Statistical Modeling of Rainfall and Drought in North West Bangladesh

A Thesis submitted In Fulfillment of the Requirements for the Degree of

PhD in Disaster Science and Management

Submitted by

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Certification

It is hereby certified that student bearing Registration No. 84, Session 2013-14, has carried out the research work entitled "**Statistical Modeling of Rainfall and Drought in North West Bangladesh**" for fulfillment of his PhD degree from University of Dhaka, Bangladesh, under my academic supervision in the Department of Disaster Science & Management, University of Dhaka.

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Abstract

Drought is a region specific phenomenon, its characteristics vary from one climate regime to another. Though Bangladesh is a riverine country, the northwestern part of the country is vulnerable to drought. Thus, drought characterization should receive much attention. Since, the temporal shift in rainfall is the dominant factor in the climatic variations, in order to better understand and predict the possibility of a drought disaster and plan necessary water management activities it is important to carry out precipitation conveyance and modelling. The general conception that droughts occur twice in a decade in Bangladesh is found not applicable through analysis of climate data for the last two decades. However, it is often argued that the recent submission of droughts is a temporal phenomenon which does not indicate a reduction of drought frequency in Bangladesh.

The study attempted to assess variability, trends, anomaly, volatility and transition in rainfall in the drought-prone northwest region of Bangladesh to have a better insight on the causes of its occurrence, the possibility of the persistence of present trends in droughts and scope of its predictability. The Innovative Trend Analysis results revealed a fluctuation of trends in different parts of the study period. Analysis of rainfall anomaly also revealed a rapid shift in rainfall regime from wet to dry or dry to wet in a short period. The results indicate that the present trend of declining droughts may not persist. The rainfall region can rapidly shift from present wet longer wet or near wet phase to a severe dry phase and trigger droughts in the region. It was observed that Rain Anomaly fluctuate significantly over time like the rainfall. However, there is no consistency or apparent pattern in variation. The results indicate a sudden occurrence of droughts in the region or the droughts in the region is less predictable. The seasonal Rainfall Anomaly Index values were also calculated, and similar random fluctuations were observed.

Therefore, it can be remarked that high variability of rainfall has made the droughts less predictable in northwest Bangladesh.

The results indicate that analysis of variability and trends are not enough for a complete understanding of the cause of change in droughts. Besides, such analyses are not enough to understand whether the decreasing trend in droughts will persist in the near future or there will be a rainfall regime shift which would alter drought trends. The novelty of the study is the application of GARCH-Jumps and Markov chain for analysis of predictivity of droughts. The results can indicate whether the recent submission of droughts in Bangladesh is a reduction of droughts or it is a temporary submission and the country may be affected by droughts again in the near future. Another novelty of the study is the application of Normalized Difference Vegetation Index (NDVI) to relate meteorological drought and hydrological drought with land cover changes. It is not necessary the changes in the vegetation was solely influenced by the meteorological and hydrological drought but there could be other possible reasons such as changes in the vegetation pattern, changes in the irrigation system, use of fertilizers , attack from pest or due to some other natural hazards or anthropogenic activities. This indicates that detailed investigations should be carried out to conclude.

To verify the less predictivity of droughts revealed in the analysis, volatility and jumping behaviour of rainfall was estimated using GARCH-jump model. Application of GARCH-jump model suggests that the rainfall data are characterized by both volatility dynamics and time-varying jumps. These outcomes indicate that recent rainfall intensity are not stable and are difficult to project. Such findings signal that in future, there might be a volatile level of rainfall and therefore, amount of rainfall could either decrease or increase. Finally, to verify the less predictability of drought scenario a Markov Chain model was developed to evaluate transition behaviour of rainfall and develop drought proneness index. Higher-order transition probabilities (up to 10^{th} step) were calculated which were finally used for the calculation of DI. The results revealed that DI values change significantly within a short period. From application of Markov Chain, eratic behaviour of rainfall pattern observed, indicating drought proneness scenario fluctuate, which form severe, moderate and mild drought process occurs. Hence it is evident that due to the eratic behaviour of rainfall pattern, drought proneness scenario fluctuate in north-west region of Bangladesh. Thus instability of rainfall distorts the predictibility of future variation in drought.

The study indicates that droughts in the study area is highly random having large volatility and rapid shifting nature. Large volatility and rapid shifting nature of rainfall have made the predictability of droughts high uncertain in the region. The rainfall region can rapidly shift from present wet longer wet or near wet phase to a severe dry phase and trigger droughts in the region. Analysis can be performed to identify whether there is any specific drought movement path/locus over the country, i.e., to identify the case where drought is initiated in a station in a specific month and then it moves to another station in the next month. The trend of drought movement path can be used as important information for drought warning system in the country. The finding of the study can help disaster risk mitigation policy planning. The procedure used in this study for systematic analysis of rainfall data with robust statistical methods can be replicated for analysis of predictivity of any other climatic phenomena in Bangladesh and any other regions.

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Chapter One

Introduction

1.1 The Problem Statement

Though Bangladesh is a riverine country, the northwestern part of the country is vulnerable to drought. According to (Habiba et al., 2013), in the north-western part of Bangladesh, the average crop production decrease 25–30 % due to the effect of drought. Drought is a costly natural hazard impacting socio-economic activity, agricultural livelihoods and natural environments through water scarcity (Rahman et al., 2016, Habiba et al., 2013; Mishra, A. K. and Singh, 2010; Sheffield, J. and Wood, 2008; Shahid et al., 2008). Since, the temporal shift in rainfall is the dominant factor in the climatic variations, in order to better understand and predict the possibility of a drought disaster and plan necessary water management activities it is important to carry out precipitation conveyance and modelling (Islam et al., 2005). Changes in drought or wetness in developing countries such as Bangladesh does not receive enough concentration and comprehensive study has not carried out on the driving forces of these events (Rahman et al., 2017).

Most of the studies on drought in Bangladesh involves trend analysis of rainfall in order to determine drought. But it is hard to explore changes in drought or wetness due to the subjectivity of rainfall to the climate change. That is why previous studies on rainfall variability and trends in Bangladesh could not identify trends of rainfall (Shahid, S. 2010).

According to Endo et al. (2015), rainfall index showed no clear trend, and was dominated by decadal variations. In the circumstances, the **questions** arises:

(a) Are there specific trends in the rainfall?

(b) Are there dependency relationships in the rainfall of present and past?

(c) Is there anomaly in the rainfall?

(d) Is the rainfall data characterized by volatility dynamics and jumps?

(e) Is the rainfall shifting its time backward or forward?

(g) Apart from rainfall change can drought be explained through changes in vegetation?

(f) Is the rainfall volatility distorts drought predictability?

However, the recent government statistics of Climate Change Cell of Bangladesh Government indicates a reduction of drought in recent years. The general conception that droughts occur twice in a decade in Bangladesh is found not applicable through analysis of climate data for the last two decades. However, it is often argued that the recent submission of droughts is a temporal phenomenon which does not indicate a reduction of drought frequency in Bangladesh.

Drought scenario cannot be explored properly without addressing these issues. Only trend analysis of rainfall data is not enough to get answer of the above mentioned questions. Previous studies attempted to analyze the trend in rainfall, but no previous study attempted to assess the volatility dynamics and jumping behavior of rainfall data. Also anomaly in the rainfall and dependency relationship of rainfall in current time on rainfall in previous time were ignored in the previous studies The existing uncertainty in drought trend emphasizes the need for further analysis of rainfall pattern to make a factual conclusion. The present study have been conducted to get answer of these research questions and fill the gap in the previous studies.

1.2 Objectives of the Study

I. To assess variability, trends and anomaly in rainfall in North-West region of Bangladesh to have a better insight on the causes of drought occurrence.

II. To examine meteorological, hydrological and agricultural drought variability and their relationship in North-West region of Bangladesh.

III. To analyze variability in drought characteristics and drought severity in North-West region of Bangladesh.

IV. To investigate the volatility of rainfall and the shift/transition of rainfall regimes of Bangladesh to understand the possibility of the persistence of present trends in droughts and scope of its predictability.

V. To compare the study findings with neighbouring regions.

1.3 Novelty of the Study

The novelty of the study is the application of GARCH-Jumps and Markov chain for analysis of predictivity of droughts. The results can indicate whether the recent submission of droughts in Bangladesh is a reduction of droughts or it is a temporary submission and the country may be affected by droughts again in the near future. Another novelty of the study is the application of Normalized Difference Vegetation Index (NDVI) to relate meteorological drought and hydrological drought with land cover changes. The finding of the study can help disaster risk mitigation policy planning. The procedure used in this study for systematic analysis of rainfall data with robust statistical methods can be replicated for analysis of predictivity of any other climatic phenomena in Bangladesh and any other regions.

1.4 Organization/Outline of the Thesis

The study has been presented in ten chapters as follows:

Chapter 1 presents the problem statement and objectives of the study.

Chapter 2 describes the literature review on drought analysis.

Chapter 3 gives details of methodology adopted in this research work.

Chapter 4 assess rainfall variability through non-parametric tests, detects trend in rainfall through trend analysis and explores anomaly in the rainfall through Rainfall Anomaly Index (RAI).

Chapter 5 analyzes meteorological drought variability using Standardized Precipitation Index (SPI) and assesses hydrological drought variability using Standardized Water Level Index (SWI).

Chapter 6 examines agricultural drought variability using Normalized Difference Vegetation Index (NDVI) and its relationship with meteorological and hydrological droughts.

Chapter 7 quantifies degree of dryness & determine onset of drought using Aridity Index (AI) and SPEI. It also explores drought severity using Stochastic Component Time Series (SCTS).

Chapter 8 investigates the volatility of rainfall using GARCH-jump model and the shift/transition of rainfall regimes of Bangladesh using Markov Chain to understand the possibility of the persistence of present trends in droughts and scope of its predictability.

Chapter 9 compares the findings of the study with neighbouring regions, West Bengal of India.

Chapter 10 draws the conclusion of the study as well as provides recommendation for future research scopes on the basis of present study.

Chapter Two

Literature Review

2.1 Introduction

The main objective of this chapter is to review concept of drought and relevant studies on drought in Bangladesh and other countries. The study is trying to investigate the weakness and strong points of earlier studies. The study also aims to find out the research gap and fulfill its demand.

2.2 Concept of Drought

Drought means 'severe water shortage', resulting from deficiency of precipitation. It is region specific phenomenon, its characteristics vary from one climate regime to another. It is a creeping hazard, it develops slowly but stay long time. To measure drought as a physical phenomenon, people tend to define droughts in three main ways:

Meteorological drought: This occurs due to the change in weather patterns due to drastic changes. The humidity increases, the rainfall becomes low, the temperature rises, water shortage and dry winds are the common characteristics of meteorological drought.

Hydrological drought: this is a type of drought in which there is a considerable decrease in the level of water in lakes, ponds and rivers due to less rainfall and an increase in temperature. Prolonged metrological drought can lead to hydrological drought.

Agricultural drought: In agricultural drought atmospheric moisture level decreases which thereby affects the soil moisture. This reduces the expected agricultural production and hence, result in the imbalance of demand and supply of food.

2.3 Literature Review

Implications of Changes in Drought Scenario

Increased water vapour in atmosphere due to increased evapotranspiration under warmer climate has altered seasonal and geographical variation of rainfall (Shahid et al., 2017; Wang et al. 2016). The changes in rainfall variability have changed the probability of rainfall extremes and thus, hydrological disasters like floods and droughts (Pour et al., 2020a). Higher implications of climate change in drought characteristics have been reported in several studies in recent years (Dai, 2011; Ahmed et al., 2016; Mohsenipour et al., 2018; Qutbudin et al., 2019). Droughts are most destructive to people's livelihood compared to any other hydrological disasters (Sharafati et al., 2019; Sediqi et al., 2019; Pour et al., 2020b). Droughts mainly affect agriculture and thus the livelihood of millions of people depending on agriculture every year. It has been reported that globally crop damage due to droughts is four folds higher than that incurred from floods (Damania et al., 2017). Therefore, changes in droughts can have severe implications in society and the economy of a region.

Contradictory Results in Drought Trends

The climate change influence on precipitation and droughts is different in different regions. More recurrent and intense droughts have been noticed in recent years in most of the globe (Dai 2011; Spinoni et al., 2017; Marvel et al., 2019; Shiru et al. 2018; Ahmed et al., 2019; Bi et al., 2019; Chattopadhyay et al., 2020). At the same time, an increase in rainfall reliability and thus, lessening of droughts have also been reported in some regions (Ficklin et al., 2015; Mishra et al., 2019). This indicates a large spatial heterogeneity in drought trends at a global scale. The IPCC (2014) also reported a large spatial variability in drought trends; more frequent in the Mediterranean and Western Africa while lessening in central northern America and northwestern Australia. Besides, different changes in different characteristics of droughts in the same region have been reported. Liu et al. (2017) reported increasing recurrence but a decreasing duration of droughts in the Haihe River basin of China. Shiru et al. (2018) found droughts covering large area are decreasing, but smaller areal coverage droughts are increasing in Nigeria.

Contradictory results in drought trends have also been reported for South Asia. Dai (2011) showed a global increase in droughts over the period 1950–2008 with South Asia as one of the major regions of increasing dryness. In contrast, a recent study of Mishra et al. (2019) showed decreasing frequency and severity of soil moisture droughts in India. A shift in droughts has also noticed in Bangladesh with the changes in rainfall variability (Morteza et al., 2018). Several studies reported a possible increase in droughts in the country due to climate change (Miyan, 2015; Alamgir et al., 2019).

Erratic behavior of rainfall and drought scenario in Barind area have been explored in several studies; Alam et. al. (2012) revealed that pre-moonsoon rainfall is consistent but monsoon rainfall has erratic behavior which shifts its position from time to time and occurs in certain discrete pockets, thus resulting in diverse drought vulnerability scenario. After that other researchers applied both Standardized Precipitation Index (SPI) & Marov chain to understand drought dynamics in Barind region; the study revealed significant temporal correlation but poor spatial correlation between SPI and Markov Chain drought indices, which is similar to the findings of the Alam et. al. (2012).

Uncertainty in Drought Prediction due to Rainfall Volatility

Droughts mainly occur due to variability in rainfall over time. A shift in rainfall regimes or transition from wet to dry period initiates a drought episode (Omidvar et al., 2019;

Sobhani et al., 2020). Uncertainty in the magnitude of change in rainfall or volatility makes the prediction of drought uncertain (Achour et al., 2020). Large volatility in rainfall means it has a wider range of value or the variability of rainfall is high (Yusof and Kane, 2013). This indicates rainfall anomaly can change significantly between wet and dry regimes in a short period (Swain et al., 2018) or a positive anomaly (wet period) can turn into a negative anomaly (dry period) at any time. Therefore, rainfall volatility can be an indicator of predictivity of droughts in a region. Swain et al. (2018) reported an increase in rainfall volatility and increase the probability of rapid shift between wet and dry episodes in many regions of the globe. Nijsse et al. (2019) also reported increased volatility in global climate due to climate change. The assessment of rainfall volatility to regional scale is important to understand the possible change in climate shift frequency and drought recurrence.

Assessment of Drought Volatility and Regime Shift

Probability of transition of climate from wet to dry state or vice versa can also be used as an indicator of the probability of droughts in a region. The capability of Markov chain (MC) (Brémaud, 1999) to understand the order of possible events can be used to analyze the sequence of climate states like wet, normal and dry to understand the climate regime shifts (Rezaeianzadeh et al., 2016; Rahmat et al., 2017). It can also indicate a possible change in the current wet state of climate to a dry state (Khadr, 2016). Therefore, a large number of studies employed MC for assessment of possible future shift in rainfall regime and occurrence of droughts (Avilés et al., 2016; Rahmat et al., 2017; Yeh et al., 2019).

Volatility and regime shifts can be measured in a scale of the day, week, month or year. Though droughts are mostly measured in monthly scale, it often cannot be captured in monthly rainfall in a tropical humid region. Usually, no rainfall for consecutive eight days can affect rain-fed crops in Bangladesh (Silvaraju et al., 2007), which is not possible to evaluate using monthly rainfall data. Therefore, it is important to use daily rainfall data for the estimation of volatility and rainfall regime shift to understand the predictability of droughts in Bangladesh.

Chapter Three

Methodology

3.1 Geography and climate of the study area

The North-West (N-W) region of Bangladesh is selected for the present study, since it is the most drought prone area of the country. The region is bounded by the two major rivers in two sides, the Jamuna in the east and the Ganges in the South. Out of eight hydrological units of Bangladesh, the NW region has the most extreme climate. Due to subtropical location, temperature variations are more pronounced in N-W region. The study area consists of north and northwest districts of Bangladesh and covers an area of 34,359 km^2. The location of the study area on the map of Bangladesh is shown in Figure 3.1. The topography of the region is very flat with a slight gradient from the north to the south except a mild uplifted land in the southwest (Figure 3.2a). The rainfall in the study area varies from 1350 mm in the southwest to nearly 2950 mm in the far north (Figure 3.2b). The monthly mean of daily maximum temperature in the region varies from 25.4ºC in January to 35.9ºC in April and the minimum temperature between 10.2ºC in January to 26.2ºC in August. The climate of the study area can be divided into four seasons, winter (Dec-Feb), pre-monsoon (Mar-May), monsoon (Jun-Sep) and post-monsoon (Oct-Nov) (Pour et al., 2018). Seasonal variability of rainfall in the area is very high. About 60% of the rainfall occurs in monsoon and less than 3% in winter. Year to year variability of rainfall is also high and therefore, droughts are recurrent phenomena in the region. On average, droughts occur twice in a decade in the region.

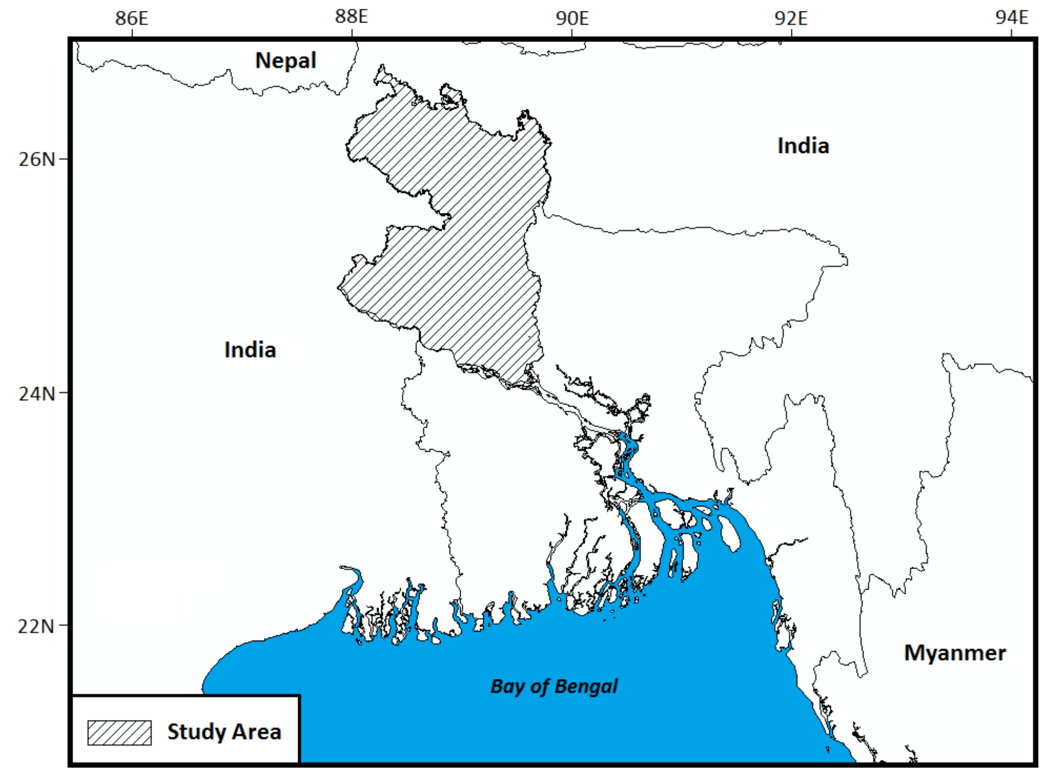


Figure 3.1: Location of the study area on the map of Bangladesh.

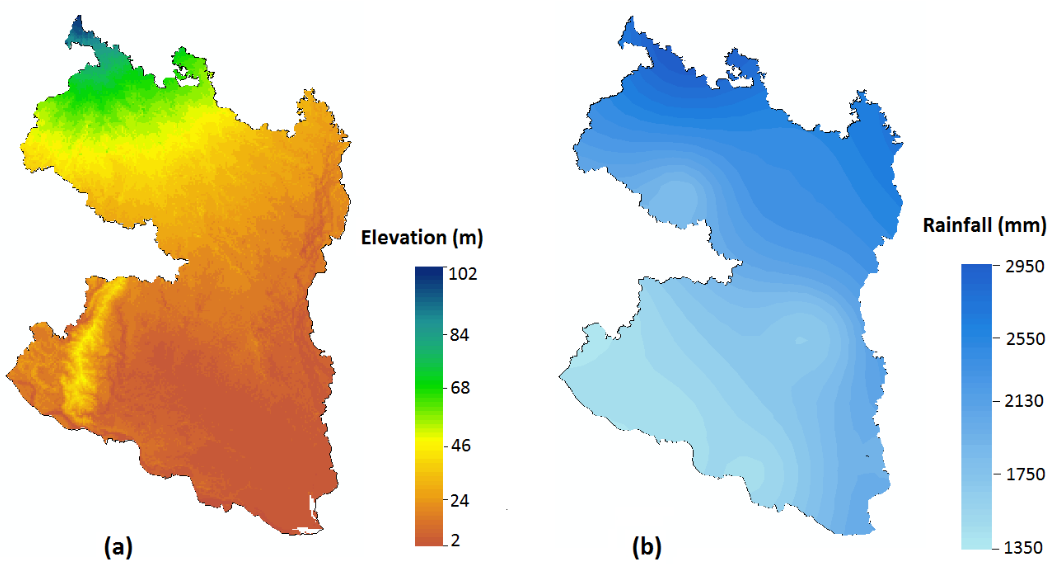


Figure 3.2: (a) topography; (b) spatial distribution of annual rainfall

3.2 Data and Sources

Daily rainfall daily from five locations of the study area for the period 1966–2016 were collected from the Bangladesh Meteorological Department. Also Ground water data for the period of 1966-2016 were collected from Bangladesh Water Development Board (BWDB). The data used for Normalized Difference Vegetation Index (NDVI) has been derived from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1) Version 6, which was collected from the year 2000 to 2020. The data is freely available from (https://lpdaacsvc.cr.usgs.gov/appeears/).

