Observed meteorological drought trends in Bangladesh identified with the

Effective Drought Index (EDI)

**ABSTRACT**

Countries dependent on small-scale agriculture, such as Bangladesh, can be vulnerable to the effects of climate change and variability. Changes in the occurrence and severity of drought are an important part of this issue and form the subject of this paper. We examined the characteristics of meteorological drought occurrence and severity using the Effective Drought Index (EDI), including the drought events, drought chronology, onset and ending of drought, consecutive drought spells, drought frequency, intensity and severity, using North-Bengal of

Bangladesh as a case study. The rainfall and temperature dataset of the Bangladesh Meteorological Department (BMD) for the study region throughout 1979–2018 is utilised. The trends of drought are detected by using the Mann-Kendall test and Sen Slope estimation. We evaluated the performance of EDI using the Standardized Precipitation Index (SPI), historical drought records and rice production. This study finds that seasonal and annual droughts have become more frequent over the period studied in all seasons except the pre-monsoon. In addition, the largest decrease in seasonal EDI is found in the monsoon, both in the Teesta floodplain and Barind tract regions. In the decades prior to the late 2000s, a drought spell typically starts between March and May (±15 days) and ends with the monsoonal rainfall in June/July. In the years since the late 2000s, monsoon and post-monsoon droughts spells have significantly increased. Overall, the peak intensity of droughts are higher in the Barind tract than in the Teesta floodplain, and the frequency and severity of moderate to severe drought are increasing significantly in the Barind tract. The drought frequency has increased by at least 10% in North Bengal of Bangladesh over the periods of 1979–2018. Though EDI is strongly correlated with the SPI index, our analysis shows that, surprisingly, rice production is actually decoupled from meteorological drought (as identified by the EDI and SPI). Hence, this research suggests that there are other significant influences on rice yield beyond meteorological drivers. This could include effects from differing irrigation infrastructure, technology and management strategies in the study regions. Challenges to agricultural production may be exacerbated in coming years, should the identified increasing meteorological drought trends continue.

**Keywords:** EDI, Meteorological drought, Drought occurrence and severity, Onset and ending, Agricultural loss, Barind Tract, Teesta Floodplain, Bangladesh.

**1. Introduction**

Drought is a complex meteorological and sociological phenomenon (Spinoni et al., 2019; Wilhite and Glantz, 1985). It is often difficult to quantify and diagnose the start and endpoints of droughts (Akter and Rahman, 2012; Keka et al., 2012; Lowe et al., 2018; Murad and Islam, 2011; Oesting and Stein, 2018; Paul, 1995). It is the most widespread natural disaster, affecting many areas worldwide. Agriculture is the most susceptible sector (Wu et al., 2017). The characteristics and nature of drought hazards are not like a flood, cyclone or storm surge since droughts cannot easily be tracked and measured as a distinct event (Alamgir et al., 2015). Droughts may occur simultaneously or sequentially (Mo, 2008), associated with multiple variables (Wilhite, 2005) which are interconnected, thus hard to distinguish (Hao and Singh, 2015). There is no universal definition of drought (Hao and Singh, 2015). It is a creeping hazard that develops slowly and has a prolonged duration, and its occurrence can be very patchy geographically (Keka et al., 2012; Murad and Islam, 2011).

The impact of meteorological drought on agriculture is through the reduction of available agricultural water resources, which causes crop water stress and decreases in yield (Lu et al., 2017). An analysis conducted by Karim et al. (2012) indicates that rice production would decline by 33% in the major rice-growing areas of Bangladesh in 25 to 45 years due to a 14% increase in irrigation demand (Md Abiar Rahman et al., 2017; Rahman et al., 2012; Rimi et al., 2009). Although higher atmospheric CO2 levels may have a beneficial impact due to the fertilisation effect (Lal et al., 2005; Samarakoon and Gifford, 1995), high temperatures during the flowering period affect the photosynthetic rate for C3 and C4 types of crops by increasing water demand and reducing the grain size and quality (Cruz et al., 2007; Hamim, 2005; Hijioka et al., 2014). The rice yield is projected to decline by 10% for each 1°C rise in growing-season minimum temperature during the dry period (Peng et al., 2004). The positive benefit of CO2 for C3 and C4 types of crops is projected to be played out in the next 25-40 years (Easterling, 2005; Lal et al., 2005). Due to the adverse effects of climate change, the suitable climates for plant growth and the number of suitable growing days are projected to decline (Mora et al., 2015).

