Frequency of Droughts in Northwestern Bangladesh

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Abstract

The Northwest part is highlighted as the most exposed drought-prone region in Bangladesh. This research investigates and predicts the frequency of droughts, applying respectively standardized precipitation indices and autoregressive integrated moving average modeling, using the daily rainfall data for 30 years from 1988 to 2017. Estimated indices, mostly agreed with the previous contributions, depict that most of the northwestern region have experienced severe to extreme drought in 1992, 1994, 1995, 2000, 2006, 2010, 2012, and 2014. With the uncertainty less than 51-21%, this work has also been forecasted that some parts of the region may undergo severe drought in the coming years in 2023, 2026, 2028, and 2031. Since agricultural production from the region substantially contributes to the national economy, initiatives are desirable to increase surface water supply for the region to address drought.

Keywords: Drought; Climate; Rainfall; Forecast; Bangladesh

1. Introduction

Bangladesh is among the countries most susceptible to the impacts of climate change and different parts of the country are exposed to various climatic threats. The southern part is vulnerable to sea-level rise and cyclone, while the northwestern part experiences extreme weather and droughts. Besides, floods, erosion, and landslides are very common in other parts of the country. Rainfall is among the variables that are responsible for changes in the local climate [1, 2]. The Asian monsoon region for instance, with a long history of droughts, has been experiencing irregular rainfall patterns [3]. Around 80% of the global agricultural land is rain-fed while the rest is under irrigation [4]. Shortage of adequate rainwater results in devastating droughts, and thereby affects agriculture by substantially damaging the crops in the northwestern part of Bangladesh [5]. Rockström [4] identified a water deficit of 5800 km^3 per year that would be required to use in agriculture over the coming 50 years in order to secure food for under-nourished and growing populations [4]. Hence, it has been argued that drought may become new normal because of anthropogenic climate change, and hence, measures are required to address drought and the consequences [6] for which prediction of drought is a prerequisite.

Bangladesh has been experiencing high-frequency droughts along with Afghanistan, Bhutan, and Nepal because of the irregular distribution of monsoon rainfall. Most of the areas in Bangladesh suffer from a long dry period from November to May. There was almost no rainfall for several months in some areas in the northwest, southwest and central zones during 1998-1999; and more frequent droughts, mostly in pre-monsoon and post-monsoon along with monsoon seasons, were reported in the year 1951, 1957, 1961, 1972, 1976, 1979, 1986, 1989 and 1997 [3, 7] that affected around half of the country and total population [8]. The droughts of 1973, 1979, and 1994-1995 were the worst in the recent past [9, 10]. Hotspots of most of the above drought periods belong to the northwestern part of the country.

Drought is a natural phenomenon comprising a long period of dry weather that causes adverse consequences on life and assets. Drought risk imposes both ex-post and ex-ante impacts. While the ex-post impacts are more visible and realized after a drought has been experienced, the ex-ante impacts arise due to merely the threat of drought having sustained impacts [11]. A shorter time-scaled drought, known as meteorological drought, can cause a serious hydrological imbalance in an area [12]. Increased withdrawals of water to address drought risk, and the resulting shifts in water flows in the water balance may affect both nature and economic sectors [4] along with agriculture. Environmentally vulnerable landscapes experience the most threats since agricultural production is affected by many factors including drought [4]. Drought affects crop systems, food security, and subsequent social and economic impacts which are more evident in drought-prone areas [13-16]. In addition, lower yields and reduced grain production as a result of drought contribute to spikes in wholesale prices, put low-income communities under great financial threat due to higher price of commodities, result in insufficient animal feed and subsequent rise in the price of meat, poultry, and other animal-based food products [6]. Hence, drought requires substantial investigation including the estimation and prediction.

This research aims to study the meteorological drought in the northwestern part of Bangladesh. It is the key indication, and when it prolongs, it causes hydrological and agricultural droughts, resulting in water shortages. Rainfall is assumed to be the driving force of drought that can be estimated with the Standardized Precipitation Index (SPI) introduced by McKee et al. [17, 18]. SPI, a drought indicator, describes the deficit or excess rainfall on a temporal scale for a specific region. It allows to study multiple droughts according to the use of various timescales in it, e.g. timescales less than or equal to 3 months (3M) for meteorological drought, less than or equal to 6M for agricultural drought and greater than 12M for hydrological drought [19, 20]. Although not free from criticisms, the SPI has become a popular tool to evaluate climatic variability and successfully has been implemented to evaluate drought condition, for instance, of Texas, USA [21], Mexico [22] and Brazil [23]. On the other hand, ARIMA model cannot outperform over other techniques to estimate climate indices, but it in general provides more accurate projections, which are more reliable and interpretable particularly for location-specific temperature and precipitation forecasts of changing climate [24, 25]. Accordingly, this research aims to investigate recent meteorological droughts in the region and also to predict the same.

2. Materials and Methods

2.1 Study Location

Two divisions, Rajshahi and Rangpur, are located in the northwestern part of Bangladesh that extends from 23^{0}80' to 26^{0}38' N latitude and from 88^{0}01' to 89^{0}70' E longitude with an area of about 34513 km^2 as shown in Fig 1. Most of the region is low-lying plain land except the Barind Tract. It is surrounded by India in the west and north, Dhaka division in the east, and Khulna division in the south, and the area is lying at the west of the river Jamuna and the north of the river Padma.