Rainfall data of Bangladesh contains many missing records. If rainfall of a year is found missing for higher than 2% then the whole record for the year was removed. The data available at different stations are shown in Figure 3.3. Both subjective and objection approaches were used for the assessment of the quality of rainfall records. Initial screening was performed through data inspection such as negative values, no rainfall in monsoon months, more than 50 mm rainfall in winter months, etc. Rainfall data were also used to generate time series plot and histogram for each station individually to detect any inconsistency (Pour et al., 2020c). Besides, the double mass curve was prepared for annual rainfall for all the stations to reveal any break in data series. Finally, sequential student t-test was conducted to test any difference among different subsets of rainfall data (You et al., 2012). No inconsistency was observed in time series and histogram or breaks in the double mass curve at any station. No abnormal data values were also noticed in during data inspection and numerical checks. The student's t-test revealed no difference between any two subsets of rainfall data. Therefore, the quality of collected rainfall records was considered sufficient for different statistical analysis performed in this study.

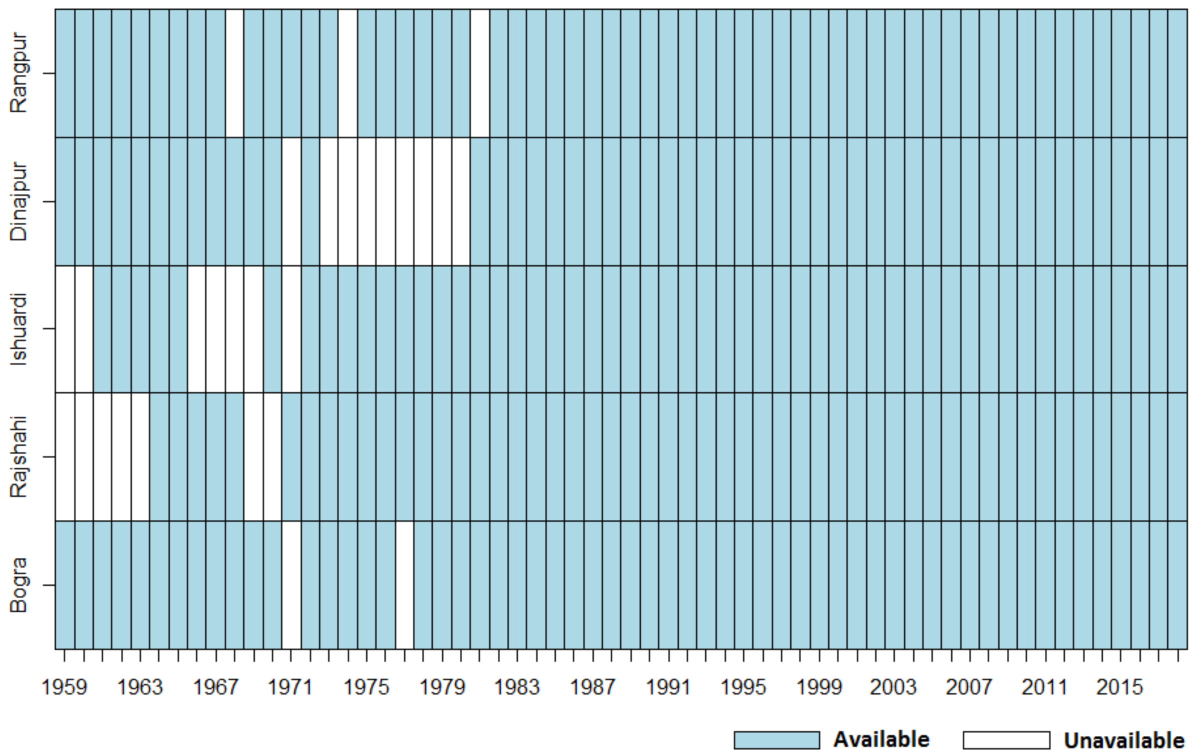


Figure 3.3. Data availability at different stations for the study period

Data on ground water level were collected from Bangladesh Water Development Board (BWDB) stations from different districts of Rajshahi and Rangpur division, the study area covered these two divisions of Bangladesh. In the Rajsahi Division, apart from the meteorological stations data were collected from 32 BWDB stations from 8 districts. In Rajshahi district, data were collected from BWDB stations Tanore, Godhagari and Sardah. In Bogura district, data were collected from BWDB stations Dhunot, Nandigram, Shibganj and Nawkhila. In Natore district, data were collected from BWDB stations Gurudaspur, Joari, Lalpur, Natore Sadar, Singra and Puthia. In Naogaon district, data were collected from BWDB stations Atrai, Badalgachi, Manda, Mohadebpur, Naogaon Sadar, Nazipur and Sapahar. In Nawabganj district, data were collected from BWDB stations Shibganj, Bholahat, Nawabganj Sadar, Nachole and Rohanpur. In Pabna district, data were collected from BWDB stations Atghoria, Faridpur, Sujanagor and Pabna Sadar. In Sirajganj district, data were collected from BWDB stations Sirajganj Sadar and Ullapara. In Joypurhat district, data were collected from BWDB station Khetlal.

In Rangpur division, apart from meteorological stations, data were collected from 26 BWDB stations of 9 districts. In Dinajpur district, data were collected from BWDB stations Ghoraghat, Hilli, Khansama, Kantanagar, Nawabganj, Phulbari and Setabganj. In Panchagarh district, data were collected from BWDB stations Latu, Bhithargarh, Boda, Debiganj, Panchagarh Sadar and Tentulia. In Lalmonirhat district, data were collected from BWDB stations Hatibandha, Lalmonirhat Sadar and Patgram. In Nilphamari district, data were collected from BWDB stations Dimla and Saidpur. In Gaibandha district, data were collected from BWDB stations Bhawaniganj and Gobindaganj. In Kurigram district, data were collected from BWDB stations Bhurungamari and Ulipur. In Rangpur district, data were collected from BWDB stations Badarganj and Kaunia. In Thakurgaon district, data were collected from BWDB station Thakurgaon Sadar.

It is worth mentioning that we have divided our data into three different seasons - winter, summer and rainy seasons. According to Banglapedia (2003) there are three climatic seasons in Bangladesh: winter (November–February), summer (March–May) and rainy (June–October) rainy. Our objective is to examine whether the rainfall data behave differently in three different seasons.

3.3 Assessment of Changes in Variability in Monthly Rainfall

Rainfall variability is the major factor that determines the occurrence of droughts. Droughts occur more in the region where rainfall variability in high. A decrease in rainfall variability indicates a decrease in the probability of occurrence of droughts and vice versa.

Coefficient of variability is often used to measure variability in rainfall, while different statistical tests are used to measure the changes in variability between two periods. In this study, Levene's test (Levene, 1960) and Barlett test (Bartlett, 1937) were used to revealing any changes in variability in monthly rainfall. The rainfall data is equally divided into two periods (1959-1988 and 1989-2018) and the tests were conducted between rainfall data of those two periods to evaluate the changes in variability in monthly rainfall.

The coefficient of variability (CV%) in monthly rainfall for all months of a year and the months for a season were estimated in this study used following equation,

$$CV\ (\%) = \frac{\sigma}{\mu} \times 100 \quad (3.1)$$

Where μ and σ are the mean and standard deviation of rainfall for the study period. Among the four seasons changes in rainfall variability was estimated for two seasons, monsoon and pre-monsoon as droughts are more prevalent and destructive during those two seasons.

Levene's test is a non-parametric test used to verify the difference in variances between two sets of data. This method estimated spread of data from sample median to assess differences in variance. It is considered as a robust test due to its independence on underlain data distribution (Khan et al., 2006, Ayman et al., 2011). Levene's test statistics is defined as:

$$W = \frac{\dfrac{\sum_{i=1}^{k} N_i (\bar{D}_i - \bar{D})^2}{(k-1)}}{\dfrac{\sum_{i=1}^{k} \sum_{j=1}^{N_i} \left(D_{ij} - \bar{D}_i\right)^2}{(N-k)}} \quad (3.2)$$

Where k the number of groups is, N_i is the sample size of group i. $\overline{D_i}$ represents the average of N_i absolute deviations, $\overline{D}$ is average of all N absolute deviation,

The Barlett test is applicable where the variances are based on equal or unequal numbers of the degree of freedom. Bartlett's test is more sensitive than Leven's test to data distribution. Barlett test calculations are based on the corrected Chi-Square value by the following equation

$$x_{corr}^2 = 2.3026 \frac{\sum df \left(log_{10} \left[\frac{\sum df(S^2)}{\sum df} \right] \right) - \sum[df(log_{10} S^2)]}{1 + \frac{1}{3(K-1)} \left[\sum \frac{1}{df} - \frac{1}{\sum df} \right]} \qquad (3.3)$$

Where S^2=variance, df is the degrees of freedom for each group and K is the number of groups being compared.

3.4 Assessment of Trend in Rainfall and Drought

The rate of change in rainfall or drought index was estimated using Sen's slope (SS) estimator and the significance of the change was estimated using a modified version of Mann-Kendall (MMK) test. Besides Innovative trend test was employed for graphical assessment of trends to evaluate changes in trends over the study period. These techniques are illustrated below:

3.4.1 Sen's Slope (SS) Estimator

The non-parametric SS estimator (Sen, 1968) was used to assess the rate of change in rainfall. The SS estimator estimates the rate of change (Q) as the median of the slopes (Q_i) of all the consecutive pairs of data,

$$Q_i = \text{median} \left[\frac{x_j - x_k}{j - k} \right] \qquad (3.4)$$

Where, $\boldsymbol{x_i}$ and$\boldsymbol{x_k}$ are data values at times ***j*** and ***k*** respectively.

3.4.2 Modified Mann-Kendal (MMK) Test

The MK test (Mann, 1945 and Kendall, 1975) was used to assess the significance of the change estimated using SS estimator. The MK test estimates the significance of change using Z statistics,

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, \text{for } S > 0 \\ 0, \quad\quad \text{for } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, \text{for } S < 0 \end{cases} \quad (3.5)$$

Where,

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k); \text{ and } \text{sgn}(x_j - x_k) = \begin{cases} +1 \text{ if } (x_j - x_k) > 0 \\ 0 \quad \text{if } (x_j - x_k) = 0 \\ -1 \text{ if } (x_j - x_k) < 0 \end{cases}$$

The null hypothesis of 'no trend' is rejected at 0.05 significance level if Z is out of range of ±1.96.

The significance of MK test is affected by autocorrelation in data series which is common in rainfall data (Khan et al., 2019; Nashwan et al., 2019; Pour et al., 2019; Pour et al., 2020d). Therefore, MMK test introduced by Yue et al. (2002) through a trend-free pre-whitening (PW) method was adopted in the present study. The PW is performed using the following equation:

$$Y_i = x_i - (\beta \cdot i) \quad (3.6)$$

where β represents Theil-Sen's slope of different pairs of data. The final series (Y_i'') by removing autocorrelation (r_1) is estimated using equations (7) and (8).

$$Y_i' = Y_i - r_1 \times Y_{i-1} \quad (3.7)$$

$$Y_i'' = Y_i' + (\beta \times i) \quad (3.8)$$

The MK test is conducted over the time series of Y_i'' to avoid any influence of autocorrelation in trend significance.

3.4.3 Innovative Trend Analysis

ITA allow an analysis of trends or no-trend in various parts of time series through visual examination output and therefore, it can be utilized for the recognition of sub-trends (Girma et al., 2020; Pour et al., 2020). In ITA, the data series is divided into two sub-series (y_1 and y_2) of same sample size (*n*) order ascendingly. A scatter plot is then made from the two sub-series. The data points above or below the diagonal line of the plot specifies rising and declining trend in respectively. The ITA trend statistics, S_{ITA} is estimated as (Şen, 2017),

$$S_{ITA} = \frac{2(\bar{y}_2 - \bar{y}_1)}{n} \quad (3.9)$$

where $\bar{y}_1$ and $\bar{y}_2$ are the mean of two sub-series. The confidence interval (CI) of the trend at a significance, α is estimated from standard deviation (σ_s) of S_{ITA} as,

$$CL_{(1-\alpha)} = 0 \pm S_{ITA}\sigma_s \quad (3.10)$$

When the points in the scatter plot cross the CI, the hypothesis of 'no trend' is rejected.

3.5 Assessment of Anomaly in Rainfall

Rainfall anomaly was estimated based on Discrete Rainfall Anomalies (DRA) and Rainfall Anomaly Index (RAI) (Van Rooy, 1965). DRA for annual and seasonal scales were estimated as the deviation of annual or seasonal rainfall of each year from the mean of annual or seasonal rainfall for the entire period. The estimation of RAI was based on the means of the ten highest ($\bar{M}$) and lowest ($\bar{m}$) precipitation records for the study period as below:

$$RAI = 3 \times \frac{P-\bar{P}}{\bar{M}-\bar{P}} \quad (3.11)$$

Where $\bar{P}$ is the mean precipitation for the whole study period and P is specific precipitation record. Dry and wet years can be categorized based on RAI as given in Table 3.1.

Table 3.1. Categorization of dryness or wetness according to rainfall anomaly index

RAI values	Class description
≥ 3.00	Extremely wet
2.00 – 2.99	Very wet
1.00 – 1.99	Moderate wet
0.50 – 0.99	mild wet
0.49 – -0.49	Normal
-0.50 – -0.99	mild dry
-1.00 – -1.99	Moderate dry
-2.00 – -2.99	Very dry
≤ -3.00	Extremely dry

3.6 Assessment of Meteorological Drought

3.6.1 Standardized Precipitation Index

SPI (McKee et al. 1993) is estimated as the probability of rainfall for a period in months compared to the same period in other years. Rainfall data is generally fitted using a probability distribution function (PDF) for estimating SPI (Thom 1958; Edwards & al 1997). The previous study reported gamma as the best PDF for fitting rainfall of Bangladesh (Alamgir et al., 2015). Fitting of the gamma distribution to rainfall (x) can be expressed as,

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad (3.12)$$

where α, β and Γ(α) represent shape, scale and gamma function. The α, β and Γ(α) of gamma PDF are estimated for the different time scale of interests e.g., 1, 3 or more months to estimate droughts for different durations. The parameter values are used to estimate the cumulative probability of a rainfall amount over a defined period in term of complete recorded rainfall as,

$$G(x) = \int_0^x g(x)dx = \frac{1}{\hat{\beta}^{\hat{a}}\Gamma(\hat{\alpha})} \int_0^x x^{\propto_{pro}-1} e^{-x/\beta_{pro}}\, dx \qquad (3.13)$$

The gamma function is not defined for zero rainfall and therefore, the cumulative probability becomes,

$$H(x) = q + (1 - q)G(x) \qquad (3.14)$$

where q represents probability zero rainfall. The drought is categorized according to SPI as presented in Table 3.2. The standard probability of occurrence of a certain category of droughts is also presented in Table 3.2 (Moreira et al., 2008).

Table 3.2. Climate categorization based on SPI and the standard probability of their occurrence (Mckee et al. 1993)

SPI Values	Climate Category	Probability (%)
2.00 or more	Extremely wet	2.3
1.50 – 1.99	Very wet	4.4
1.00 – 1.49	Moderate wet	9.2
-0.99 – 0.99	Near normal	68.2
-1.00 – -1.49	Moderately drought	9.2
-1.50 – -1.99	Severely drought	4.4
-2.0 or less	Extremely drought	2.3

3.6.2 Standardized Precipitation Evapotranspiration Index (SPEI)

The Standardized Precipitation Evapotranspiration Index (SPEI) considers both precipitation and temperature in its calculation, which is widely used worldwide for operational drought monitoring. It is a better index then SPI and it can detect onset of drought and can specify the spatial and temporal changes in drought characteristics. The following four steps were followed to compute SPEI for our study:

Step1: At the 1st step, the monthly potential evapotranspiration (PET) was computed based on the data of monthly minimum and maximum temperature by using the Thornthwaite equation (Thornthwaite 1948):

$$\mathrm{PET} = 16K\left(\frac{10T}{I}\right)^{m}, \quad (3.15)$$

where *T* is the monthly-mean temperature (°C); *I* is a heat index,

Step 2: At the 2nd stage, monthly water balance was calculated as the difference between monthly precipitation (P) and PET:

$$D_i = P_i - \mathrm{PET}_i, \quad (3.16)$$

Step 3: At the 3rd step, a three parameter log-logistic distribution was used to fit the data series of monthly water balance.

Step 4: At the last stage, the original values were normalized to obtain standardized units, and thus SPEI was obtained.

The SPEI package of statistical software R was used to estimate the monthly SPEI in the study. It should be noted that, in case of interpretation of SPEI values we negative SPI value is indicator of dryness and it becomes drought as the value reaches a value of “−1.0” or less.

3.6.3 Aridity Index (AI)

Like as SPEI, Aridity Index is another index that considers both precipitation and temperature in its calculation procedure, thus this index provides indication of dryness. We employed the United Nations Environmental Program (UNEP, 1994) defined aridity index (AI):

$$AI_U = \frac{P}{PET} \quad (3.17)$$

Where P is the mean annual precipitation and PET is the potential evapotranspiration, that is the amount of evaporation that would occur if a sufficient water source were available. To estimate potential evapotranspiration, we obtained day lengths from www.timeanddate.com for each region separately. We took the day lengths and then calculated mean day length (in hour). Heat index and alphas (α's) were subsequently calculated to finally attain PET and aridity index.

3.6.4 Stochastic Component Time Series (SCTS) Technique

Drought severity can be assessed using the Stochastic Component Time Series (SCTS) Technique. The SCTS is given by the equation (Alatise and Ikumawoyi, 2007) as follows:

$$Z_t = \frac{\epsilon_t - \bar{\epsilon}}{S_t} \quad (3.18)$$

Where, Z_t = Stochastic Component Time Series for each year
$\boldsymbol{\epsilon}_t$ = Total annual rainfall (mm) for each year
$\bar{\epsilon}$ = Mean annual rainfall (mm) for each year
S_t = standard deviation of rainfall (mm) for each year

The interval between minimum and maximum SCTS values are divided by three to get the probable drought classes as Low, Moderate, High and Very High drought.

3.7 Assessment of Hydrological Drought

3.7.1 Standardized Water Level Index (SWI)

The indices described so far do not take ground water level in consideration, though ground water level has significant impact on soil moisture and hence drought. For interpretational purpose, it should be highlighted here that since the measurement of groundwater level is down from the surface, the positive value of SWI indicates drought and negative values of SWI indicate 'no-drought' or normal condition. The SWI is calculated by normalizing seasonal groundwater levels and by dividing with the standard deviation:

$$SWI = \frac{W_{ij} - W_{im}}{\sigma} \quad (3.19)$$

Where, W_{ij} = seasonal water level at i-th well and j-th observation,

W_{im} = the long term seasonal mean and

= its standard deviation

3.8 Assessment of Agricultural Drought

3.8.1 Normalized Difference Vegetation Index (NDVI)

NDVI is popularly used to determine the vegetation area and trends in vegetation over the years. It is the ratio between two spectral bands namely, Near Infrared band (NIR) and Red band from visible spectra (Sellers, 1985). It highlights the green leaves of plants and hence effectively shows the plant area. The rationale behind this is that the Near Infrared is reflected by the green leaves and it shows bright in the NIR band and the Red light is absorbed by the green plants and hence they are dark in the Red Band (Gates, 1980). This opposite behavior is utilized in the ratio to highlight the green plants in an area and subdue the other land cover types.

$$NDVI = \frac{NIR-RED}{NIR+RED} \tag{3.20}$$

As it is a ration, it has no unit but rather the value generally ranges from -1 to +1 where positive value indicates better amount of vegetation (de Oliveira et al., 2016). It is directly related to the energy absorption of plants (Myneni et al., 1995). This ration is much more accurate in determining the vegetation area than a simple NIR to Red ratio.

3.9 Assessment of Volatility in Rainfall & Drought

3.9.1 Generalized Auto-Regressive Heterocsedasticity (GARCH) Model

GARCH (Bollerslev, 1986) model was used for the assessment of rainfall volatility and jumping behaviour. The heteroscedasticity or unequal variance of rainfall may exhibit autocorrelation which means a conditional variance depends on past variances (Enders, 2004). The GARCH estimates a serial dependency of volatility and includes the past rainfall in estimating future volatility (Bollerslev et al. 1994). The GARCH model first defines the conditional mean equation as follows:

$$r_t = \pi + \phi r_{t-1} + \varepsilon_t \tag{3.21}$$

where, r_t denotes the logarithmic difference of rainfall data at time *t* and ε_t is the error which follows either a normal or a Student's *t* distribution. The GARCH (1,1) model introduced by Engle (1982) and Bollerslev (1986) takes the following form:

$$h_t^2 = \omega + \alpha\varepsilon_{t-1}^2 + \beta h_{t-1}^2 \tag{3.22}$$

where, h_t^2 refers to conditional variance at time *t* and ε_{t-1}^2 indicates the volatility at time *t*-1.