Many indices have been used globally for drought characterisation over the past few decades based on the effectiveness, data availability and climatic characteristics (Bandyopadhyay and Saha, 2016). The strength and weakness of currently used drought indices can be found in Svoboda et al. (2016). The Standardised Precipitation Index (SPI) is the most popular meteorological drought index (Byun et al., 2010). However, upon analysing the limitations of the current drought indices, the Effective Drought Index (EDI) has been proposed as a useful tool to distinguish and characterise droughts (Byun and Wilhite, 1996 and Byun and Wilhite 1999). EDI can be used for monitoring droughts on a daily, weekly, monthly, or seasonal basis or for any other specific period, and can be applied worldwide (Byun and Wilhite, 1999; Deo et al., 2017; Smakhtin and Hughes, 2007). This index's main strength is the ability to detect the onset and end of drought and drought conditions earlier than any other index (Jain et al., 2015). Most of the current indexes (e.g. SPI, RDI and PDSI) are not considered consecutive or accumulated stress of drought. Drought severity is calculated mostly from the climatological mean of water deficiency for some predefined duration without considering the diminishing of water resources over time. Due to the use of monthly data, the indices have limited usefulness in monitoring ongoing drought. Moreover, considering the multiple data requirements, many indices are not feasible for some regions (e.g. PDSI). Thus, it can be concluded that EDI may be most effective in characterising drought in some regions. Studies have confirmed that the EDI is more efficient than the SPI in assessing both short term (e.g. Daily, weekly and monthly) and long-term (e.g. Seasonal and annual) droughts (Byun et al., 2010; Dogan et al. 2012).

Bangladesh is considered as the most vulnerable country in the world due to its socio-economic conditions, geographical location and adverse impacts of climate change and climate variability (Akter and Rahman, 2012; Ali et al., 2019; Islam and Nursey-Bray, 2017; Shahin et al., 2014). The country is less resilient to cope with the effects of climate change because of its population density, small size, a fragile economy, developmental inequality, and low adaptive capacities (Naser, 2015). It is also the world's most dynamic hydrological and the most prominent active delta system with several river courses and shifting depocenters (Ahmed and Kim, 2003; Barua, 1997; Nicholls et al., 2018), increasingly exposed to frequent and extreme climatic events (Delaporte and Maurel, 2018). Many of the country's people are dependent on agriculture for their livelihood, while agriculture contributes 14.23% to the GDP and employs about 40.62% of the labour force (Finance Division, 2018). However, climate change is expected to affect agriculture significantly and decrease agricultural GDP by 3.1% each year (World Bank, 2012). Crop failure creates pressure on smallholding farmers' lives and livelihoods due to risks in their smallholder agriculture while burdened with borrowed money for the purchase of seeds and other farm inputs (Khan and Shah, 2011). This is ultimately going to adversely affect the nation's food security (Misra, 2017; Rahman, 2017), especially on subsistence farming (Habiba et al., 2014). Farming communities of Bangladesh remain some of the most vulnerable groups (Sugden et al., 2014). However, high poverty rates, dependency on agriculture (Habiba et al., 2014; Shahid and Behrawan, 2008) and high variability of annual and seasonal rainfall have made the Barind tract and Teesta floodplain regions of the northern and north-western parts (known as North Bengal) of Bangladesh highly vulnerable to droughts compared to other parts.

Droughts are recurrent events in North-Bengal (Paul, 1995), particularly over the period from December to April, which have significant impacts on agricultural production and the natural environment (Alamgir et al., 2015; Food and Agricultural Organization, 2006; Hossain et al., 2014; Islam, 2009; Karim et al., 1990; Miyan, 2015; Rahman, 2015; Ruane et al., 2013; Sikder and Xiaoying, 2014). Although there have been tremendous improvements in irrigation systems in Bangladesh in recent decades, agricultural activities remain dependent on seasonal rainfall (Akter and Rahman, 2012). Several studies have stated that in the recent decades, North-Bengal has experienced significant increases in rainfall variability, long seasonal-scale dry spells and numerous instances of below-normal rainfall, significantly hampering crop growth (Islam, 2009). Also, variability in temperature has a substantial effect on crop yields (such as rice and wheat) in North-Bengal (Amin et al., 2015; Miah et al., 2017). In both the Barind tract and the Teesta floodplain regions, droughts occur mainly in two growing seasons, Oct-Feb and Mar-May periods. Oct-Feb period droughts affect Boro and Aus rice, wheat, pulses, sugarcane and potatoes, especially where irrigation is limited. Boro rice is cultivated during the winter season; thus, it highly depends on irrigation. Aus rice, on the other hand, is a kind of rice that grows under rain-fed conditions during March-August. Monsoon drought, affecting Aman rice and other crops grown in the highland and medium-highland areas of the regions (Keka et al., 2012). Aman rice is a type of rice grown during the rainy season (July-August).