2.2 Data

Daily rainfall data for 30 years from 1988 to 2017 recorded by the Bangladesh Meteorological Department (BMD) in six meteorological stations namely Rajshahi, Ishwardi, Bogura, Rangpur, Saidpur, and Dinajpur have been used for this research. Locations of the stations are shown in Fig. 1. Recorded data are found to be complete except two days (9th and 10th Aug in 1988) in Rajshahi and three years (1988-1990) in Syedpur because of the missing data. The missing values have been filled up using the cubic spline interpolation technique for two days data in Rajshahi. While, for Syedpur the analyses have to be done for the data from 1991 to 2017. Additionally, as this is often important to verify the data set either homogeneous or not before applying to statistical technique and as identical or homogenous property provides better estimations, the datasets were inspected for homogeneity using Standard Normal Homogeneity Test [26] and Von Neumann ratio Test [27]. Both statistical tests have confirmed that the data to be analyzed from all of the stations are homogenous.

Figure 1. Location map of northwestern part in Bangladesh.

2.3 Methods

2.3.1 Standardized Precipitation Index (SPI)

Standardized precipitation index, SPI is defined as a scale of the deviated rainfall from the normal rainfall probability distribution function with zero-mean and unit-standard deviation [1, 28, 29]. This is the application of a gamma probability density function for gamma distribution. The standard normal Z-value with the zero-mean and unit-variance is SPI obtained from a gamma distribution. The monthly SPI takes the form from the monthly rainfall, x, obtained from the daily rainfall, through gamma probability density, g(x) for gamma distribution and cumulative probability function, H(x), as described below.

$$g(x) = \frac{x^{\alpha-1} e^{\frac{-x}{\beta}}}{\beta^{\alpha}\Gamma(\alpha)} \quad \text{for} \quad x, \alpha, \beta > 0 \qquad (1)$$

where, $\beta = \frac{1+\sqrt{1+\frac{4U}{3}}}{4U}$; $\alpha = \frac{\bar{x}}{\beta}$

$U = \overline{x_{ln}} - \frac{\sum \ln(x)}{N}$ and $\overline{x_{ln}} = \ln(\bar{x})$.

The cumulative probability is then written as $G(x) = \int g(x)dx$. Since Eqn. 1 is undefined at $x = 0$ (no rainfall event), the final cumulative probability becomes $H(x) = q + (1-q)G(x)$, where, q is the probability of zero or for no rainfall. $H(x)$ is then transformed to the standard normal random variable Z along with the approximate conversion provided by Abramowitz and Stegun [30].

$$SPI = Z = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad 0 < H(x) \le 0.5 \qquad (2)$$

$$SPI = Z = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad 0.5 < H(x) \le 1 \qquad (3)$$

where,

$$t = \sqrt{\ln\left(\frac{1}{H(x)^2}\right)} \quad 0 < H(x) \le 0.5$$

$$t = \sqrt{\ln\left(\frac{1}{(1.0 - H(x))^2}\right)} \quad 0.5 < H(x) \le 1$$

$c_0 = 2.515517$; $c_1 = 0.802583$; $c_2 = 0.010328$; $d_1 = 1.432788$; $d_2 = 0.189269$ and $d_3 = 0.001308$.

SPI indices can be classified further as shown in Table 1.

Table 1. Classification of SPI values [31]

SPI	Classification	Probability (%)
2.0 and above	Extremely wet	2.3%
1.50 to 1.99	Severely wet	4.4%
1.00 to 1.49	Moderately wet	9.2%
0.99 to -0.99	Near normal	34.1%
- 1.00 to – 1.49	Moderately drought	9.2%
- 1.50 to – 1.99	Severely drought	4.4%
- 2.00 and less	Extremely drought	2.3%

2.3.2 Autoregressive Integrated Moving Average (ARIMA) Model

Autoregressive integrated moving average (ARIMA) modeling is commonly applied to fit the time series data to understand and predict future data. The idea is given in the Box-Jenkins model that the time series is stationary [32]. There are various techniques for assessing internal structure in time series data used for modeling and forecasting but there are various limitations too for such assessing. The ARIMA technique is found to be better option to estimate the future values of the time series and this work has estimated future SPI indices with ARIMA technique. Monthly SPIs from 1988 to 2017 to be obtained using Eqns. 2-3 for the monthly rainfall time series. Predictions are to be done from 2008 to 2032 using SPIs for each month from 1988 to 2017 as input time series and later the maximum, minimum and average SPIs in each year have to be obtained. Model parameters in this connection are to be estimated for each input studying stationary, seasonality, and order of the time series characteristics with autocorrelation (ACF) and partial autocorrelation (PACF) functions. The uncertainties of the predicted estimations have to be estimated studying errors involved in it from 2008-2017.

