI failed to recognize. In this study, we have identified droughts for the 1980s, 1990s, 2000s, and 2010s decades. Our results can be compared with Miah et al. (2017), Nury and Hasan (2016), and Rahman and Lateh (2016). The reason for over-estimation or underestimation might be only precipitation as an input variable in SPI calculation. On the other hand, SPEI performed very well to detect historical droughts event in

Bangladesh because it has potential evapotranspiration (PET) parameter as an extra input than SPI. This finding is consistent with Zhang et al. (2009). They have reported that SPEI showed real drought scenarios because higher air temperature and less rainfall result in higher evaporation. Vicente-Serrano et al. (2010) showed that SPEI also can reveal the influence of evaporation and rainfall on drought while Joetzer et al. (2013) expressed that the utilization of PET showed high consistency with the hydrological drought index. From our study, we observed that precipitation and PET

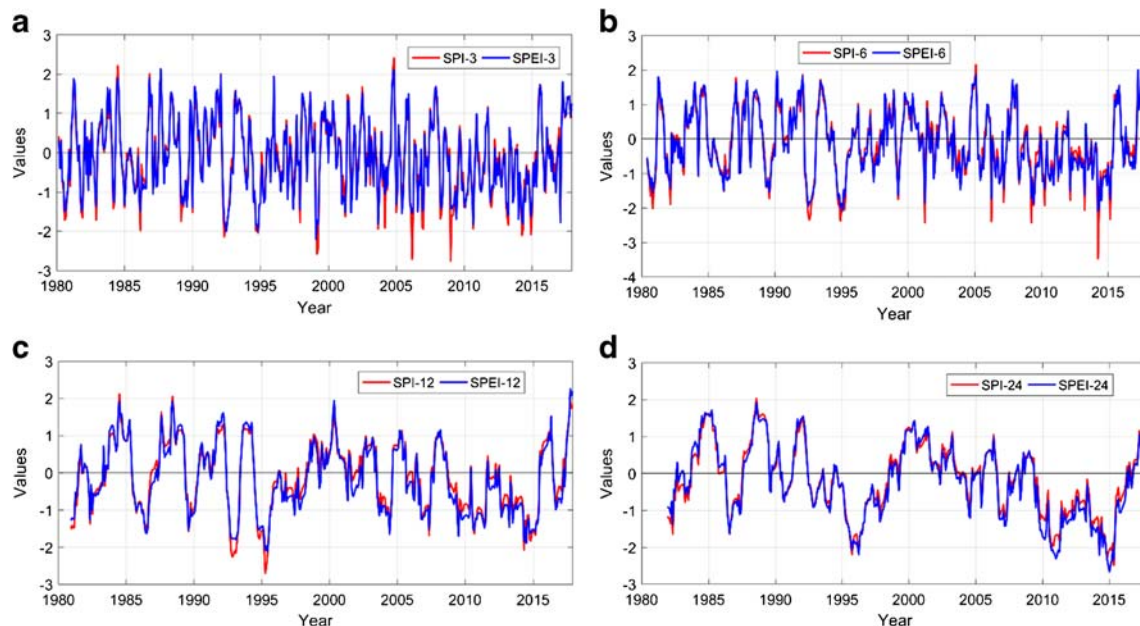
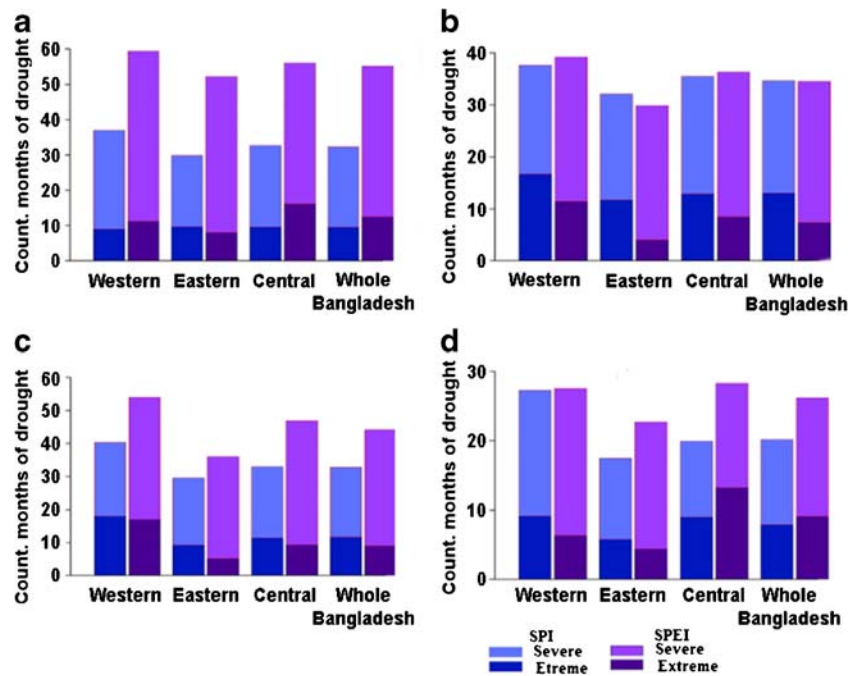