The construction of Farraka and Teesta dams has had an impact on downstream water flows during the rainy seasons and has also led to less water flow in the dry seasons because of the char land (a tract of land that is surrounded by water) (Ho, 2016; Mondal and Islam, 2017). As a result, the occurrence of floods during the monsoon period and severe droughts during the dry season in the Teesta and Barind tract regions cause insufficiency and imbalance in the water supply (Habiba et al., 2011; Islam and Sarker, 2017; Mondal and Islam, 2017; Rahman, 2013; Md Abiar Rahman et al., 2017). Therefore, agricultural production in the Barind Tract and Teesta floodplain areas are vulnerable to water shortages and poor water management. For all of these reasons, understanding the dynamics of different droughts is very important (Akter and Rahman, 2012; Delaporte and Maurel, 2018; Freitas and Billib, 1997).

EDI has been used recently in Bangladesh (Kamruzzaman et al., 2019b). However, so far, no comprehensive study has been undertaken to evaluate and assess seasonal or growing period droughts in the important agro-ecological zone of the Barind tract and the Teesta floodplain area in North-Bengal. No comprehensive research has been conducted either on the onset and end of the drought in this region. Thus, it is difficult to draw conclusions about past events and plan for future impacts. Such work is necessary to detect and monitor future drought spells and their intensity to support policymaking. This study aims to:

1. explore the use of the EDI in the analysis of drought characteristics overtime on daily, seasonal and annual bases in the Barind tract and the Teesta floodplain;
2. measure the strength of the relationship between seasonal meteorological droughts and agricultural losses; and
3. document the spatio-temporal variations and trends of historical meteorological droughts in the region by quantifying the onset, extent, severity and cessation of meteorological droughts in North Bengal.

**2. Materials and Methods**

**2.1 Study Area**

The study area encompasses the Barind tract and the Teesta floodplain, which are two of the main agro-ecological zones in Bangladesh. It is located to the west of Brahmaputra River and the north of Ganges (Padma) River in the north-western part of Bangladesh (Fig. 1). This area consists of the major parts of Rajshahi and Rangpur divisions. The Barind tract occupies about 8,720 km², while the Teesta floodplain inhabits about 2071 km2  (Faisal et al., 2005; Mondal and Islam, 2017). Most of the Barind tract lands are high to medium high lands, whereas most of the Teesta floodplain lands are medium-high to medium lowlands. High land is considered to be above the normal flood-level (a flood whose inundation area exceeds 21% of the total land of the country) while medium highland and medium lowland are commonly flooded between 90-180 cm deep during the flood season (Mirza, 2002). Non-calcareous grey floodplain and non-calcareous brown floodplain soils are the predominant soil types on the Teesta floodplain whereas the deep red-brown terrace soil and deep grey terrace soils are the major components of the Barind tract soils (Bangladesh Bureau of Statistics, 2019). The spatio-temporal distribution of rainfall, temperature, humidity and wind speed in this region can be characterised into pre-monsoon (March-May), monsoon (June–September), post-monsoon (October-November) and winter (December – February) seasons.

**2.2 Data**

**2.2.1 Climatic data**

Forty years (1979-2018) of daily rainfall and temperature data for the Teesta floodplain (Rangpur and Dinajpur weather stations) and the Barind Tract (Bogra and Rajshahi weather stations) regions are obtained from the Bangladesh Meteorological Department (BMD)(Fig. 1).

**2.2.2 Yield Data**

The production of different types of rice data for the study area is obtained from the Bangladesh Bureau of Statistics (BBS).

**2.2.3 Missing data and data infilling methods**

A small number of missing data days are infilled prior to analysis (Table 1). Of the four sites, three sites have less than 0.59% of days of missing data across all months in the study period. Most months have no missing data over the full period. One site (Rangpur) has 2.56% of days in July, August and September missing, and smaller proportions of data missing in April and December. In this study, missing data for a specific day for a given station is infilled by the average of the nearest two stations for that day. The infilled data are then visually examined using boxplots to identify any potential outliers, with none being found. The small proportion of missing data is, therefore, deemed not to influence the results significantly.

**2.2.4 Time Series analysis of rainfall**

The boxplot in figure 2 shows the total monthly rainfall distribution at meteorological stations of the Barind tract and Teesta floodplain. The probability distributions of rainfall at annual, seasonal and daily time step are shown in supplementary figures 3, 4 and 5. Results show that the annual PDF for all regions portray a symmetric or bell shape pattern which indicates the normal distribution of the data. On the other hand, for seasonal PDFs, we can see a positively skewed and asymmetric distribution in winter and post-monsoon season while symmetric or normal distribution exists in pre-monsoon and monsoon season. For the daily PDFs, we can see that for all seasons and regions, an asymmetric distribution exists for rainfall. Overall, we can say that for annual, pre-monsoon and monsoon seasons any kind of symmetric distribution is suitable for analysis, while for winter, post-monsoon and daily rainfall, any kind of asymmetric distribution or positively skewed distribution is fit for analysis. Autocorrelation functions for the different observations are shown in supplementary figure 6. We found no serial correlation or autocorrelation among the data which indicate that data has no specific pattern and series are absolutely random, and will not hamper our analysis.