3. Results and Discussions

3.1 Suitable SPI Timescale

The SPI can be computed for multiple timescales for assessing the different types of droughts. 1 month (1M) to 24M SPIs are the best practical range of application [33, 34] and recommended for studying meteorological, agricultural, and hydrological droughts [19]. This work has estimated 1M, 3M, 6M, 12M, and 24M SPIs for the daily rainfall data recorded at Rajshahi station as test case to understand the suitable timescales for studying meteorological drought and shown 3M and 6M as the right options, which have applied later for all stations as described in the following sections.

Figs. 2(a-e) show the estimated SPI indices in different timescales. The estimations as shown in Fig. 2(a) render that the computed SPI indices, more than 50% of 1M for the months November to February and more than 80% for the month December, have appeared to be less than -1.5, which implies that the area was under extreme to severe drought in most of the years from 1988 to 2017. However, the results are not convincing enough to delineate the area under severe drought in each of the years. Instead, the 1M analysis may be attributed to the dry months of the years. The 3M SPI analyses have visualized a better drought scenario of the area as shown in Fig. 2(b). Here, 17-24% SPI indices for the months January to March and 24% for the month February are found less than -1.5. In the year 2010, the indices for most of the months have found below -1.5 (Fig. 2(b)) except April, June, November, and December. Hence, the year 2010 has been identified as a severe to extreme drought year. In addition, the estimated indices in the year 2001 have been found below -1.5 for four successive months from January to April in 3M SPI analysis, but the year 2001 is yet to be considered as severe to extreme drought year in this work as the severity of drought is not reflected in 6M,12M and 24M time scales analyses (Figs. 2(b-e)). The year 1992 is determined as drought year in 6M analysis and shown signatures in 3M analysis. It is thus comprehended that 3M or 6M or any other timescale SPI analysis alone has not appeared suitable for studying drought. On other hand, 1M SPI analysis as shown earlier is not convincing enough for studying drought severity.

The estimated 6M SPI indices as shown in Fig. 2(c) has visualized the years 1992 and 2010 as severe drought years since the indices fall below -1.5 for the months June to December in 1992 and for the months: March, May, July, and October through December 2010. The remaining months of the years are mostly seemed to be normal. Estimated 12M and 24M SPI indices, as shown in Fig. 2(d) and Fig. 2(e), also indicate the year 2010 as a severe drought year. In the following sections, drought is termed for severe to extreme drought. Neither the year 1988 nor 1989 is considered a drought year since the estimated SPIs are found to be erroneous or overestimated showing very high magnitude in the initial years.

Kumar et al. [29] and WMO 2012 [19] have explained that where the rainfall is normally low during a month in the regions, the large negative or positive SPIs may mislead to understand the climatology even though the departure from the mean is relatively small. Data from the region shows many pieces of evidence of low rainfall during particular months, while, the calculated 1M SPI analysis has identified most of the years as drought years, which are not acceptable according to the realistic observations. Hence, 1M SPI analysis is not suitable to assess the meteorological drought years as also mentioned by Kumar et al [29] and WMO 2012 [19]. On other hand, 6M, 12M, and 24M SPI analyses have estimated the year 2010 as a drought year. While the 6M SPI analysis has also identified the year 1992 as another drought year. According to the analyses shown above that 1M is not so suitable, while, 3M, 6M, 12M, and 24M have given almost similar results. However, 3M and 6M analyses additionally have produced signatures or identified more effective meteorological droughts. Besides, as the study area is most important for agricultural production in the country and as suggested 1-6M and 6-24M timescales respectively suitable for agricultural and hydrological drought [19], this work has concentrated on 3M and 6M SPI analyses as the right choices for studying overall meteorological drought in the study area. Because the agricultural or hydrological drought follows the meteorological drought. Using such analyses, the drought status for the whole study area has determined and explained in the following section.

