The Dhaka University Journal of Earth and Environmental Sciences
https://www.banglajol.info/index.php/DUJEES

Meteorological Drought in Bangladesh using Standardized Precipitation Index: A Spatiotemporal Approach

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ARTICLE INFORMATION

Received : 12 July 2021
Accepted : 23 December 2021

Keywords:
drought
climate change
trend
spatiotemporal
Bangladesh

ABSTRACT

Drought observation and analysis have a significant impact on lives and properties. This research aims to identify the drought trend with its spatiotemporal distribution in seven climatic zones of Bangladesh. Mann-Kendall test and Standardized Precipitation Index (SPI) were used to identify the trend and spatiotemporal phenomenon visualized by Inverse Distance Weighting Interpolation. The findings demonstrate a substantial declining drought trend for short-term period to annual of SPI-3, SPI-6 and SPI-12 concerning the northern part of the northern zone, north-western, western, southwestern, and south-central zones whereas only increasing trend among these zones are found for SPI-3 of south-central zone. Furthermore, southeastern and north eastern zone are found for increasing trend of drought vulnerabilities for all the classes of SPI-3, SPI-6 and SPI-12. The northern part of the northern zone, north western and western are found for highest drought prone zones as it obtained SPI-12 of >-0.026, >-0.024 and >-0.025 respectively. The study recommends that mechanisms and maintenance for water management be taken in order to integrate drought response strategies for drought-prone climatic zones.

Introduction

A scarcity of water presence with low or no rainfall in a region refers to drought. It is a recurrent theme, indicating insufficient evapotranspiration formation (Pal et al., 2000; Mishra and Singh, 2010). According to several research, the consequence of drought is marked as a rainfall deficit of more than 25% or 30% (CWC, 1996; Venkateswarlu, 1992). Drought has a variety of negative consequences for agriculture, the habitat, and the community. Environmental degradation influences global warming, leading to higher rainfall patterns and increased warmth and dryness in several places worldwide (Habiba et al., 2013a; IPCC, 2007). Potentially Bangladesh is the most climate-prone country, and in recent decades, temperatures have risen, meaning global climate change will accelerate over the next several decades, perhaps leading to significant water scarcity and drought (Rahman and Lateh, 2017; Uddin et al., 2020).

Drought has been the second-worst devastating calamity, according to a global perspective (Nagarajan R., 2010). Bangladesh has been deemed a drought-prone region compared to other calamities such as flooding, cyclones, and ocean acidification. Droughts hit the nation in 1951, 1957, 1958, 1961, 1966, 1972, and 1979, affecting 31.63 percent, 46.54 percent, 37.47 percent, 22.39 percent, 18.42 percent, 42.48 percent, and 42.04 percent of the country's total land area, respectively (Banglapedia, 2014b). Drought has resulted in a 25-30% drop in agricultural yield (Habiba et al., 2013a), even though 53 percent population of Bangladesh's lives in drought-prone areas (Ahmed, 2006). Moreover, major farming continues to be performed in some parts of the country, necessitating the use of water and crucial theories, which may threaten food safety. Several study signifies some more destructive causes like the loss of crops, life and wealth which concern drought vulnerabilities, yet this problem receives less attention (Rahman and Saha, 2007; WBB, 1998; Alexander, 1995; Shahid and Behrawan, 2008). As a result, thorough research is required to reduce the adverse impact of drought conditions in Bangladesh.

Different approaches for water stress evaluation have been used in recent literature, the most frequent of which became the Standardized Precipitation Index (SPI) relied on climatic parameters (McKee et al., 1993). Additionally, World Meteorological Organization (WMO) signifies SPI for every nationals, which provides essential drought history that may contribute to drought monitoring and management (WMO, 2009).

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DOI: https://doi.org/10.3329/dujees.v10i3.59067

Similarly, surface water supply index (SWSI) (Shafer and Dezman, 1982), the Palmer Drought Severity Index (PDSI) (Wayne C. Palmer, 1965), and Bhalme–Mooley drought severity index (BMDI) (Bhalme and Mooley, 1980) are used for drought categorization in literatures.

Several variety of drought assessments have been undertaken in Bangladesh (Hossain et al., 2020; Sarker et al., 2020; Zinat et al., 2020). The majority of research, however, focuses attention on drought delineation and incomplete or haphazard evaluation. Consequently, while the majority of the research focuses mostly on the hydrological modeling of Bangladesh as a unit, this research focuses on drought spell variation patterns in seven climate regions in Bangladesh, including the geographical extent of protracted drought differential trends. This directs attention to analyzing the particular circumstances of dry seasons in Bangladesh's particular region. This investigation utilized monthly precipitation records to examine significant spatial and temporal variations in droughts via estimating SPI. To the authors' knowledge, no study has contributed to drought evaluation in seven climatic zones of Bangladesh and SPI with a recent dataset as well as Mann-Kendall (MK) for drought trend detection. Therefore, the objectives of this research are to explore the spatiotemporal evaluation of drought intensity assessment in seven climate zones of Bangladesh with a recent monthly dataset of rainfall. The study's findings could be useful for identifying susceptible water shortages areas depending on spatial variability and mitigating, as well as assigning disaster risk reduction responses.