**2.3 Analytical techniques**

**2.3.1 Identification of drought occurrences using EDI**

|  |  |
| --- | --- |
|  | Eq. 1 |

EDI is based on the concept of daily Effective Precipitation (EP) (Byun and Wilhite, 1999). EP is the summed precipitation, P, which is a time-dependant reduction function based on the current and antecedent rainfall with time (Deo et al., 2017; Kamruzzaman et al., 2019b). If Pm is the daily rainfalls and n is the preceding period, then EP for the current day can be calculated as:

where, i is the duration of summation (the highest value of i is 365). For example, the EP for 3 January, where n= 3, can be calculated as:

|  |  |
| --- | --- |
|  | Eq. 2 |

where *P1*, *P2* and *P3* are precipitation values during the current day (3 January), the previous (2 January), and 2 days before the current day (1 January), respectively. Similarly, the EP for 31 December is calculated as:

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| --- | --- |
|  | Eq. 3 |

In this study, the daily EPs for the range of n for each year and the climatological mean EP (MEP) for the range of n are calculated for 1979-2018. Finally, the EDI is calculated through the standardisation process calculated as:

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| --- | --- |
|  | Eq. 4 |

where ST(EP) is the standard deviation of each day's EP. The monthly, seasonal and annual EDI are also calculated using Eq 1 where *Pm* is the monthly rainfall total for the current month and *n* is the duration of the preceding months. The EP for the current month is calculated as (Smakhtin and Hughes, 2007):

|  |  |
| --- | --- |
|  | Eq. 5 |

The drought severity is classified and shown in the Table 01.

***2.3.2 Estimation of Drought Severity and Duration (Onset and Ending)***

The Severity of Drought (DS) and Peak Drought Intensity (PDI) are computed (Deo et al., 2017) as:

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| --- | --- |
|  | Eq. 6 |
|  | Eq. 7 |

where i is the date after the onset of negative EDI value, is the continuous days with negative EDI value during the drought (DD) period. A drought period is the cumulative number of days with continuous negative EDI values starting from the day with the onset of negative EDI to the last day with negative EDI value.

The annual total of negative EDI values in a year which is termed as the Accumulated EDI (AEDI) is used to calculate the annual severity of the drought. The chronological annual dryness and intensity are computed using YEADI365 and YEADIND  (Kim et al., 2009). YAEDI365 is the sum of negative EDI divided by 365 days, which indicates the annual dryness of an area. In contrast, the YEADIND is the sum of negative EDI divided by the total number of days of negative EDIs, which indicates the annual intensity of drought. If YEADI365 is equal to YEADIND for a particular year, it means drought conditions existed over the whole year (Kim et al., 2009).

|  |  |
| --- | --- |
|  | Eq. 8 |
|  | Eq. 9 |
|  | Eq. 10 |

In this study, based on the drought duration and the peak drought intensity values, the top 20 cases of the highest drought spell are identified and analysed.

***2.3.3 Identification of the Consecutive Drought Spells***

In this study, a drought episode that exists for more than three months (>90 days) is considered a long-term drought spell, while a consecutive dry period that lasts for more than one month (>30 days) and less than three months (<90 days) is considered as a medium-term drought spell. A drought spell that lasts for more than one week (>7 days) but less than one month (<30 days) is considered as a short-term drought spell.

***2.3.4 Estimation of the Drought Frequency***

The frequency of daily drought per year (DFY) for EDI<0 and EDI<-1 over 1979-2018 is analysed by using the following equation(Zhao et al., 2018):

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| --- | --- |
|  | Eq. 11 |

Moreover, we analysed drought frequency for different months and different starting and ending periods. For example, for the drought period starting in January and ending in June, the six-month EDI frequency is calculated. In the same way for the winter season beginning in December and ending in February, the three-month drought frequency is computed. Thus, for any drought period (DFP) starting and ending between January to December, monthly to twelve-month drought frequencies are calculated as:

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| --- | --- |
|  | Eq. 12 |

***2.3.5 Analysis of the Pattern of Meteorological Drought***

The pattern of drought over the 1979-2018 period is analysed using the Mann-Kendall (MK) test and Sen Slope estimation (Hamed, 2008; Neeti and Eastman, 2011; Yürekli, 2015).To determine whether the median slope is statistically different than zero, we calculated the confidence interval of the time slope (Gilbert, 1987; Gocic and Trajkovic, 2013; Hollander et al., 2014). Moreover, we calculated the upper and lower limit of the slope. The slope is statistically different from zero when the upper and lower limits of the slope have the same sign (Gocic and Trajkovic, 2013).