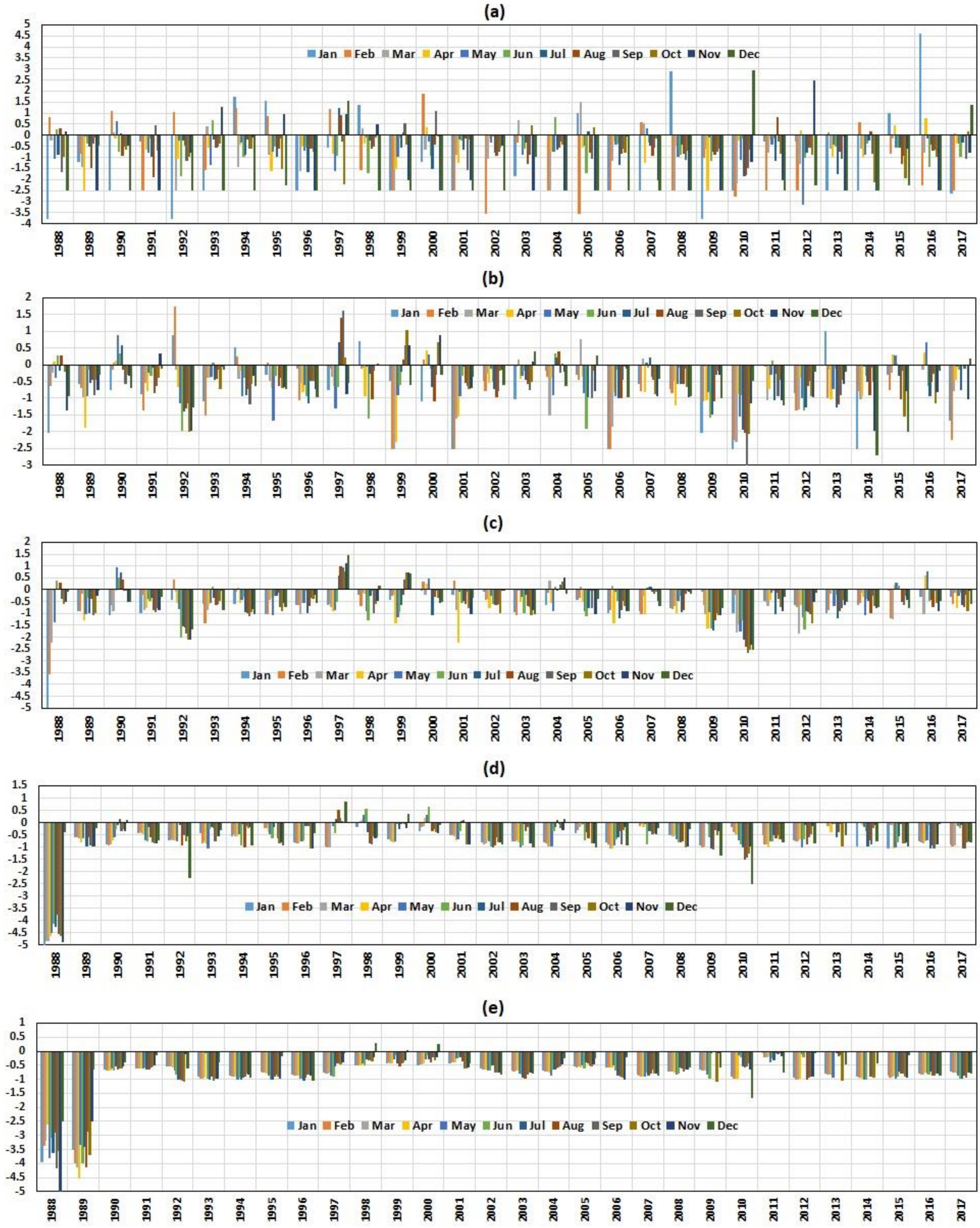

Figure 2. SPI analysis, a) 1M, b) 3M, c) 6M, d) 12M and e) 24M for the months January to December for Rajshahi region from 1988 to 2017.

3.2 Recent Droughts

The 3M and 6M SPIs are computed for all the twelve months in a year using daily rainfall recorded at the other five stations: Ishwardi, Bogura, Rangpur, Dinajpur, and Saidpur for 1988-2017. The 1992 and 2010 have been identified as drought years for Rajshahi station as shown in the previous section. The year 2001 is not determined as a drought year but shown strong signatures of drought.

Estimated 3M and 6M SPI indices have determined the years 2010 and 2012 as severe to extreme drought years since the monthly indices in the years have fallen below -1.5 in Ishwardi region. Similarly, the years 2006, 2012, and 2016 in Bogura; 1994, 1995, 2000, 2006, and 2014 in Rangpur; 1992, 2006, and 2014 in Dinajpur; and

1994 and 2000 in Saidpur region have been identified as drought years. Identified and predicted (explained in the later section) drought years are summarized in the following Table 2.

Table 2. Estimated severe to extreme drought years in northwestern part in Bangladesh

Region	Identified drought year	Predicted drought year
Rajshahi	1992, 2010	2023
Ishwardi	2010, 2012	2031
Bogura	2006, 2012, 2016	2026,2028, 2031
Rangpur	1994, 1995, 2000, 2006, 2014	None
Dinajpur	1992,1994, 2006, 2010	2023, 2026
Saidpur	1994, 2000	None
Note: Drought year predicted with the uncertainty, 51-21% and identified from overall monthly indices not from the minimum index in the year as shown in Figs 3-8.		

CEGIS 2013 [7] had reported that the years 1995 and 1996 experienced severe drought at Rajshahi and Rangpur regions based on rainfall data analysis from 1982 to 2008 [7]. Miyan, Adnan, and Hossain also had reported 1989, 1992, 1994, and 1995 as drought years [3, 8, 35]. This work does not agree with the findings reported by CEGIS [7] except for the year 1995 as drought year in Rangpur. The year 1992 for Rajshahi region is well agreed as drought year as observed by Miyan, Adnan and Hossain [3, 8, 35]. Nury and Hasan argued that Rajshahi was confronted by extremely dry events in the year 1992, 1999, and 2010 using data for the period 1983-2012 [36]. These drought years are well agreed with the findings estimated in this research as shown in Table 2. The year 1999 has not been identified as a drought year; however, may be considered to a certain extent as a drought year, since 3M SPI indices were found below -1.5 for three successive months from February to April while 6M analysis did not reflect the same.

3.3 Drought Forecasting

The estimations of maximum, minimum, and average SPI indices as progress with the time are seemed to be better assessments since the averages are obtained well lying in between maximum and minimum indices. Monthly SPIs have been predicted for the years 2008-2032 using the estimated SPIs of 3M and 6M time scales from 1988-2017. The predicted maximum, minimum and average SPIs for the years 2008 to 2017 have shown errors respectively 35%, 51% and 21% in 3M time scale, and 50%, 49% and 28% in 6M time scale. Estimated and predicted maximum, minimum and average indices for the six stations are shown in Figs. 3-8.