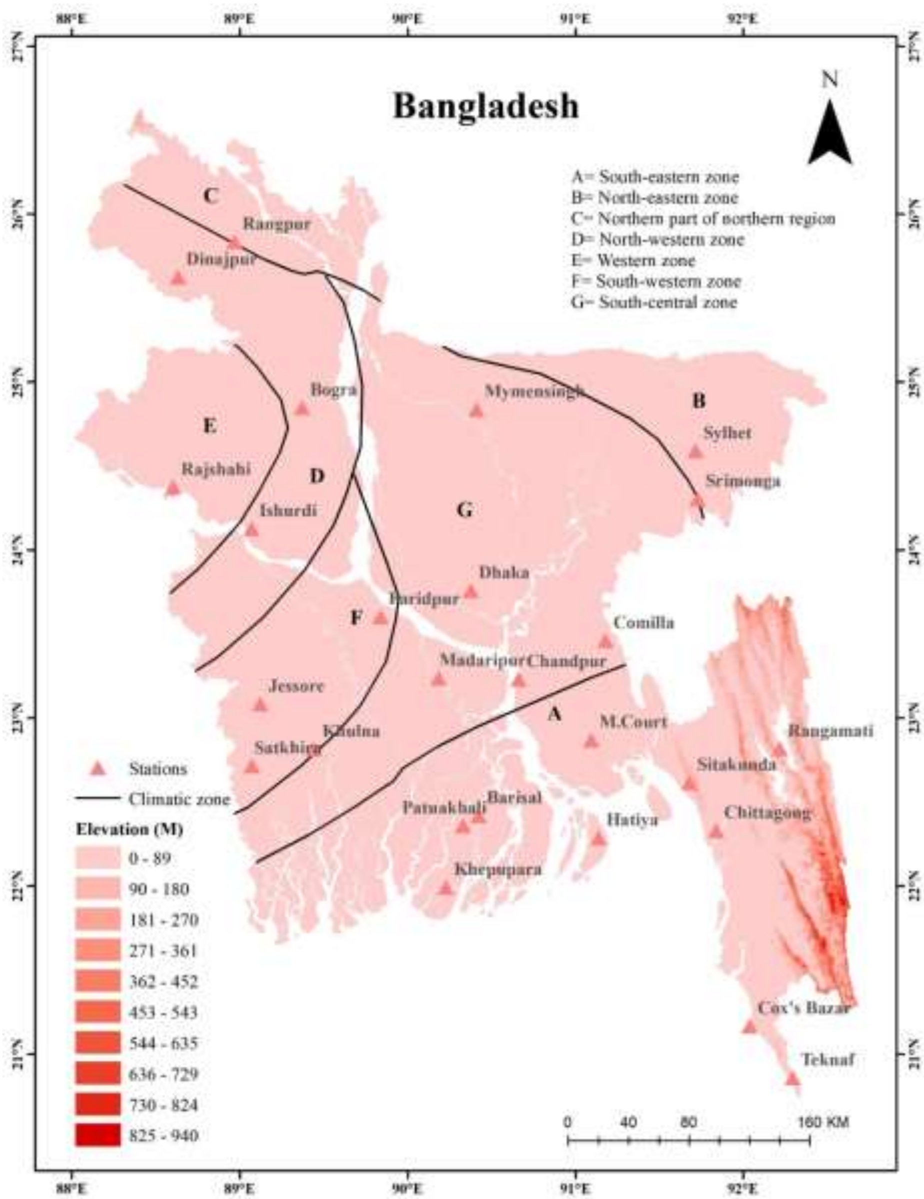

Figure 1: The Map of Bangladesh Showing the Meteorological Stations (The color variation represents the land elevation.) Source: Adopted and Modified after data.humdata.org

Materials and Methods

Study Area

The absolute geographic location of Bangladesh is 20°34' N – 26°38' N latitude to 88°01' E – 92°41' E longitude, with a total area of 147610 km^2. Except for mountainous parts in the south-east and south-west, the nation is mostly level (Figure 1). Winter (December to February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October to November) seasons are all experienced in the region (Banglapedia, 2014c). Bangladesh's prominent natural climate subject is subdivided into five climate regions: the south-eastern region (A), the north-eastern region (B), the northern part of the northern region (C), the north-western region (D), the western region (E), the south-western region (F), and the south-central region (G) (Figure 1) (Banglapedia, 2014a). The average yearly precipitation is 2428mm, with a maximum temperature between 30°C and 40°C and the minimum temperature between 5.2°C and 10°C (BMD, 2013). Therefore, the monsoon season receives upwards of more than 80% of its rainfall, whereas the warmest and coolest seasons are found in summer and winter (January), correspondingly (Islam et al., 2018; Rahman and Islam, 2019).

Data Acquisition and Pre-Processing

The monthly precipitation record for 27 weather stations of Bangladesh was collected during the period of 1979–2018 (40 years) from the Bangladesh Agricultural Research Council (BARC) for calculating the Standardized Precipitation Index (SPI). In addition, the Bangladesh Meteorological Department provided data for 2019. Several investigations in our study area employed BARC and BMD records to evaluate various rainfall factors (Dash et al., 2012; Rafiuddin et al., 2011; M. N. Rahman et al., 2021; Rokonuzzaman et al., 2018; Shakoor et al., 2017). A total of 41 years' (1979–2019) data was considered in this study. The stations are chosen to maintain the homogeneous coverage of the geographic area. Less than 1% of missing data was found while obtaining and processing datasets. The spatial and temporal drought pattern was visualized by the Inverse Distance Weighted (IDW) techniques.

Standardized Precipitation Index (SPI)

The SPI is widely utilized in the drought index that supports the likelihood of precipitation based on multiple timescales, e.g 1-, 3-, 6-, 9-, 12- and 18-months (McKee et al., 1993; Azimi & Azhdary Moghaddam, 2020; Mayasari et al., 2017; Pathak and Dodamani, 2020; Shiau, 2020) where SPI-3 provides short or medium drought possibilities, SPI-6 describes seasonal conditions of drought and SPI-12 represents annual drought observation (Pramudya & Onishi, 2018). Historical precipitation data for a particular period from this approach could be contrasted with totals from an equivalent period. It also makes analyzing wet and dry phenomena simpler. Besides, every station has monthly precipitation values for a gamma frequency density model for measuring SPI:

$$\gamma(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \; for\; x > 0$$

If alpha > 0 was its target value, beta > 0 seems to be the state variable, x > 0 seems to be the rainfall quantity, and the α component has to be the gamma product. The gamma function dimensions alpha and alpha are not efficiently estimated by the probability formulations. β within each station and each timeframe:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right)$$

$$\beta = \frac{\bar{x}}{\alpha}$$

Therefore, it makes possible to properly characterize the amount of precipitation either at location in accordance with the following calculation accumulated probabilities:

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

Given that x = 0 has an ambiguity in probability distributions and 0s in rainfall, the aggregate probability obtains: $H(x) = q + (1 - q)G(x)$

At which likelihood is q. To get the SPI we can then convert cumulative probability H(x) to the normally dispersed value (McKee et al., 1993). This allows an identification attribute to be calculation for SPI. McKee et al., (1993) categorized drying and moist cases as mentioned in 'Table 1' compliant with SPI parameters.

Table 1: Index of Drought Severity

Category	SPI	Probability of Occurrence (%)
Extreme drought	−2.00 and less	2.3
Severe drought	−1.50 to −1.99	4.4
Moderate drought	−1.00 to −1.49	9.2
Near normal	−0.99 to 0.99	34.1
Moderate wet	1.00 to 1.49	9.2
Severely wet	1.50 to 1.99	4.4
Extremely wet	2.0 and above	2.3

Mann-Kendall Trend Test

The Man-Kendall-testing is based on a historical data's monotonous increasing or decreasing trend (Mann, 1945; Kendall, 1975). Among various significance, we employed a 90% confidence interval.

There is no need for material – auto-correlation. The input does not have to be spread evenly or sequentially (Milan and Slavisa, 2013). It is a non-parametric assessment that is commonly applied around the planet. The MK Complex contains the following statistics for such periodicity $x_1, x_2 \ldots\ldots, x_n$:

$$S = \sum_{l=1}^{n=1} \sum_{j=k+1}^{n} Sign(x_j - x_i)$$

Since x_i and x_j that i and j (j>i) results are recorded, the sign(s) is established by (x_j-x_i)

$$Sign(x_j - x_i) = \begin{cases} 1 \;\; if(x_j - x_i) > 0 \\ 0 \;\; if(x_j - x_i) = 0 \\ -1 \;\; if(x_j - x_i) < 0 \end{cases}$$

S deviation is calculated as follows:

$$var = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_t f_t(f_t - 1)(2f_t + 5)\right]$$

Here n denotes the volume of records, t denotes how the linked scores vary, while ft denotes the probability of order t occurrences.

The normally distributed result Z was calculated using the equation below:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} \; if \; S > 0 \\ 0 \; if \; S = 0 \\ \frac{S-1}{\sqrt{VAR(S)}} \; if \; S < 0 \end{cases}$$

The study considered acceptation of significance where Z statistics is >1.645.