***2.3.6 Evaluation of the EDI Performance***

Drought is a seldom studied hazard in Bangladesh, and very few studies have been conducted on the monitoring and prediction of droughts by government or non-government organisations in Bangladesh (Brammer, 1987; Miyan, 2015; Rahaman et al., 2016). The drought history and drought-related records are not well documented (Kamruzzaman et al., 2019b). Only brief discussions of crop damages and production losses are found in some reports published by the Bangladesh Bureau of Statistics (BBS). Thus, it is difficult to identify and recognise a drought year based on BBS reports only. Hence, in addition to BBS results, we cross-checked our results with existing peer-reviewed published sources conducted in the study area (Selvaraju and Baas, 2007**,** Rafiuddin et al., 2011**,** Alamgir et al., 2015**,** Mondol et al., 2016)**,** Rahman and Lateh, 2016**,** Nury and Hasan, 2016**,** Mamun et al., 2018**,** Kamruzzaman et al. 2019). Since the study area is also prone to floods, and agricultural production is understood to be low during years with flood conditions, this study computed correlations between the EDI and agricultural production in non-flood years (EDI<0.99) only. To evaluate the performance of EDI values, we also performed index to index evaluation and compared the EDI results with the Standardised Precipitation Index (SPI) (McKee et al., 1993). For this evaluation, we conducted Pearson correlation (r) and Co-efficient of Determination (R2) between EDI and SPI for different seasons and annual scale. Finally, we plotted the SPI and EDI data in quantile-quantile (Q-Q) plots to determine the extent to which the EDI and SPI share a common probability distribution.

**3. Results**

***3.1 Daily Drought Occurrence***

Figure 3-4 shows the daily drought occurrences in the Barind tract and the Teesta floodplain regions based on EDI values and drought severity classification. The results show substantial inter-annual variability in drought over time in both regions. In most years, the first 100-120 days of the calendar year, experiences mild drought with some moderate drought in this period. Drought conditions tend to increase from March to May, although there is high variability in the drought severity during this period. April and May (days 91–151) have the highest number of drought days across the full period. Though from mid-June to September (days 166-273) is largely drought-free, some dry spells are found in this period with some severe drought conditions in the year of 1983, 1992, 1994, 1996, 2009-10, 2012-13, and 2018. During October-November the number of drought days has increased after 2008. Overall, the number of drought days and drought occurrences are higher in Barind tract than Teesta floodplain.

***3.2 Seasonal to Annual Drought Occurrence***

Seasonal and annual occurrences of drought throughout 1979-2018 are shown in figure 5. The study area faces mild to moderate drought conditions during the winter period. The pre-monsoon season is the most drought-prone season in North-Bengal of Bangladesh when the Barind tract and the Teesta floodplain experiences all severe categories of drought. Analysis indicates that the study area frequently experiences drought conditions between 1991 and 1997, including an extreme drought condition during 1994-1995. In addition, these two areas also suffer from severe to extreme drought in 1979, 1982, 1995, and 2012. Different locations in the study area are hit by moderate to severe drought in 1981, 1986, 1989, 1992, 1996, 2007, 2010, and 2014. However, drought severity decreases during the pre-monsoon season.

The monsoon drought is found to be increasing in both the Barind tract and the Teesta floodplain (Fig. 5). Extreme droughts hit the Teesta floodplain during the growing seasons in 1994 and 2018, while severe droughts hit the Barind tract in 1982, 2010, 2016, and 2018. Recent decades show an increase in drought during the monsoon and Kharif periods. Overall, the frequency and severity of monsoon and Kharif drought have increased throughout 1979-2018. The post-monsoon drought is also found increasing (Fig. 5). Annual EDI analysis finds that over 1979-2018, at least two severe to extreme droughts hit the Teesta floodplain while three severe to the extreme and six moderates to severe droughts hit the Barind Tract. The results suggest that the annual drought severity has also increased and the North Bengal experiences dry conditions once every two to three years.

***3.3 Chronological Annual Dryness***

Figure 6 shows the chronological annual dryness. The result indicates that in the Teesta floodplain, the intensity (YAEDI(ND)) and annual dryness (YAEDI(365)) are both high in 1994 and 2018 in comparison to other years, while similar conditions prevail in the Barind tract in 1992, 2006, 2010, and 2012. However, the intensity for both regions is higher in 1979 and 2010 than in other years. It indicates that there is a prolonged dry period in those years. The chronological annual dryness results also suggest that the intensity and annual dryness are higher in the Barind tract than the Teesta floodplain.

