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Article

Evaluating the Spatiotemporal Characteristics of Meteorological Drought in Bangladesh using Effective Drought Index

Mohammad Kamruzzaman [1,2], Syewoon Hwang[3*], Jaepil Cho[4], Min-Won Jang[5], and Hanseok Jeong[6]

[1]PhD Student, Dept. of Agricultural Engineering, Institute of Agriculture and Life Science, GNU, Rep. of Korea;

[2]Senior Scientific Officer, Bangladesh Rice Research Institute, Gazipur-1701, Bangladesh;
e-mail: milonbrri@gmail.com

[3]Dept. of Agricultural Engineering, Institute of Agriculture and Life Science, GNU, Rep. of Korea;
e-mail: swhwang@gnu.ac.kr

[4]Research Department, APEC Climate Center, Busan, Rep. of Korea; e-mail: jpcho89@gmail.com

[5]Dept. of Agricultural Engineering, Institute of Agriculture and Life Science, GNU, Rep. of Korea;
e-mail: mwjang@gnu.ac.kr

[6]Dept. of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA; e-mail: hanjeong@illinois.edu

*Correspondence: swhwang@gnu.ac.kr; tel.: +82-55-772-1934

Abstract: This study aims to assess the spatiotemporal characteristics of meteorological droughts in Bangladesh during 1981–2015 using the Effective Drought Index (EDI). Monthly precipitation data for 36 years (1980-2015) obtained from 27 metrological stations, were used in this study. The EDI performance was evaluated for four sub-regions over the country through comparisons with historical drought records identified at the regional scale. Analysis at a regional level showed that EDI could reasonably detect the drought years/events during the study period. The study also revealed that the overall drought severity had increased during the past 35 y; the most significant increasing trend was observed in the central region. The characteristics (severity and duration) of drought were also analysed in terms of spatiotemporal evolution of the frequency of drought events. It was found that the western and central regions of the country are comparatively more vulnerable to drought. Moreover, the southwestern region is more prone to extreme drought, whereas the central region is more prone to severe droughts. In addition, the central region was more prone to extra-long-term droughts, while the coastal areas in the southwestern as well as in the central and north-western region were more prone to long-term droughts. The frequency of droughts in all categories significantly increased during the last quinquennial period (2011 to 2015). The seasonal analysis showed that the north-western areas were prone to extreme droughts during the Kharif (wet) and Rabi (dry) seasons. The central and northern regions were affected by recurring severe droughts in all cropping seasons. Further, the most significant increasing trend of the drought-affected area was observed within the central region, especially during the pre-monsoon (March-May) season. The results of this study can aid policymakers in the development of drought mitigation strategies in the future.

Keywords: meteorological drought; Effective Drought Index; Bangladesh; frequency of drought

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1. Introduction

Drought is a short-lived, and perhaps the most complex of chronic natural calamities that is characterised by the lack of precipitation and can cause substantial economic loss as well as human suffering [1]. According to Wilhite and Glantz [2], droughts are classified as meteorological, agricultural, hydrological, and socio-economical droughts. Meteorological drought occurs when the rainfall deficit for a stated period (day, month, season or year) exceeds a certain threshold, usually defined as a proportion of the long-term average (minimum 30 y). Meteorological drought is typically an expression of precipitation's departure from normal over a specific period [3]. At present, drought is regarded as one of the most frequent natural disasters in Bangladesh [4], given its adverse impact on agricultural production and the environment. Moreover, the frequency and intensity of droughts have been continuously increasing in recent years, which have had a significant effect on agricultural production [5].

Droughts are mostly seasonal phenomenon in Bangladesh because of the wide variation in seasonal rainfall. Most of these droughts primarily occur in pre-monsoon (March-May) and post-monsoon (October–November) period [6]; however, in some extreme cases, the pre-monsoon droughts can persist into the monsoon season due to delay in the onset of monsoon rains. Moreover, the vulnerability to drought varies by region. Some studies have projected that, in the near future, precipitation would increase in most of the regions of Bangladesh but decrease in the southwestern region [7]. Spatiotemporal characteristics of historical droughts can provide relevant data for predicting future droughts [8]. Therefore, spatiotemporal characteristics of meteorological droughts over Bangladesh must be monitored to anticipate their negative impacts and mitigate potential losses and damages. Moreover, accurate assessment and mapping of droughts can play a vital role in understanding the characteristics of regional drought for using in drought monitoring, and early warning might help planning the efficient use of water resources and agricultural production.

Drought indices are used to characterise droughts in terms severity, duration, and areal extent [9]. Over the years, several drought indices (DIs) have been proposed and developed to identify the spatiotemporal pattern of droughts and quantify their intensity. Most of the drought indices have been developed for a specific region and are limited in terms of their applications to different climatic conditions given the inherent complexity of drought phenomena. However, a universal drought index that can be generalised across all regions has not been developed [10].

Several studies have been conducted on drought assessment in Bangladesh and its impacts [11-19]. Most of these studies quantify drought severity by using the standardized precipitation index (SPI) [20], while very few studies have been conducted using the Palmer drought severity index (PDSI) [21], and the Standardized Precipitation Evapotranspiration Index (SPEI) [22]. PDSI and SPI are the most widely used indices in current meteorological drought studies; however, both these indices have limited application. For example, PDSI was initially developed for quantifying drought severity in the Great Plains in the USA. Moreover, soil moisture calculation using PDSI has been known for its inaccuracy and complex procedure [23]. On the other hand, SPI is calculated based on averaged monthly precipitation for a certain period. Therefore, the time steps involved in SPI tend to produce several different values for the same period. Thus, SPI does not take into account the water resources generated by rainfall that may have already been lost due to outflow as well as the effect of evaporation. Moreover, SPI assigns tends to assign equal weight to temporally different precipitation events, thereby resulting in inaccuracy in predicting drought severity [24]. SPEI, which

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takes into account both rainfall and potential evapotranspiration (PET), requires a large amount of data for determining drought severity. Moreover, the use of different PET calculation methods produces different SPEI values for the same period. To overcome these limitations, Byun and Wilhite [25] developed Effective Drought Index (EDI). EDI is calculated only using rainfall data as in the case of SPI; however, there are some differences. First, EDI values can be calculated in daily time steps as well as in monthly time steps. Second, EDI utilises a variable time period for taking into account total precipitation. For example, although the primary summation period is 365 days or 12 months, if the drought continues beyond 365 days or 12 months, the summation period is extended to include the additional days or months; on the other hand, SPI considers only a fixed period. Third, the precipitation is summed using the time-reduction function. Hence, when compared to other drought indices, EDI was found to be more responsive to drought conditions, and could capture the real essence of the meteorological drought situations in the study area. Several that have examined the suitability of drought indices have suggested that EDI quantifies droughts more precisely than other DIs [26, 27, 28, 33, 34]. In particular, Kamruzzaman et al. [34] empirically demonstrated the superiority of EDI over SPI when monitoring both long-term and short-term droughts in Bangladesh.

Although there are several studies that have attempted to investigate droughts in Bangladesh, most of them utilised weather information from a few stations, without considering nationwide weather data. [15, 16, 18, 19, 35]. Only a handful of studies have utilised nationwide weather data by using mainly SPI indices [4, 12, 14, 17, 32]. Literature review suggest that droughts in Bangladesh have usually been investigated in terms of the season and year of their occurrence. Most of the studies have characterised the drought events in terms of severity and frequency; however, very few studies have considered the areal extent of drought [19, 29]. For example, Alamgir et al. [4] investigated meteorological drought for different cropping seasons of Bangladesh using SPI indices; the study revealed the variation in the spatial characteristics of droughts corresponding to different seasons. In [14], researches assessed drought years in terms severity of meteorological drought using both 3- and 6-month time scales of SPI during the period between 1971–2010. In [17], estimated the metrological drought event over Bangladesh that occurred during 1961–1990 using SPI and PDSI; the drought was compared with the historical drought record. The study showed that that regional analysis can detect 80% of the past drought events. Mondal et al. [12] modelled the spatial and temporal variations of meteorological drought year and severity in different areas of Bangladesh using SPIs during 1981-2010. However, no previous study was found to characterise the drought events considering drought duration. Therefore, there is a need for comprehensive study on the spatiotemporal characteristics concerning frequency, severity, duration, and the areal extent of meteorological drought event to better understand the conditions of drought in different regions of Bangladesh.