For the assessment of jumping behaviour, Jorion (1988) proposed a GARCH model with jumps as below:

$$R_t = \pi + \mu R_{t-1} + \epsilon_t \quad (3.23)$$

where R_t is the log change of rainfall at time t; π is a constant of autoregression (AR) [AR(2)] represent the returns; ϵ_t is the error at time *t* which has two components,

$$\epsilon_t = \epsilon_{1t} + \epsilon_{2t} \quad (3.24)$$

Where, ϵ_{1t} is a mean-zero innovation with normal stochastic process,

$$\epsilon_{1t} = \sqrt{h_t} z_t, \quad z_t \sim NID(0,1)$$

$$h_t = \omega + \alpha\epsilon_{1t-1}^2 + \beta h_{t-1} \quad (3.25)$$

Hence, the volatility of ϵ_{1t} follows a standard GARCH(1,1) process.

The second component, ϵ_{2t} can be used to define the inconsistency between the jump component and the anticipated total jump size $(\theta\lambda_t)$ between *t*-1 and *t*,

$$\epsilon_{2t} = \sum_{l=1}^{n_t} U_{tl} - \theta\lambda_t \quad (3.26)$$

where U_{tl} represents jump size, which has a normal distribution with a mean and variance of θ and d^2, respectively; and $\sum_{l=1}^{n_t} U_{tl}$ represent jump component with the number of jumps, n_t. Considering n_t follows a Poisson distribution, the jump intensity can be presented as,

$$\lambda_t = \lambda_0 \quad (3.27)$$

where λ_t is the conditional jump intensity parameter, and $\lambda_0 > 0$. The log-likelihood function can be presented as $L(\Omega) = \sum_{t=1}^{T} \log f(R_t | I_{t-1};\, \Omega)$, where $\Omega = (\pi, \mu, \omega, \alpha, \beta, \theta, d, \lambda_0)$ are the model parameter vectors of equations (3.24) – (3.27). The interpretation of rainfall volatility was made based on the values of these parameters.

3.10 Assessment of Irregular Transition in Rainfall and Drought

3.10.1 Markov Chain

MC was used to assess the irregular transition of rainfall and its impacts on dryness or wetness. If the probability of wetness of a period (e.g. week) only depends on the wetness of the previous period, it can be expressed as random variables $X_0, X_1, \ldots, X_n$ distributed identically, where

$$X_n = \begin{cases} 0 & \text{if the } n\text{th week is dry} \\ 1 & \text{if the } n\text{th week is wet} \end{cases} \tag{3.28}$$

MC for different steps was estimated and the dryness index was developed considering the transition matrix:

$$\begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} \tag{3.29}$$

where, $P_{ij} = P(X_1 = j | X_0 = i)\ and\ i, j = 0{,}1$. Note $P_{00} + P_{01} = 1$ and $P_{10} + P_{11} = 1$. Here, P_{11} means the probability of next week to be wet if the present week is wet. Using equation (3.29), a higher transition probability matrix can be calculated to estimate a dryness index as (Banik et.al. 2002):

$$DI = P11 \times P01 \tag{3.30}$$

The *DI* can have a value in the range of 0 to 1. A higher value of *DI* indicates a lower degree of dryness. Susceptibility of an area to drought can be defined based on *DI* value as given in Table 3.3.

Table 3.3. Susceptibility to droughts based on dryness index

Drought Index	Drought susceptibility
0.000 – 0.125	Chronic
0.0125 – 0.180	Severe
0.180 – 0.235	Moderate
0.235 – 0.310	Mild
0.310 – 1.00	Occasional

Chapter Four

Anomaly, Trend and Changes in Rainfall Variability

4.1 Anomaly in the Rainfall

Discrete seasonal rainfall anomalies were calculated as the deviation of mean seasonal rainfall of each year from the long-term seasonal mean rainfall. Rainfall anomaly averaged for the study area are presented in Figure 4.1. The discrete rainfall anomaly showed that seasonal and annual rainfall anomalies fluctuate frequently over time due to high variability in rainfall. Since the negative values of the rainfall anomalies indicate droughts, it is evident from the figure that the drought condition also fluctuates significantly due to the high variability and instability in the rainfall.

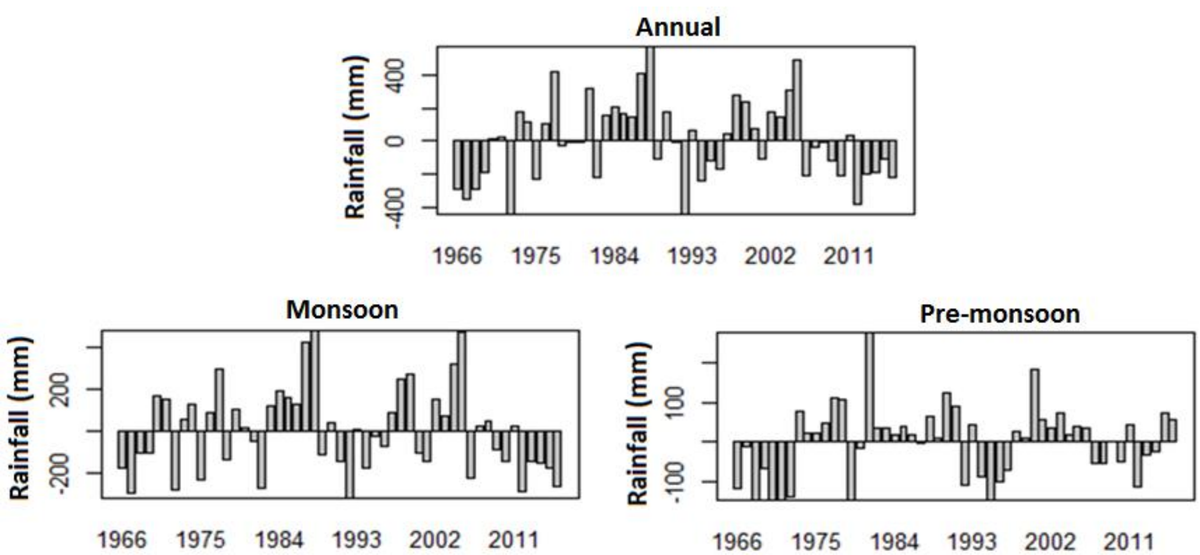


Figure 4.1: Annual and seasonal discrete rainfall anomalies averaged for the study area

To verify whether high anomaly in the rainfall creates droughts in the study, RAI values for different years were estimated. The RAI time series averaged for the study area is shown in Figure 4.2. It was observed that RAI fluctuate significantly over time like the rainfall. However, there is no consistency or apparent pattern in variation. The results indicate a sudden occurrence of droughts in the region or the droughts in the region is less predictable. The seasonal RAI values were also calculated, and similar random fluctuations were observed. ***Therefore, it can be remarked that high variability of rainfall has made the droughts less predictable in northwest Bangladesh.***

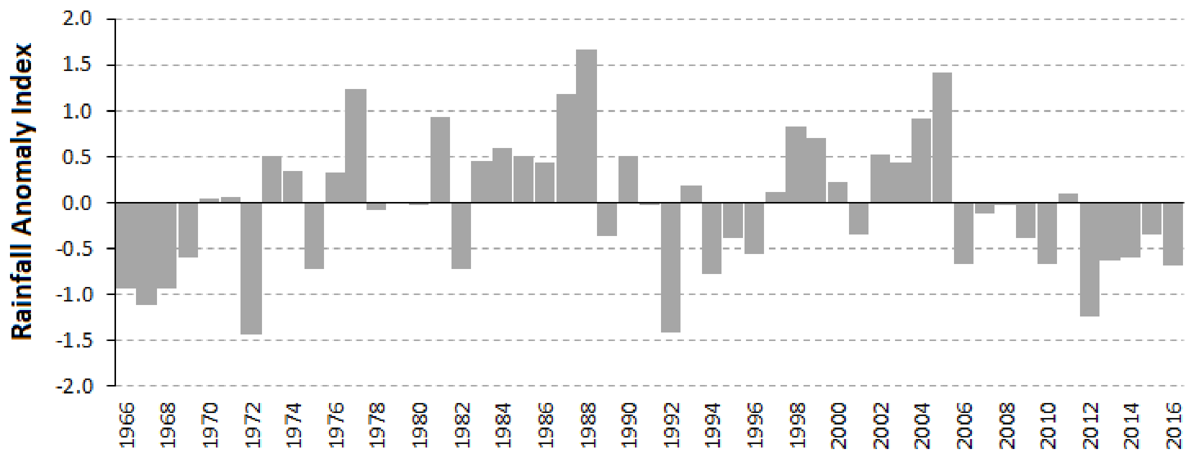


Figure 4.2: Annual Rainfall Anomaly Index for the period of 1966-2016 estimated by averaging rainfall over the study area.

The values of annual RAI and respective drought classification are given in Table 4.1. From the table it is seen that due to high anomaly in rainfall variation the values of RAIs fluctuate very much from year to year, that is there is no consistency in the RAI values from one year to another year. As a result the drought situation also fluctuates very much from year to year. It is evident from the table that drought situation changes in every one year or two year, in few cases a drought situation may continue for at most three years. The seasonal RAIs were calculated and similar situation were observed. These findings confirm that due to the high variability and instability of the rainfall the drought scenario fluctuates very much in the North-West region of Bangladesh, which distorts the predictability of future variation in dryness or wetness for this region.

Table 4.1: Annual Rainfall Anomaly Index and Drought Classification for the period of 1966-2016.

Year	RAI (Annual)	Drought Classification	Year	RAI (Annual)	Drought Classification
1966	-0.93	Slightly dry	**1992**	-1.42	Moderately dry
1967	-1.12	Moderately dry	**1993**	0.18	Near Normal
1968	-0.93	Slightly dry	**1994**	-0.78	Slightly dry
1969	-0.60	Slightly dry	**1995**	-0.39	Near Normal
1970	0.05	Near Normal	**1996**	-0.56	Slightly dry
1971	0.07	Near Normal	**1997**	0.12	Near Normal
1972	-1.44	Moderately dry	**1998**	0.82	Slightly Wet
1973	0.51	Slightly Wet	**1999**	0.70	Slightly Wet
1974	0.34	Near Normal	**2000**	0.23	Near Normal
1975	-0.73	Slightly dry	**2001**	-0.35	Near Normal
1976	0.32	Near Normal	**2002**	0.53	Slightly Wet
1977	1.23	Moderately Wet	**2003**	0.43	Near Normal
1978	-0.08	Near Normal	**2004**	0.91	Slightly Wet
1979	-0.01	Near Normal	**2005**	1.42	Moderately Wet

1980	-0.03	Near Normal	**2006**	-0.67	Slightly dry
1981	0.94	Slightly Wet	**2007**	-0.12	Near Normal
1982	-0.72	Slightly dry	**2008**	-0.03	Near Normal
1983	0.45	Near Normal	**2009**	-0.39	Near Normal
1984	0.60	Slightly Wet	**2010**	-0.67	Slightly dry
1985	0.50	Near Normal	**2011**	0.10	Near Normal
1986	0.43	Near Normal	**2012**	-1.24	Moderately dry
1987	1.19	Moderately Wet	**2013**	-0.64	Slightly dry
1988	1.67	Moderately Wet	**2014**	-0.60	Slightly dry
1989	-0.36	Near Normal	**2015**	-0.34	Near Normal
1990	0.50	Near Normal	**2016**	-0.69	Slightly dry
1991	-0.02	Near Normal			

4.2 Trends in the Rainfall

Trends in annual and seasonal rainfall at different locations of northwest Bangladesh for the period 1959-2018 are presented in Table 4.2. The values in the table represent the rate of rainfall change in mm/decade. The bold numbers indicate significant change at 95% level of confidence (5% level of significance). The results revealed a significant increase in pre-monsoon (March-May) rainfall at 4 stations and decrease at one station. The monsoon (June-September) rainfall was noticed to decrease at 4 out of 5 stations and annual rainfall at 2 stations. Overall, the results revealed a decrease in annual and monsoon rainfall and increase in pre-monsoon rainfall in the region.

Table 4.2: Trends in annual and seasonal rainfall in Northwest Bangladesh

	Annual	Monsoon	Pre-Monsoon
Rangpur	3.27	-0.06	***2.47***
Dinajpur	*-5.33*	***-6.22***	***1.53***
Ishuardi	***-6.55***	***-5.20***	***-1.44***
Rajshahi	***-6.72***	***-7.98***	***1.61***
Bogra	-0.97	***-3.56***	***1.87***

ITA was conducted to visual inspection of trends over the period and its significance. ITA of annual rainfall for the period 1959-2018 for five stations are presented in Figure 4.3. A decreasing trend in annual rainfall at a 95% confidence interval (5% level of significance) was noticed in recent years at most of the stations. The trends were significantly positive or insignificant in the early years. The results indicate a large decrease in rainfall in most of the stations have made the overall decrease in rainfall for the entire study period as detected by the MK test.

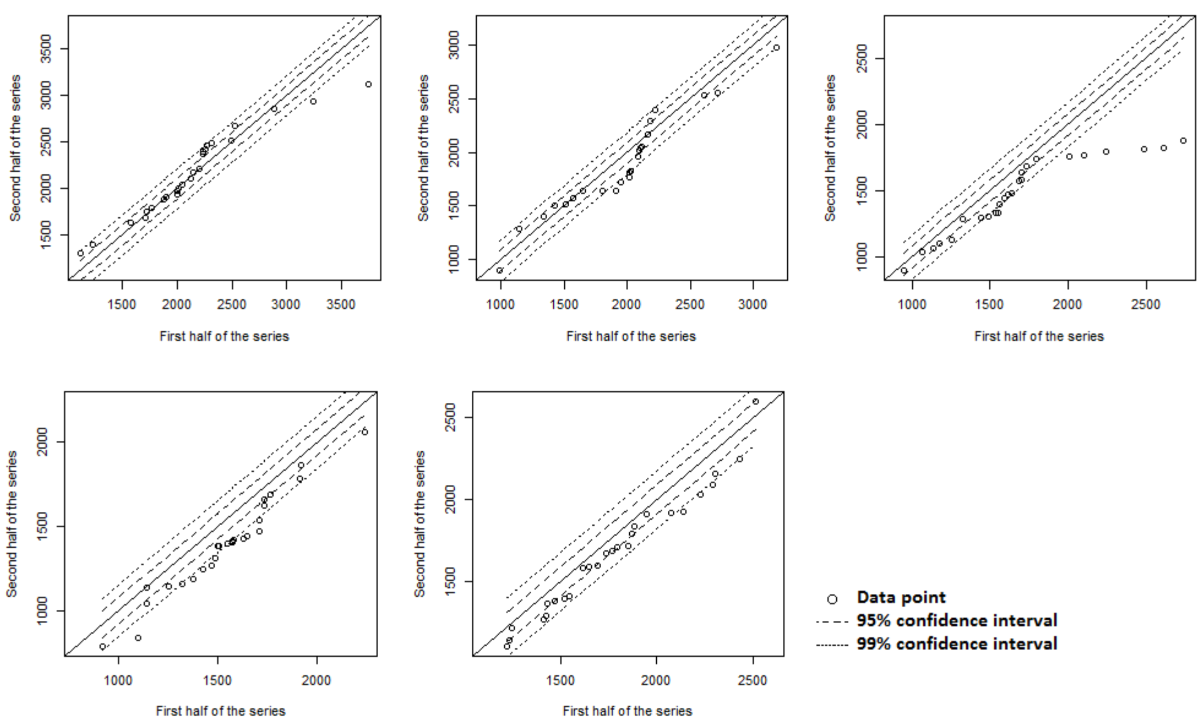


Figure 4.3: Innovative trend analysis of annual rainfall for the period 1959-2018

4.3 Changes in Rainfall Variability

The coefficient of variability in monthly rainfall during early (1959-1988) and late (1989-2018) periods were estimated and statistical tests were conducted to evaluate the significance in the different of variability between the two periods. Obtained results are presented in Table 4.3. A significant change in variability estimated using both Levene's and Barlett tests are marked using bold in the table. The tests were conducted for annual, monsoon and pre-monsoon seasons. These two seasons were considered as nearly 85% rainfall in Bangladesh occurs during these two seasons and thus, the country experiences severe damage in agriculture when droughts coincide with these seasons. Results revealed a significant decrease in annual rainfall variability at 3 out of 5 stations in the study area. A decrease in monsoon (June-September) rainfall variability was observed at one and pre-monsoon (March-May) rainfall at three stations. The results revealed more reliability in both annual and seasonal rainfall in northwest Bangladesh in recent years compared to the early period.

Table 4.3: Changes in the coefficient of variability of monthly rainfall between the early and late period.

Station	Annual		Monsoon		Pre-Monsoon	
	Early	Late	Early	Late	Early	Late
Rangpur	119.7	**112.1**	50.9	47.1	127.3	139.2
Dinajpur	129.3	118.0	55.5	46.0	144.1	**130.8**
Ishuardi	118.2	**110.2**	57.9	**45.7**	135.5	**115.5**
Rajshahi	114.9	112.4	45.9	47.7	140.4	**115.9**
Bogra	119.8	**110.8**	48.8	46.9	125.6	132.5

The analysis of monthly rainfall for the five decades shows (Figure 4.4) significant changes in rainfall pattern. Rainfall decreased in the month of June, July, September and October in the last decade (2006-2015) than previous decade (1996-2005). But interestingly, the rainfall increased in December, January and February in the last decade (2006-2015) than the previous decade (1996-2005). From all these findings there is a clear indication that rainfall pattern has been changing in recent years. Rainfall is decreasing in rainy season, but no such pattern is found for the summer season. But in recent years, summer season is facing less drought incidence than the previous years. One reason may be that the rainfall pattern is shifting its trend to backward months, more specifically, rainy season is now starting earlier from April. That is why the winter season rainfall is increasing.

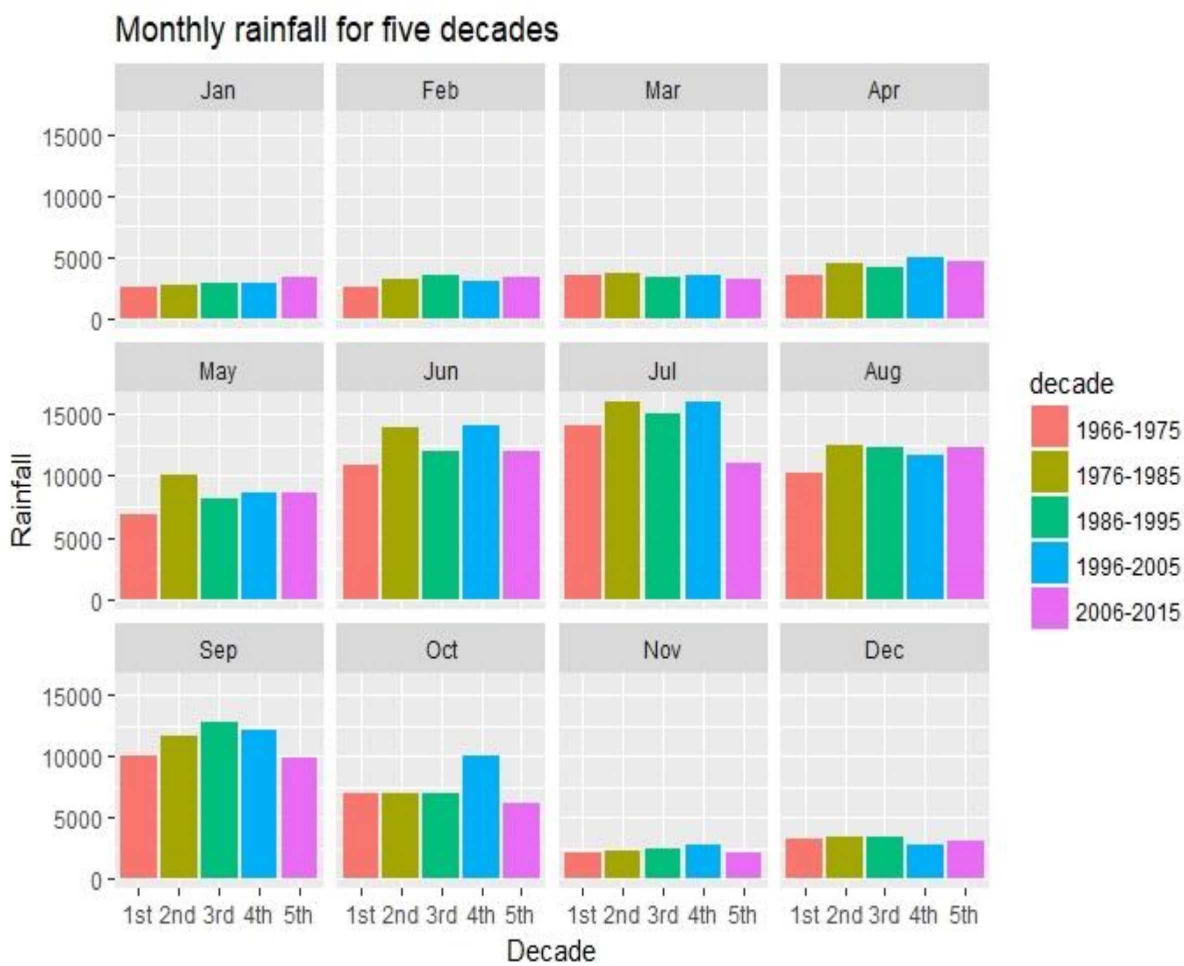


Figure 4.4: Monthly Rainfall in five decades

4.4 Magnitude of Changes in the Rainfall

4.4.1. Magnitude of Changes in Annual Rainfall

The distribution of magnitude of changes of annual rainfall during the period of 1966-2016 over Rajshahi division is shown in the **Figure 4.5.** It shows that rainfall decreased maximum 11.44 mm/year in Badolgachi area of Naogaon district. The other region which have shown decrease of rainfall in the range of 11.44 – 7.922 mm/year are Dhunot area of Bogura district and Singra area of Natore district. It is obvious from the figure that most of the region under Rajshahi division have shown decrease in rainfall in the range of 4.404 – 0.886 mm/year, most of the region of the districts Naogaon, Rajshahi, Natore, Pabna & Sirajgonj experienced this rate of decrease in rainfall. Yet, there are regions in the Rajshahi division which have shown positive change in rainfall, rainfall increased 2.632 – 6.15 mm/year in those area. Nawabgonj area have experienced the maximum rate of increase in annual rainfall, the amount being 6.15 mm/year.