Fig. 5 SPI and SPEI values for the whole Bangladesh. **a** 3-, **b** 6-, **c** 12-, and **d** 24-month timescales

Fig. 6 Frequency of severe and extreme drought events in Bangladesh (1980–2017) in terms of SPI and SPEI. (a) 3-, (b) 6-, (c) 12-, and (d) 24-month timescales



spread distinctive climatic inconstancy of drought severities. This statement supports the finding of the earlier study by Miah et al. (2017). They found that PET assumes an imperative part of the hydrological cycle in Bangladesh, and its variation is fundamentally influenced by precipitation (Shahid and Behrawan 2008; Alamgir et al. 2015; Islam et al. 2017).

Figure 6 shows the number of severe and extreme drought events at different timescale over Bangladesh. It is evidently observed that SPEI outnumbered than SPI in terms of severe drought. For the 3-month timescale, SPEI detected more extreme droughts than SPI except for the eastern part (roughly 12 months). In case of severe drought, SPEI recognized almost 60 months while SPI detected less than 40 months. For the 6-month timescale, a similar pattern was found in severe droughts for both SPI and SPEI but extreme drought fluctuated. In the case of long-term droughts, both SPI and SPEI have recognized nearly 40 months as severe and extreme droughts in Bangladesh.

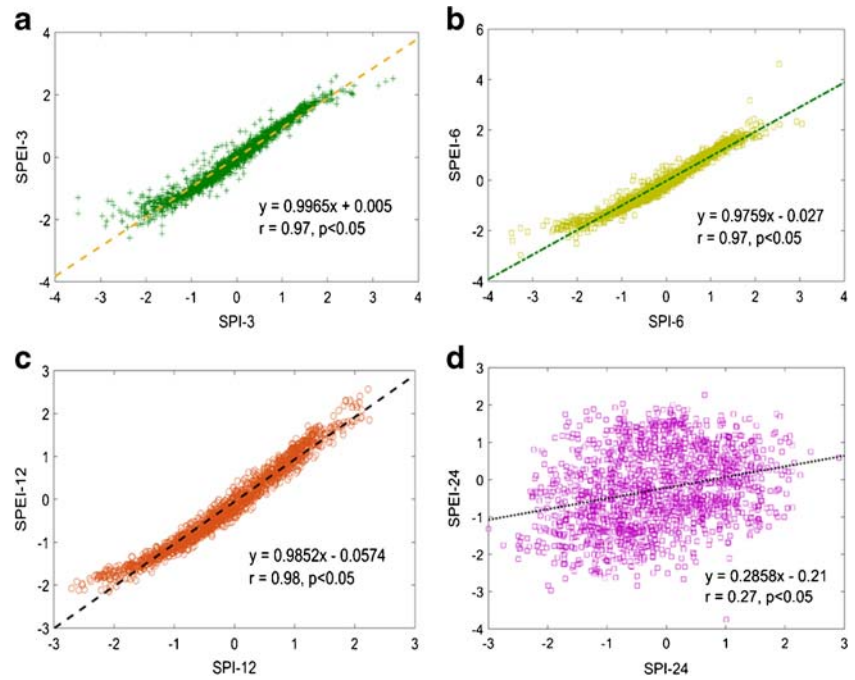
Correlation and performance analysis of SPI and SPEI