To that end, this study attempts to explore the suitability of EDI for evaluating the spatiotemporal characteristics of meteorological drought across different regions in Bangladesh. Precipitation data from 27 stations for the period between 1981–2015 were used to gain insights into the regional drought characteristics across Bangladesh. Moreover, in this study, frequency, severity, and duration of drought events as well as their spatiotemporal patterns are analysed. In addition, the spatial attributes of seasonal drought and temporal characteristics of the areal extent of drought are presented.

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2. Materials and Methods

2.1 Study area

The study area covers Bangladesh, which is situated in the latitudes between 20°34′ and 26°38′ N and longitudes between 88°01′ and 92°41′ E in South Asia. Bangladesh is bounded by India along the west, north, and northeast borders; it borders Myanmar in the south-east. The Bay of Bengal demarcates the southern border with a long coastline (Figure 1). Although the elevation in the northern part of the country can go up to 105 meters above sea level, most of the area in Bangladesh is less than 10 meters above sea level. The predominance of agriculture land is evident, given that 3/4th of the total geographical area is under cultivation, followed by forest cover including orchards, as shown in Figure 2.

Bangladesh is among the most vulnerable countries to the increasing effects of global climate change. It regularly experiences natural disasters such as floods, drought, tornadoes, and tidal bores [39]. In the recent past, Bangladesh has experienced drought at regular intervals; on average, Bangladesh experiences drought at least once in 2.5 y [12]. Although drought is a periodic occurrence in many parts of the country, the northwest region of Bangladesh is the most susceptible to drought because of the high variability in rainfall [19]. This area is also comparatively dry and is characterised by sandy soils, receiving much lower rainfall than the national average [36]. Moreover, the sandy soils have lower moisture retention capacity and high infiltration rate [37]. In addition, the Farakka barrage constructed in the upstream of the Ganges River has also had significant impact on the regional microclimate, aggravating the drought scenario.

To analyse drought conditions over the entire country, Bangladesh meteorological department (BMD) stations have been separated into four sub-regions, as shown in Figure 1, considering the topography, land use, and rainfall anomalies. The four regions are termed: (i) northern region (R1; 5 stations), (ii) southwestern region (R2; 9 stations), (iii) central region (R3; 4 stations), and (iv) eastern region (R4; 9 stations).

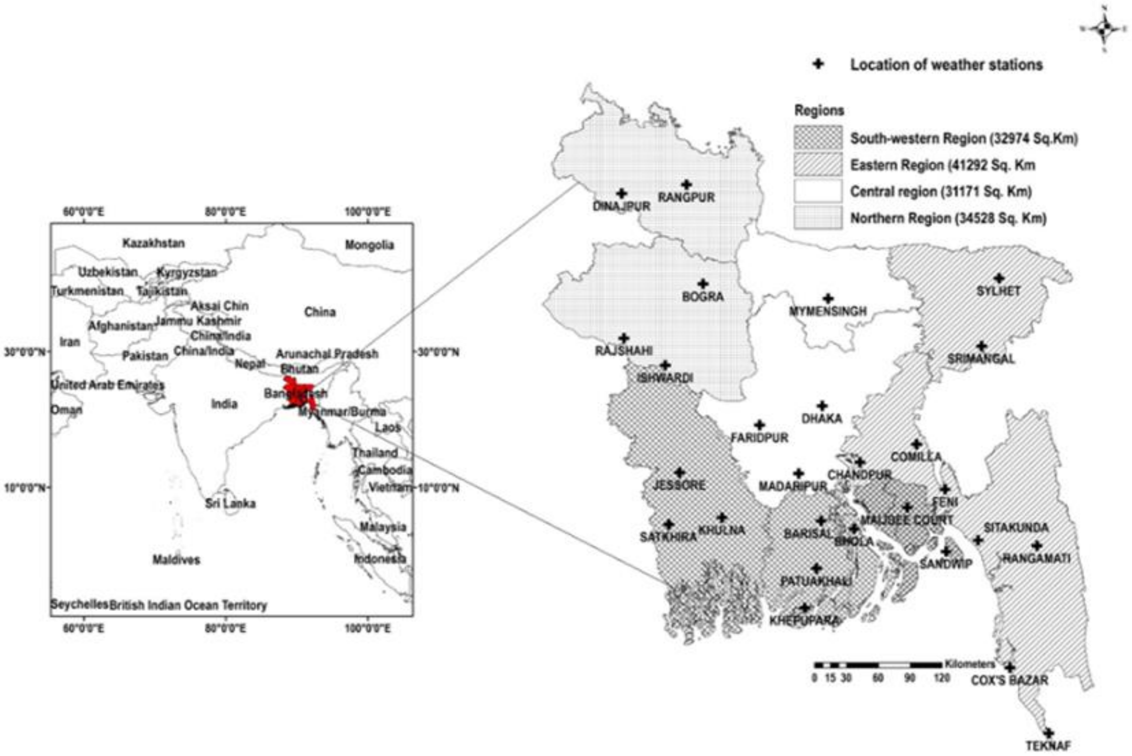

Figure 1: Location of meteorological station and regions in the study area

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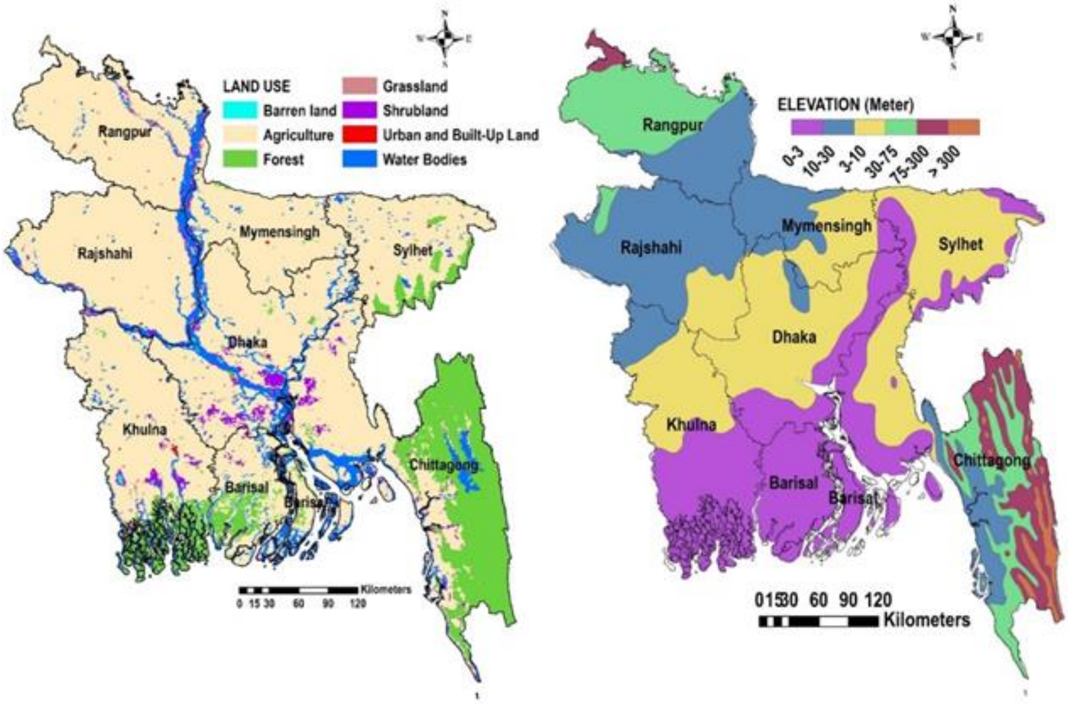

Figure 2: Land use map (left) and elevation map (right) of Bangladesh

2.2 Rainfall data

Bangladesh has a subtropical monsoon climate, characterised by wide seasonal variations in temperatures, rainfall, and humidity. The four recognised seasons are as follows: a hot, humid summer from March to May; a wet, warm, and rainy monsoon season from June to September; autumn from October to November; and a dry winter from December to February. Moreover, the cropping season in Bangladesh is categorised into *Pre-kharif* (March-June), *Kharif* (July-October), and *Rabi* (November-February).