Inverse Distance Weighting Interpolation

Inverse weighting distance (IDW) has been used for this investigation since it is a popular and simple method of interpolation (Rahman et al., 2021). This method was widely performed to locate difficult-to-find geographic and hydrologic data. According to this method; each measuring source possesses regional impact that decreases as distance. An incorrect site measures its result of an intentional level depending on distance examined. The equation for the Inverse distance approach is as follows:

$$Z(S_0) = \sum_{i=1}^{N} \lambda_i Z(S_i)$$

The following are the weights ofλ_i:

$$\lambda_i = \frac{d_{i0}^{-p}}{\sum_{i=1}^{N} d_{i0}^{-p'}} , \sum_{i=1}^{N} \lambda_i = 1$$

p is indeed the strength there, whereas d_{i0} seems to be the spacing across this objective as well as the samples.

Results

Spatiotemporal Drought Trend

The Mann-Kendal test is used to examine the SPI intensity trend for Bangladesh's seven climate zones from 1979 to 2019. Droughts are recognized in the research region using SPI multiple-step statistical model. The task is designed to examine the short, medium, and long periods of drought for SPI for 3 months, SPI for 6 months, and SPI for 12 months. Minimum SPI represents a dry period, whereas maximum SPI indicates wet periods for non-winter months for the years 1979-2019.

Three-Months Standardized Precipitation Index (SPI-3) Variability

In order to compile the upper and lower spatial patterns for maximum and minimum SPI-3 trends in Bangladesh displayed in Figures 2, 3, and 4, respectively, the SPI-3 are computed and adjusted at every 27 weather stations. The names of the locations in the figures are yellow determined on 90% confidence acceptance. The maximum increase of SPI-3 is found for +0.0077 for the south-eastern zone, whereas the minimum SPI-3 calculated for the western zone and northwestern zone of -0.0285 (Figure 2). However, Figure 3 indicates the increase of the wet period for the northern part of the northern region, western region, and southwestern region. On the other hand, the extreme drought-prone areas are identified as Rajshahi, Dhaka, and Faridpur situated at western, south-central and southwestern zones respectively (Figure 4).

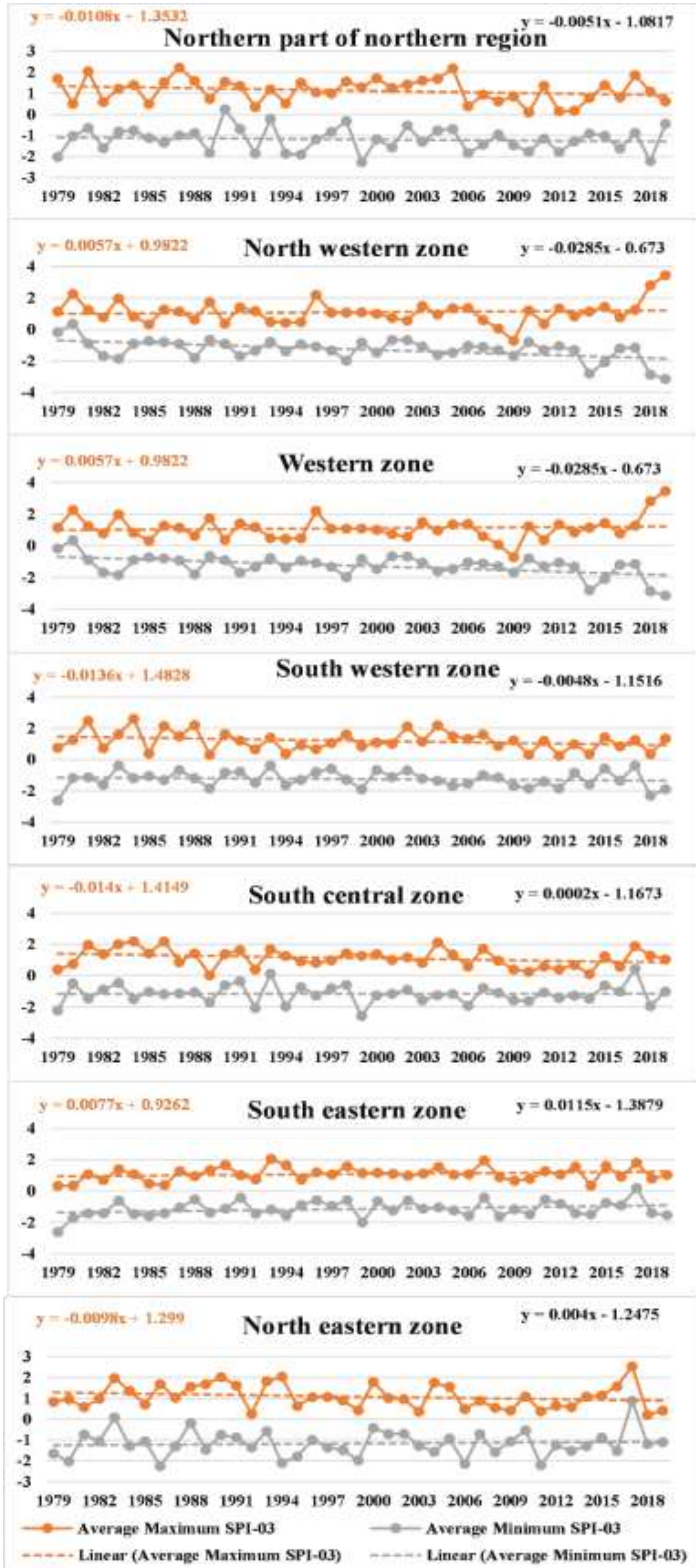

Figure 2: Average Maximum and Minimum SPI-3 of Seven Climatic Zones during 1979-2019