***3.4 Indexing Drought Severity***

The drought severity index is constructed to understand whether the annual severity of drought shows consistency in consecutive years (Fig. 7-8). Figure 7(a) shows that the highest severity of drought occurs in the year 2010 in the Barind tract when the total negative EDI exceeds -400. In contrast, the Teesta floodplain reaches the peak of drought severity in 1994, and the total negative EDI is about -360. During 2010, the drought lasts for the whole year in the Barind tract while in 1994, a prolonged drought condition exists for more than 300 days in the Teesta floodplain. The other notable years for severe annual droughts in the Barind tract are 1982, 1992, 2006, 2009, 2012, 2013 and 2018, while the remarkable severe drought severity years in the Teesta floodplain are 1979, 1981, 2001, 2006, 2014, and 2018. The total number of dry days increases significantly in recent decades compared to the first decades of 1979-2018 period (Fig. 7(b)). The highest number of total dry days and the peak drought intensity takes place in the year of 2010 in the Barind tract. Severe peak drought intensity is prevalent in 1979 and 1989 in this area. Severe to extreme peak in drought intensity occurs in the Teesta floodplain in 1979, 1994, 1995, and 2014. The peak intensity is found low during 1984-1988 and 1998-2005 periods in both the areas (Fig. 7(c)). The results indicate that the study area suffers from severe to extreme drought on average once every ten years.

***3.5 Frequency of Drought***

The highest drought frequency (about 56% of the year) is found in 2010 in the Barind tract, whereas this condition prevails in the Teesta floodplain in 1994 when EDI less than -1 exists for more than half a year (Fig. 9). The frequency and magnitude of drought are also high during these two years. During the first 20 years of the 1979-2018 period, the frequency of daily drought conditions is higher in 1979, 1982, 1989, 1992, and 1994 than in other years, while in the recent 20 years the frequency of daily drought conditions is higher in 1999, 2006, 2010, 2013, 2015, 2016, and 2018. In the Teesta floodplain, the days with EDI less than -1 occur in 1979, 1981, 1989, 1994, 1995, 2001, 2006, 2014, 2017, and 2018. However, the frequency of drought is relatively low in 1983-1986 and 2002-2005. In general, the frequency of moderate to severe droughts is increasing significantly in the Barind tract (Fig. 9).

The frequency of drought in different starting and ending months are shown in Figure 10. The results suggest that drought is mainly seasonal and occurs more in pre-monsoon and winter. The drought frequency is higher in the Barind tract than the Teesta floodplain (Fig. 10). According to a threshold of EDI less than -0.5, drought occurs less during the monsoon period in the Teesta floodplain. However, in the Barind tract, drought occurs more in the monsoon and Kharif periods. The value of EDI less than -1 indicates that almost no major drought occurs in winter in the Teesta floodplain. However, at least 12%-16% of the moderate to severe drought days are found from pre-monsoon to monsoon time in the Teesta floodplain according to EDI less than -1 and at least 15%-20% of the drought days are found from pre-monsoon to winter in the Barind tract.

***3.6 Consecutive Drought Spells, Onset and Ending of Drought***

The consecutive drought spells in the Barind tract and the Teesta Floodplain region are shown in figure 11. The results indicate that about 28 long dry spells (>90 days) exist in the Teesta floodplain while about 19 long dry spells (>90 days) are found in the Barind tract. However, drought spells that last for more than one month but less than three months and more than one week but less than one month are found more in the Barind tract than the Teesta floodplain. The top 20 drought cases are shown in Table 2 based on the duration and peak drought value. The results indicate that the highest prolonged duration of the drought is from the beginning of July 2000 to the end of May 2001 in the Teesta floodplain while in the Barind tract the longest drought spell exists from the end of September 2009 to mid-January 2011. Negative EDI reaches the highest peak at -2.13 during the drought episode starting from the end of May 2017 to the end of December 2018 in Teesta floodplain while in Barind tract, negative EDI reaches the highest spike at -2.52 during the last week of September 2009 to mid-January 2011. Though the number of consecutive long-term drought spells are fewer in the Barind tract than in the Teesta floodplain, the duration of the droughts are longer in the Barind tract. Moreover, the peak drought values are also higher in the Barind tract than in the Teesta floodplain.

***3.7 The Pattern of Seasonal Drought***

The results show that the seasonal and annual EDI values are exhibiting a decreasing pattern during all seasons except pre-monsoon period based on the Mann-Kendall test and Sen Slope estimation in both the Barind tract and the Teesta floodplain (Table 4). The largest overall decreasing pattern in seasonal EDI is found in the monsoon period in both regions, while the Barind tract has a higher decrease at the annual scale relative to the Teesta floodplain. At a 5% level of significance, a decrease of EDI is found in monsoon and at the annual scale in the Teesta floodplain, but in the monsoon, Kharif, and at the annual scale in the Barind tract. Also, a significant increasing trend of EDI during pre-monsoon is found in the Teesta floodplain. Overall, the decreasing pattern of EDI is more evident in the Barind tract than the Teesta floodplain. If these trends continue, drought conditions may further exacerbate in the coming years.