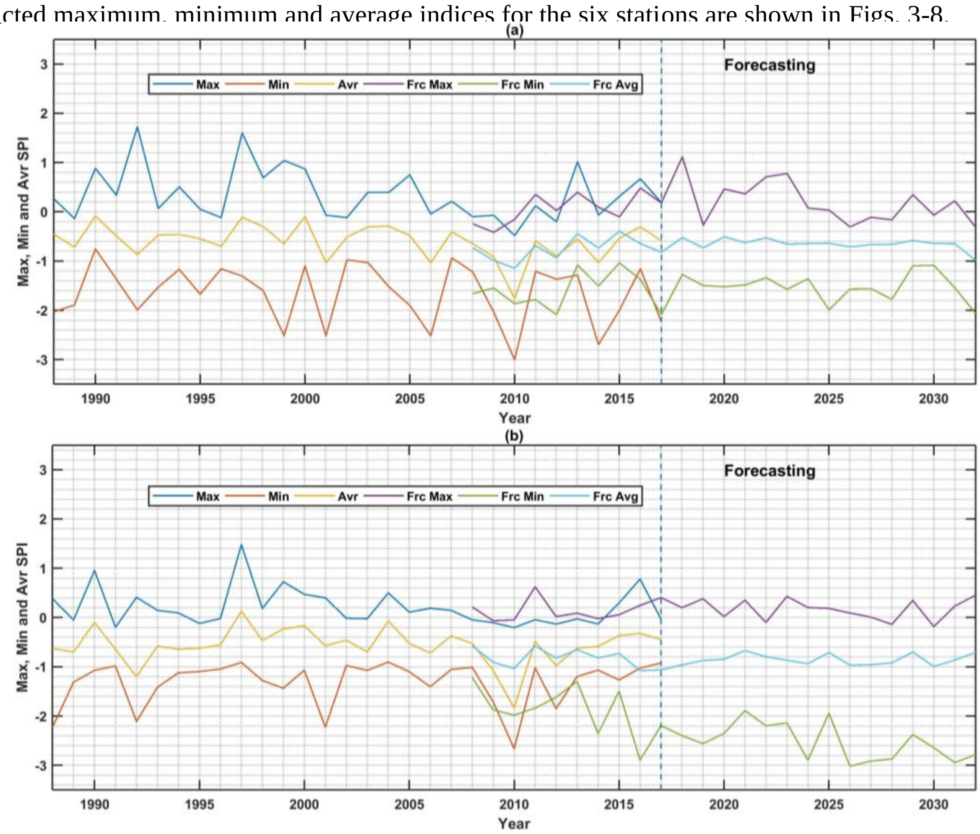

Figure 3. Estimated and predicted maximum, minimum and average indices, using a) 3M and b) 6M analyses for Rajshahi, vertical dotted line separates the recent and future periods.