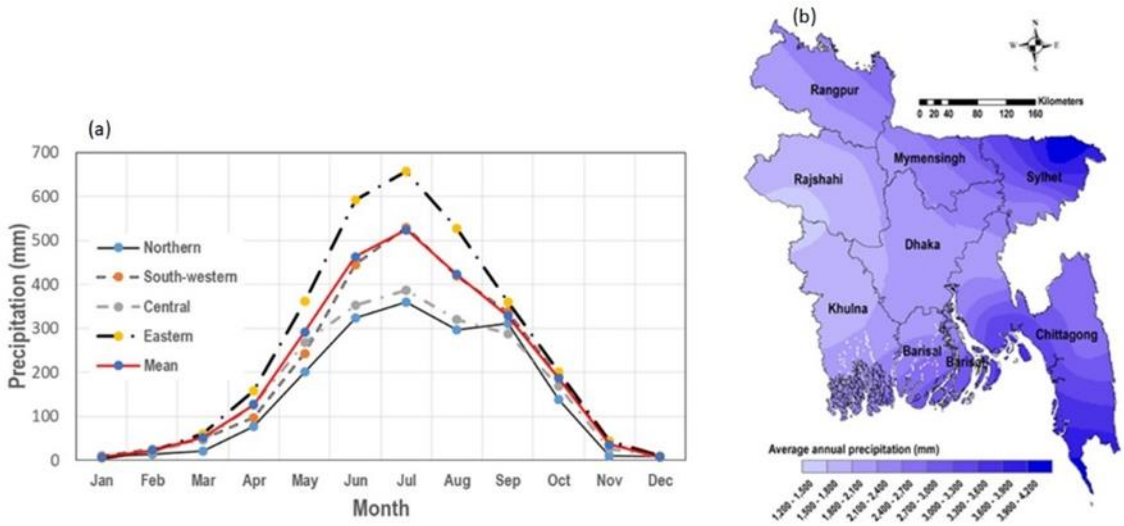

Figure 3: (a) Monthly distribution of rainfall four different regions of Bangladesh and (b) Spatial distribution of rainfall from 1980 to 2015

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At present, there are 35 weather stations in Bangladesh operated by the BMD. However, continuous rainfall records of more than 30 y are available only at 27 stations. In the present study, the time series of monthly rainfall between 1980 and 2015 for the 27 meteorological stations were used to diagnose the droughts. One of the major challenges with observational data is missing data. Roughly <2% of the data was missing, which was replaced by the averaged values of the same month from neighbouring stations. Figure 3(a) shows the monthly rainfall distribution in four different regions as well as over Bangladesh. The average annual rainfall recorded was 2462.14 mm from 1980 to 2015. Approximately 80% of the annual rainfall is received during the monsoon months (June to October) because of the weak humid depressions that are conveyed from the Bay of Bengal into Bangladesh by the damp monsoon winds [38]. The spatiotemporal variability of rainfall is one of the main features of the climate of Bangladesh. Figure 3(b) shows the spatial distribution of mean annual rainfall in Bangladesh during the study period. As shown in the figure, rainfall in Bangladesh fluctuated from about 1400 mm in the western region to more than 4000 mm in the eastern region of the country from 1980 to 2015. Moreover, the higher rainfall received in the northeast can be attributed to the additional uplifting effect of the Meghalaya plateau.

2.3 Historical drought data

The history of drought in Bangladesh has been poorly documented. However, major historical drought events of Bangladesh within the study period (1981-2015) were obtained from different sources and study reports [6, 17, 39, 40, 41]. Most of the drought records were prepared based on the crop damage data due to extreme and severe drought events in different parts of the country, as shown in Table 3. Post-independence, Bangladesh has experienced droughts in 1973, 1978, 1979, 1981, 1982, 1989, 1992, 1994, and 1995. However, the droughts of 1973, 1979, and 1994–1995 were the most severe in recent history, leading to a loss of 3.5 million tons of rice (in terms of agricultural production) in the north-western region alone[6]. Moreover, during the 2006 drought in the north-western part of Bangladesh, the average crop production reduced by 25–30% [42, 43]. According to the Bangladesh Bureau of Statistics (BBS) [38], between 2009 and 2014, natural disasters in the country accounted for damages (agricultural products and infrastructure) to the tune of 22521.60 million USD; of these, 5.74 % damage and casualties were attributed to droughts, which accounted for 126.33 million USD. In addition to agricultural crops, drought also affected orchards, forests, and the environment. Overall, 20 drought-years were recorded during the study period, as shown in Table 1.

2.4 Calculation of Effective Drought Index (EDI)

Effective Drought Index (EDI) was developed by Byun and Wilhite [25] to monitor the duration and severity of droughts using the concept of effective precipitation (EP). They defined effective precipitation as a function of the current month’s rainfall and weighted rainfall over a defined preceding period, computed using a time-dependent reduction function. The EDI calculation process used in this study is as follows:

$$EP_i = \sum_{n=1}^{i}[(\sum_{m=1}^{n} \mathrm{Pm})/n] \quad (1)$$

$$DEP = EP - MEP \quad (2)$$

$$EDI = DEP/ST(DEP) \quad (3)$$

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First, the stored water due to precipitation is accumulated over one year, while also considering the losses due to evaporation. In Eq. 1, EP is the monthly cumulative effective precipitation; *Pm* is the precipitation for *m* months before the particular month, *n* is the duration of the preceding period, and *i* is the duration of aggregate rainfall, initialised at 12 months (overall precipitation duration). Therefore, the actual drought index is calculated for a period of one year from the onset of precipitation.

Second, the mean effective precipitation (MEP) is calculated for each calendar month. The MEP is calculated for the i^{th} value of each calendar month. Therefore, the MEP of January is the mean of 30 values for January collected over a period of 30 y.

Third, the deviation of EP (DEP) is determined from the MEP (Eq. 2). A negative DEP indicates a drier than the average climate. If the DEP is continuously negative, *i* in Eq. 1 is increased by the number of months for which DEP is negative. In other words, the number of dry months is added to 12 months. For example, if the negative DEP continues for two months, *i* is 14, and Eqs. 1, 2, and 3 are re-calculated. Finally, the DEP is standardised, where ST (DEP) indicates the standard deviation of each month's DEP. Using these functions, the EDI helps us consider the standardised deficit, or surplus, of the deposited water quantity.

EDI was initially developed to monitor drought conditions for periodic time steps. Subsequently, it was extended to monitor droughts on a monthly basis [27, 30, 31, 44-46].

2.5 Definition of drought characteristics

The level of dryness is classified according to the EDI classification proposed by Kim et al. [26], as shown in Table 1. In this study, droughts were categorised based on duration, as shown in Table 2.

Table 1: Drought classification based on severity [26]

EDI value	Category
-1.00 to -1.49	Moderate Drought
-1.50 to -1.99	Severe Drought
-2 or less	Extreme Drought

Table 2: Drought classification based on drought duration

Duration (Months)	Category
Months ≤ 3	Short-term
6 >= Month > 3	Medium-term
12 >=Month > 6	Long-term
Months > 12	Extra long-term

A negative value implies that the region is drier; conversely, a positive value (>0) indicates that the region is wetter. In this study, each drought event is analysed in terms of drought duration and severity.

In this study, the date of drought onset is considered to be the month in which the EDI first reaches -1.0, and the termination date is considered to be the month when the EDI regains the value of -1.0. The duration between the start and the end date is defined as the drought duration, as shown in Figure 4.

Drought frequency is represented by the number of events (months) per quinquennial as well as by the number of events per 35 y (the whole period).