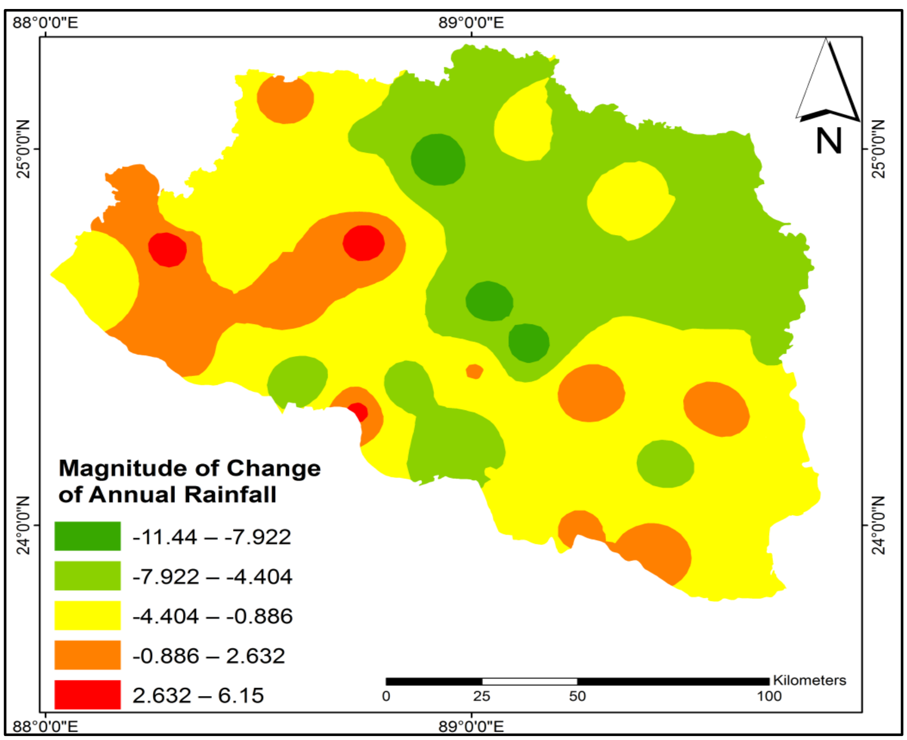


Figure 4.5: Distribution of magnitude of changes of annual rainfall during the period of 1966-2016 over Rajshahi division.

The distribution of magnitude of changes of annual rainfall during the period of 1966-2016 over Rangpur division is shown in the **Figure 4.6.** In Rangpur division, the maximum decrease in rainfall was observed in Lalmonirhat district, rainfall decreased 43.18 mm/year in the Patgram area of this district. The other areas of Rangpur Division which have experienced significant decline in annual rainfall are Hatibandha (-32.34 mm/year) of Lalmonirhat District, Ghoraghat(-32.34 mm/year) of Dinajpur District and Bhithargarh (-25.40 mm/year) of Panchagarh District. In this Division, most of the areas have experienced decrease in annual rainfall, only few stations have experienced increase in rainfall. Among them Latu (20.95 mm/year) of Panchagarh District and Syedpur (8.25 mm/year) of Nilphamari District are mentionable.

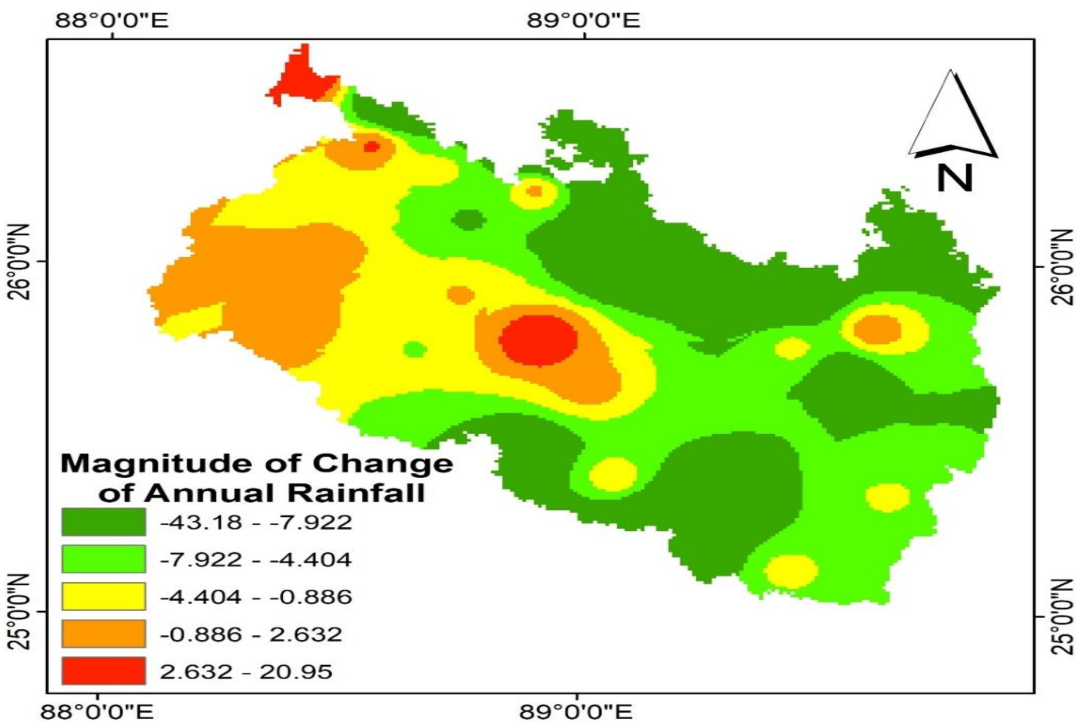


Figure 4.6: Distribution of magnitude of changes of annual rainfall during the period of 1966-2016 over Rangpur division

4.4.2. Magnitude of Changes in Winter Season Rainfall

The distribution of magnitude of changes of winter rainfall during the period of 1966-2016 over Rajshahi division is shown in the **Figure 4.7.** It shows the regions which have experienced 0.71- 0.00 mm/year decrease in rainfall (yellow coloured regions). It is noteworthy that rainfall decreased maximum 0.71 mm/year in Joari area of Natore district. The other region which have shown significant decrease of winter rainfall are Dhunot (-0.67mm/year) area of Bogura district, Mohadebpur area (-0.46 mm/year) of Naogaon district, Nandigram (-o.40 mm/year) area of Bogura district and the area in the vicinity of Rajshahi Meteorological station (-0.41 mm/year) in Rajshahi district. It is obvious from the figure that most of the region under Rajshahi division have shown slight increase in winter rainfall ranging from 0.00 – 0.25 mm/ year. The region which have experienced significant increase in rainfall are Khetlal (0.25 mm/year) area of Joupurhat district and Shibgonj (o.24 mm/year) area of Nawabgonj district.

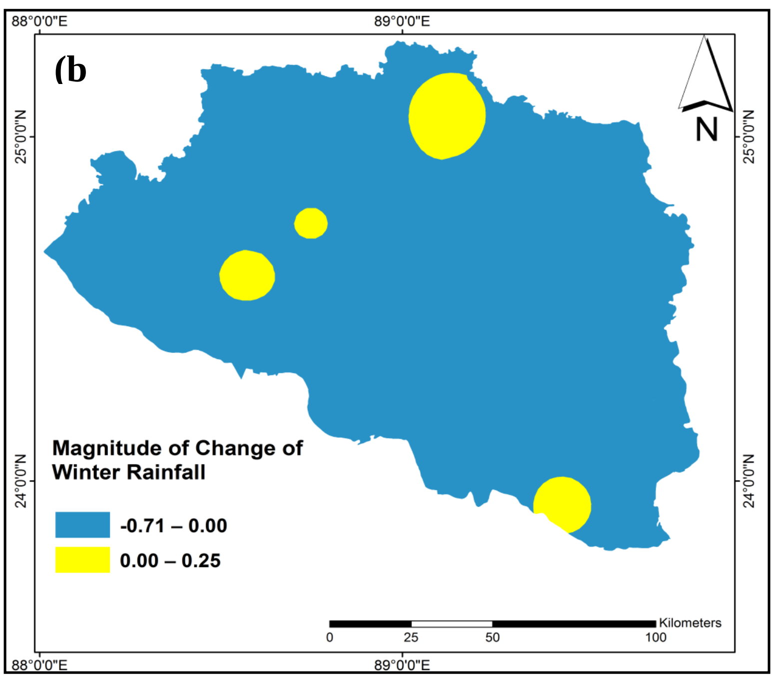


Figure 4.7: Distribution of magnitude of changes of winter rainfall during the period of 1966-2016 over Rajshahi division.

The distribution of magnitude of changes of winter rainfall during the period of 1966-2016 over Rangpur division is shown in the **Figure 4.8.** The scenario in respect of magnitude of change in rainfall in Rangpur division in winter has a similarity with that of Rajshahi division, which is that most of the area have shown increasing trend (positive change) in rainfall, but in the Rangpur division there are some regions which show no change (0.00 mm/year) in winter rainfall. The region which have no change in winter rainfall under Rangpur division are Latu (Panchagarh District), Boda (Panchagarh District), Debigonj (Panchagarh District), Patgram (Lalmonirhat District) & Ulipur (Kurigram District). In Rangpur division, the maximum decrease in winter rainfall was observed in Bhwanigonj area of Gaibandha district in the rate of -6.6 mm/year. The maximum area of the district of Gaibandha, Kurigram, Rangpur & Dinajpur have experienced decrease in winter rainfall.

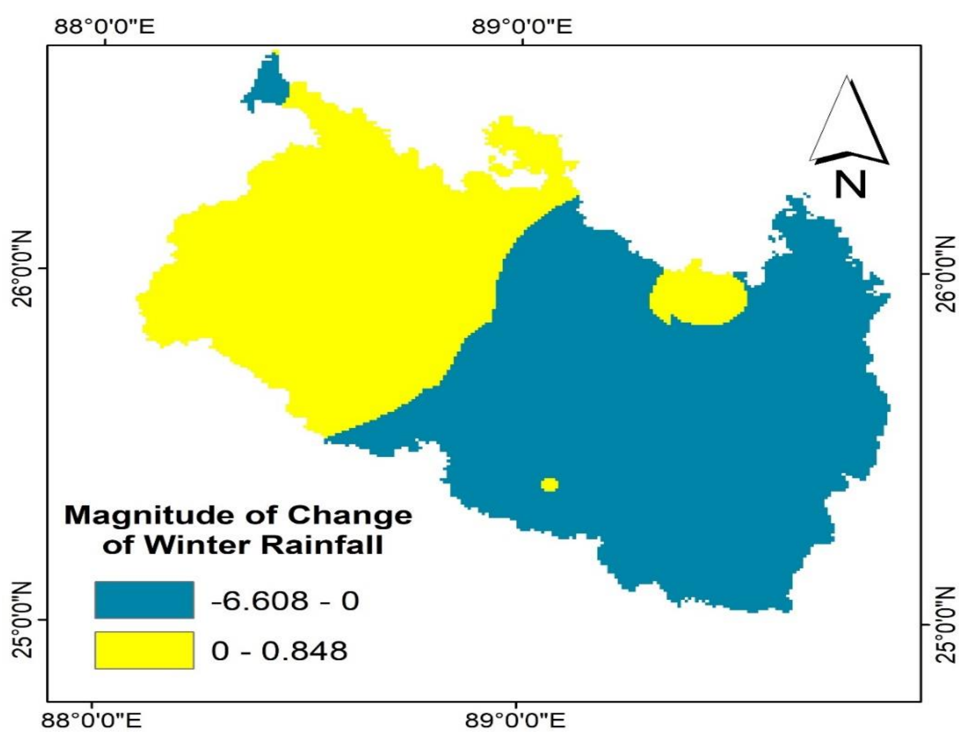


Figure 4.8: Distribution of magnitude of changes of winter rainfall during the period of 1966-2016 over Rangpur division.

4.4.3. Magnitude of Changes in Summer Season Rainfall

The distribution of magnitude of changes of summer rainfall during the period of 1966-2016 over Rajshahi division is shown in the **Figure 4.9.** It is seen that the maximum decrease in summer rainfall is 1.96 mm/year while the maximum increase in summer season rainfall is 2.30 mm/year. This implies that the summer season rainfall is increasing in the region, this comply with the other findings of this study; specially the findings of linear trend analysis and decadal change in rainfall analysis explored increasing trend in summer season rainfall. The regions under Rajshahi division which showed significant decrease in summer rainfall are Singra (-1.96 mm/year) of Natore District, Lalpur (-1.94 mm/year) of Natore District and Dhunot (-1.94 mm/year) of Bogura District. Also most of the regions of Bogura District showed decreasing trend in summer rainfall. Though Singra & Lalpur of Natore showed significant decrease in summer rainfall, but Gurudaspur area of Natore showed maximum increase in summer rainfall, which is 2.30 mm/year. The figure also shows that there was significant increase in summer rainfall in the Nawabganj district, especially in the Shibganj area (1.51 mm/year).

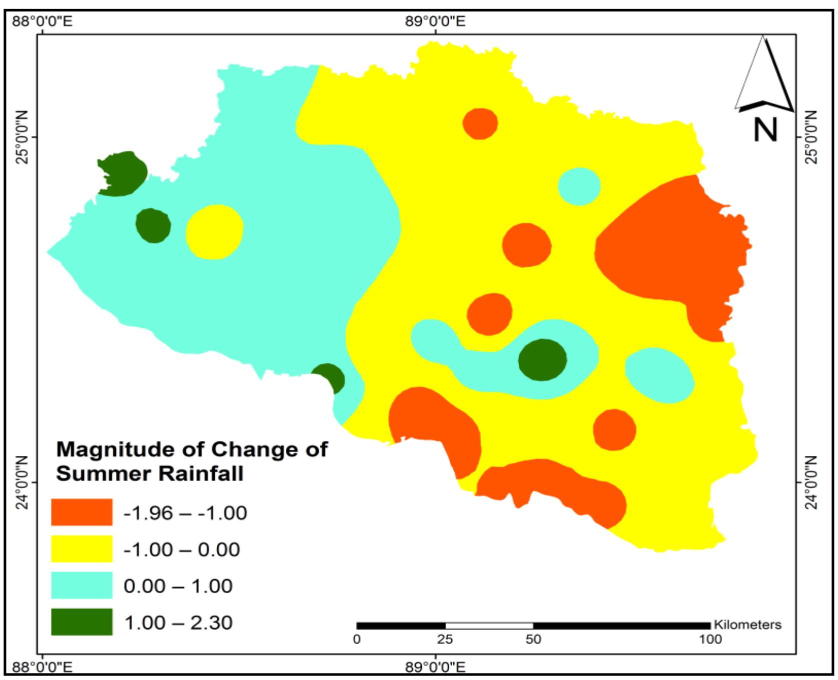


Figure 4.9: Distribution of magnitude of changes of summer rainfall during the period of 1966-2016 over Rajshahi division.

The distribution of magnitude of changes of summer rainfall during the period of 1966-2016 over Rangpur division is shown in the **Figure 4.10.** It is seen that the maximum decrease in summer rainfall is 6.42 mm/year while the maximum increase in summer season rainfall is 10.18 mm/year. This implies that the summer season rainfall is increasing in the region, this comply with the other findings of this study; specially the findings of linear trend analysis and decadal change in rainfall analysis explored increasing trend in summer season rainfall. The regions under Rangpur division which showed significant decrease in summer rainfall are Patgram (-6.42 mm/year) of Lalmonirhat District, Kantanagar (-5.55 mm/year) & Ghoraghat (-3.91 mm/year) of Dinajpur District. In this division, Latu of Panchagarh District have shown maximum increase in summer rainfall, which is 10.18 mm/year. On average, Rangpur Division have experienced 0.04 mm/year increase in summer rainfall.

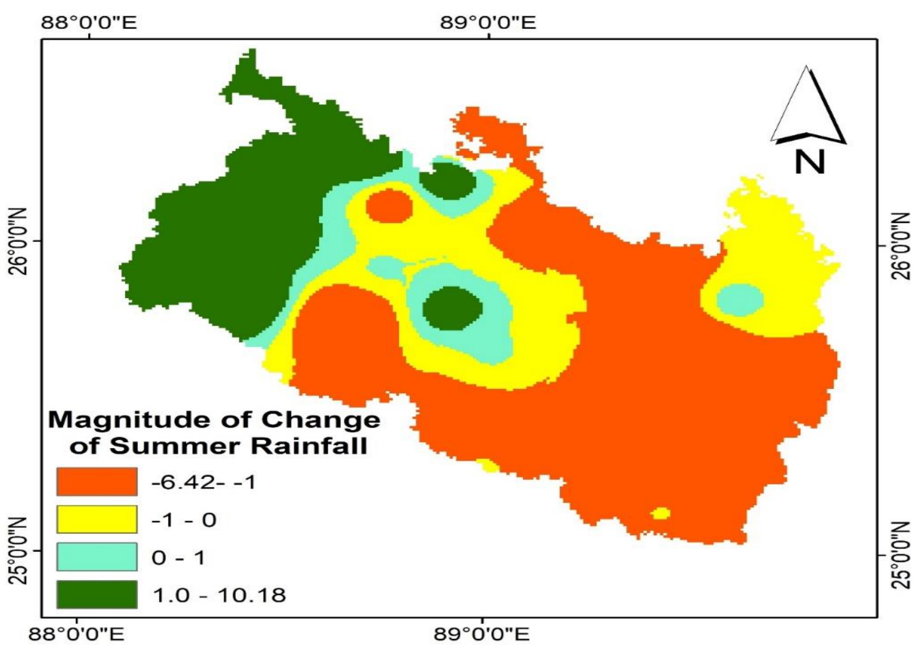


Figure 4.10: Distribution of magnitude of changes of summer rainfall during the period of 1966-2016 over Rangpur division.

4.4.4. Magnitude of Changes in Rainy Season Rainfall

The distribution of magnitude of changes of rainy season rainfall during the period of 1966-2016 over Rajshahi division is shown in the **Figure 4.11.** It has been observed that the maximum decrease in rainy rainfall is 11 mm/year while the maximum increase in rainy season rainfall is 4.62 mm/year. Also most of the areas of Rajshahi Division have shown decreasing trend in rainy season rainfall, only few areas have shown increasing trend in rainy season rainfall. This implies that the rainy season rainfall is decreasing in the region. Overall, the Rajshahi Division have experienced 3.00 mm/year decrease in rainy season rainfall. The regions under this division which showed significant decrease in rainy rainfall are Badalgachi (-11.00 mm/year) of Naogaon District, Rajshahi (-8.93 mm/year) and Sinra (-8.91 mm/year) of Natore District. In this division, Nawabganj Sadar of Nawabganj District have shown maximum increase in rainy rainfall, which is 4.62 mm/year.

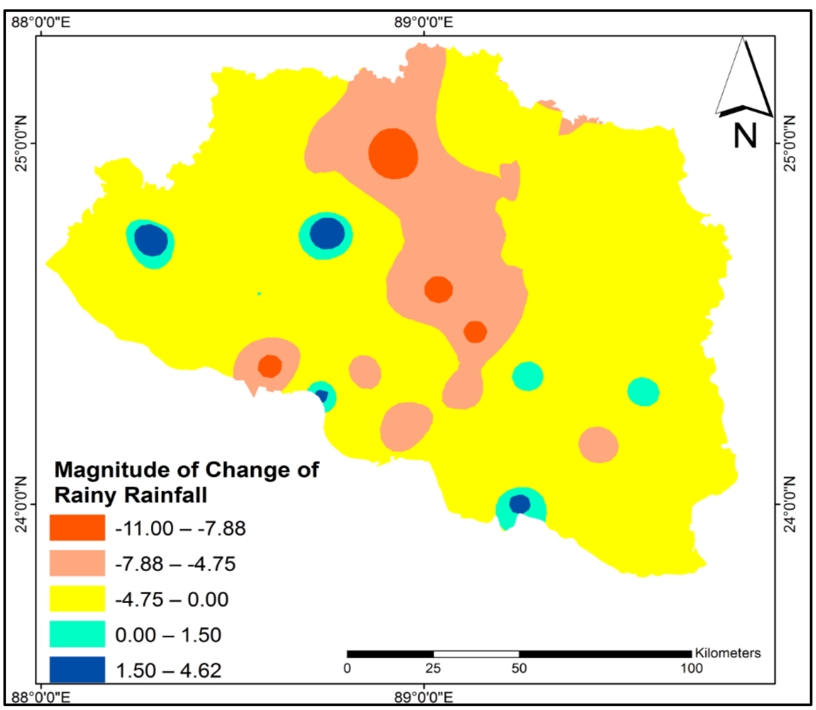


Figure 4.11: Distribution of magnitude of changes of rainy rainfall during the period of 1966-2016 over Rajshahi division.

The distribution of magnitude of changes of rainy season rainfall during the period of 1966-2016 over Rangpur division is shown in the **Figure 4.12.** It has been observed that the maximum decrease in rainy rainfall is 33.1 mm/year while the maximum increase in rainy season rainfall is 6.43 mm/year. Also most of the areas of Rangpur Division have shown decreasing trend in rainy season rainfall, only few areas have shown increasing trend in rainy season rainfall. This implies that the rainy season rainfall is decreasing in the region. Overall, the Rangpur Division have experienced 6.76 mm/year decrease in rainy season rainfall. The regions under this division which showed significant decrease in rainy rainfall are Patgram (-33.12 mm/year) of Lalmonirhat District, Bhithargarh (-29.27 mm/year) of Panchagarh District and Ghoraghat (-24.88 mm/year) of Dinajpur District. In this division, Latu of Panchagarh District have shown maximum increase in rainy rainfall, which is 6.43 mm/year.