***3.8 Evaluation of EDI and EDI-Rice Production Relationship***

The historical records of drought matched with our calculated EDI values. Historical records of drought are shown in Table 4. Different sources and reports indicate that during the 1979-2018 period, droughts occurred in the years 1979, 1981, 1982, 1989, 1992, 1994, 1995, 2001, 2006, 2009, 2010, 2012, 2014, and 2018. Though agricultural production is increasing significantly year by year (Fig. 12), the drought conditions and agricultural production over 1979-2018 indicate a negative relationship (Table 4; Fig. 12 and 13). We did not find any significant relationships among the EDIs and rice production in the study region, which might be related to the uncertainty in the spatial and temporal distributions of the droughts. With precipitation alone accounts for, the EDI does not consider the effects of irrigation and other water sources. Thus, we analyse the performance of EDI with SPI, which is closely related to soil moisture. Figure 14 shows the Q-Q plot with a coefficient (r) and the coefficient of determination (R) between EDI and SPI. The results indicate that EDI is strongly correlated with SPI, which reveals that EDI can effectively measure meteorological drought.

**4. Discussion**

This paper assessed the characteristics of meteorological drought occurrence and severity in two important agro-ecological zones, namely, the Barind tract and the Teesta floodplain in North-Bengal, Bangladesh using EDI at different timescales. The analysis and results of our study indicate that the patterns of drought variability are significantly different in both short term and long-term periods. It is evident that the northern and north-western part of the country experiences persistent, mild to moderate drought over the winter periods (Fig. 3). Though pre-monsoon is considered highly vulnerable to drought, a decreasing trend is observed in the drought severity, frequency and variability in both the Barind tract and the Teesta floodplain (Fig. 3-5). Bangladesh receives two-thirds of the annual rainfall in monsoon (Shahid and Khairulmaini, 2009). Our analysis indicates that the monsoon and Kharif period droughts are significantly increasing. The overall severity of the drought has also increased over the period 1979-2018 (Fig. 7). Other studies have also equally noted this increasing pattern of drought severity, frequency and variability in North-Bengal (Alamgir et al., 2015; Kamruzzaman et al., 2019a; Miyan, 2015; Mohsenipour et al., 2018; Mondol et al., 2017, 2016).

The increasing trend of drought severity for a longer overall timespan of the dataset is important since extreme drought events almost always lead to the loss of agricultural production. As observed in many other studies, the future change of drought variability is projected to be more crucial and significant especially in the Barind tract and the Teesta floodplain (Bari et al., 2016; Hasan et al., 2018; Miah et al., 2017; Mondol et al., 2018; Nury et al., 2017; Mohammad Atiqur Rahman et al., 2017; Rahman and Lateh, 2016; Ruane et al., 2013), mainly because drought represents a non-linear combination of numerous meteorological and land-surface variables, including precipitation, temperature, wind speed, radiation, humidity and soil moisture.

The analysis of climatic variability, the trends of rainfall and temperature in the study area indicate that except pre-monsoon and post-monsoon in the Teesta floodplain, the long-term average rainfall during winter, monsoon, and annual rainfall for the last 40 years have a decreasing trend (Fig. 15). Besides, apart from the mean maximum temperature in winter of Barind tract regions and pre-monsoon of both areas, the long term yearly mean maximum and minimum temperature in all other seasons and annual scale have increased (Fig. 15). These findings are similar to those from other studies (Ahasan et al., 1970; Basher et al., 2018; Islam, 2009; Mondol et al., 2018; Mullick et al., 2019; Nury and Hasan, 2016; Md Abiar Rahman et al., 2017; Rahman et al., 2012; Rahman and Lateh, 2016; Syed and Al Amin, 2016)

Since precipitation deficit is the main driver of meteorological droughts, it is expected that the deficit in future precipitation would bring more droughts. However, changes in rainfall variability may impact differently. High variability of rainfall is observed in the study area in terms of amount and spatiotemporal distributions (Fig. 15). Subsequently, it has resulted in frequent drought episodes with varying intensities both in the Barind tract and the Teesta floodplain (Fig. 11).

We analysed the frequency of drought for different starting and ending months and seasons (Fig. 9-10). We find an increasing trend in the drought frequency both in Barind tract and Teesta floodplain (Fig. 9). However, a threshold of EDI less than -0.5 indicate more frequency of drought during winter and pre-monsoon, while we find more moderate to severe drought according to a threshold of EDI less than -1 during pre-monsoon when almost no moderate or severe drought happens in winter (Fig. 10). Overall, the frequency of drought in different starting and ending periods is higher in Barind tract.