Figure 7 shows Pearson's correlation between SPI and SPEI at different timescales. There was a linear significant correlation between SPI and SPEI for 3- and 6-month timescales ($r = 0.97$ at $p < 0.05$), for the 12-month timescale ($r = 0.98$ at $p < 0.05$), but only a low correlation was found for the 24-month timescale ($r = 0.27$ at $p < 0.05$). SPI was strongly correlated with SPEI, and both indices displayed an upward trend. Similar to this study, Adnan et al. (2017) found that SPEI exhibited a good capability to monitor drought condition in Pakistan. The finding is in good agreement with the results

of Homdee et al. (2016) in the Chi River basin, Thailand. Mahmoudi et al. (2019) found that SPI and EDI (effective drought index) were identified as the first and second optimal indices for drought monitoring in Iran, which is in disagreement with this study. By contrast, Kamruzzaman et al. (2019) revealed the superiority of EDI over SPI when monitoring both long-term and short-term droughts in Bangladesh. This inconsistency may be ascribed to the flat low-laying topography of our study area that enables uneven oceanic-atmospheric circulation patterns. The relationship between lagged SPI and SPEI indices was investigated by the cross-correlation method (Fig. 8). The weak correlations were found for short-term droughts (0.05 and 0.15) while the strong correlations were found for long-term droughts (0.60 and 0.85), with a 1-month time lag. The strongest correlation in terms of severity and peaks was found between SPI and SPEI for 3-, 6-, 12-, and 24-month timescales (0.95, 0.96, 0.98, and 0.99 respectively). During the study period all significant trends were positive for both SPI and SPEI drought index. It was obvious that severe droughts happened frequently after the positive change year. This may support the statement by Stocker et al. (2013) and Cook et al. (2014) that global warming has intensified drought during the twenty-first century in a number of region worldwide.

Cross-wavelet transform has been used to find out the relationship between SPI and SPEI in different regions in Bangladesh (Fig. 9). The results show that there was a strong positive correlation between SPI and SPEI. Figure 9a, b show a significant resonance cycle of 16–40 months during 1986–1991, 1993–1996, and 2001–2004 (eastern and western part). The variation in the phase angle suggests that SPI was toward

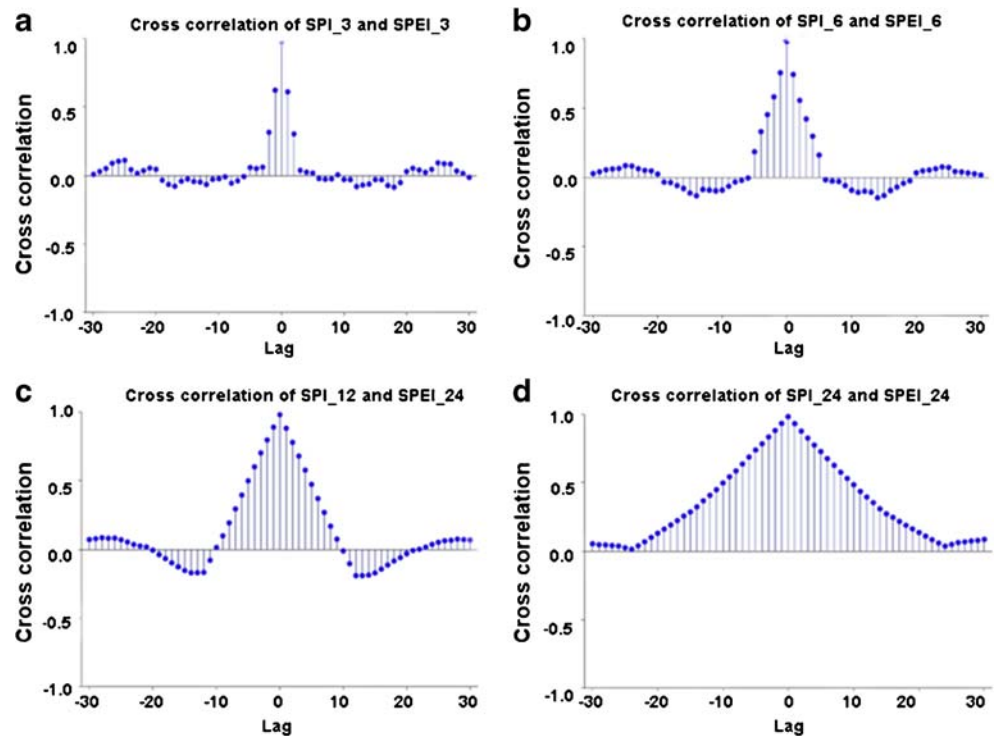
Fig. 7 The correlation between SPI and SPEI at different timescales



of SPEI. We observed almost a similar pattern for the central part of Bangladesh (Fig. 9c). For whole Bangladesh, the resonance cycle confirmed that SPI and SPEI were positively correlated during the 1980s, 1990s, and 2000s decades (Fig. 9d).