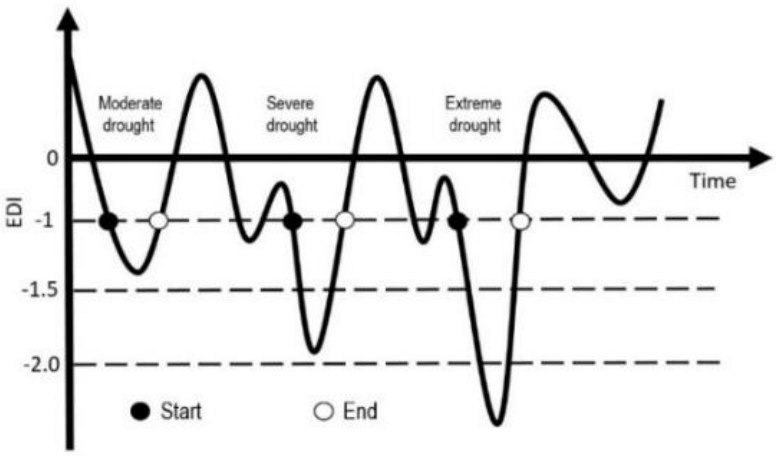

Figure 4: The schematic illustration of drought characteristics (duration, severity) with EDI time series

In addition to duration and severity, areal extent is also regarded as a major characteristic of metrological drought. In this study, the Inverse Distance Weight (IDW) algorithm was used to spatially extrapolate the monthly EDI data to the entire study area. Then, the interpolated maps are analysed for the four different regions to estimate the areas under different severities of droughts for each month. In this study, the zonal statistics as a table function of ArcGIS software (v10.6) was used to calculate the areal extent.

3. Results and discussions

3.1 Reconstruction of Historical drought

The meteorological drought over Bangladesh was analysed using the EDI method by using monthly rainfall time series data (1981–2015). Average rainfall data from the stations in the individual sub-regions were used for calculating EDI. According to Dash et al., [17], the regional average rainfall data of neighbouring stations provide better information for drought diagnose when compared to the individual station analysis. Moreover, given that drought is a regional phenomenon, detecting historically recorded drought events using monthly rainfall time series data from the stations is a challenging task.

The historical records of major drought events in Bangladesh were used in the study for validating the results obtained using EDI. In Bangladesh, historical drought records only recognise severe and extreme drought events as major droughts. Therefore, in this study, extreme ($EDI \leq -2.0$) and severe ($-2.0 < EDI \leq -1.5$) droughts were considered for the evaluation of the results obtained using EDI. In addition, the results of a previous study obtained using SPI [12, 14] were used as the benchmark for the present study. The results show that the proposed method can detect historically recorded droughts better than SPIs.

Figure 5 shows the major droughts events (severe and extreme) occurred in different parts of Bangladesh in 1981, 1982, 1983, 1985, 1986, 1987, 1989, 1992, 1993,1994, 1995, 1999, 2004, 2006, 2009, 2010, 2011, 2012, 2013, 2014, and 2015. It was found that the drought years obtained from EDI calculations based on regional analysis could partially or fully detect most of the recorded drought

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years, with the exception of 1984 and 1988. However, the EDI values suggest that different parts of Bangladesh experienced droughts in 1993, 1999, 2003, 2004, and 2007, which were not included in historical drought records. This may be attributed to the relatively shorter duration of these droughts, which lasted for 1, 1, 2, 1, and 1 months in 1993, 1999, 2003, 2004, and 2007, respectively. In addition, poor documentation practices may also be responsible for the exclusion of these droughts in the historical drought records. It should be noted that droughts in Bangladesh are recorded based on the only crop damage criterion. Further, the results of this study pertaining droughts 2003 and 2004 were partially supported by SPI-based studies [12, 14]. Therefore, it can be said that EDI can be used to reproduce the real essence of drought events.

Table 3. Historical records of drought years and drought-affected areas and the results of drought detection using EDI (this study) and SPI (previous studies) over Bangladesh (1981-2015)

Year	Historical major drought*		EDI based major drought		SPIs based major drought	SPI-3 based major drought [14]***
	Recorded	Affected areas	Classified	Affected areas		
1981	recorded	WC	Partially identified	ER	-	Identified
1982	recorded	WC	Partially identified	SWR	-	Identified
1983	recorded	WC	Partially identified	NR	Identified	-
1984	recorded	WC	Not identified		-	-
1985	recorded	WC	Partially identified	ER	Identified	Identified
1986	recorded	WC	Partially identified	SWR and ER	-	-
1987	recorded	WC	Partially identified	ER	-	-
1988	recorded	WC	Not identified	-	-	-
1989	recorded	ER, SWR, and CR	Identified	ER, SWR, and CR	-	-
1992	recorded	WC	Identified	WC	Identified	-
1993	-	-	Identified	SWR and ER		
1994	recorded	NR, SWR, and CR	Identified	WC	Identified	-
1995	recorded	NR, SWR, and CR	Identified	WC	Identified	-
1997	-	-	-	-	-	Identified
1999	-	-	Identified	ER	-	Identified
2002	-	-	-	-	Identified	-
2003	-	-	Identified	CR	-	-
2004	-	-	Identified	SWR	Identified	Identified
2006	recorded	NR	Identified	NR	Identified	Identified
2007	-	-	Identified	NR	-	-
2009	recorded	NR, SWR, and CR	Identified	CR	Identified	-
2010	recorded	NR, SWR, and CR	Identified	NR, SWR, and CR	-	Identified
2011	recorded	NR, SWR, and CR	Partially identified	NR and CR	Identified	-
2012	recorded	NR, SWR, and CR	Partially identified	NR and CR	-	-
2013	recorded	NR, SWR, and CR	Identified	NR, SWR, and CR	-	-
2014	recorded	SWR, CR, and ER	Identified	WC	-	-
2015	recorded	SWR	Identified	SWR	-	-

WC=Whole country, NR=Northern region, SWR=South-western region, CR=Central region, ER= Eastern region

*Observation Source: Banglapedia [4], CCC [40], Dash et al. [17], BBS [39], Personal communication with BMD staff (2017)

**SPIs (SPI-1, SPI-3, SPI-6, SPI-9, and SPI-12) based study source: Mondal et al. [12]

*** SPI-3 based study source: Rahman and Lateh [14]

+Partially indicates the cases that EDI detected the recorded partial areas.

3.2 Temporal variation of drought

To examine the temporal variation in the characteristics of drought, we used linear regression methods to detect the changing trends in the magnitude of EDI values at a significance level of p =.01 for different regions of Bangladesh. The temporal variations in the severity of droughts occurring in the northern, southwestern, central, and eastern regions are illustrated in Figure 4(a)–(d). The declining EDI values observed from the analysis signifies an increasing drought severity for the study area. The most significant decreasing trend in EDI values was observed in the central region; however, this decreasing trend was milder in the eastern region. No significant trend was observed in the north and south-west regions of Bangladesh. It can be said that the meteorological drought severity shows an overall increasing trend in the study area.