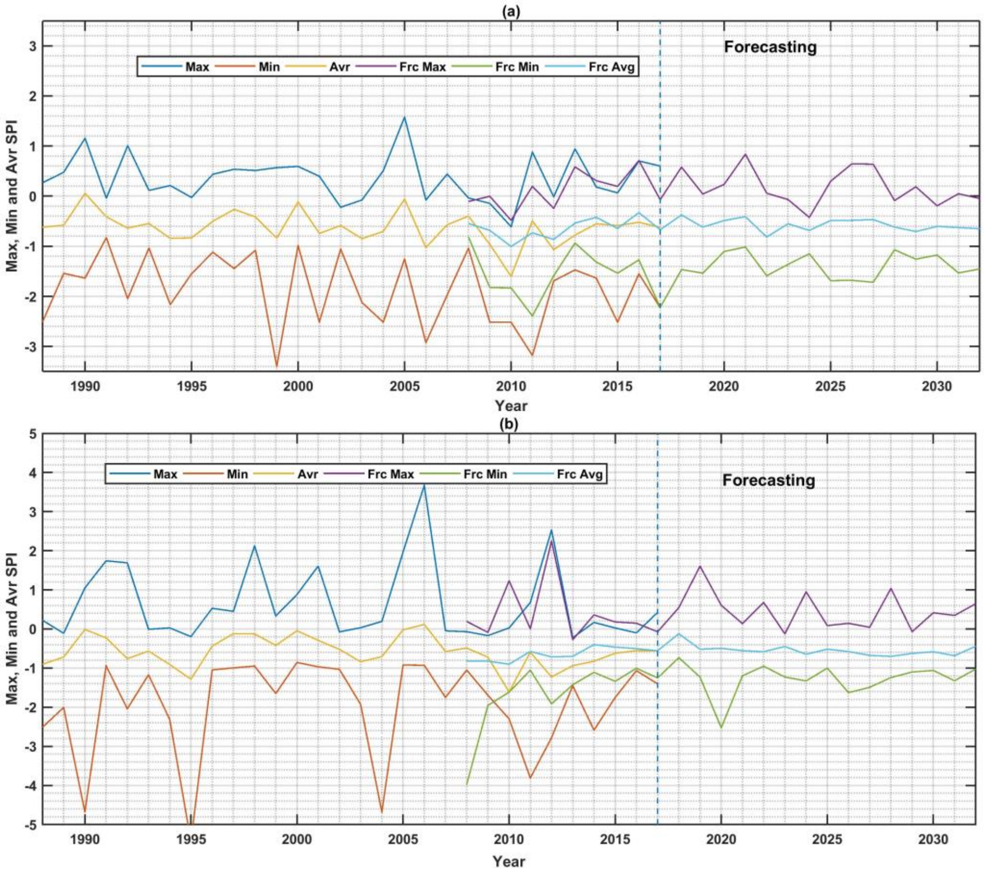

Figure 4. Estimated and predicted maximum, minimum and average indices, using a) 3M and b) 6M analyses for Ishwardi, vertical dotted line separates the recent and future periods.

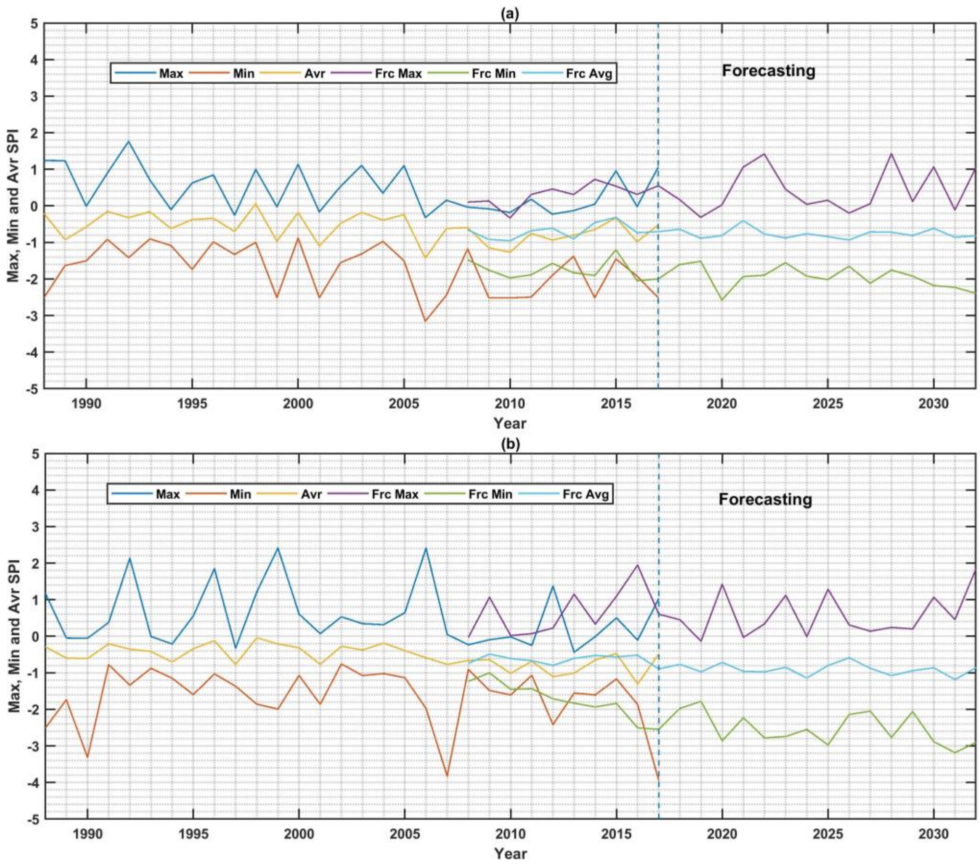

Figure 5. Estimated and predicted maximum, minimum and average indices, using a) 3M and b) 6M analyses for Bogura, vertical dotted line separates the recent and future periods.