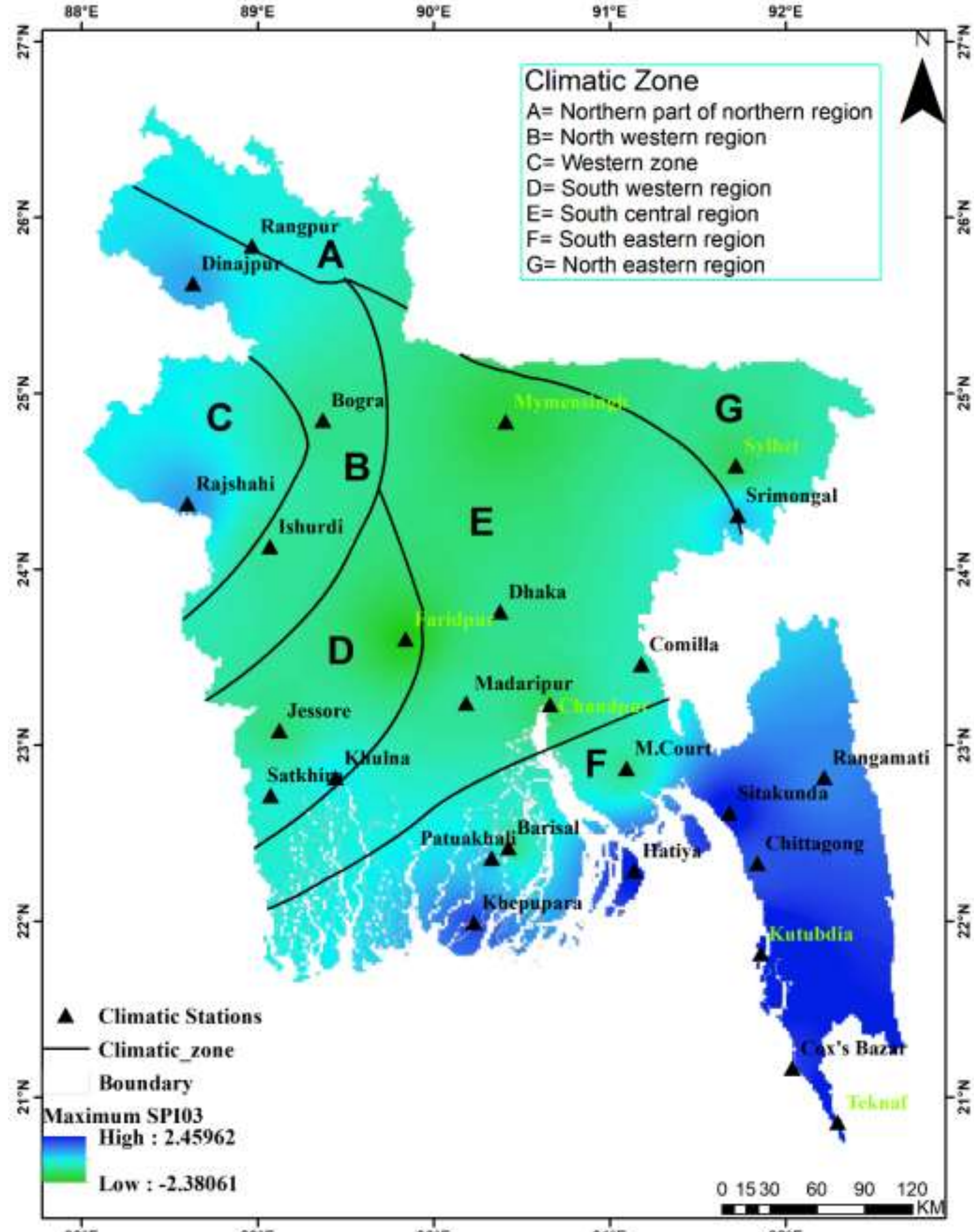

Figure 3: The Spatial Pattern of Maximum SPI-3 Trends during 1979-2019

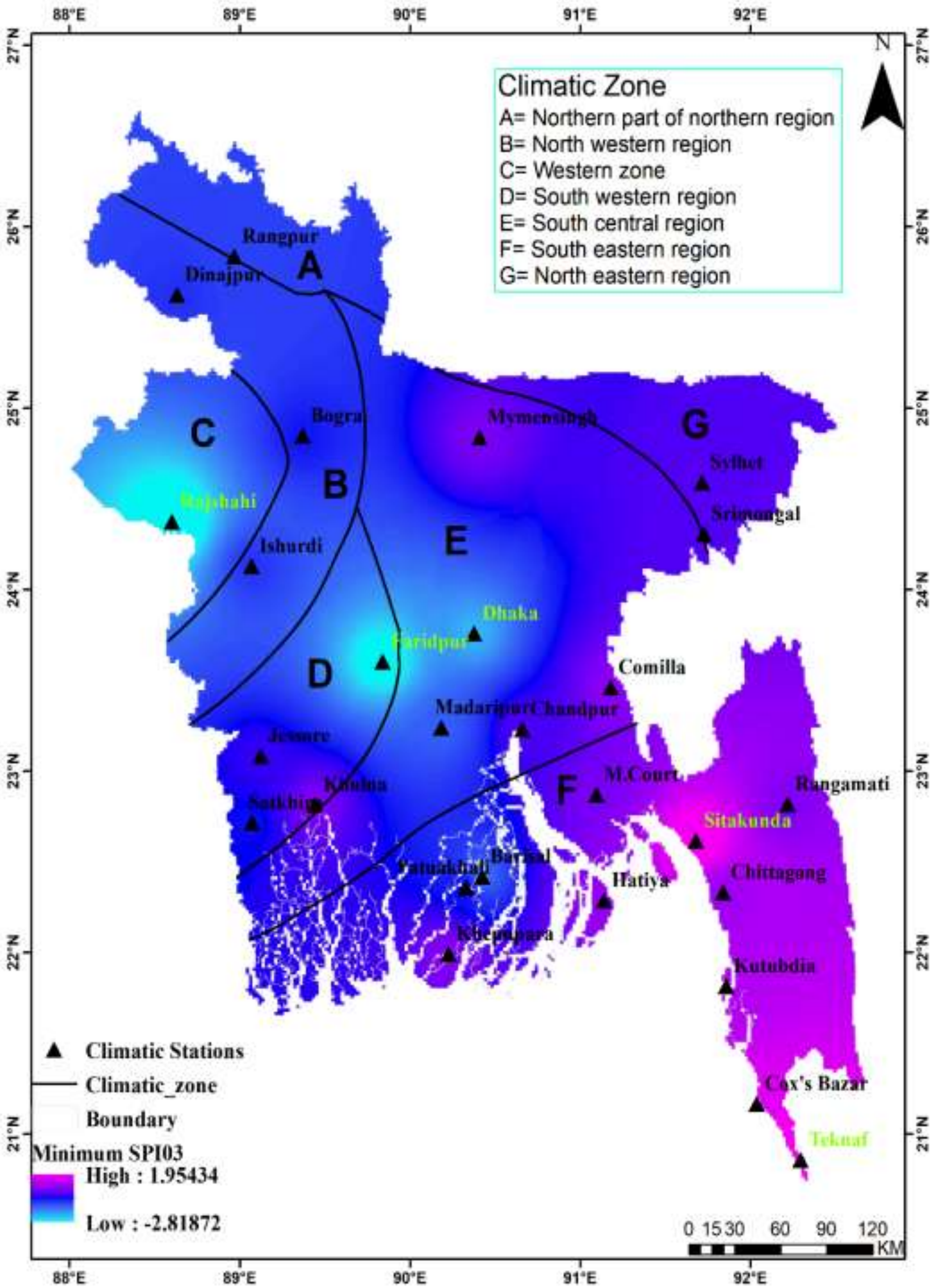

Figure 4: The Spatial Pattern of Minimum SPI-3 Trends during 1979-2019

Seasonal Standardized Precipitation Index (SPI-6) Variability

For the preparation of the projections for the maximal and minimal SPI-6 climatic variables of advances in Bangladesh displayed in Figures 5, 6, and 7, the periodic variation tendency is computed and extrapolated for the required 27 weather stations. The names of the locations in the figures are yellow depending on 90 percentage credibility. A maximum increase of SPI-6 is found for +0.0083 for the south-eastern zone, whereas minimum SPI-6 is calculated for the northern part of the northern zone, northwestern zone, western zone, and south-central zone and of -0.0135, -0.0089, -0.0248, -0.0127, and -0.0012 accordingly (Figure 5). However, Figure 6 indicating the increase of wet period for the northern part of the northern zone, the southern part of the southwestern zone, and the south-eastern zone. On the other hand, the extreme drought areas are identified as Rajshahi, Dhaka, Faridpur, and Barisal, which is less than -2.0 drought index situated at western, south-central, southwestern, and south-eastern zones, respectively (Figure 7).