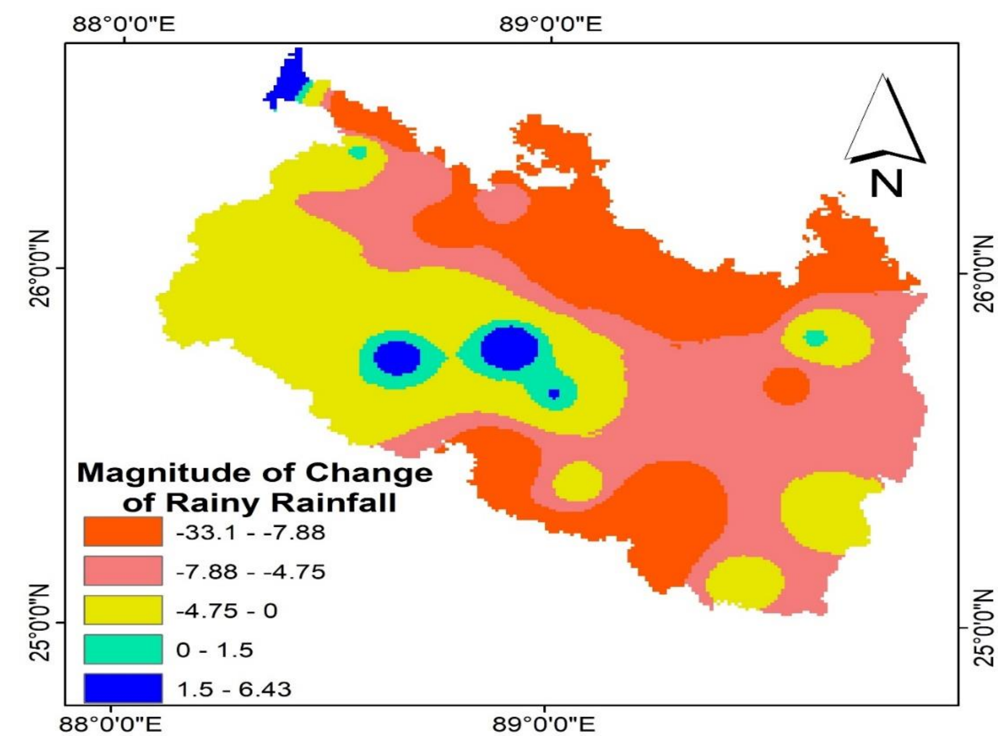


Figure 4.12: Distribution of magnitude of changes of rainy rainfall during the period of 1966-2016 over Rangpur division.

The magnitude of change (estimated by Sen's slope estimator) in rainfall in different stations are given in the tables 4.4 and 4.5. Detailed result on Sen's slope estimator and Men-Kendal Test are given in **Appendix.**

Table 4.4: Magnitude of change in rainfall (estimated by Sen's slope estimator) in stations of Rajshahi division

Name of Station	District	Magnitude of change in Rainfall (mm/year)			
		Winter	Summer	Rainy	Annual
Dhunot	Bogura	-0.67	-1.93	-5.63	-8.15
Khetlal	Joypurhat	0.25	-1.12	-3.28	-3.71
Nandigram	Bogura	-0.40	-1.31	-4.69	-5.10
Nawkhila	Bogura	-0.10	-1.48	-3.25	-4.34
Shibganj	Bogura	-0.37	-0.83	-7.25	-8.00
Sirajganj	Sirajgonj	-0.40	-1.18	-3.00	-4.64
Ullapara	Sirajgonj	-0.18	0.70	0.70	1.20
Gurudaspur	Natore	0.00	2.30	1.60	4.00
Joari	Natore	-0.71	0.62	-6.05	-3.82
Lalpur	Natore	-0.30	-1.94	-6.37	-7.94
Natore	Natore	-0.41	0.60	-0.39	-0.23
Singra	Natore	0.00	-1.96	-8.91	-10.70
Atghoria	Pabna	-0.33	-0.83	-4.96	-5.31
Faridpur	Pabna	0.00	-1.29	-6.00	-6.25
Pabna	Pabna	-0.43	-1.37	2.22	0.19
Sujanagar	Pabna	0.14	-1.07	0.11	0.29
Tanore	Rajshahi	0.13	0.14	0.06	0.41
Godagari	Rajjshahi	-0.30	0.20	-0.68	-0.65
Puthia	Natore	-0.05	-0.77	-5.78	-6.44
Sardah	Rajshahi	0.00	1.51	2.04	3.84
Bholahat	Nawabgonj	0.00	1.44	-3.20	0.00
Nawabganj	Nawabgonj	-0.14	1.41	4.62	6.15
Nachole	Nawabgonj	0.00	-1.00	-2.70	-2.91
Rohanpur	Nawabgonj	-0.05	0.92	-4.69	-3.42
Shibganj	Nawabganj	0.24	1.51	0.00	1.97
Atrai	Naogaon	-0.33	-0.55	-8.78	-9.71
Badalgachi	Naogaon	-0.22	-0.57	-11.00	-11.44
Manda	Naogaon	0.07	1.20	3.65	5.33
Mohadebpur	Naogaon	-0.46	0.29	-6.14	-4.26
Naogaon	Naogaon	-0.17	0.77	-4.21	-2.95
Nazipur	Naogaon	-0.32	-1.11	-4.94	-4.91
Sapahar	Naogaon	-0.13	0.48	-0.50	0.00
Bogra MS	Bogura	-0.20	0.33	-3.78	-3.19

Ishwardi MS	Pabna	-0.09	-1.60	-3.09	-4.36
Rajshahi MS	Rajshahi	-0.41	0.77	-8.93	-7.31

Table 4.5: Magnitude of change in rainfall (estimated by Sen's slope estimator) in stations of Rangpur division

Name of Station	District	Magnitude of change in Rainfall			
		Winter	Summer	Rainy	Annual
Badarganj	Rangpur	-0.26	0.26	1.65	1.88
Bhawaniganj	Gaibandha	-6.61	-2.81	-2.98	-4.01
Bhithargarh	Panchagarh	0.38	1.45	-29.27	-25.40
Bhurangamari	Kurigram	-0.45	-0.45	-15.87	-23.34
Boda	Panchagarh	0.00	2.40	-4.95	-3.04
Ghoraghat	Dinajpur	-0.58	-3.91	-24.88	-32.34
Debiganj	Panchagarh	0.00	-2.29	-9.23	-8.29
Dimla	Nilphamari	0.85	2.75	-5.13	-0.21
Gobindaganj	Gaibandha	0.00	-0.97	-3.15	-3.34
Hatibandha	Lalmonirhat	-0.58	-1.96	-19.96	-32.34
Hilli	Dinajpur	-0.49	-0.84	-9.18	-9.06
Kaunia	Rangpur	-0.26	-2.22	-5.09	-3.19
Khansama	Dinajpur	0.13	0.09	-2.00	-0.66
Kantanagar	Dinajpur	0.26	-5.55	2.80	-4.59
kurigram	Kurigram	-0.16	0.78	0.83	2.45
Lalmanirhat	Lalmonirhat	0.33	-2.26	-17.02	-18.36
Nawabganj	Dinajpur	0.03	-1.18	-1.83	-1.31
Panchagarh	Panchagarh	0.64	3.42	0.83	3.22
Latu	Panchagarh	0.00	10.18	6.43	20.95
Patgram	Lalmonirhat	0.00	-6.42	-33.12	-43.18
Saidpur	Nilphamari	-0.01	2.28	4.11	8.52
Thakurgaon	Thakurgaon	0.20	2.57	-3.70	0.97
Phulbari	Dianjpur	-0.25	-1.99	-14.30	-16.93
Setabganj	Dinajpur	0.29	3.59	-3.12	0.42
Tentulia	Panchagarh	-0.24	2.66	3.58	7.05
Ulipur	Kurigram	0.00	-1.92	-9.14	-12.30
Rangpur MS	Rangpur	-0.09	1.98	3.24	5.50
Dinajpur MS	Dinajpur	0.07	1.49	1.17	3.52

Chapter Five

Meteorological and Hydrological Drought Variability

5.1. Introduction

In this chapter seasonal rainfall trends over the time period 1966–2016 has been assessed using daily rainfall data recorded at 5 northern meteorological stations of Bangladesh viz. Bogra, Dinajpur, Ishurdi, Rajshahi and Rangpur. Standard Precipitation Index (SPI) followed by gamma distribution was used to evaluate meteorological drought vulnerability based on frequency and severity of drought events. Also Standardized Water-Level Index (SWI) was used to evaluate hydrological drought variability, using data from 77 wells from the study area for the period 1977-2017. Also correlation between SPI and minimum ground water level was assessed. The detailed methodology of calculating SPI and SWI are given in Chapter Three (Methodology).

5.2. Standard Precipitation Index (SPI)

Precipitation is not normally distributed for time scales of twelve months or less time steps (McKee et al., 1995). According to Guttman (1999), gamma distribution is favorable to the normal distribution. Akaike information criterion (Akaike, 1974) for both Gamma distribution and normal distribution were calculated for model selection (Table 5.1).

Table 5.1: Akaike Information Criterion (AIC) for Gamma Distribution and Normal Distribution

Station	Gamma Distribution			Normal Distribution		
	Parameters					
	Shape (α)	Rate (β)	AIC	Mean (μ)	SD (σ)	AIC
Bogura	21.18	0.01	837.75	1698.00	369.00	839.85
Rajshahi	20.82	0.01	766.41	1488.72	323.10	766.87
Dinajpur	20.03	0.01	851.82	1869.98	428.84	856.72
Ishwardi	16.14	0.01	768.22	1542.42	398.45	774.28
Rangpur	23.98	0.01	857.19	2138.44	449.16	862.00

From table 5.1, in all five cases, we can see that AIC for gamma distribution is always smaller than that for normal distribution, which justifies the use of gamma distribution for modeling rainfall data. Other skewed distribution like exponential distribution and weibull distribution were compared and it was found that Gamma distribution is favorable to all distributions. Hence in order to compute SPI, precipitation data were normalized using gamma function. Positive SPI values indicate greater than median precipitation and negative values indicate less than median precipitation. McKee and others (1993) used the classification system shown in the SPI value table below (Table 5.2) to define drought intensities resulting from the SPI.

Table 5.2: SPI values and drought severity classes

SPI values	Drought Condition
2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-.99 to .99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
-2 and less	extremely dry

5.3. Meteorological Drought Variability

Droughts in Bangladesh are mostly seasonal. Droughts for a long period e.g. annual scale do not occur in Bangladesh like most of the tropical countries. Therefore, droughts only during monsoon and pre-monsoon months were considered in this study. It should be noted that the crops in Bangladesh are cultivated mostly during these two periods. The SPI was estimated for 4- and 3-month periods to evaluate droughts during monsoon (June to September) and pre-monsoon (March to May) seasons. The time series of 3-month SPI at five study locations are shown in Figure 5.1. The SPI value at the last of a season was separated to assess the changes in drought in that season. For example, 3-month SPI value of May indicates the rainfall deficit from March to May and therefore, used to estimate the changes in pre-monsoon droughts. Similarly, the 4-month SPI value of September was used to assess the changes in monsoon droughts.

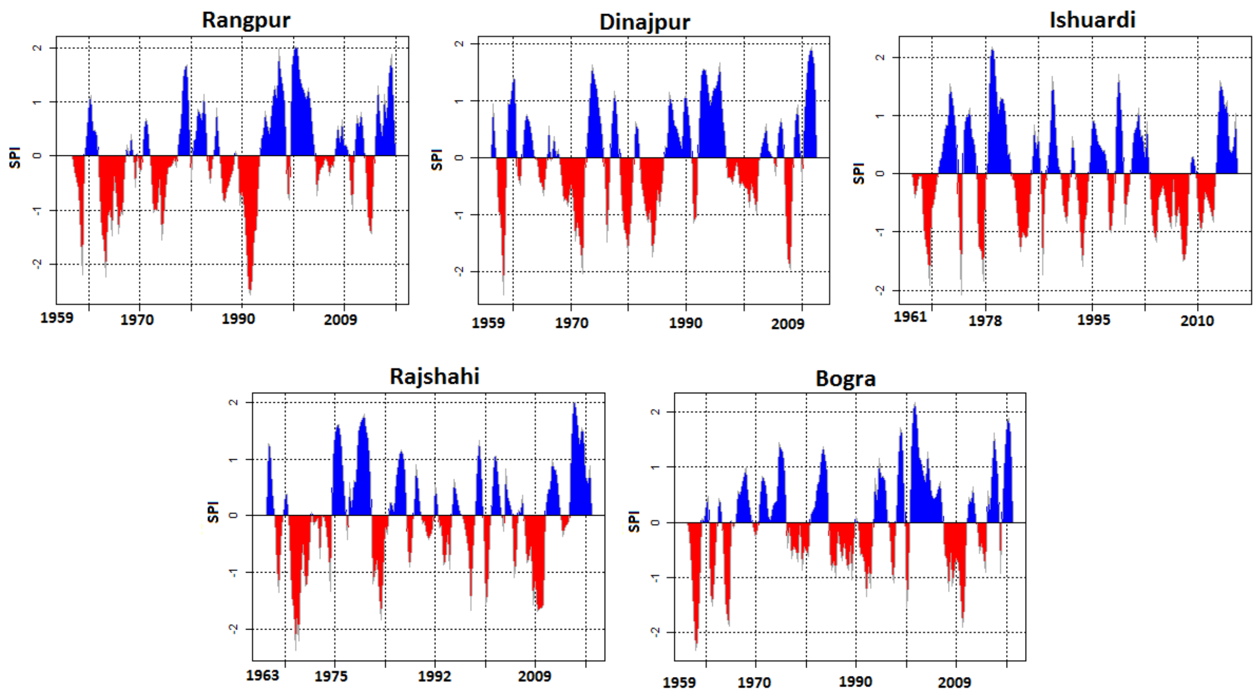


Figure 5.1: Standardized precipitation index for a time scale of four months at different locations of the study area

The time series of monsoon SPI for the five study locations are shown in Figure 5.2. The MK trend test was used to assess the changes in monsoon SPI to understand the changing pattern of monsoon droughts. The trend lines are shown using a red line over the SPI time series in Figure 5.2. The rate of change in monsoon SPI per decade is provided in Table 5.3. The bold numbers in the table represent a significant change. The results show a decrease in SPI or increase in droughts at a 95% level of confidence (5% level of significance) at two out of 5 stations.

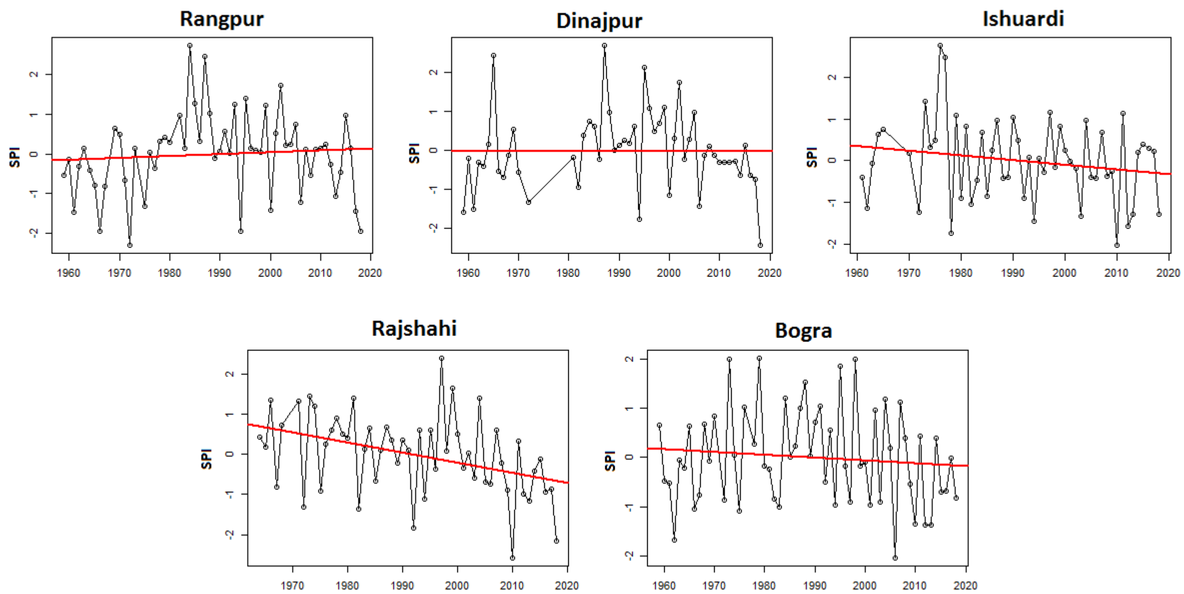


Figure 5.2: Trends in monsoon droughts for the period 1959-2018 at different locations of the study area

The time series of pre-monsoon SPI for the study locations are presented in Figure 5.3, while the trends in pre-monsoon SPI are presented in Table 5.3. The pre-monsoon drought was found to decrease (increase in SPI values) at 4 out of 5 stations, while it was found to increase at one station at a 95% level of confidence (5% level of significance). The rainfall in pre-monsoon months was found to increase at the locations where drought was noticed to decrease, while the rainfall was found to decrease at the location where drought was noticed to increase. The variability in pre-monsoon rainfall was noticed to decrease at three locations include the station where drought is increasing. Therefore, it can be remarked that changes in mean monsoon rainfall may be linked to the changes in droughts in the study area. The increase or decrease in mean pre-monsoon rainfall in recent years has influenced the calculation of rainfall deficit for recent years. This resulted in higher or lower values of SPI in later periods and an increasing or decreasing trend in SPI.

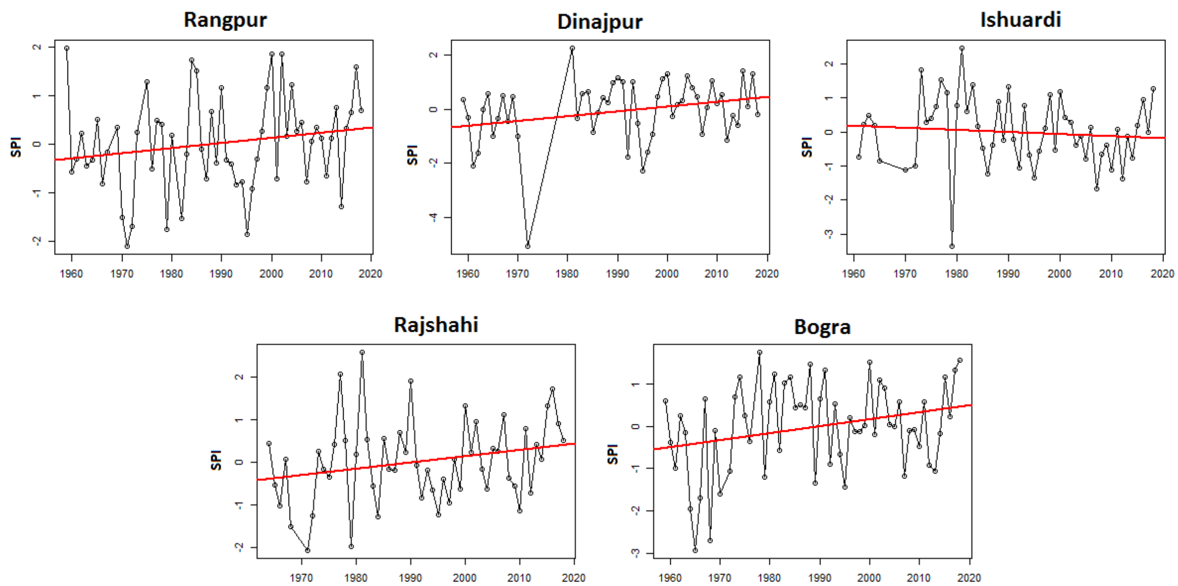


Figure 5.3: Trends in pre-monsoon droughts for the period 1959-2018 at different locations of the study area

A similar interpretation can be made for monsoon droughts as the droughts were found to increase at the stations where monsoon rainfall was found to decrease. However, the results were not consistent for all the stations. A decrease in monsoon rainfall was noticed at 4 out of 5 stations, while the increase in monsoon droughts was noticed only at 2 out of 4 stations where monsoon rainfall was decreasing.

Table 5.3: Trends in monsoon and pre-monsoon droughts

	Rangpur	Dinajpur	Ishuardi	Rajshahi	Bogra
Monsoon	0.00418	-0.00239	**-0.00943**	**-0.03048**	-0.00584
Pre-monsoon	**0.00848**	**0.01454**	**-0.01539**	-0.00235	**0.01156**

The twelve months SPI box plot shows that the driest region, among the five regions, is the district of Bogura since its SPI distribution is more adjacent to negative values. The district of Dinajpur is drier in terms of having lowest value of SPI, but in general Bogura is drier. The least dry region is the district of Rajshahi, followed by Ishwardi and Rangpur, respectively.