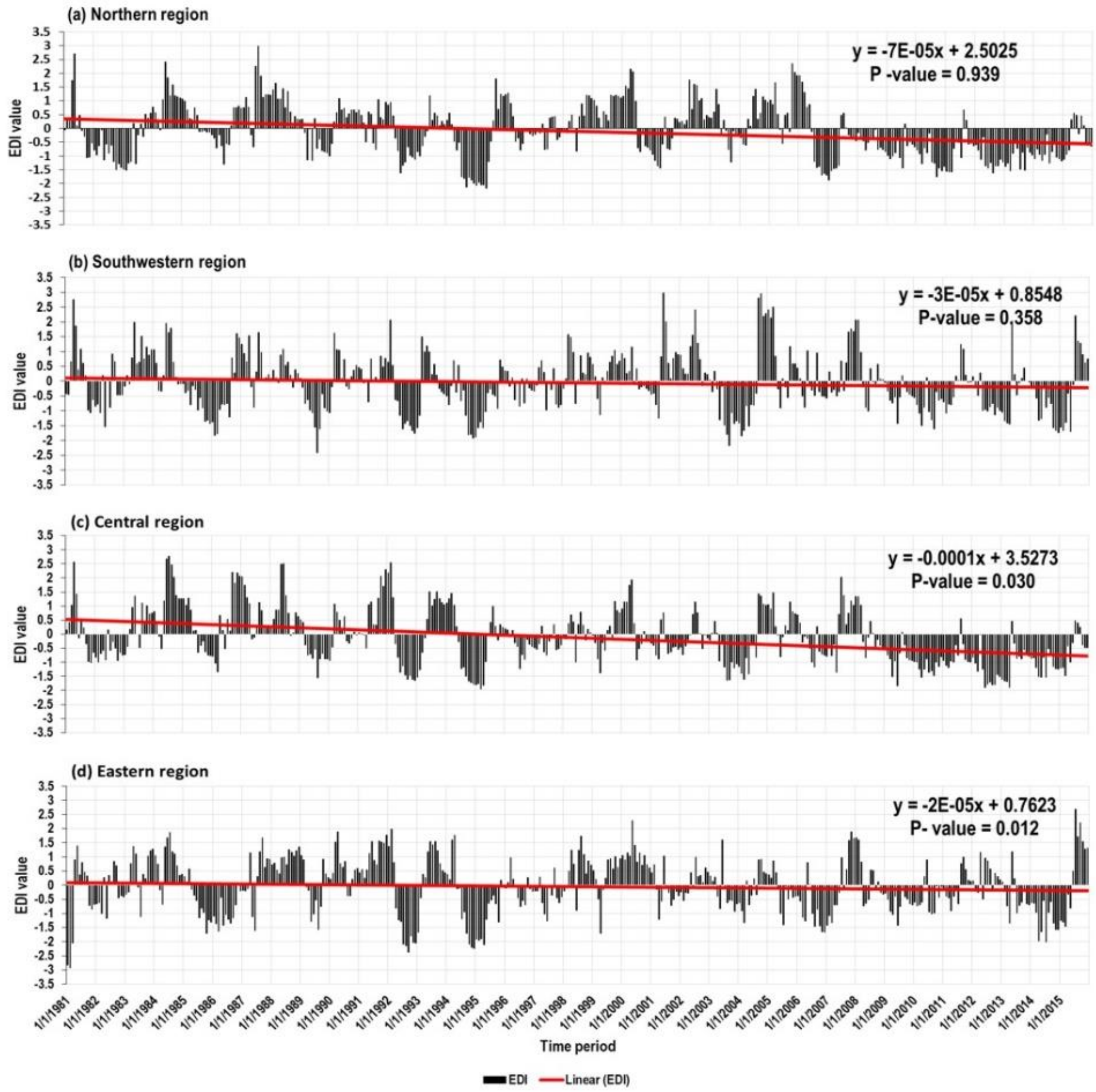

Figure 5: EDI values calculated from observed rainfall data at (a) northern, (b) south-western, (c) central and (d) eastern sub-regions of Bangladesh during 1981-2015.

3.3 Drought severity

The severity of a drought event was defined based on the lowest EDI value for each event. The total study period was divided into seven quinquennial periods (1981-85, 1986-90, 1991-95, 1996-00, 2001-05, 2006-2010, 2011-2015) for understanding the temporal changes in the frequency of droughts over time. For each period, the number of events for each level of severity was enumerated at each

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station and averaged over the separated region, as shown in Table 4. The drought events showed an increasing trend in terms of drought frequency.

The results showed that the highest number of drought events (24) was observed in the central region (R3) and the lowest number (15) was observed in the eastern part (R4). For the regions R1–R4, 5.39%, 6.67%, 7.66%, and 3.27% of the total drought events were classified as severe; on the other hand, 3.19%, 2.86%, 1.23%, and 2.18% were classified as extreme. The remainder of the drought events (67.73%) were classified as moderate droughts. The highest number of extreme drought events, accounting for 1.36% of the total drought events was observed in the eastern region during 1981-1985, followed by 1.09% in the southwestern region during the last quinquennial period. No extreme drought events were observed in all regions during 1995-2000. Likewise, no extreme drought events were observed in the northern region, eastern region, and central region during 1986–90, 2001–2010, and 1986–2010, respectively. However, the highest number of extreme drought events (3.19%) was observed in the northern region (R3), while the lowest number (1.23%) was observed in the central region during the study period. Moreover, increased frequencies of extreme drought were found in the south-western and central region, followed by the northern region, during the last quinquennial.

Table 4: Regional drought events by severity

Classification (Severity)	Spatial range	Northern region (R1)	South-western region (R2)	Central region (R3)	Eastern region (R4)
No. of Station		5	9	4	9
1981 to 1985	Moderate	1.00 (1.23%)	2.22(2.72%)	1.50(1.84%)	1.11(1.36%)
	Severe	0.60 (0.74%)	0.44(0.54%)	0.50(0.61%)	-
	Extreme	0.40 (0.49%)	0.33(0.41%)	0.25(0.31%)	1.11(1.36%)
1986 to 1990	Moderate	1.60 (1.96%)	2.00(2.45%)	1.00(1.23%)	1.44(1.77%)
	Severe	0.20 (0.25%)	1.00(1.23%)	0.75(0.92%)	0.78(0.95%)
	Extreme	-	0.22(0.27%)	-	0.11(0.14%)
1991 to 1995	Moderate	1.60 (1.96%)	1.33(1.63%)	2.00(2.45%)	1.56(1.91%)
	Severe	0.80 (0.98%)	0.56(0.68%)	1.25(1.53%)	0.56(0.68%)
	Extreme	0.80 (0.98%)	0.56(0.68%)	-	0.22(0.27%)
1995 to 2000	Moderate	1.80 (2.21%)	2.44(3.00%)	2.50(4.90%)	1.11(1.36%)
	Severe	0.20 (0.25%)	0.56(0.68%)	0.5(1.23%)	0.11(0.14%)
	Extreme	-	-	-	-
2001 to 2005	Moderate	1.60 (1.96%)	1.78(2.18%)	4.00(4.90%)	1.89(2.31%)
	Severe	0.20 (0.25%)	0.89(1.09%)	1.00(1.23%)	0.22(0.27%)
	Extreme	0.20 (0.25%)	0.11(0.14%)	-	-
2006 to 2010	Moderate	1.80 (2.21%)	2.44(3.00%)	2.75(3.37%)	1.89(2.31%)
	Severe	1.00 (1.23%)	1.00(1.23%)	1.25(1.53%)	0.22(0.27%)
	Extreme	0.80 (0.98%)	0.22(0.27%)	-	-
2011 to 2015	Moderate	2.80 (3.43%)	3.44(4.22%)	2.75(3.37%)	1.67(2.04%)
	Severe	1.40 (1.72%)	1.00(1.23%)	1.00(1.23%)	0.78 (0.95%)
	Extreme	0.40 (0.49%)	0.89(1.09%)	0.75(0.92%)	0.33(0.41%)
Average number of regional		19.20 (±5.36)	23.44(±8.40)	23.75 (±3.30)	15.22(±7.89)

Parenthesis are expressed as the percentage of total drought events occurred during the study period

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The highest number of severe drought events (1.72% of total drought events) was observed in the northern region (R1) during the last quinquennial, followed by the central region (1.53% of total drought events), during 1991–95 and 2006–10, respectively. On the other hand, the lowest number (0.14% of total drought events) was observed in the eastern region during 1995-2000. No severe drought events were observed in the eastern region during 1986-1990. Moreover, all categories of droughts showed shown an increasing trend in terms of frequency over the study period (with the exception except extreme drought in the eastern region). Thus, from the above, the northern region clearly experiences extreme droughts, whereas the central region experiences severe drought. Moreover, all categories of droughts have shown increased frequency during the last quinquennial from 2011–2015.

In addition, the spatial pattern of drought frequency by drought category (moderate, severe, extreme) was investigated based on the total number of drought events occurring during the entire study period. The total number of drought events accumulated during the study period at each station for each level of severity (Table 1) were then interpolated using the IDW algorithm (Figure 6). The spatial analysis of drought can help in identifying the areas frequently affected by drought as well as delineating the most drought-prone areas. Figure 6 illustrates the spatial pattern of the averaged drought frequency over the study period by drought category, based on the level of severity. The results suggest that the occurrence of drought events varies by regions as well as severity. Comparatively, it was observed that moderate droughts occurred more frequently than severe and extreme droughts during the study period.

The western part of north Bangladesh and a small portion along the coastal area in the southwest region were extreme drought-prone regions as shown in Figure 6(a). The severe drought-prone regions were found in the northern, southwest, and the central areas (Figure 6(b)). Further, the spatial pattern suggest that most of Bangladesh is moderately drought-prone, and a higher drought frequency was observed in the south-western regions (Figure 6(c)). The spatial analysis of the occurrence of droughts (different categories) indicates that the northern, south-eastern, and central regions of the country are comparatively more vulnerable to drought. Extreme droughts were observed most frequently in the western part of the country. However, the eastern part of the country was observed to be less vulnerable to droughts.