Drought duration is one of the key elements of drought characteristics (Huang et al., 2019; Zargar et al., 2011). It is the interval between the onset and ending time of a drought, which can vary from months to years. In this study, we have calculated and analysed the onset and end of droughts in the study area. As EDI calculation is performed on a daily basis, it provides accurate drought information not only for well-defined, prolonged, widespread, and intensive droughts but also for very localised and short-term droughts. Our results indicate that the onset and end time of droughts in the study area mostly follow the monsoonal rainfall pattern. In decades prior to the late 2000s, a drought spell typically starts between March to May (± 15 days) and ends with the monsoonal rainfall in June/July (Fig. 3-4). In the years since the last 2000s, winter, and post-monsoon droughts days have significantly increased in North Bengal (Fig. 8).

The annual peak drought intensity in the Barind tract is high during 1979, 1982, 1989, 1994-95, 2006 and 2010 with the highest peak in 2010; whereas in the Teesta floodplain, during 1979, 1989, 1994-95, 2006-14, 2018 the annual peak drought intensity is high with the highest peak in the year 2014. Overall, the total annual dry day and peak drought severity are higher in the Barind tract than in the Teesta floodplain.

The historical drought data of Bangladesh indicate that drought during 1980-81 resulted in a loss of about 0.44 million tons of rice production (BBS, 1982). During the 1983-84 and 1984-1985 periods, a loss of about 0.59 and 1.32 million tons of rice production occurred due to drought conditions (BBS, 1986). The 1994-1995 drought condition was very severe, from which a reduction of at least 3.5 million tons of rice production was resulted (Paul, 1995). About 25–30% reduction of average crop production happened in 2006 because of drought. Moreover, about 5.74% of the damages and losses related to agriculture products and infrastructure were caused by drought between 2009 and 2014 (Kamruzzaman et al., 2019b, 2019a).

Though we found that EDI has a significant relationship with SPI, EDI and rice production is found to have a negative relationship. The moving decadal correlations between EDI and different types of rice show that EDI is only positively correlated with Aman rice during the first eleven moving decades, whereas for Boro rice, EDI is positively correlated only during 1982-1995 (Fig. 12). Although Aus rice is found to have moving decadal correlation with EDI in a few years, almost no consecutive decadal correlation is found. EDI did not successfully account for agricultural losses in North-Bengal. Thus, this analysis indicates that the impacts of meteorological drought on agriculture in the study area could be compensated by other factors such as irrigation.

**Conclusions**

In this study, we characterised the meteorological drought occurrence and severity in the Barind tract and the Teesta floodplain using Effective Drought Index (EDI). Moreover, we evaluated the use of EDI and its correlation with rice production in the study area. The major findings of our study are as follows:

1. The winter drought is regular throughout the study period and often with mild severity. Though the pre-monsoon is the peak time for drought occurrence, drought intensity and durations are found to be decreasing in recent decades in this season. On the other hand, the monsoon and Kharif (May-October) period's drought occurrence was found to be increasing in recent decades. The post-monsoon drought has also increased in recent decades.
2. The consecutive drought spells indicate that drought occurs mainly on a seasonal basis with most droughts lasting between one and three months in the study region. Overall, the peak drought value and the intensity of consecutive drought spells, and the seasonal and annual dryness are higher in the Barind tract than in the Teesta floodplain.
3. The frequency of drought in different starting and ending months suggests that drought frequency is high in the pre-monsoon and winter. The number of total dry days and the frequency of drought percentage is also higher in the Barind tract than the Teesta floodplain. Though almost we find no moderate to severe drought in winter, on average, at least 12% to 16% of the moderate to severe drought days are (based on EDI<-1) found between pre-monsoon to the monsoon, while at least 15%-20% of the drought days are found between pre-monsoon to winter in the Barind tract. The results suggest that North Bengal experiences dry conditions once every two to three years and is affected by at least one severe drought in every ten years.
4. Indexing of the drought severity indicates that the annual severity of drought shows consistency with consecutive drought severity. Notably, the pattern of the severity of the meteorological drought is found to decrease in pre-monsoon and increase in monsoon season. Overall, the decreasing patterns of EDI during the monsoon period, and at the annual scale, are significant both in the Barind tract and the Teesta floodplain. If these multidecadal trends continue, drought conditions may exacerbate in the coming years.
5. The EDI analysis along with other different sources and reports indicate that during the 1979-2018 period, a drought occurred in 1979, 1981, 1982, 1989, 1992, 1994, 1995, 2001, 2006, 2009, 2010, 2012, 2014, and 2018.
6. EDI drought analysis, SPI and historical drought data have a good match while EDI poorly correlated with agricultural production. Thus, this study concludes that agricultural production and water stress in the Barind tract and the Teesta floodplain regions might be affected by factors other than by meteorological drought alone.

**Declaration of Competing Interest**

The authors declare that there are no conflicts of interest regarding this publication.

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**Data Availability**

The data that support the findings of this study are available on request from the corresponding author.

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