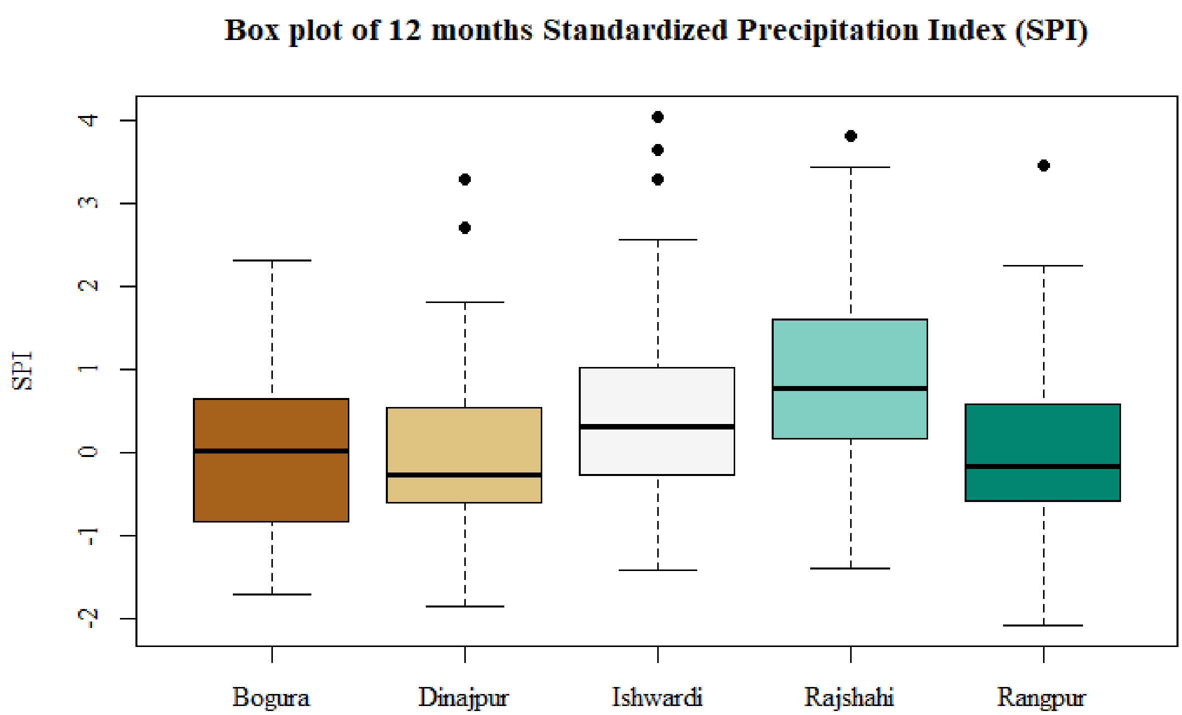


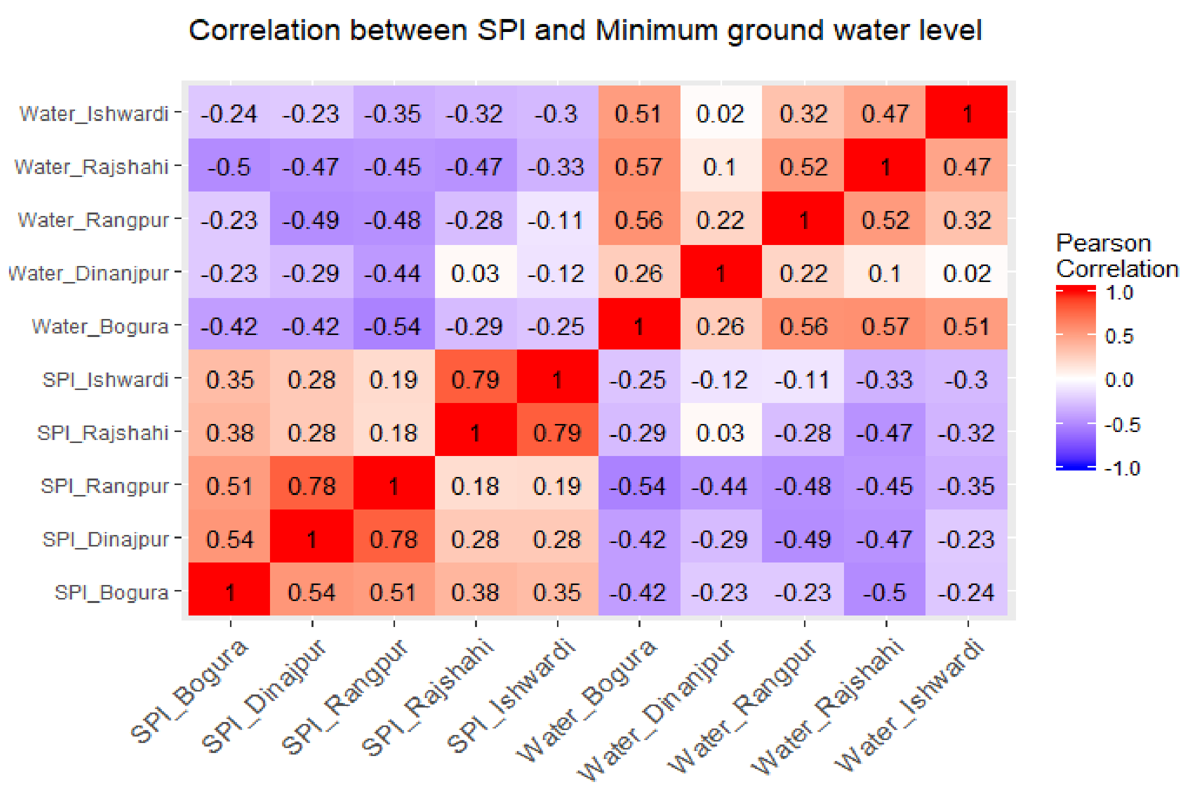
Figure 5.4: Box plot of 12 months SPI for different stations

The results indicate that analysis of variability and trends are not enough for a complete understanding of the cause of change in droughts. Besides, such analyses are not enough to understand whether the decreasing trend in droughts will persist in the near future or there will be a rainfall regime shift which would alter drought trends.

5.4 Correlation of SPI with ground water level

The correlation matrix of SPI of five different districts and their respective minimum ground water levels shows that SPI's are fairly moderately correlated to one another, and the same can be claimed concerning the level of ground water of the regions. The SPI's and ground water level of each district are not, however, positively correlated, rather, they are negatively correlated, maximum correlation being -0.47. This implies, SPI and minimum ground water level do not have similar trend.

Table 5.4: Correlation between SPI and minimum ground water level for different stations



5.5 Hydrological Drought Variability

In this study ground water data of five different regions, namely Rajshahi, Bogra, Dinajpur, Rangpur, and Ishwardi (Pabna) since the year 1977 until 2017 were used to find the indices. The indices identify a significant portion of years as experiencing drought. To carry out our analysis, data from a total of 77 wells from five different regions were used. The data were then transformed to obtain trimonthly, half-yearly, and yearly ground water level. The months of March, April, and May were considered for trimonthly estimation, and May to October were considered for half-yearly estimation. Since ground water level is measured down from the surface, positive anomalies correspond to drought and negative anomalies correspond to 'no-drought' or normal condition.

Table 5.5: SWI values and drought condition.

Standardized Water level Index (SWI)	Interpretation
SWI > 0	Drought exists
SWI < 0	There is no drought

As we stated earlier, we have considered the years since 1977 until 2017, a total of 41 years. Of these 23 years are identified as having drought. However, only ten of those years correspond to the years before 2000, and 13 of them are after 2000. Thus, out of just 18 recent years, 13 are identified as having drought, while out of 23 former years, only 10 years experienced drought condition. The scenario for six month SWI is like that of trimonthly output, the values show an increasing trend. The only difference is that in this case, the drought condition is more severe after the year 2005. In general, 63 percent of the years with drought are after 2005. Also eye-catching is the fact that out of those 14 years, 75% are with drought.

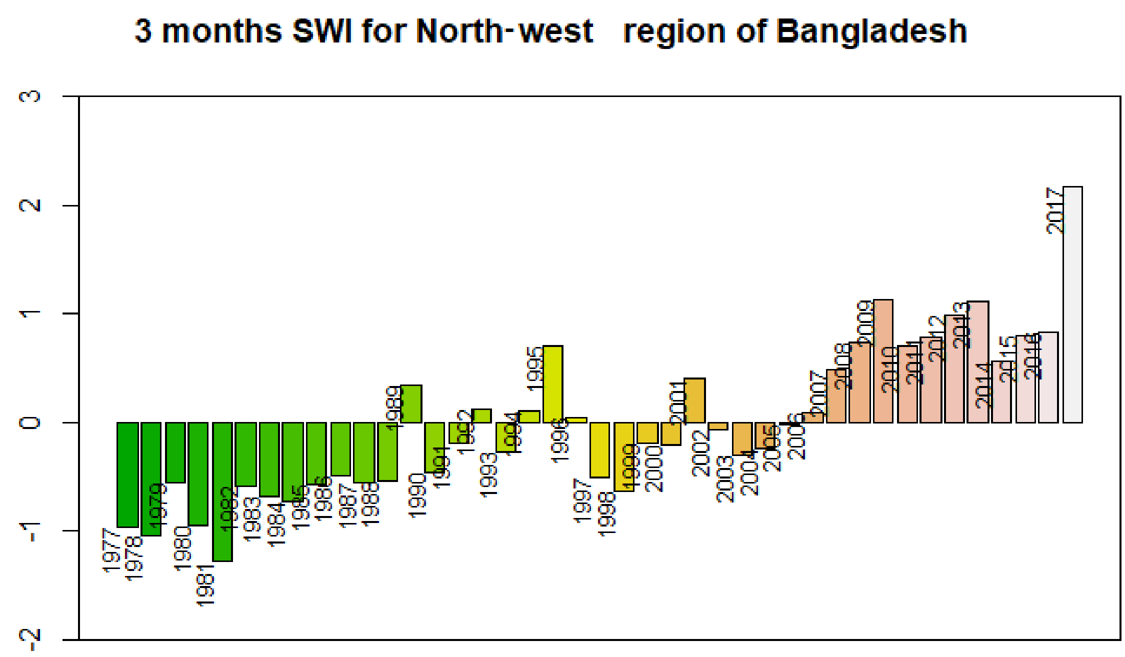


Figure 5.5: Three Months SWI for North-west region of Bangladesh

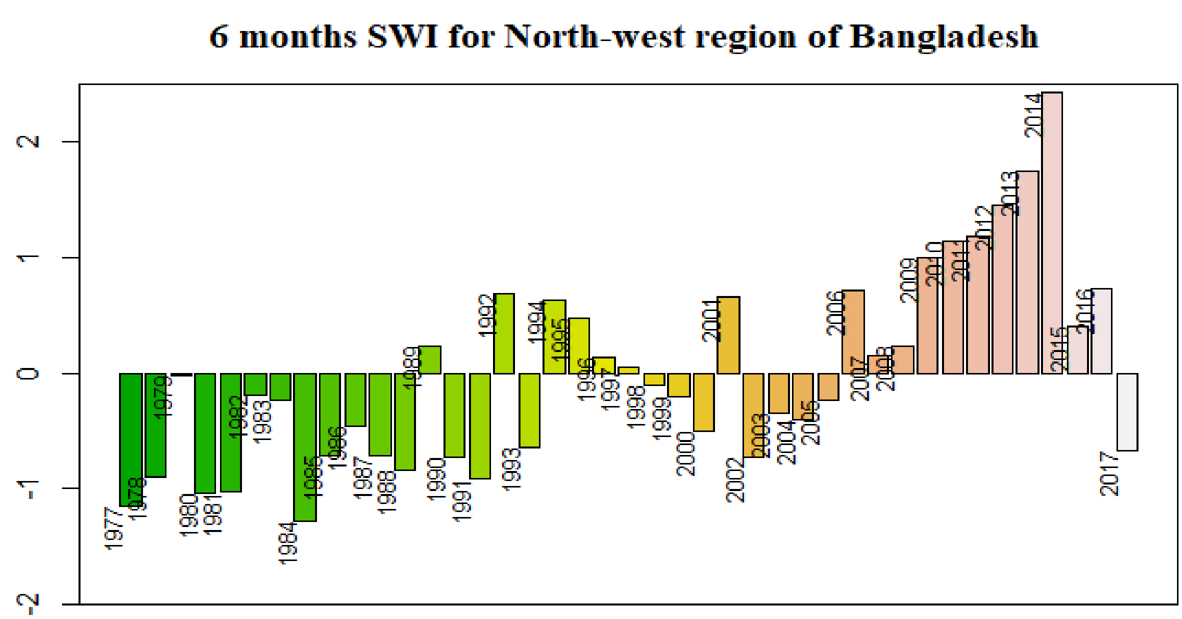


Figure 5.6: Six Months SWI for North-west region of Bangladesh

Chapter Six

Agricultural Drought Variability

6.1 Introduction

This chapter involves time series analysis of normalized difference vegetation index (NDVI) to assess agricultural drought variability. The variation in SPI and SWI were used against NDVI in order to assess the drought situation. The data used for NDVI has been derived from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1) Version 6, which was collected from the year 2000 to 2020. The data is freely available from (https://lpdaacsvc.cr.usgs.gov/appeears/). All these data were then processed in ArcGIS 10.3 desktop software and Stata. Detailed method of NDVI calculation is given in Chapter Three (Methodology). The data is collected from the best pixel value within a 16 days time frame. An automatic algorithm chooses the best value. The cloud amount and satellite viewing angle are considered as well (Didan et al., 2015). The data used for NDVI in the study ranges from the year 2000 to 2020. Only the month of March has been considered, as it is a dry month and free of cloudy weather, thus provides much more accurate data for dry time. This data has been used in several papers and is considered well suited (Fensholt et al., 2009; Huete et al., 2002). The downloaded data is multiplied with the scale value of 0.001 as per the user manual instructions, and classed into four groups suitable for this study area and which are adapted from the previously published papers (Hashim et al., 2019; Yadav & Borana, 2019). The groups are water, sparse, vegetation, moderate vegetation, and dense vegetation. The area percentage for each class is calculated and plotted.

6.2 Land Cover Changes

The Normalized Vegetation Index (NDVI) of Rajshahi, Rangpur, Bogra, Pabna and Dinajpur districts were carried out to see the land cover changes over the time from 2000 to 2020. The NDVI values which ranges from – 1 to +1 has been classified in to five different classes according to a reference given above in the methodology. The different classes are water, and sparse, medium and thick vegetation. The classes are represented in the map with different color representation. The water is represented by cyan color, sparse vegetation by yellow, medium vegetation by light green and thick vegetation by darker green. Sparse, medium and thick vegetation means the density of the vegetation. NDVI values between 0.226 and 0.37 correspond to areas with sparse vegetation; moderate vegetation tends to vary between 0.37 and 0.51; anything above 0.51 indicates the highest possible density of green leaves. Therefore, the thick vegetation can be either large trees or shrubs with large canopy. ***NDVI maps for each district for the year 2000 is given here and the rest of the maps from 2001 to 2020 is given in the Appendix.***

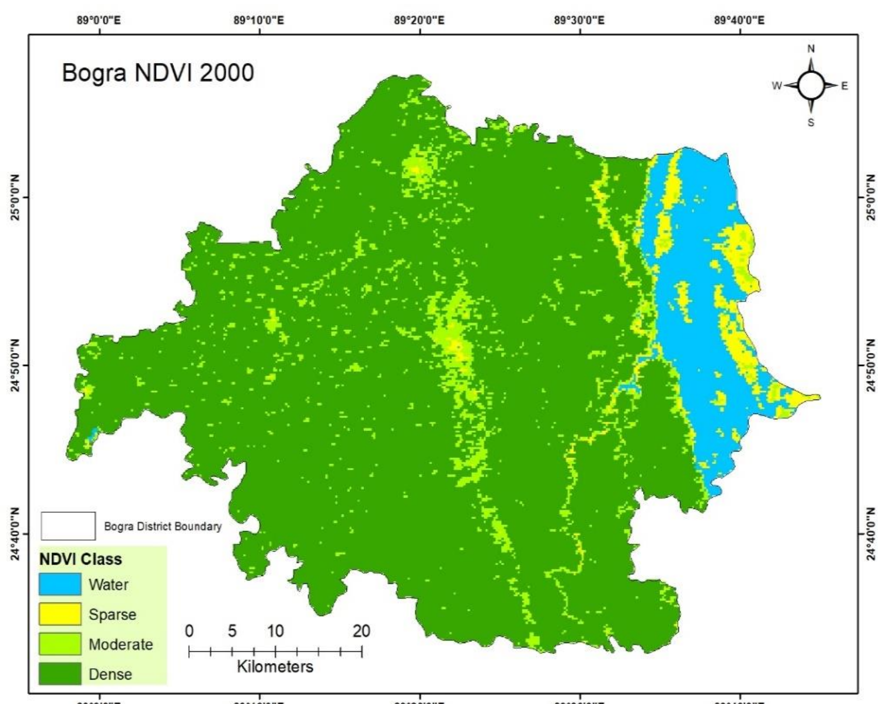


Figure 6.1: NDVI map for Bogra district in the year of 2000

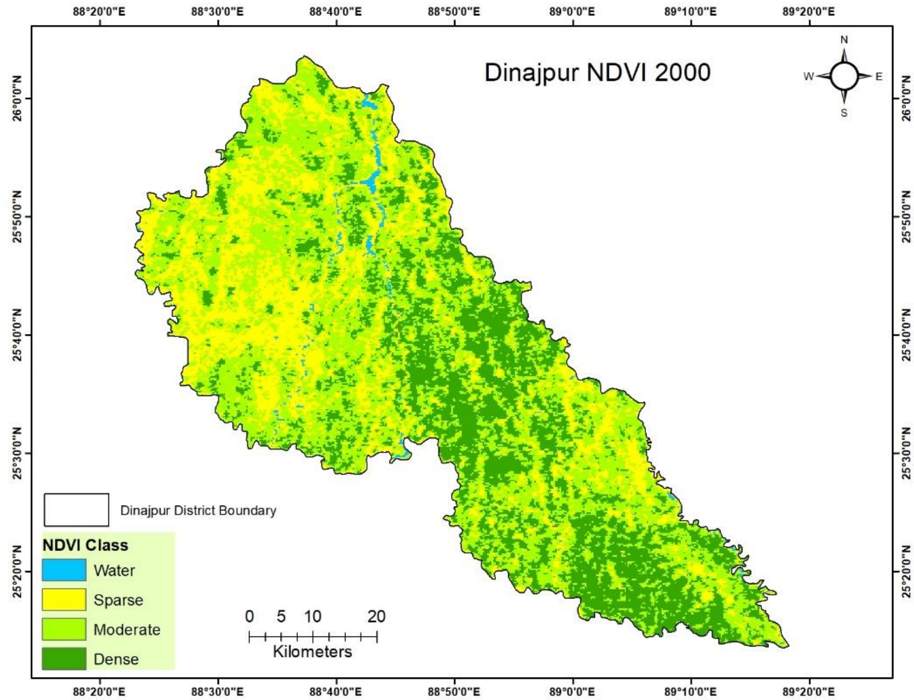


Figure 6.2: NDVI map for Dinajpur district in the year of 2000

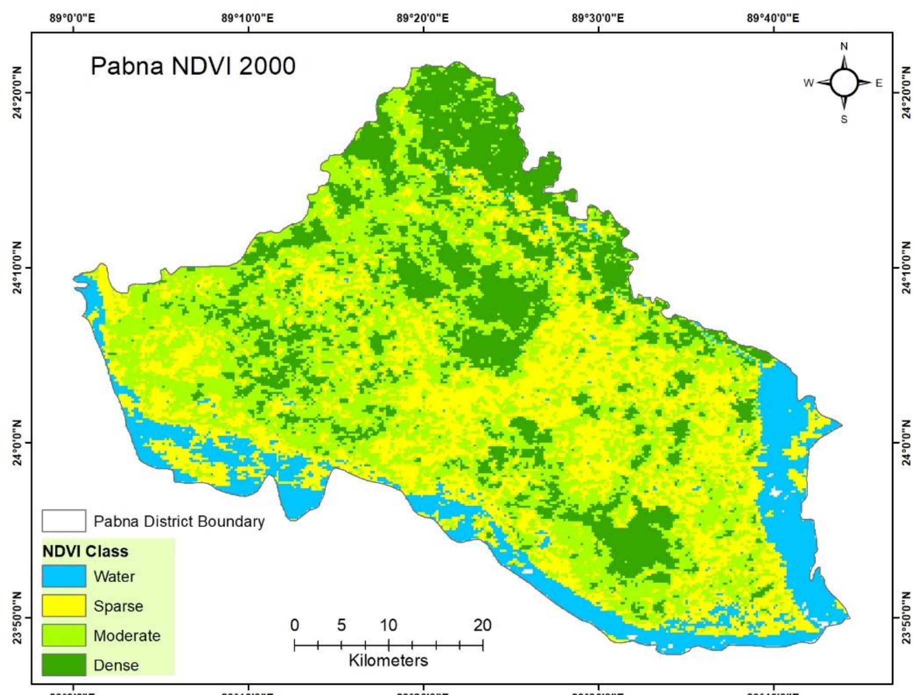


Figure 6.3: NDVI map for Pabna district in the year of 2000

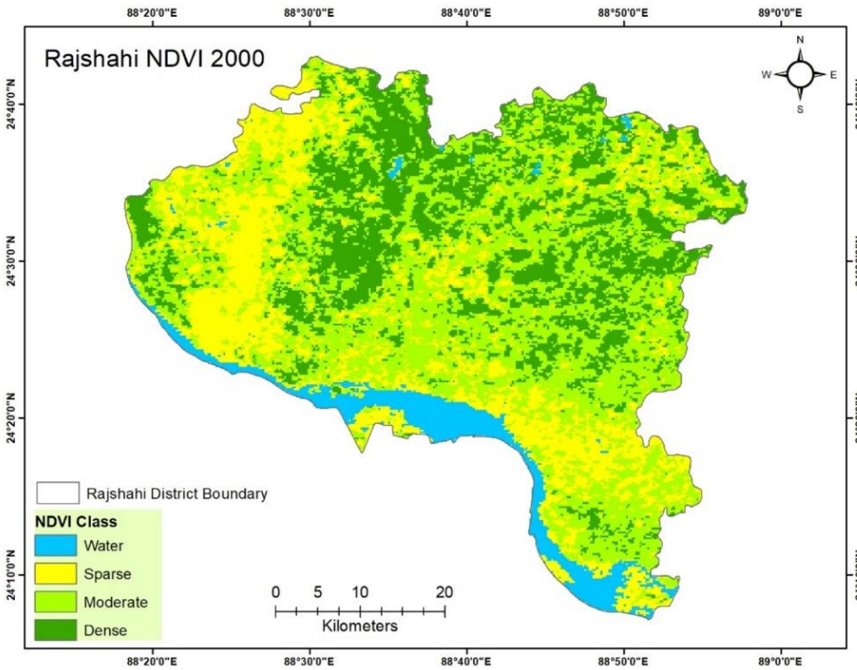


Figure 6.4: NDVI map for Rajshahi district in the year of 2000

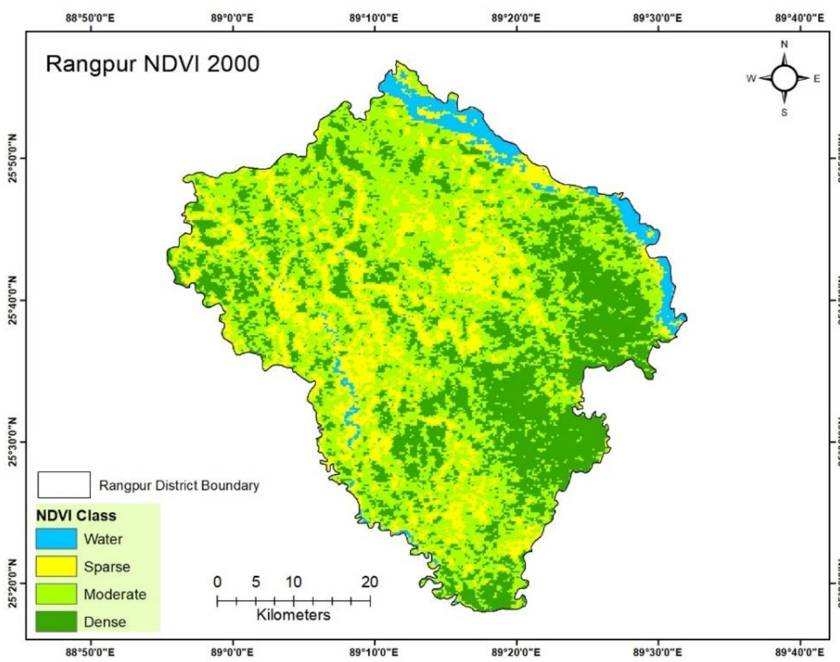


Figure 6.5: NDVI map for Rangpur district in the year of 2000

6.3 Trend Analysis of NDVI

The study area is five districts in the northwestern part of Bangladesh. Overall, the NDVI value fluctuations vary differently in different districts. However, the increase of dense vegetation over time is a general trend seen in every area. The NDVI time series plots are presented and described below. In these plots, the green line denotes dense vegetation class, yellow shows moderate and orange lines indicates the sparse vegetation class. Furthermore, the blue line shows the water class. It is important to note that, these plots show the changes in vegetation type over time. However, it does not show changes in the absolute vegetation quantity in each area.