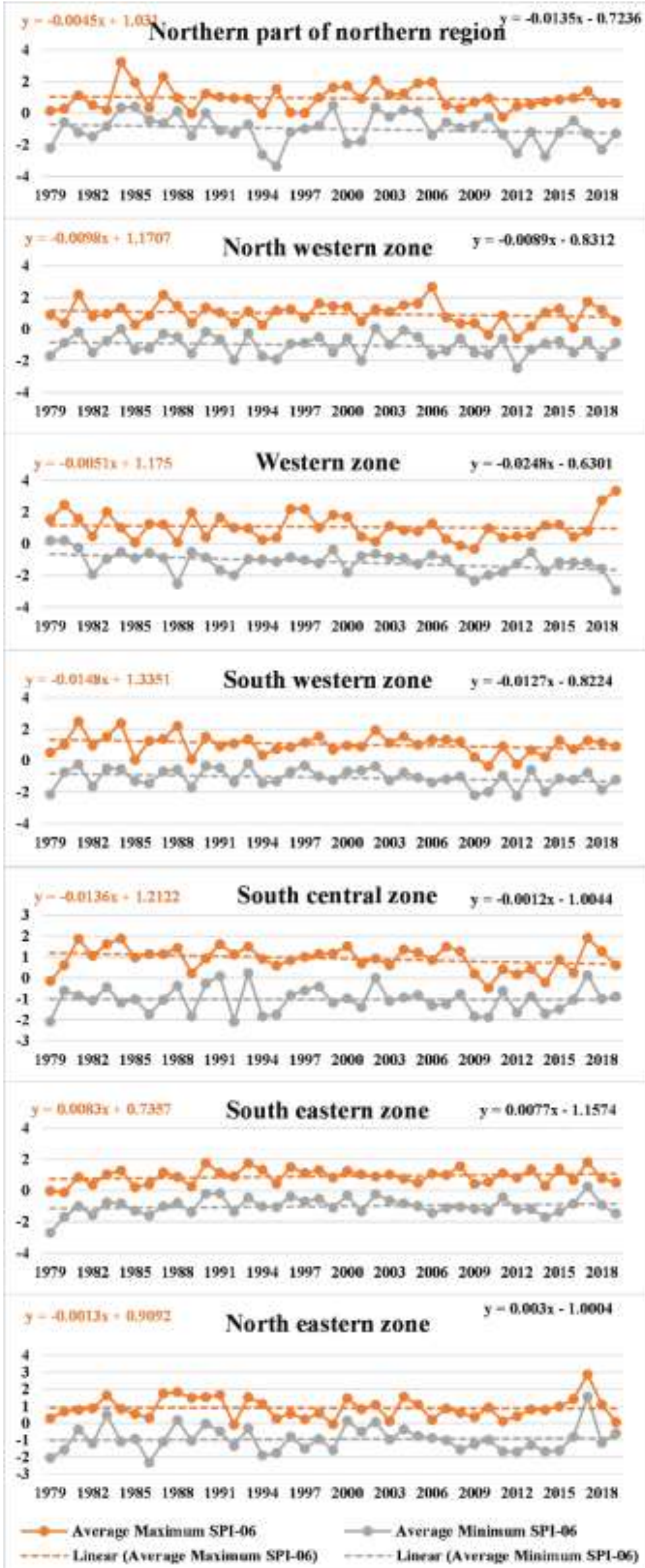

Figure 5: Average Maximum and Minimum SPI-6 of Seven Climatic Zones during 1979-2019