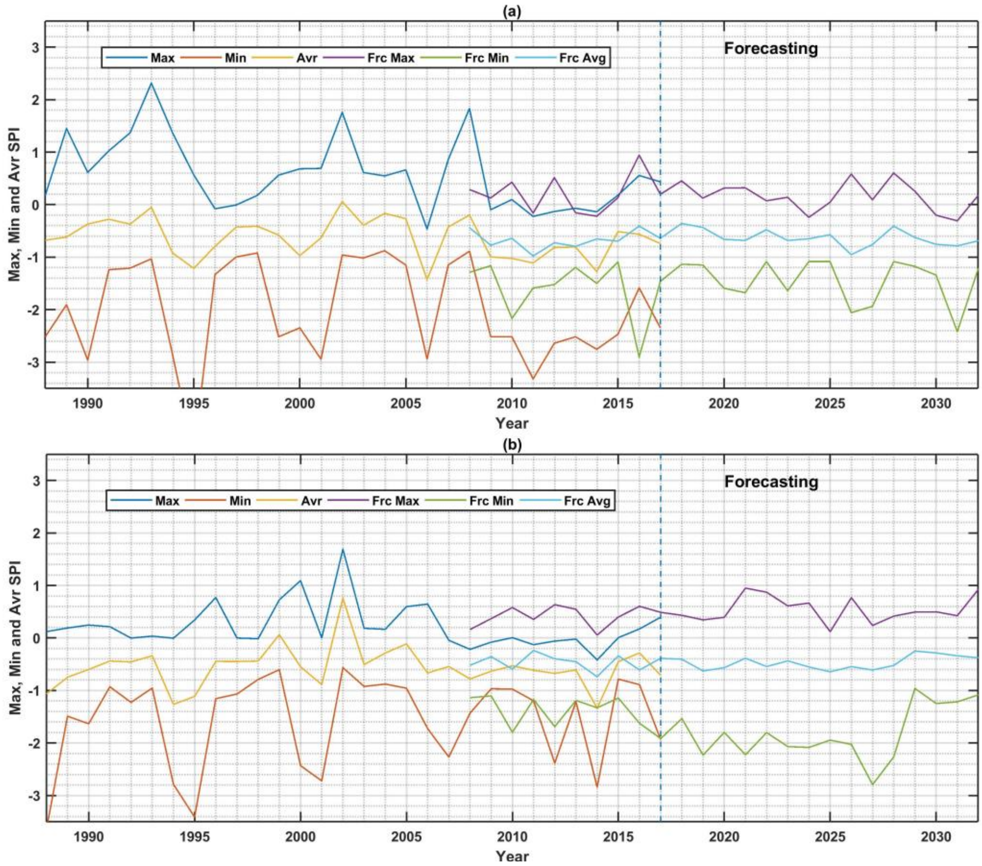

Figure 6. Estimated and predicted maximum, minimum and average indices, using a) 3M and b) 6M analyses for Rangpur, vertical dotted line separates the recent and future periods.

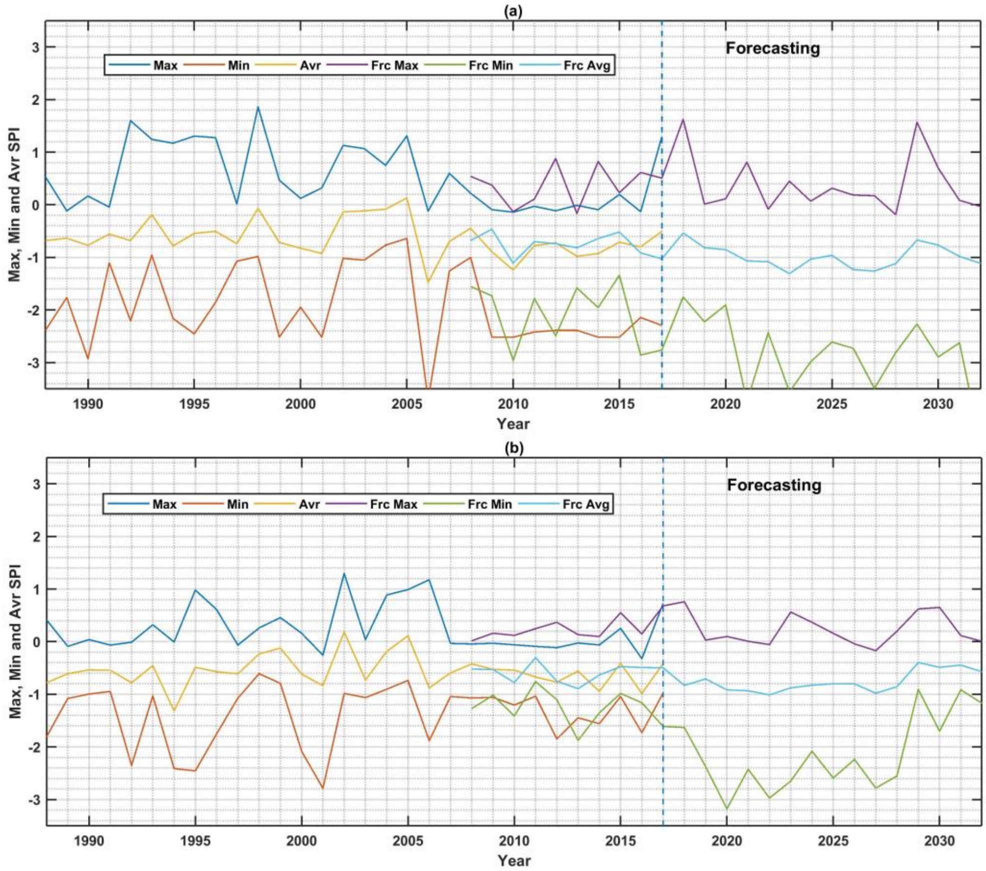

Figure 7. Estimated and predicted maximum, minimum and average indices, using a) 3M and b) 6M analyses for Dinajpur, vertical dotted line separates the recent and future periods.