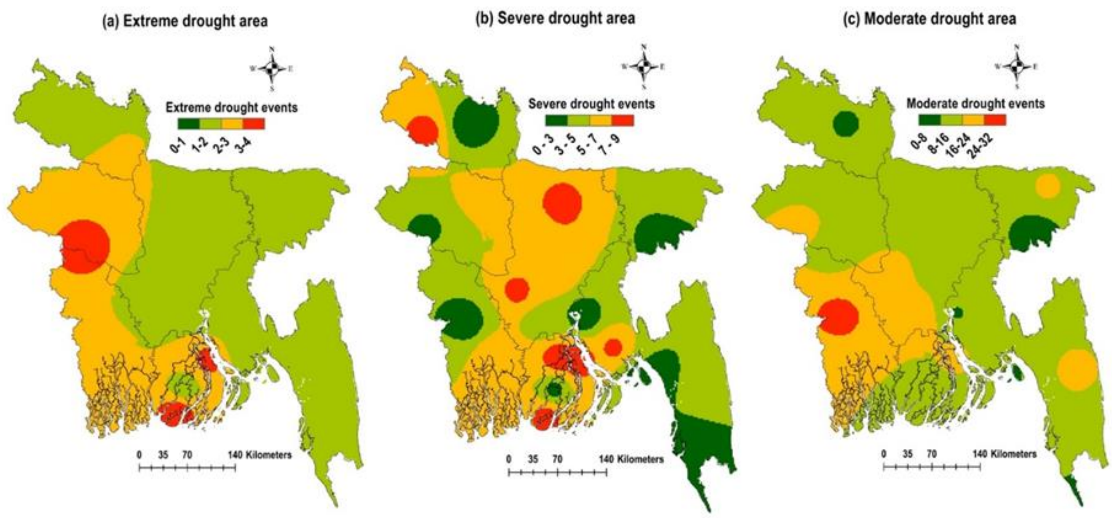

Figure 6: Spatial distribution of droughts during 1981–2015: (a) Extreme; (b) Severe; (c) Moderate severities.

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Therefore, this result agrees with the previous studies on drought occurrences in Bangladesh that were based on SPI indices. For example, Rafiuddin et al. [1] stated that the northern, south-eastern, and central regions are the most severe drought-prone regions in Bangladesh. They studied droughts over Bangladesh during the period between 1961–1990 using an SPI time scale of 1-month, 3-months, and 6-months. According to Rahman and Lateh [14], the northern, north-western, western, south-western, and central regions of Bangladesh were more prone to drought based on the 3-month time scale of SPI indices during the period between 1971–2010. However, Hasan et al. [47] pointed out that the frequency of extreme drought increased in the north-western and decreased in the eastern regions of Bangladesh, based on 3-month time scale SPI indices. They also expressed that extreme drought events reduced, while severe and moderate drought events increased. The results of this study are in agreement with previous studies; however extreme drought was shown to have increased in frequency during the last quinquennial (2010-2015) because of the recent changes in the precipitation pattern.

3.4 Drought duration

Table 5 shows the frequency of droughts by event duration at regional scale. The frequency of droughts was determined based on the average number of drought events for the stations within each region and categorised durations. It can be seen that short-term droughts lasting less than 3-months have a higher occurrence rate than the droughts lasting longer than 3-months.

Table 5 shows that short-term droughts comprised 68.51% of the total drought events occurred in all the regions (R1-R4) during the entire study period. In Bangladesh, short-term droughts are generally observed more frequently because the country receives more than 100 mm rainfall in the 9-month period between March and October; thus, droughts in Bangladesh rarely last for extended periods.

In addition, the frequency of short-term droughts showed an increasing trend over the study period for all regions; the highest frequency (4.91%) was observed in the central region during 2001–2005, .followed by the southwestern region (4.77%) during 2010–2015. The frequency of medium-term drought also showed an increasing trend in the northern and eastern regions, while a decreasing trend was observed in other regions. In particular, the highest number of medium-term droughts (1.47%) were observed in the northern region during 2006-2010. Interestingly, occurrence of long-term drought showed a decreasing trend in the southwestern region. The highest number of long-term drought events (1.23%) were observed in the central (R3) region during the period between 1986–1990. The results suggest that occurrence of extra long-term droughts in the eastern region decreased and an increasing trend was observed in in other regions. The highest number of extra long-term drought events (1.53%) was observed in the central region during the last quinquennial period. In northern and southwestern regions, occurrence of all categories of droughts showed an increasing trend during the last quinquennial; however, no medium-term and extra long-term droughts occurred in the central and eastern region. In general, a lower frequency of drought occurrence was observed in the eastern region for the entire study period.

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Table 5. Regional drought events by duration

Classification (Duration)	Spatial range	Northern region (R1)	South-western region (R2)	Central region (R3)	Eastern region (R4)
No. of Station		5	9	4	9
1981 to 1985	Short-term	1.00(1.23%)	2.33(2.86%)	1.50(1.84%)	1.44(1.77%)
	Medium-term	0.20(0.25%)	0.44(0.54%)	0.25(0.31%)	0.11(0.14%)
	Long-term	0.60(0.74%)	0.22(0.27%)	0.50(0.61%)	0.11(0.41%)
	Extra long-term	0.20(0.25%)	-	-	0.22(0.27%)
1986 to 1990	Short-term	1.40(1.72%)	2.22(2.72%)	1.00(1.23%)	1.67(2.04%)
	Medium-term	0.20(0.25%)	0.56(0.68%)	0.50(0.61%)	0.22(0.27%)
	Long-term	0.20(0.25%)	0.44(0.54%)	1.00(1.23%)	0.22(0.27%)
	Extra long-term	-	-	-	0.22(0.27%)
1991 to 1995	Short-term	2.00(2.21%)	1.22(1.50%)	1.25(1.53%)	1.33(1.64%)
	Medium-term	0.40(0.49%)	0.33(0.41%)	0.50(0.61%)	0.11(0.14%)
	Long-term	0.40(0.49%)	0.89(1.09%)	-	0.11(0.95%)
	Extra long-term	0.40(0.49%)	-	0.25(0.31%)	0.78(0.95%)
1996 to 2000	Short-term	1.40(1.72%)	2.56(3.13%)	2.5(3.06%)	1.22(1.50%)
	Medium-term	0.20(0.25%)	0.22(0.27%)	0.50(0.61%)	-
	Long-term	0.40(0.49%)	0.22(0.27%)	-	-
	Extra long-term	-	-	-	0.11(0.14%)
2001 to 2005	Short-term	1.60(1.96%)	2.33(2.86%)	4.00(4.91%)	2.11(2.59%)
	Medium-term	-	0.11(0.14%)	0.50(0.61%)	-
	Long-term	0.40(0.49%)	0.22(0.27%)	0.25(0.31%)	-
	Extra long-term	-	0.11(0.14%)	0.25(0.31%)	-
2006 to 2010	Short-term	1.40(1.72%)	3.22(3.95%)	3.25(3.98%)	1.56(1.91%)
	Medium-term	1.20(1.47%)	0.33(0.41%)	-	0.44(0.41%)
	Long-term)	0.60(0.74%)	-	0.50(0.61%)	0.44(0.41%)
	Extra long-term	0.40(0.49%)	0.11(0.14%)	0.25(0.31%)	0.33(0.14%)
2011 to 2015	Short-term	2.60(3.19%)	4.47(4.76%)	2.75(3.37%)	2.00(2.45%)
	Medium-term	0.80(0.98%)	0.68(0.68%)	-	0.33(0.41%)
	Long-term	1.00(1.23%)	0.95(0.95%)	0.75(0.92%)	0.33(0.41%)
	Extra long-term	0.20(0.25%)	0.14(0.14%)	1.25(1.53%)	0.44(0.54%)
Average number of drought		19.20 (±5.36)	23.44(±8.40)	23.75 (±3.30)	15.22(±7.89)

Parenthesis are expressed as the percentage of total drought events occurred during the study period

The spatial patterns of drought frequency by event duration were mapped based on the number of drought events for different drought durations (short-term, medium-term, long-term, and extra long-term). Figure 7 illustrates the spatial patterns of averaged drought frequency over the study period by event duration. As shown in Figure 7(a), the extra long-term drought-prone area was mainly located in the central region. Long-term drought was found to be prominent in the northern, central, and in a small part of the southern region (Figure 7(b)). Medium drought-prone areas were observed in the northern and southern regions; however, their occurrence was more prominent in the south-western region (Figure 7(c)). Further, the spatial pattern suggests that most of the areas are very short-term drought-prone; on the other hand, a greater frequency was observed in the south-western regions (Figure 7(d)). The results indicate that, overall, the western and central regions are most vulnerable to drought.