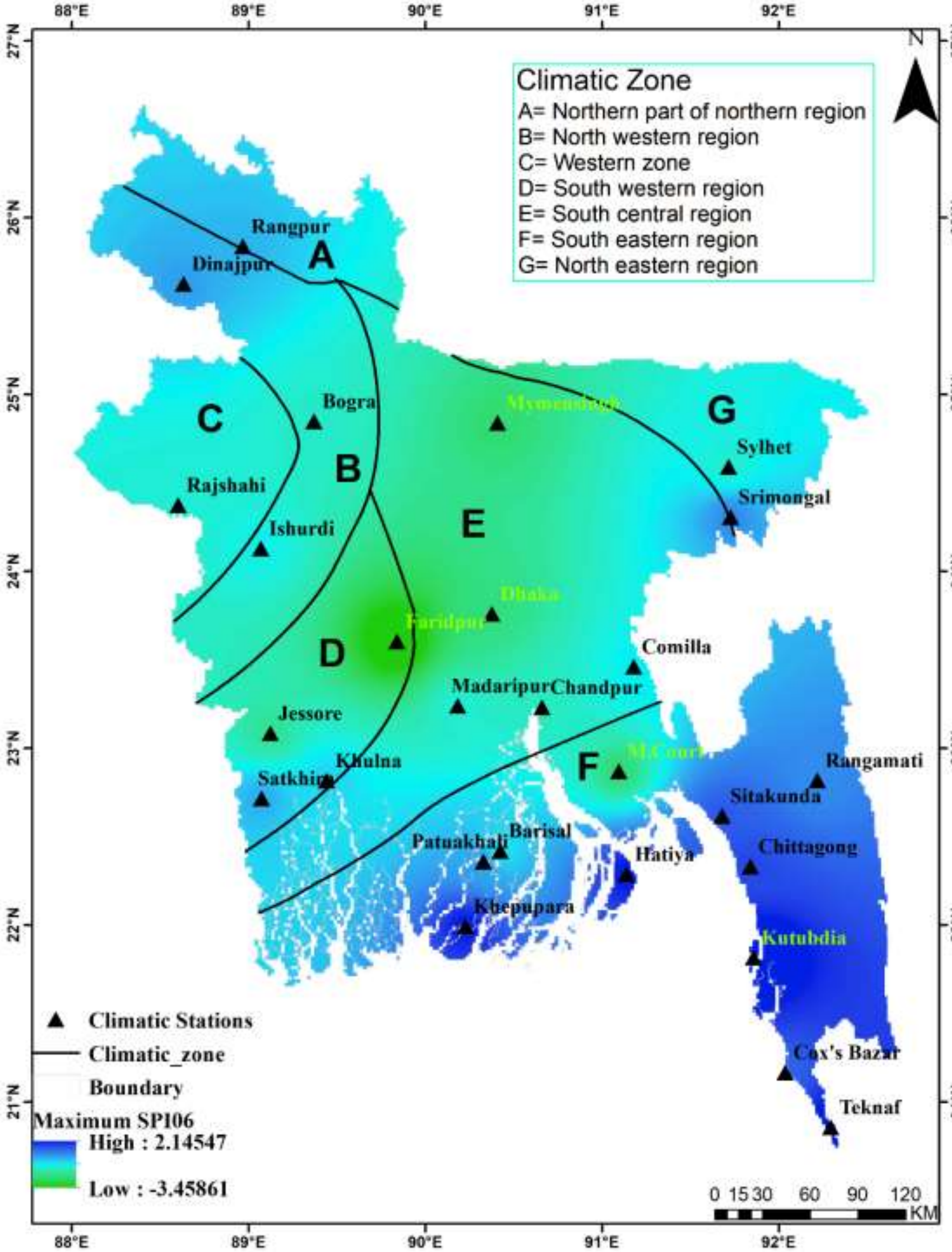

Figure 6: The Spatial Pattern of Maximum SPI-6 Trends during 1979-2019

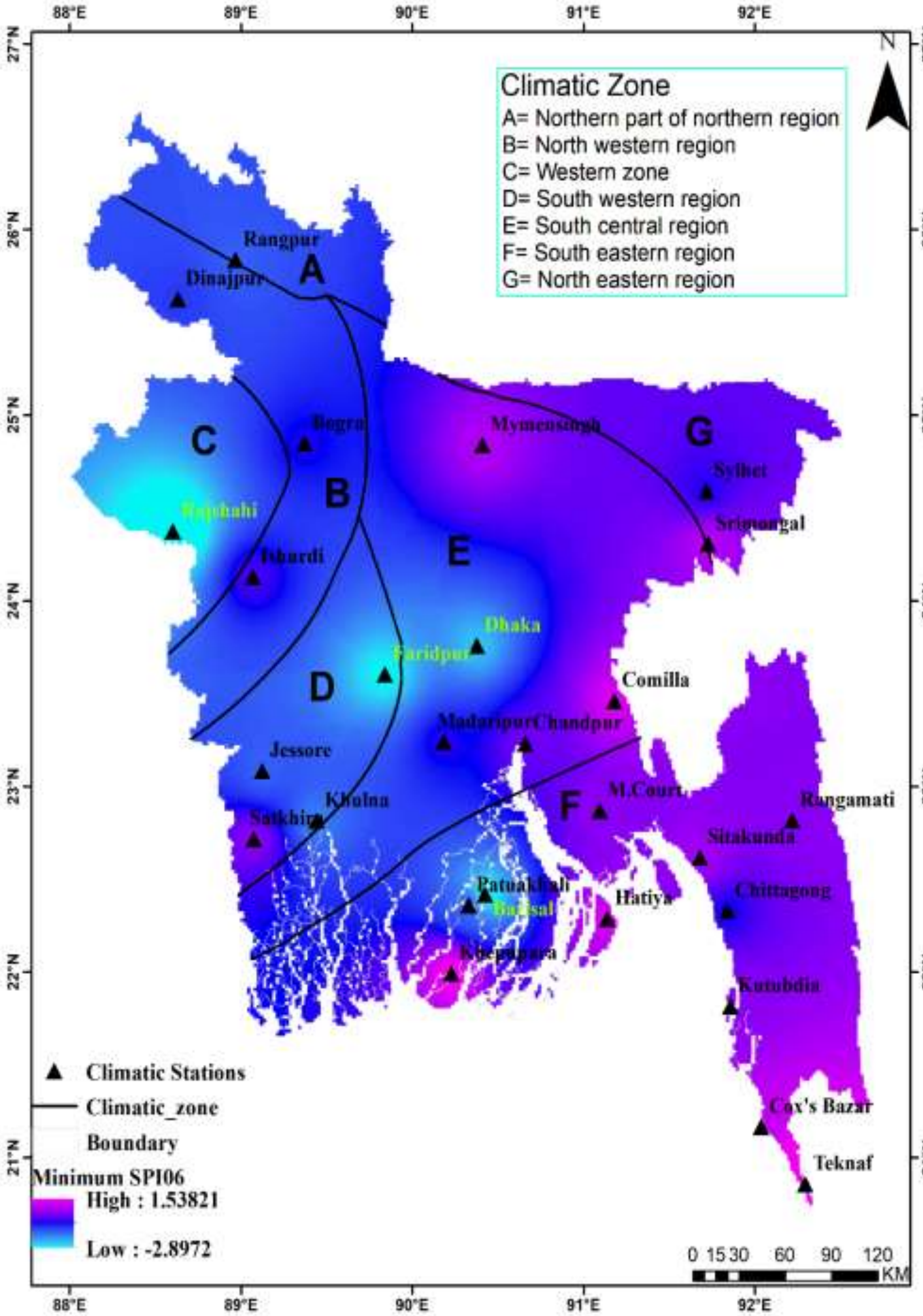

Figure 7: The Spatial Pattern of Minimum SPI-6 Trends during 1979-2019

Annual Standardized Precipitation Index (SPI-12) Variability

Yearly wet and dry period changes trend is determined by using SPI-12 to all the 27 weather stations computed and transcribed for the preparation of the maximal and minimal SPI-12 spatiotemporal data patterns in Bangladesh, as can be seen in Figures 8, 9, and 10 correspondingly. The name of the locations in the figures is yellow and is relied on 90 percent of overall credibility.

A maximum increase of SPI-12 is found for +0.0176 and 0.0024 for south-eastern zone and north-eastern zone, respectively, whereas minimum SPI-12 calculated for the northern part of northern region, north-western zone, western region, southwestern and south-central region of -0.0262, -0.0245,-0.0251, -0.0138, and 0.0068 accordingly (Figure 8). It can be pointed out that a severe less amount of magnitude was identified in the southwestern zone. However, Figure 9 indicating the increase of extreme wet periods for the southern part of the southwestern, south-central zone as well as south eastern zone. On the other hand, the extreme drought areas are identified as Rangpur, Dinajpur, Rajshahi, Dhaka, and Faridpur, which are less than -2.0 of SPI drought index situated at the northern part of northern zone, north-western, south-central, and southwestern zone and respectively (Figure 10).