Bogra District

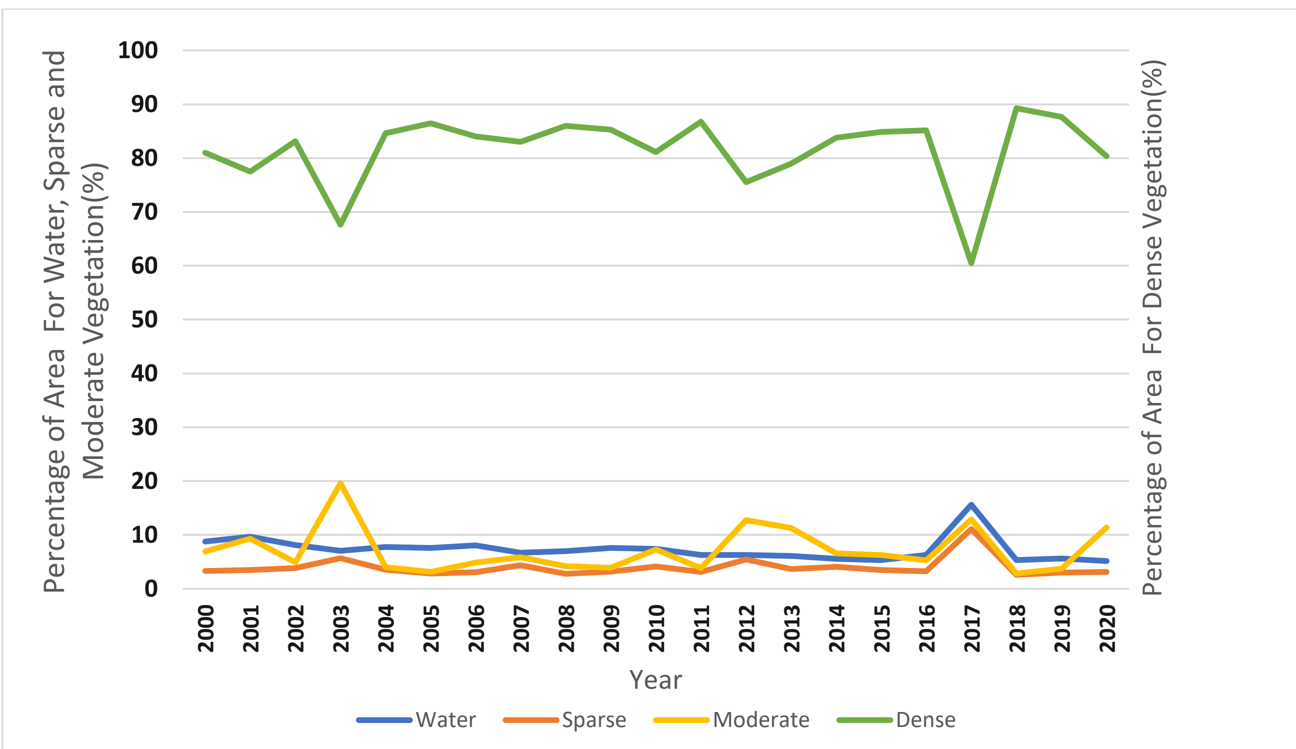


Figure 6.6. Changes over 20 years in vegetation class based on NDVI in Bogra

The dense vegetation in Bogra as been the vastly dominant class over the years. The dense vegetation class takes up around 80% of vegetation present in the area. However, during 2003 and 2017 the dense vegetation class had seen a drastic decrease. It came as low as 60%. However, in the later years, the dense vegetation has gone up. The presence of other three classes are very insignificant amount in Bogra. The notable fact here is the moderate vegetation class sees an up rise whenever the dense vegetation lowers. This is understandable as those years have seen a decrease in dense vegetation and thus those areas have turned into moderate vegetation areas for those respective years.

Dinajpur District

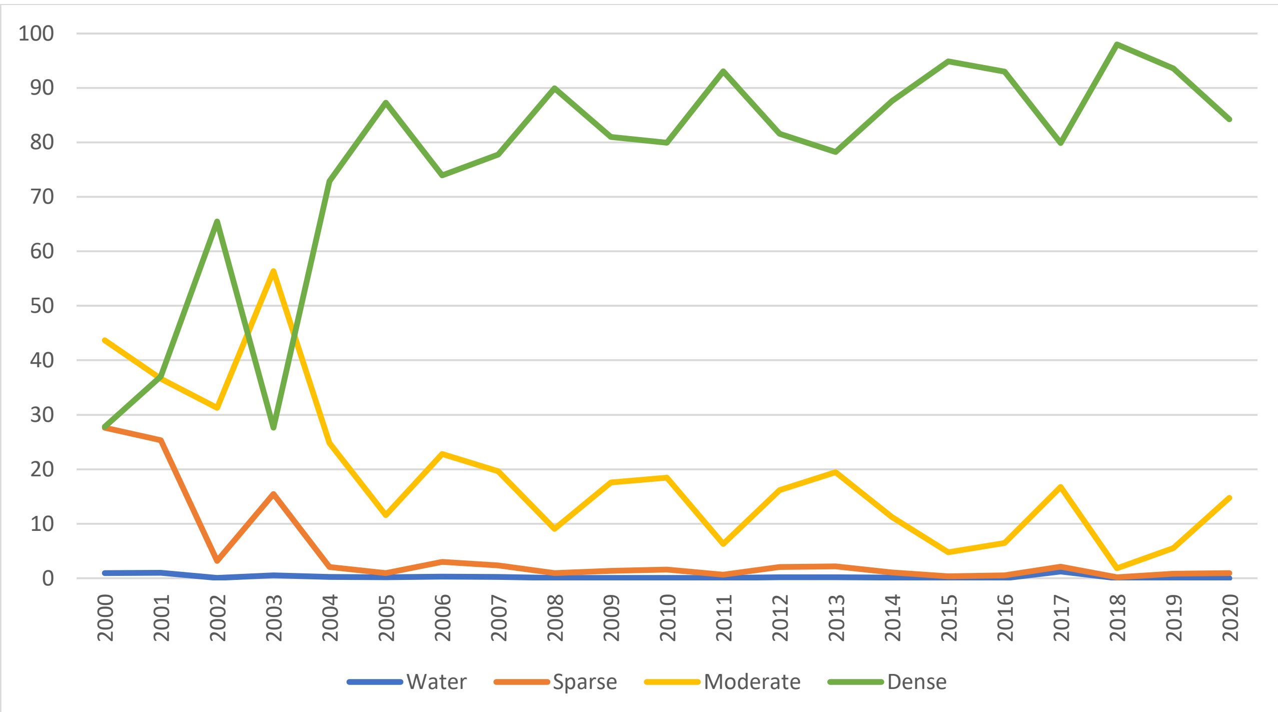


Figure 6.7: Change over 20 years in vegetation class, based on NDVI in Dinajpur

The district of Dinajpur also has a high amount of dense vegetation. In the beginning of the year 2000, the moderate vegetation was the dominant class. However, over the course of three years, this has changed. The fluctuation in the early years has been drastic as moderate vegetation was over 40% and dense and sparse vegetation has been little above 25%. The sparse vegetation has seen a drop in percentage as well as the moderate vegetation. Meanwhile, dense vegetation spiked. In 2003, a temporary increase in moderate and spare vegetation is witnessed. However, this all went down and by 2005, the moderate vegetation has been below 20% whereas the dense vegetation has been fluctuating between 80% to 98%. This fluctuation shows a trend as well. In no less than three years the dense vegetation spikes.

Pabna District

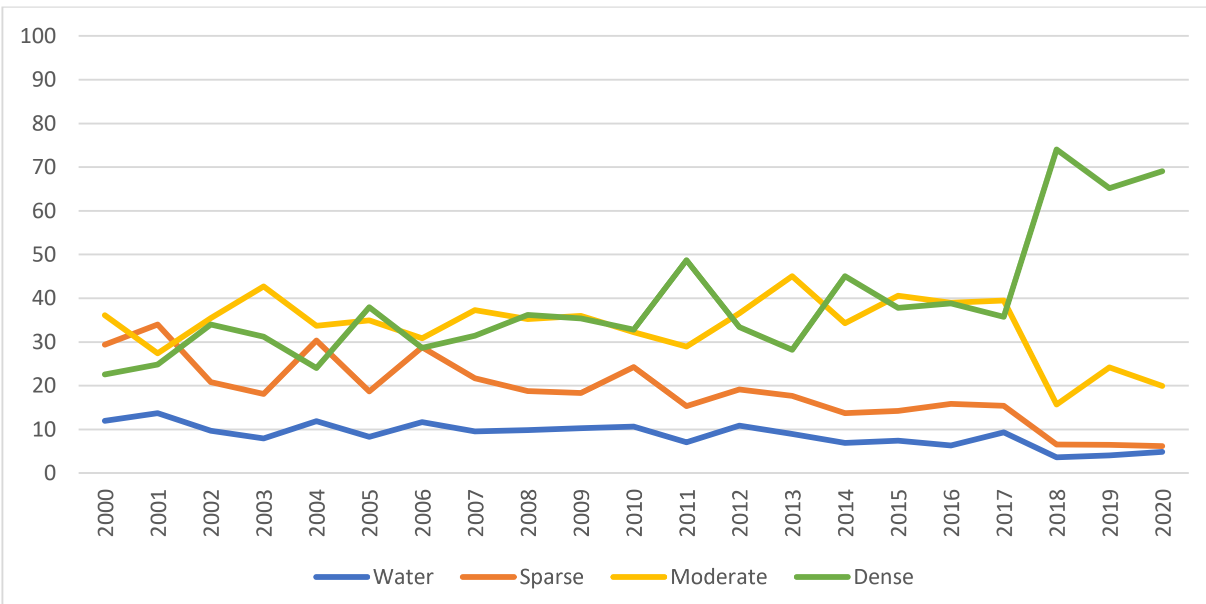


Figure 6.8: Change over 20 years in vegetation class, based on NDVI in Pabna

The vegetation class in Pabna is near evenly distributed before the year 2017. All the classes were near 30% except water. After 2017, the dense vegetation has seen an increase and has remained over 60% to date. The sparse vegetation has been gradually decreasing over the years and moderate vegetation has decreased drastically (below 20%) after 2017.

Rajshahi District

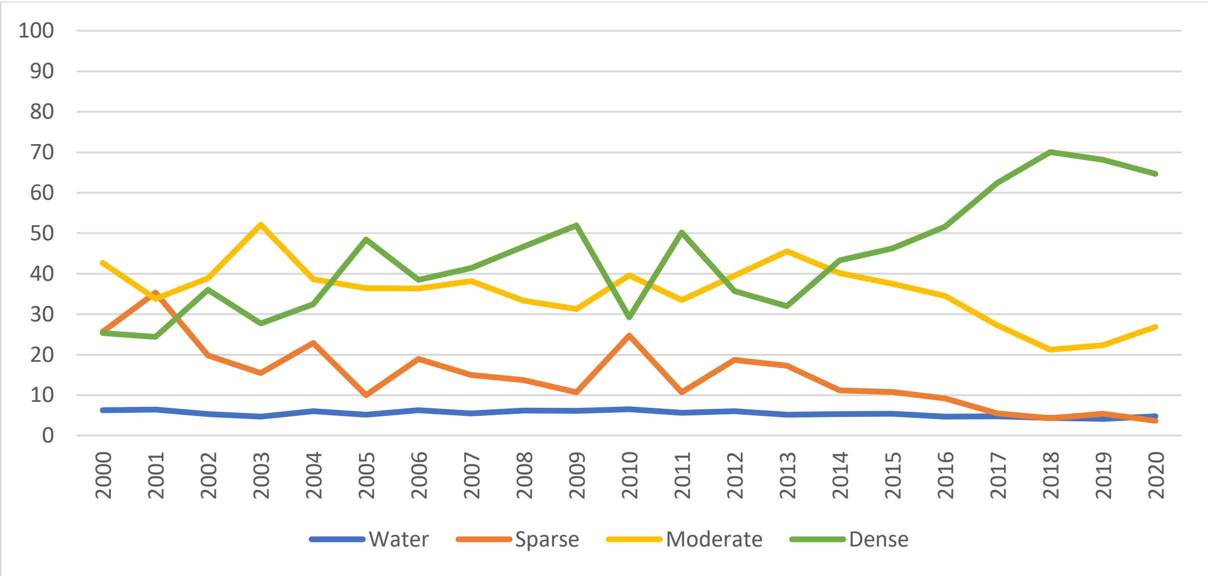


Figure 6.9: Change over 20 years in vegetation class, based on NDVI in Rajshahi

The trend in Rajshahi district is like district Pabna where initial years have no dominant vegetation class. However, over the years the dense vegetation class has been gradually increasing. Similarly, moderate, and sparse vegetation class shows a decreasing trend over the years. However, in 2003, 2010 and 2013, the moderate vegetation class had toppled the dense vegetation class. The dense vegetation has been over 60% after 2017.

Rangpur District

During the year 2000, the moderate vegetation had a higher percentage in Rangpur District. However, within 2001, the NDVI value for dense vegetation had increased dramatically and it remained to be the dominant class. The area percentage had remained between 80% to 60%. Moderate vegetation dropped down to around 30% in most years. The sparse vegetation class has been minimally present in Rangpur as well as the water class.

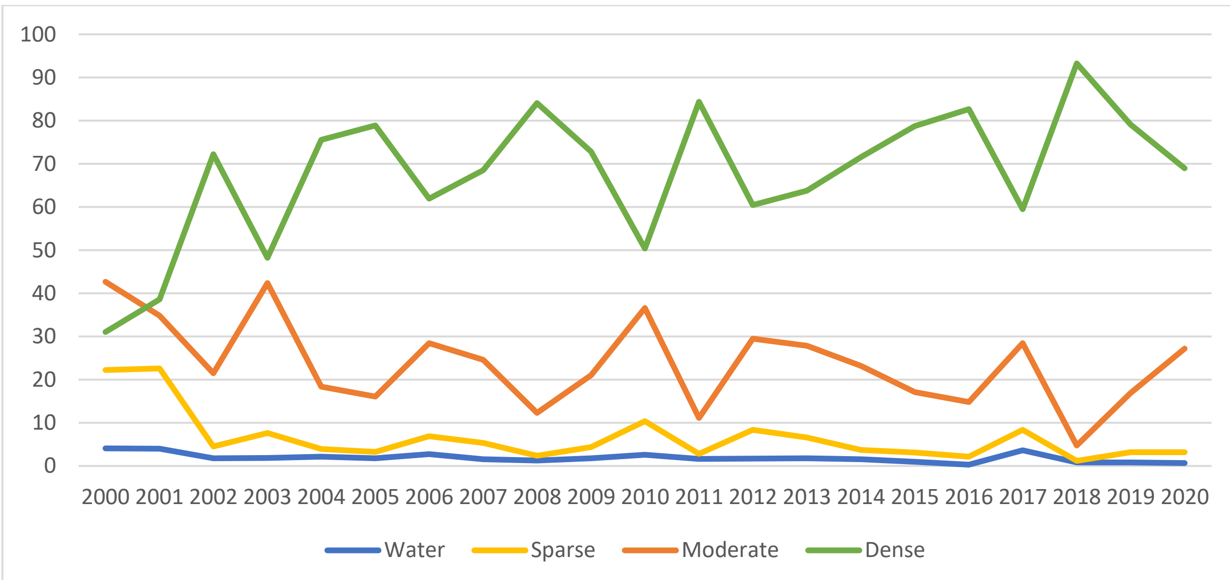


Figure 6.10: Change over 20 years in vegetation class, based on NDVI in Rangpur

In every district, overall, the dense vegetation has been increasing after 2017. The other groups have been under 20%.

6.4 Variations of NDVI and SPI

The metrological and Agricultural drought for the study areas that are Bogra, Dinajpur, Pabna, Rajshahi and Rangpur districts are monitored in this section. SPI value has been used to assess the meteorological drought and NDVI value for vegetative drought. The graphs are plotted for SPI values and the percentage of different vegetated areas in order to see how the amount of vegetation varies with drought conditions. For estimation of

NDVI value satellite images are for March is considered and as the 3-month and 6-month SPI values are for May, June, July, August, September, October and 12-month SPI considered all the months, so the drought index of the past years will be used in order to study the effect of drought on vegetation. Therefore, SPI values for previous years are considered during comparison with NDVI value. The conclusions about drought are drawn on the basis of 6 and 12 months SPI value as they are estimated from medium and long term precipitation patterns. 3-month SPI value is also considered in the analysis as it represents seasonal variations.

Bogra District

The figure 6.11 shows that Bogra district experienced mild drought in the years 1999, 2001, 2003, 2009 and 2015. On the other hand, the region experienced moderate droughts in 2005 and 2013 and severe drought in the year of 2005, 2012 and 2016. However, consideration of 3-month SPI value, which is determined from seasonal variation in the precipitation pattern, shows that many other years also experienced mild drought. The vegetation pattern greatly varies according to the SPI value of the previous year. The figure shows that the percentage of different vegetated areas decreased greatly in the drought years. There is a major decrease in sparse and moderate vegetation in the year 2002, 2004, 2011 and 2015 and the SPI value of previous years shows drought conditions. The decrease in vegetation is greater when there was a drought for more than 2 years, which thereby affects the vegetation growth for the next years. The percentage of sparse and moderate vegetation for 2011, 2014 and 2016 are the examples when the amount of vegetation decreased greatly as the region was experiencing mild to severe droughts for a long time as shown by the SPI values of the previous years. However, the figure also shows that dense vegetation gets affected when drought conditions prolonged for consecutive years.