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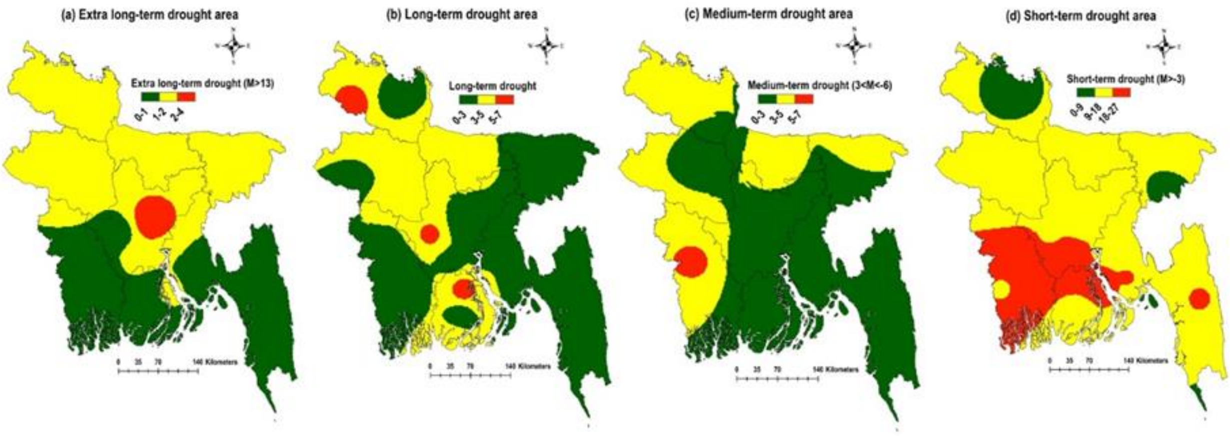

Figure 7. Spatial pattern of drought events during 1981–2015: (a) Extra long-term; (b) Long-term; (c) Medium-term; (d) Short-term drought duration

3.5 Spatial distribution of seasonal drought

In this study, in order to determine seasonal drought-prone areas, the spatial distributions of seasonal drought frequency were developed based on the averaged counts of drought events occurring during each cropping season (Pre-Kharif, Kharif, and Rabi) of Bangladesh. Seasonal droughts were analysed spatially, based on the number of drought months occurring in each season by drought category (moderate, severe, and extreme). The total number of drought months in each season accumulated by category at each station during the study period was then interpolated using the IDW algorithm (Figure 8). The spatial analysis of seasonal drought helps to identify areas that are most vulnerable to drought. In 2001, Bangladesh Agricultural Research Council (BARC) produced three different maps for pre-Kharif, Kharif, and Rabi seasons by considering soil and climate factors such as available moisture holding capacity, soil percolation rate, temperature, and rainfall uncertainty. These maps were used to validate the agricultural-drought prone areas derived the results of the present study.

The pre-Kharif season is characterised by irregular rainfall and high temperatures (>40°C in March/May). This climate trend has adverse effects on all pre-Kharif crops such as T. aus, particularly in regions where the agricultural infrastructure limited. The spatial distribution of extreme, severe, and moderate droughts during the pre-Kharif season is shown in Figure 8(a1), (b1), and (c1). The observed map indicates the small region in the north-eastern part of Bangladesh, which is covered by Rajshahi station and its neighbourhood areas, is prone to extreme droughts, as shown in Figure 8(d1). This may be attributed to the changes in precipitation pattern between 2002-2015 in this region. Rainfall data analysis for pre-kharif season indicates a decreasing trend in rainfall in Dhaka station (0.78% per year), which was more severe than that in Rajshahi station (0.27% per year) during the period between 2002-2015. Therefore, it can be said that the Dhaka station and its surrounding regions experienced extreme drought in the recent past.

During the study period, the major share of rainfall (78.5%) in Bangladesh was received during the Kharif season. Therefore, rainfall during the Kharif season is critical to the agriculture production and food security of Bangladesh. Moreover, this rainfall is the major source of groundwater recharge. Therefore, any deficit in rainfall during the Kharif season severely affects Kharif crops. In addition, non-replenishment of groundwater adversely affects groundwater-based irrigation during the Rabi and pre-Kharif seasons. Therefore, droughts occurring during the Kharif season are most hazardous

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for Bangladesh compared to any other cropping seasons [4]. According to Karim et al. [43], droughts in the period between June/July and October result from dry conditions in the highland areas, especially in the north-western region. Drought affects the critical reproductive stages of T. Aman rice, thereby reducing its yield, particularly in those areas with low soil moisture-holding capacity. In addition, such droughts also have a significant impact on fisheries and other household-level activities.

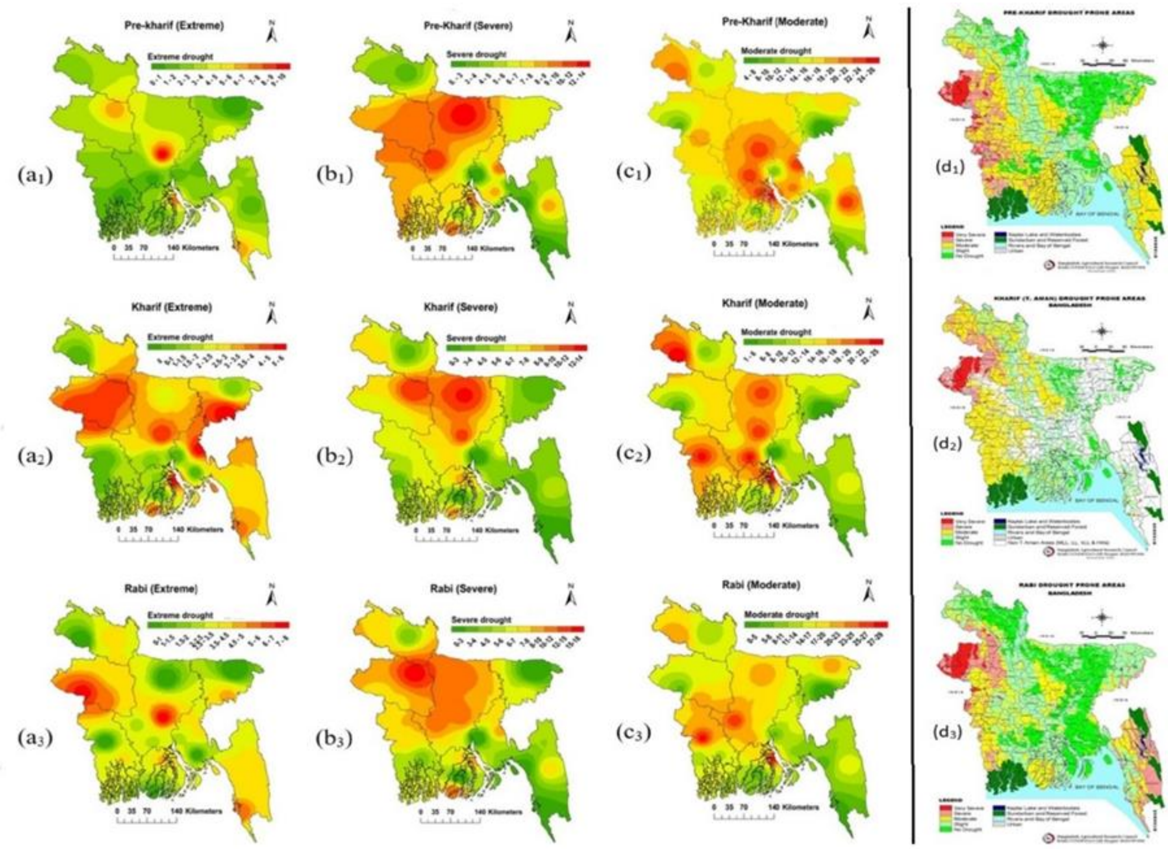

Figure 8: Spatial distribution of seasonal drought in Bangladesh during 1981-2015: Upper row indicates the Pre-Kharif (March-June) with (a_1) Extreme; (b_1) Severe; and (c_1) Moderate Severities, middle row shows the Kharif (July-October) droughts with (a_2) Extreme; (b_2) Severe; and (c_2) Moderate Severities, and bottom row indicates the Rabi (November-February) droughts with (a_3) Extreme; (b_3) Severe; and (c_3) Moderate severities. Right side column shows the corresponding observed agricultural drought map prepared by BARC in 2000