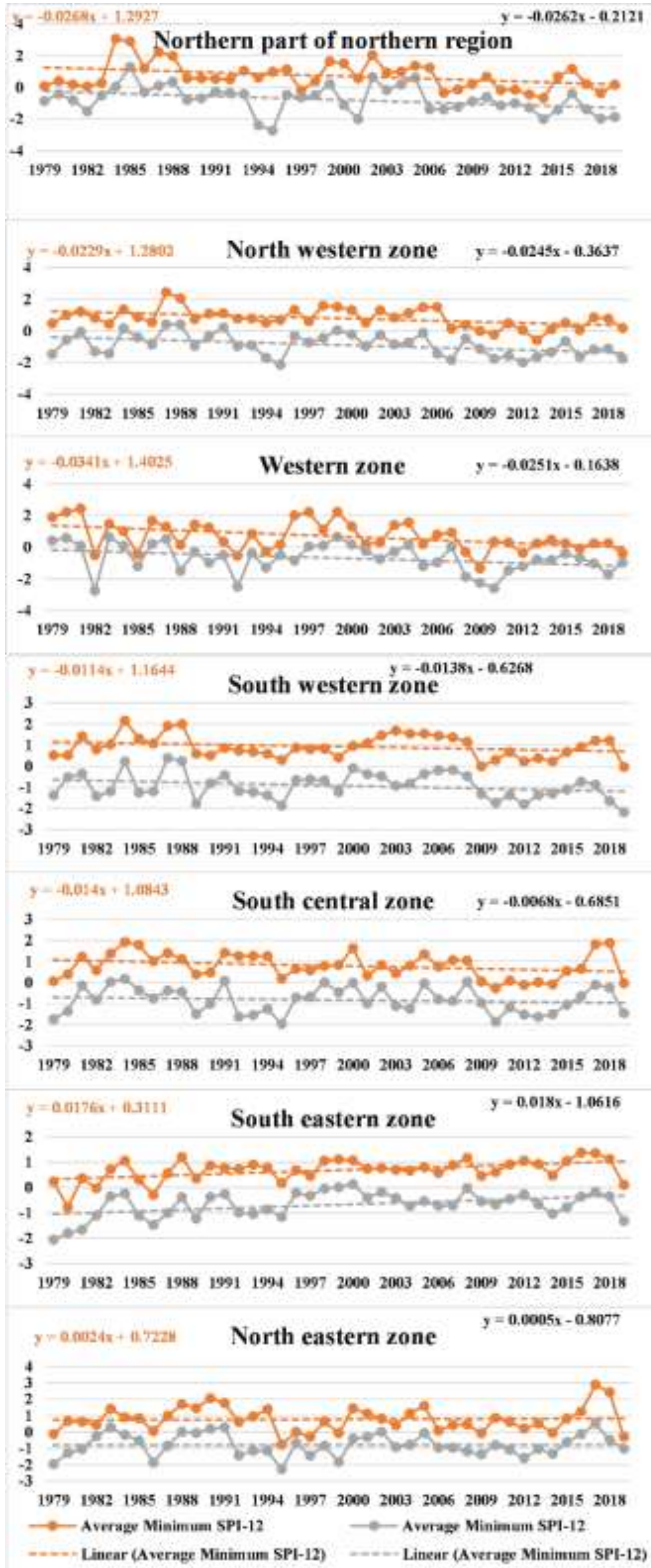

Figure 8: Average Maximum and Minimum SPI-12 of Seven Climatic Zones during 1979-2019