The correlation coefficient (r) and root mean square error (RMSE) results revealed that SPEI provided less error than SPI apart from the 24-month timescale (Table 2). This result is in agreement with those from previous studies carried out by Beguería et al. (2014) and Homdee et al. (2016) who showed

Fig. 8 Cross-correlation between SPI and SPEI based on the different time lags



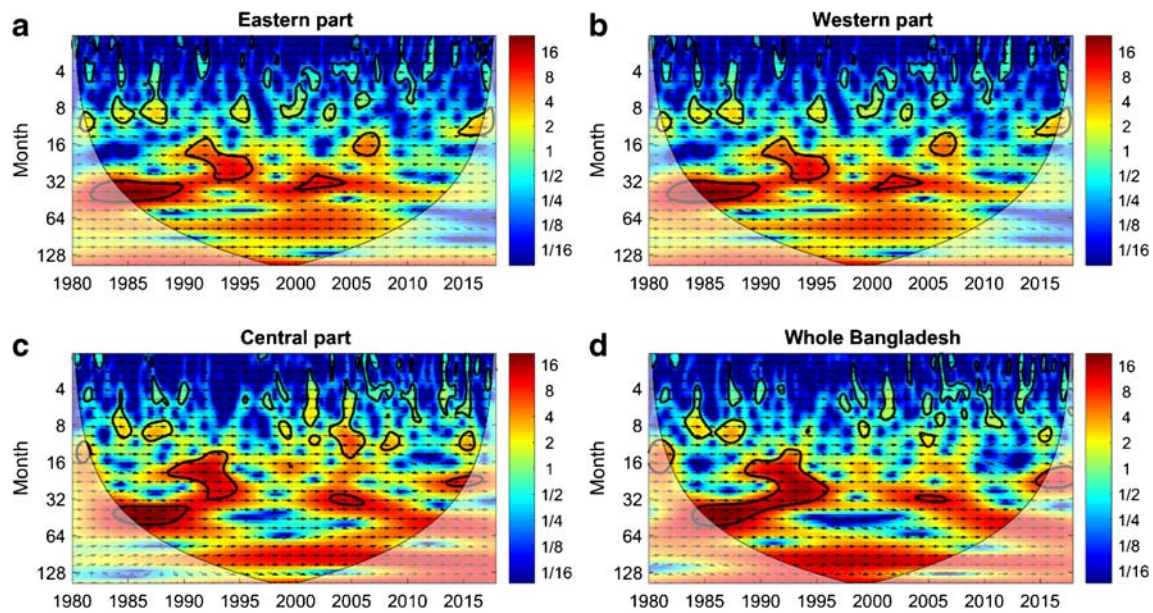


Fig. 9 Cross-wavelet transforms between SPI and SPEI. **a** Eastern part, **b** western part, **c** central part, and **d** whole Bangladesh. While the black line represents the cone of influence, the thick black contours denote the 5%

confidence level. The right-pointing arrows denote that the two signals are in phase

poor performance of SPI in semi arid climates. Byakatonda et al. (2018) found that SPEI proves more robust in characterizing droughts in semiarid areas, which is similar to our study. Our finding is also consistent with the results of a performance analysis performed by Vicente-Serrano et al. (2014), Liu et al. (2018), and Wang et al. (2015).

Responses of SPI and SPEI to climate extreme

To find out the influence of WSDI and Rx5day to drought indices, we have used the cross-wavelet method (Fig. 10). Both SPI and SPEI were positively correlated with WSDI from 2005 to 2010 (Fig. 10a, b). The change in phase angle identified that WSDI was ahead of SPI and SPEI. In other words, drought indices are positively correlated with temperature. However, the anti-phase signal suggested that drought

indices were negatively correlated with Rx5day during the 1990s and 2000s decades. More accurately, drought indices and rainfall have an opposite relation. This phenomenon suggests that when air temperature increases, precipitation decreases. Higher temperature and lower rainfall can dry the topsoil that reduces the rate of evapotranspiration through plants' leaves. This prolongs stress and might have a negative effect on plant physiologies that are irreversible, and therefore, every year crop wilt in Bangladesh. Rahman and Islam (2019) found a similar finding in Bangladesh where large scale atmospheric circulation with extrem precipitation indices showed an anti-phase resonance, indicating a significant negative relationship between them.