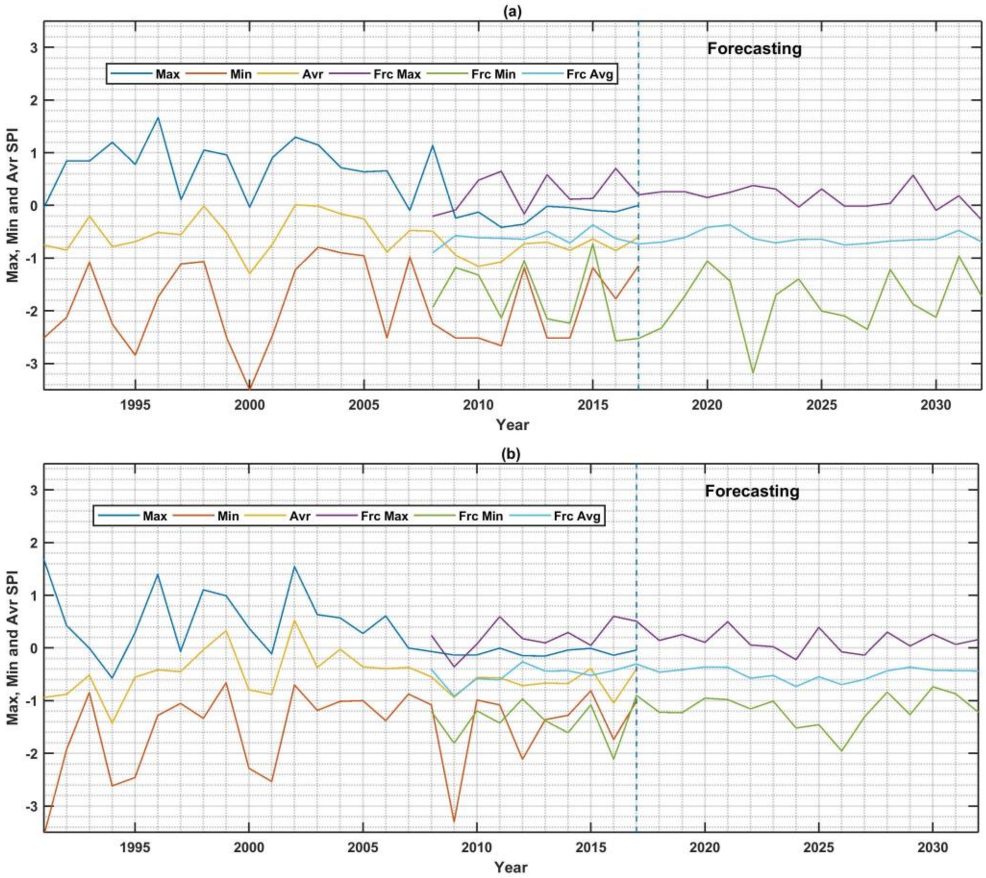

Figure 8. Estimated and predicted maximum, minimum and average indices, using a) 3M and b) 6M analyses for Saidpur, vertical dotted line separates the recent and future periods.

Predicted 3M and 6M SPI indices for the year 2018 to 2032 using the ARIMA model indicate that Rajshahi region is likely to experience severe drought in 2023. Besides, the region may face mild droughts in 2027 and 2030, and it may be normal condition in the remaining years. Similar predictions for other study regions have also been estimated. Estimated results have shown that Ishwardi may experience mild and moderate to severe droughts respectively in 2022 and 2031; Bogura may experience mild droughts in 2022, 2023, 2026, 2028, 2029, and 2032, severe droughts in 2026, 2028, and 2031; Rangpur may not face severe but mild to moderate droughts in 2020; Dinajpur may experience severe to extreme droughts in 2023 and 2026, and mild to moderate droughts in 2020, 2021, 2022, 2024 and 2025; and finally Saidpur may not experience severe but mild droughts in 2018. The study area may belong to a normal state in the remaining years.

The study area is important for agricultural productions in Bangladesh and hence meaningful drought scenarios are required for agricultural productions. Results have revealed that the area was under drought in the last eight years among 30 years from 1988-2017 and may experience the droughts of different intensities in the coming years as estimated in this research from 2018-2032. Therefore, the northwest part of Bangladesh is required more studies to understand the regional droughts. Otherwise, this silent killer would devastate the overall growth of agricultural production with a subsequent negative impact on the national economy.

5. Conclusions

The SPI analysis provides an early warning of drought and assists to estimate the drought severity of a region. It is established as one of the better options and hence adopted by most of the national meteorological and hydrological services around the world and studying droughts. Accordingly, the droughts in the northwestern region in Bangladesh have been studied using the SPI analysis with 3M and 6M timescales because this work has also shown that 1M analysis misleads to estimate the drought years and the analyses with 6M to 24M timescales mostly produce similar results with very few exceptions. Using 3M and 6M timescales analyses, this research has identified that the study area experienced severe to extreme droughts in 1992, 1994, 1995, 2000, 2006, 2010, 2012 and 2014. Findings are frightening since the SPI estimations have shown that around one-third of the total 30 years studied from 1988 to 2017 has experienced severe droughts mostly aligned with recent contributions. This research work has also predicted future severe droughts likely to be experienced in 2023, 2026, 2028 and 2031. However, the northwestern Bangladesh is importantly required more studies to realize the local droughts.

Declaration of Conflict of interest.

The authors state that they have no known conflicting financial interests or personal ties that could have influenced the research presented in this study.

Acknowledgements

Authors gratefully acknowledge anonymous reviewers and editor for putting inputs to improve the manuscript. Authors also acknowledge Bangladesh Meteorological Department for providing data to carry out this research work.

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