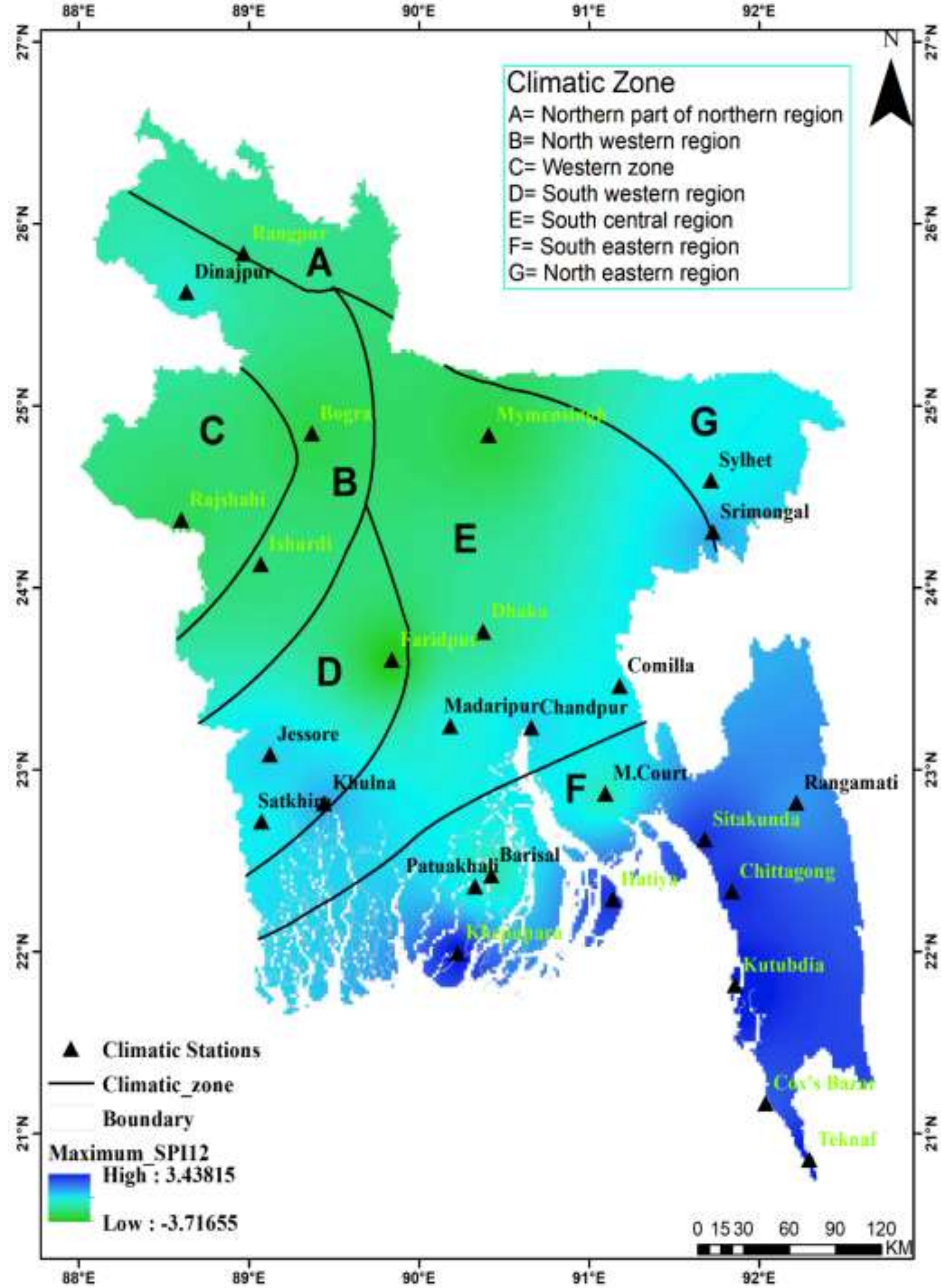

Figure 9: The Spatial Pattern of Maximum SPI-12 Trends during 1979-2019

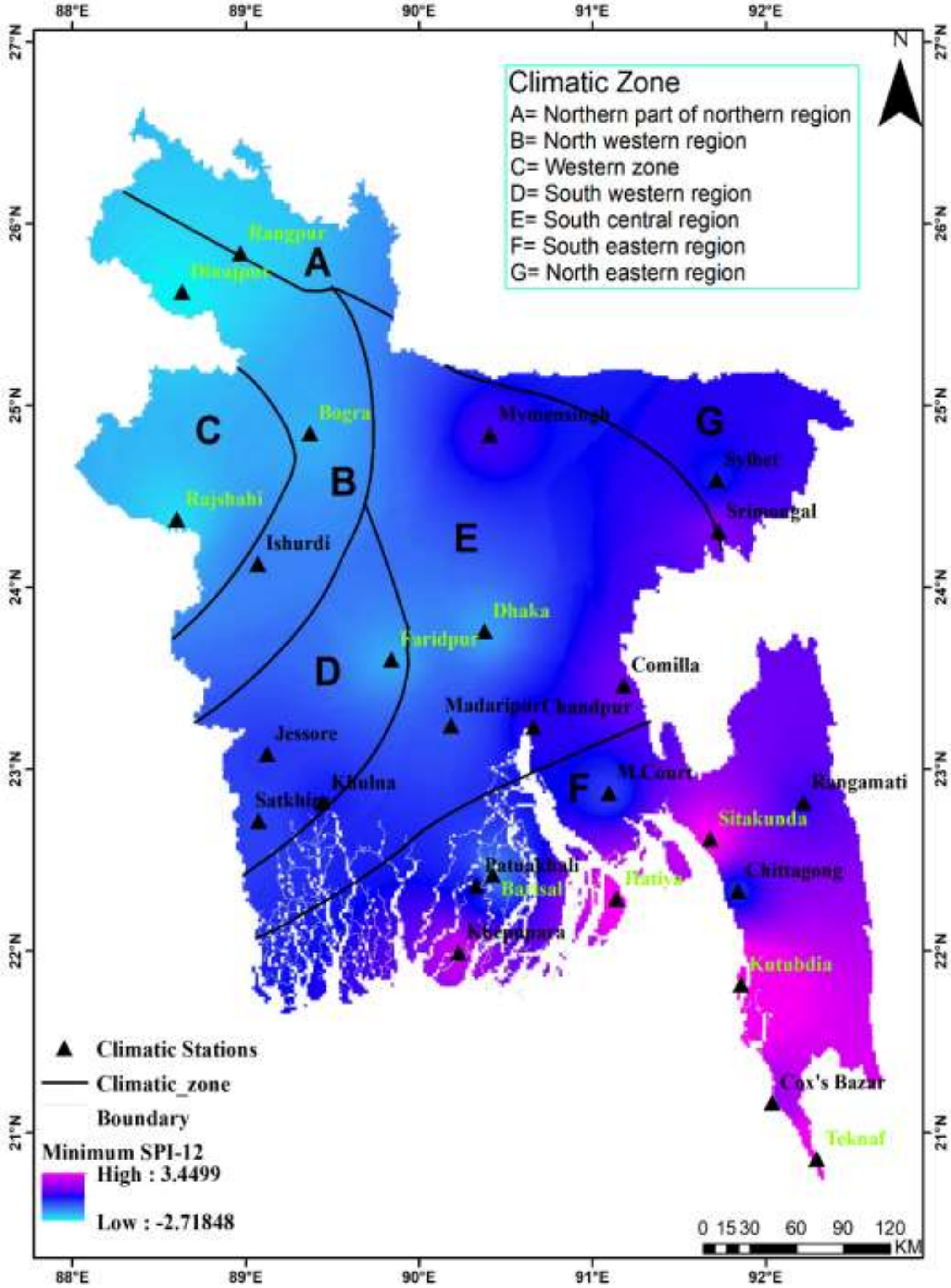

Figure 10: The Spatial Pattern of Minimum SPI-12 Trends during 1979-2019

Discussion

The study's specific goal was to examine drought trends and perform spatiotemporal analysis. The drought ratio has been determined from each station's complete records, and so it was extrapolated and graded (McKee et al., 1995). The results depict either drought was stable, decreased, or increased in various manners. However, the extreme drought events have arisen in many climatic zones in recent years, primarily in the northern half of the northern areas, the northwestern portion, and the western area. Quite precisely, drought occurrence has taken into formation heavily in western, south-central, and southwestern zone for SPI-3 and western, the south-central, the southwestern and southeastern zone for SPI-6 and northern part of northern zone, northwestern, south-central, and southwestern zone of SPI-12 respectively. The observed phenomenon demonstrating western, south-central, and southwestern zone are in common measures of extreme drought for SPI-3 and SPI-6 except southeastern zone, whereas SPI-12 added new two climatic zones of the northern part of the northern zone and northwestern zone for drought responsibilities. In addition, the trend study observes northern part of the northern zone, northwestern zone, western zone, southwestern and south-central zone are at high risk of drought capacity. The reason beyond these changes proves the spatial and temporal variation of precipitation and seasonal changes (Rahman and Lateh, 2016b). Therefore, monsoonal wind and rainfall and Himalayan properties are also responsible for the variability of drought and rainfall in Bangladesh (Shahid, 2012). Furthermore, El Nino significantly impacted Bangladesh's weather conditions, leading to decreased rainfall in the pre-monsoon, monsoon, and post-monsoon season (Choudhury et al., 2005). The likely evidence that greenhouse gases are accountable for Bangladesh's unpredictability in drought (M. R. Rahman and Lateh, 2016a). Drought fostering considerable negative impact on living organisms and food production; for instance due to extreme drought in 1978 it created a reduction of 2 million tons rice yield (Habiba et al., 2013b). Drought damages in 1982 were far more than double that year relative to flood losses (Umma and Rajib, 2014). Once again, the 1997 drought affected over 2 million ha. of crop ground (Habiba et al., 2013b). Due to the drought in the region, crop failures or reduced productivity resulted in the purchase of massive quantities of agricultural commodities (PR, 1995). In Bangladesh, rice is cultivated in the summer months, which means that abundant soil waters have been consumed, which might lead to a water shortage in the era of sustainable development (Mainuddin et al., 2020). However, it may be mentioned that excessive drought periods sustain due to the lack of rainfall and predominately drought-prone climatic zones in Bangladesh (Umma and Rajib, 2014). A probable explanation for lengthy drought conditions was the connection between ocean heat content and precipitation (Ramamasy, 2007). Bangladesh’s northwestern and southwestern part is experiencing drought in dry periods due to holding water in Farakka Barrage, which creates barriers for the continuous water flow of Padma river, causing 57% water shortages in dry period (WBB, 1998). Hence warmth and precipitation will increase shortly, can lead to a deficit of drought conditions in Bangladesh (Rahman and Azim, 2022; Chowdhury et al., 2020; Islam et al., 2018). In contrast, temperature increases can be responsible for decreased seasonal rainfall for future variabilities that may cause longer dry periods in Bangladesh (Rahman and Lateh, 2016b).

Conclusion

The study aimed to identify drought trends and spatiotemporal observation during 1979-2019 from the 27 weather stations. SPI and GIS approaches were used to find out the severe drought-prone climatic zones. Drought trend varies zone wise and spatiotemporal evaluation finds out that northern part of northern zone, northwestern zone, western zone, south-western and south-central zones have extreme drought conditions for annual observations. Medium and Seasonal trend variations of SPI-3 and SPI-6 emphasizes on extreme vulnerable drought possibilities for northern part of northern (SPI-3>-0.005 and SPI-6 >-0.013), north western (SPI-3 >-0.028 and SPI-6 >0.008) and western zones (SPI-3 >-0.028 and SPI-6 >0.24). However increased positive values of trend optimized for lowering drought possibilities of two zones only includes south eastern (SPI-3 >0.007, SPI-6 >0.008, SPI-12 >0.017) and north eastern (SPI-12 >0.002) zones. Through this evaluation, it is expected that policymakers will be benefitted from urban and rural planning, water management, agricultural planning. Further studies should emphasize drought prediction based on agricultural diversification and drought trend circumstances.

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