The spatial distribution of extreme, severe, and moderate droughts during Kharif season is shown in Figure 8(a2), (b2), and (c2), respectively. The results suggest that extreme droughts occurred frequently in the northwest and middle of the eastern part of Bangladesh. Further, occurrence of severe droughts was prominent in the central and a small part of the northern region (Figure 8(b2)). Moreover, the northern, southwestern, and central regions were found to be susceptible to moderate droughts (Figure 8(c2)). However, the observed map indicated that the eastern part of the country was not susceptible to extreme and severe droughts during the Kharif season, particularly at Srimangal station and its surrounding areas. This can be attributed to the recent changes in rainfall pattern in that area. It is evident that recently, the average rainfall has shown a decreasing trend in Kharif season; the average annual rainfall decreased at a rate of .08% per year during the period

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between 2002-2015; on the other hand, an increasing trend was observed (rate of .07% per year) during the period between 1981–2001. Therefore, the drought prone areas must be updated to reflect the recent changes in the weather characteristics over Bangladesh.

Rabi droughts are believed to occur due to the cumulative effect of dry days and low soil moisture. This drought affects all Rabi crops, such as Boro rice, wheat, pulses, and potatoes. The spatial distribution of extreme, severe, and moderate droughts during the Rabi season are shown in Figure 8(a3), (b3), and (c3), respectively. The frequency of moderate droughts during the Rabi season is higher in the central and southwestern regions (Figure 8(c3)). The spatial distributions of extreme, severe, and moderate droughts during Rabi season developed in this study exhibit considerable similarities to the observed map.

3.6 Variation of the drought-affected area

The spatiotemporal variation in the drought-affected regions was evaluated based on the monthly EDI values determined for the 27 stations during the study period. The interpolated maps were used to estimate the drought-affected areas in each month for different regions by each level of drought severity.

Linear regression methods were used to observe trends in the drought affected areas at different significance levels (p = 0.001, 0.01, and .05) for the different regions of Bangladesh to examine the variations in the drought areas. Table 6 lists the percent changes in the drought-affected areas on a decade basis. Overall, the most significant increasing trend in terms of the drought-affected regions was observed in the central region; on the other hand, a decreasing trend was observed in the eastern region during the study period.

Table 6 shows that the highest change in drought-affected area for moderate, severe, and extreme drought was 3.46 % per decade in May, 1.38% per decade in March, and 0.32 % per decade in May, respectively, within the central region. However, the most significant decreases in drought-affected area was observed for extreme and severe drought with a rate of 0.34% per decade in February and 0.39% per decade in January–March, respectively, in the eastern region. Moreover, only a statistically significant increasing trend of moderate drought was found in April within the same region. According to the drought records, the north-western regions of Bangladesh were most vulnerable to droughts [6]. However, this research indicates that the central region has recently emerged as the most drought vulnerable region, especially in March-May because of the high rainfall variation in this area.

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Table 6. Trends per decade regional series of the monthly drought area

Region	Drought category	Drought area increase/(-)decrease (% per decade) during 1981-2015											
		Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
NR	Extreme	0.15	0.17	0.22	0.01	**-0.07**	**-0.02**	0.12	0.12	0.24	0.05	0.12	0.09
	Severe	0.33	0.30	0.55	0.10	0.11	0.14***	0.87*	0.77**	0.40	**-0.18**	**-0.02**	0.06
	Moderate	1.61	1.05	1.37*	1.15	2.21***	0.36*	1.69	1.46*	1.12	1.63*	1.68*	1.20*
	Total	2.09	1.52	2.14*	1.26	2.25*	0.48**	2.68	2.35**	1.76	1.50	1.78	1.35
SWR	Extreme	**-0.02**	0.02	0.09	0.04	0.08	0.02	0.03	0.06	0.08	0.05	0.08	0.04
	Severe	0.03	0.25	0.34	0.52	0.43	0.24**	0.22	0.07	0.40	0.03	0.05	0.05
	Moderate	0.18	0.45	1.34	1.30*	1.75***	0.89	0.55	0.44	0.17	0.36	0.42	0.14
	Total	0.19	0.72	1.77	1.86	2.26**	1.15	0.8	0.57	0.65	0.44	0.55	0.23
CR	Extreme	0.05*	0.07**	0.13***	0.36	0.32*	0.00	0.08*	0.00	0.05*	0.07*	0.03	0.04
	Severe	0.71**	0.81**	1.38**	0.84	0.66**	0.49**	1.07***	0.31*	1.21**	0.59	0.56	0.62
	Moderate	1.60*	1.76*	2.15**	2.71***	3.46***	1.62**	2.08***	1.30	0.53	1.25	1.30	1.37
	Total	2.36**	2.64**	3.66***	3.91***	4.44***	2.11**	3.23***	1.61*	1.79	1.91*	1.89	2.03*
ER	Extreme	**-0.32****	**-0.34****	**-0.32****	**-0.12***	**-0.13****	**-0.07****	**-0.05**	**-0.08***	**-0.09***	**-0.13***	**-0.15****	**-0.14****
	Severe	**-0.39*****	**-0.39*****	**-0.39****	0.01	**-0.31**	**-0.23****	**-0.01**	**-0.24**	**-0.14***	**-0.3****	**-0.35****	**-0.33****
	Moderate	**-0.65**	**-0.18**	0.65	1.33*	0.96	**-0.25**	0.20	**-1.14**	**-0.59**	**-0.98**	**-0.74**	**-0.52**
	Total	-1.36	-0.91	-0.06	1.21	0.52	-0.55	0.15	-1.46	-0.82	-1.41	-1.24	-0.99

*Level of Significance 0.001 '***,' 0.01 '**,' 0.05'*'*

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4. Conclusions

In this study, EDI was used to assess the spatiotemporal characteristics of meteorological droughts between 1981 to 2015 in Bangladesh. The performance of the EDI indices in terms of detecting droughts was evaluated through comparisons with historical drought records. The results showed that EDI indices are suitable tools for detecting, monitoring and assessing drought conditions by regional analysis.

The study provides a comprehensive description about the severity, frequency, duration, and areal extent of drought during the study period (1981–2015) in Bangladesh. The results of the study showed that the central region of Bangladesh experienced an increasing trend in terms of drought occurrence and severity, duration, and areal extent; on the other hand, the opposite trend was observed in the eastern region. In terms of areal extent, the highest increasing trend was observed during March–May in the central region because of the variability in rainfall. Moreover, all categories (based on severity and duration) of drought were shown to exhibit increased frequency during the last quinquennial period from 2011 to 2015, although with some exceptions. Spatial analysis revealed that drought occurred all over the country; however, it was more prominent in the central and western parts of the country, and less frequent in the eastern region. In addition, the seasonal spatial analysis showed that extreme drought was prominent in the north-western and central parts of Bangladesh during the *Kharif* and *Rabi* seasons. The study showed that the central and northern regions of Bangladesh were more vulnerable to severe drought during all seasons. However, the north-western regions of Bangladesh were most vulnerable to droughts. However, the present study indicates that the central regions should be newly included as drought prone region because of the recent changes in the climatology, particularly in the *Pre-kharif* season. Therefore, the central region of Bangladesh should be prioritised for developing future drought management strategies.

The study also showed that EDI can be a useful tool for identifying drought-prone areas, could find potential applications for monitoring climate change-induced drought evolution at a regional and national level in Bangladesh. The information on drought derived in the present study will help researchers understand the recent spatiotemporal patterns of drought events over Bangladesh. The outcomes may be used in developing anticipative strategies to mitigate socio-economic losses as well as damages to agricultural production in the drought-prone regions of Bangladesh.

Author Contributions: Mohammad Kamruzzaman contributions as a first author. Mohammad Kamruzzaman designed the research, analyzed the data, and wrote the manuscript; Syewoon Hwang supervised the study and providing critical evaluations of the manuscript. Jaepil Cho provided important intellectual content. Min-Won Jang helped in the preparation of the manuscript and subsequent revisions and Hanseok Jeong revised the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest

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