Conclusion

In this study, we have used statistical techniques to assess the comparative performances of SPI and SPEI. Although both indices were highly correlated with each other, SPEI performed better than SPI because evaporative demand has a positive impact on defining drought conditions in Bangladesh. Our findings also suggested that climate extremes such as WSDI and Rx5day have an influence on droughts in Bangladesh. This phenomenon might affect agriculture and ecosystem in this country. Finally, it can be concluded that multi-indices of drought assessment should be required in order to draw a robust conclusion.

Table 2 Correlation coefficient (r) and root mean square error (RMSE) between SPI and SPEI. All correlations are significant at a 99% confidence level

Drought indices	R	RMSE
3-month SPI	0.97	0.98
3-month SPEI	0.97	0.75
6-month SPI	0.97	0.97
6-month SPEI	0.97	0.90
12-month SPI	0.98	0.94
12-month SPEI	0.98	0.85
24-month SPI	0.27	0.96
24-month SPEI	0.27	1

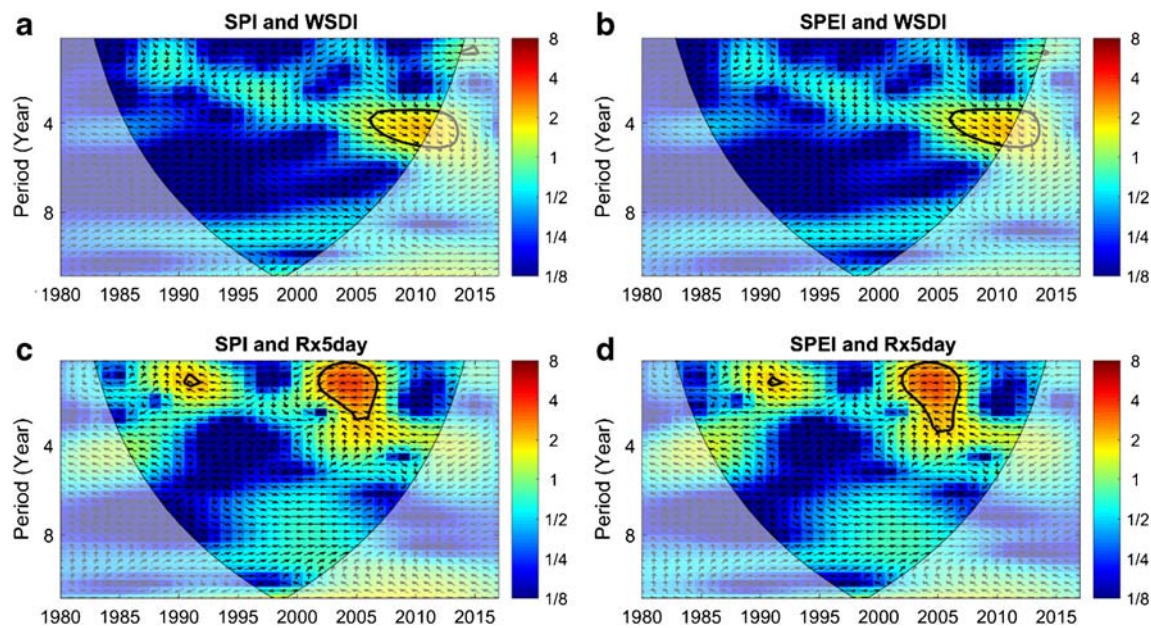


Fig. 10 Cross-wavelet transforms. **a** SPI and WSDI, **b** SPEI and WSDI, **c** SPI and Rx5day, and **d** SPEI and Rx5day. While the black line represents the cone of influence, the thick black contours denote the 5% confidence level. The right-pointing arrows denote that the two signals are in phase

while left-pointing arrows refer to anti-phase signals. Down-pointing arrows indicate that the climate indices are ahead of the drought index, while up-pointing arrows show that the climate indices lag behind the drought index

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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