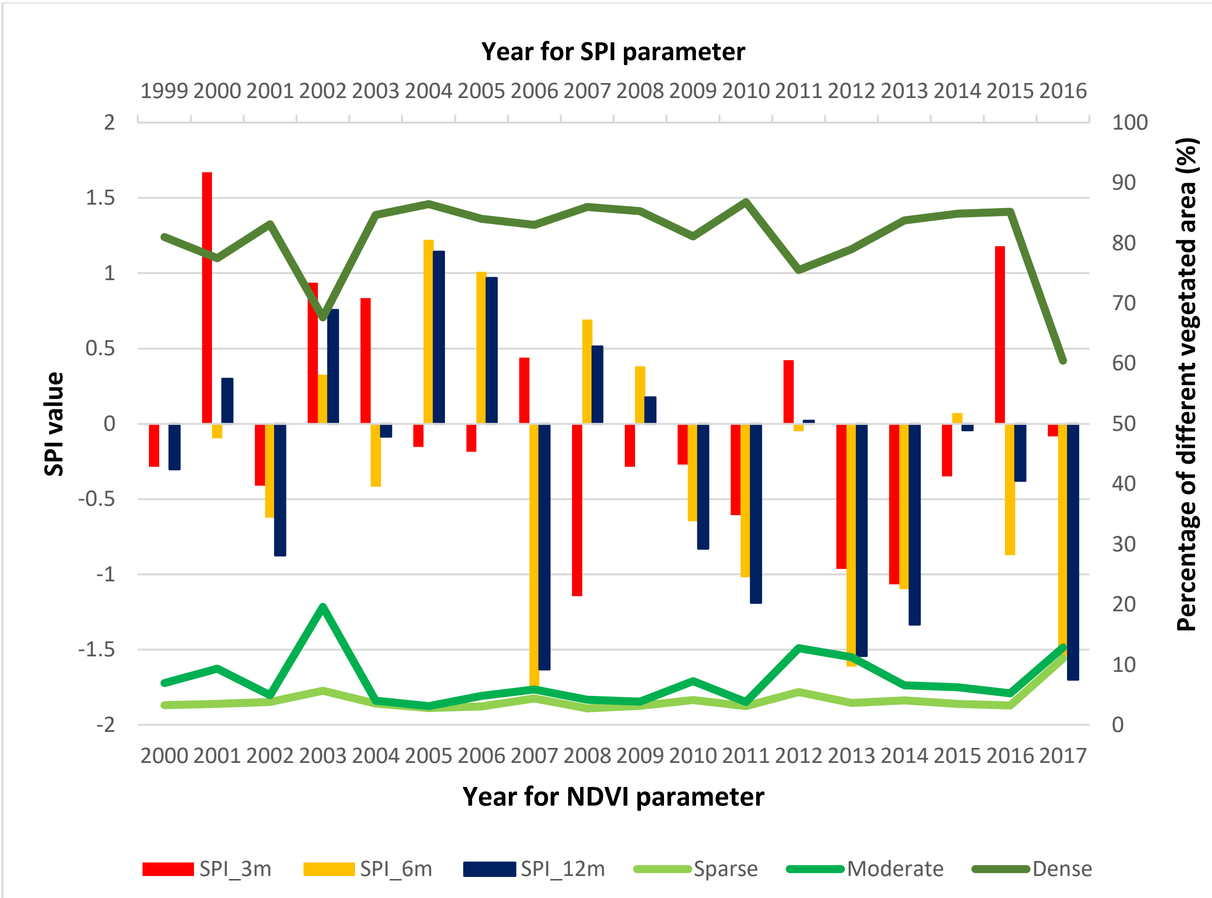


Figure 6.11: Variation of SPI (of previous year) and NDVI parameters for Bogra District

Dinajpur District

The graph 6.12 shows that the Dinajpur region had experienced mild meteorological drought conditions in 2000, 2007, 2008, 2010, 2011, 2012, 2013 and 2016. There was a moderate and severe drought in 2014 and 2015 respectively. The drought condition in this region is mostly of mild type as seen from the graph and there is a coherence between the seasonal estimation of precipitation (3-month SPI value) with the medium and long term (6 and 12-month SPI value) estimation of the precipitation pattern. The sparse vegetation decreased greatly after prolonged drought conditions from 2006 to 2016 except for the years 2009 and 2015. This also affected the percentage of moderate vegetation as it keeps fluctuating highly depending on the degree of drought condition on the previous year (SPI value of the previous year). The effect on the high-density vegetation such as moderate or dense is not that much because the drought condition of the region was mostly mild, and the those type of vegetation have a good irrigation system.

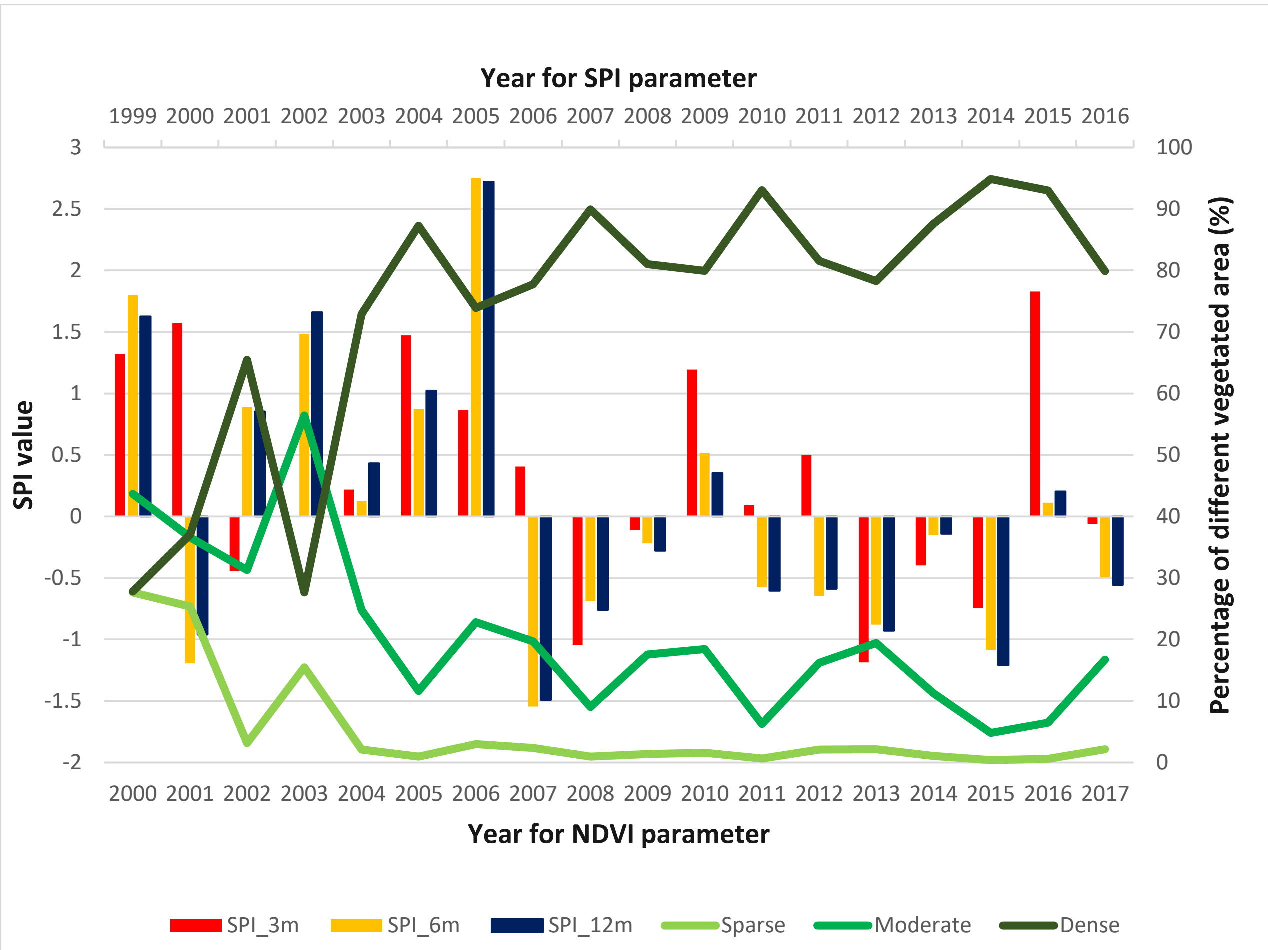


Figure 6.12: Variation of SPI (of previous year) and NDVI parameters for Dinajpur District

Pabna District

The Pabna district had experienced more meteorological drought conditions than other regions. The figure 6.13 shows that except for 2000, 2001, 2004,2005, 2011 and 2015 there were mild to moderate drought conditions in almost every year which later on affected the vegetation type of the areas greatly. The sparse vegetation decreased over the period whereas the moderate vegetation although fluctuates and decreased during high drought conditions (when the SPI value is high) but has an increasing trend. In 2010, there was a severe drought condition, which greatly decreased the moderate and sparsely vegetated area in 2011. However, the percentage of dense vegetation spiked in the respective year despite the drought conditions. One of the possible reason is the dense vegetation could be the large trees which have longer roots so they can greatly depend on the ground water even if it is far below the surface. Another reason could be that there is an irrigation system for those dense vegetation.

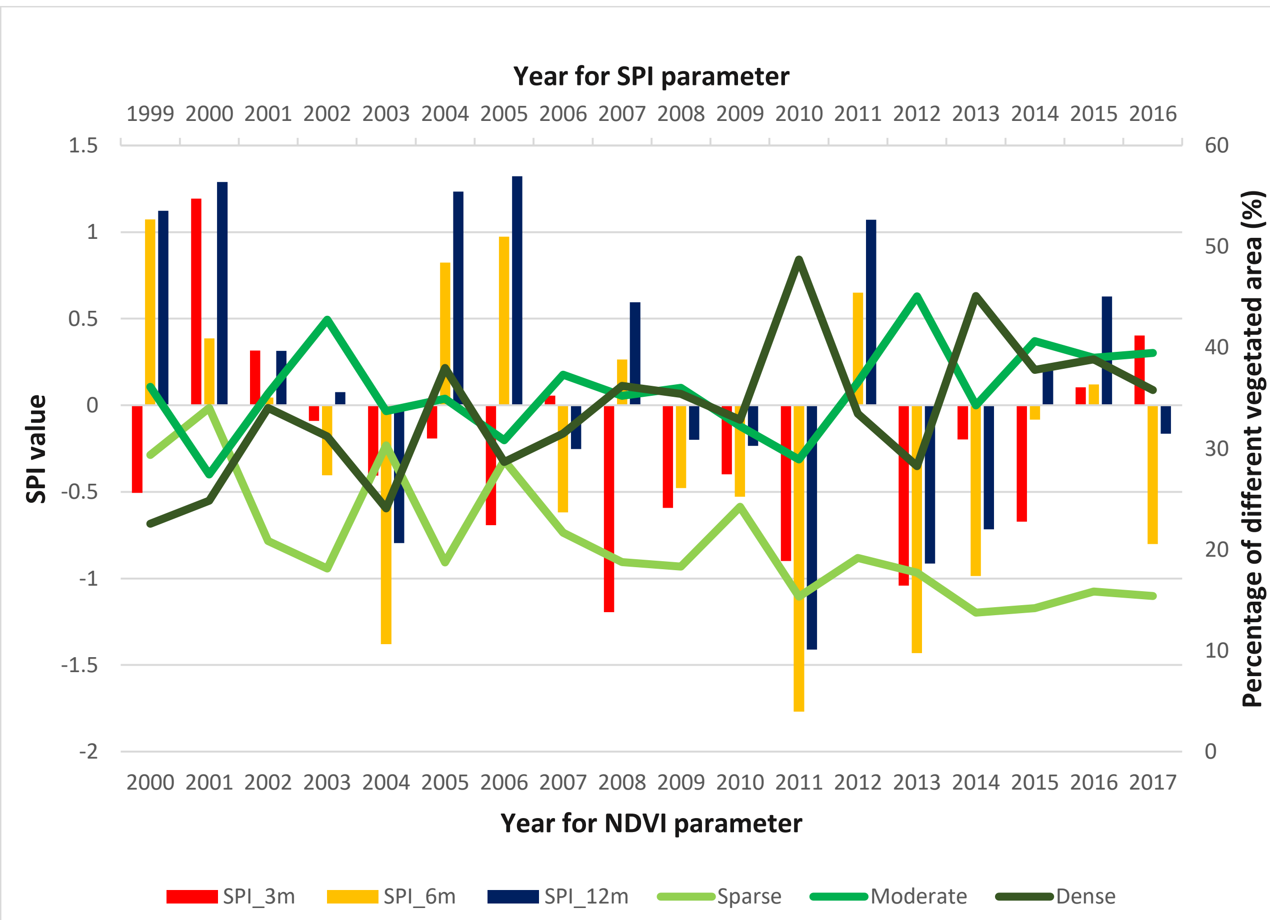


Figure 6.13: Variation of SPI (of previous year) and NDVI parameters for Pabna District

Rajshahi District

Rajshahi district had experienced drought for most of the years as shown by the SPI value in the figure 6.14. The 3 and 6-month SPI value shows a similar pattern of drought condition whereas 12-month shows lower drought conditions than two other indices. The reason behind this could be that the amount of annual precipitation was higher in those years Another noted difference is that all the other regions of the study area had experienced some degree of meteorological drought event in 2016 except for Rajshahi.

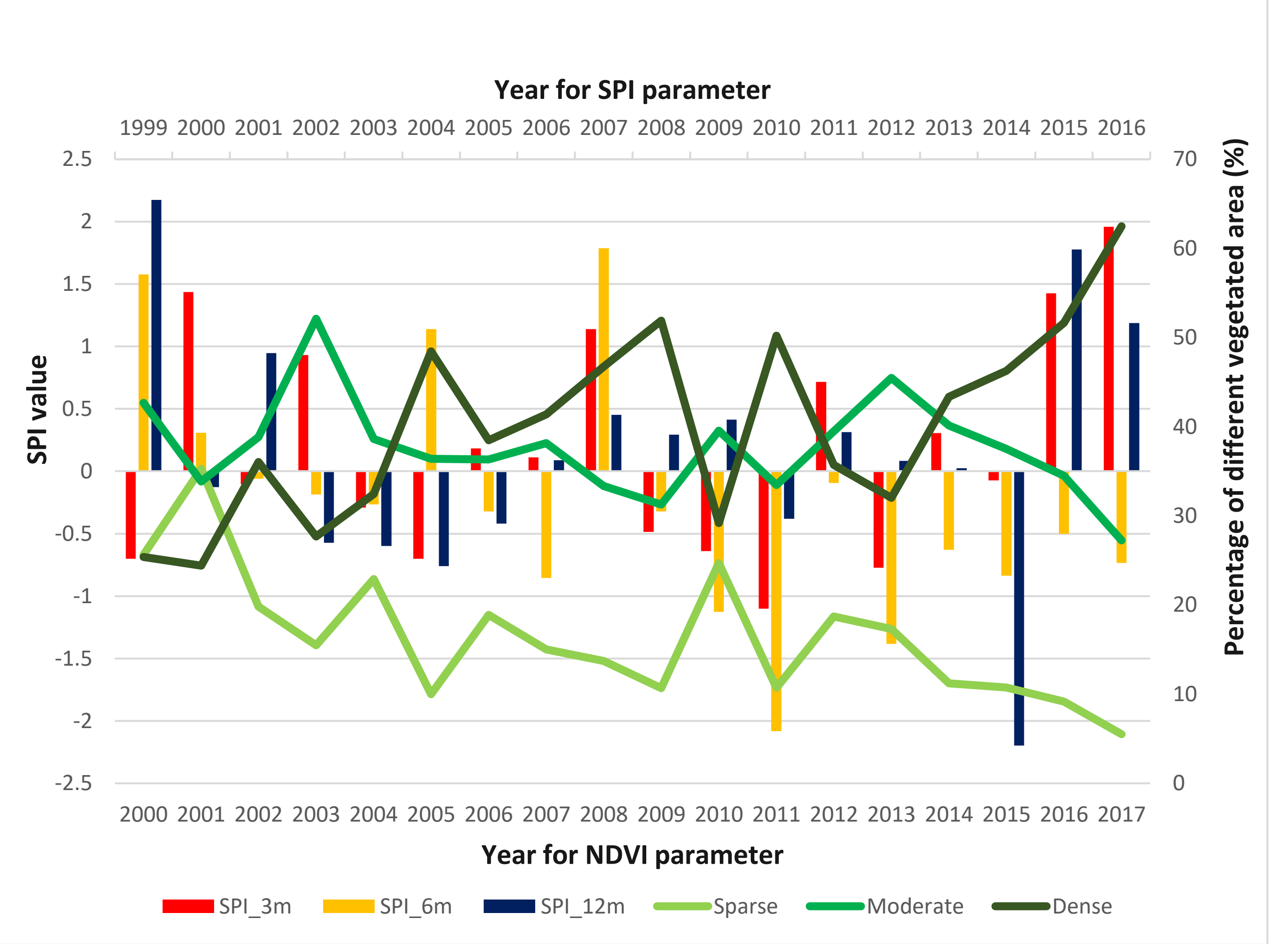


Figure 6.14: Variation of SPI (of previous year) and NDVI parameters for Rajshahi District

The percentage of the sparsely vegetated area has a decreasing trend over the time period as the meteorological drought conditions continue. However, the pattern of moderate and high-density vegetation for the region does not show any correlation with the SPI value of the previous year and is opposite with each other that is an increase of moderate vegetation decreases the dense vegetation and vice versa.

Rangpur District

There was mild to severe meteorological drought conditions from 2006 to 2014 in Rangpur district. Both the moderate and sparse vegetation fluctuates over the time but they have decreasing trend. On the other hand, amount of dense vegetation started to increase after 2001 and it has an increasing trend. The SPI value from 2000 to 2005 was high which means higher was the precipitation amount, which also contribute the growth of health vegetation.

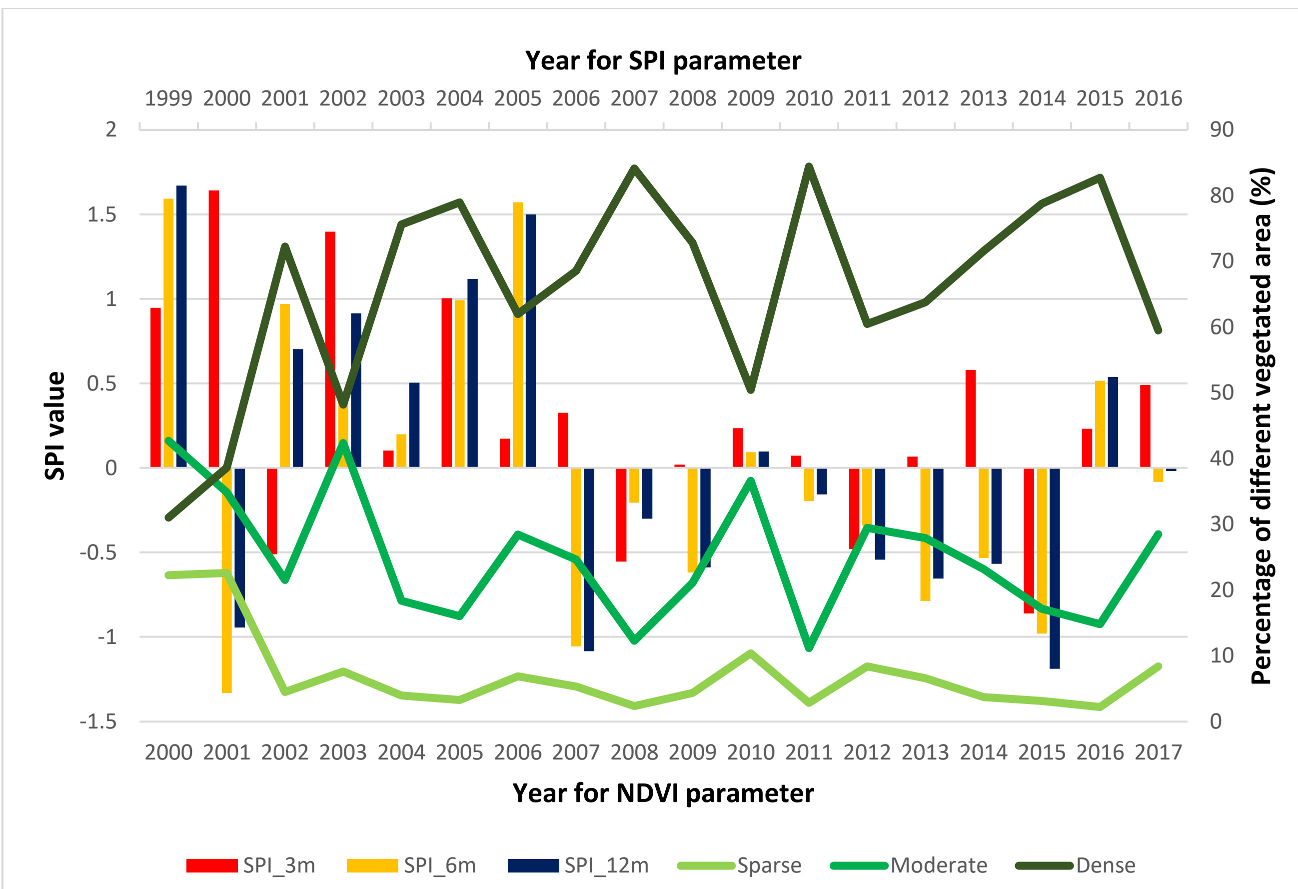


Figure 6.15: Variation of SPI (of previous year) and NDVI parameters for Rangpur District

6.5 Variations of NDVI and SWI

The hydrological and vegetative drought for the study areas that are Bogra, Dinajpur, Pabna, Rajshahi and Rangpur districts are monitored in this section. SWI is a relative measure of soil wetness of the 1-m soil layer ranging between wilting level (0%) and field capacity (100%). SWI value has been used to assess the hydrological drought and NDVI value for vegetative drought. The graphs are plotted for SWI values and the percentage of different vegetated areas in order to see how the amount of vegetation varies with drought conditions. For estimation of NDVI value satellite images are for March is considered and as the 3-month and 6-month SWI values are for May, June, July, August, September, October and 12-month SPI considered all the months, so the drought index of the past years will be used in order to study the effect of drought on vegetation. Therefore, SWI values for previous years are considered during comparison with NDVI value. The conclusions about drought are drawn on the basis of 6 and 12 months SPI value as they are estimated from medium and long term precipitation patterns. 3-month SWI value is also considered in the analysis as it represents seasonal variations. Positive value of SWI indicates drought exists.

Bogra District

The figure 6.16 shows that Bogra district had experienced hydrological drought consecutively from 2005 to 2016. Therefore, this resulted in a major decrease in dense vegetation, which on the other hand, increases the percentage of moderate vegetation greatly and sparse vegetation to some extent in the study area. The 3-month SWI value shows highest amount of drought condition in 2016 and the amount of dense vegetation decreased greatly for that time period, but the decrease does not mean that high value of SWI alone is responsible. There may be some other underlying reasons. Because, dense vegetation have a good irrigation system and is mostly supplied by deep and half-deep wells. As a result, there is almost significant change in the area percentage of the dense vegetation due to drought.

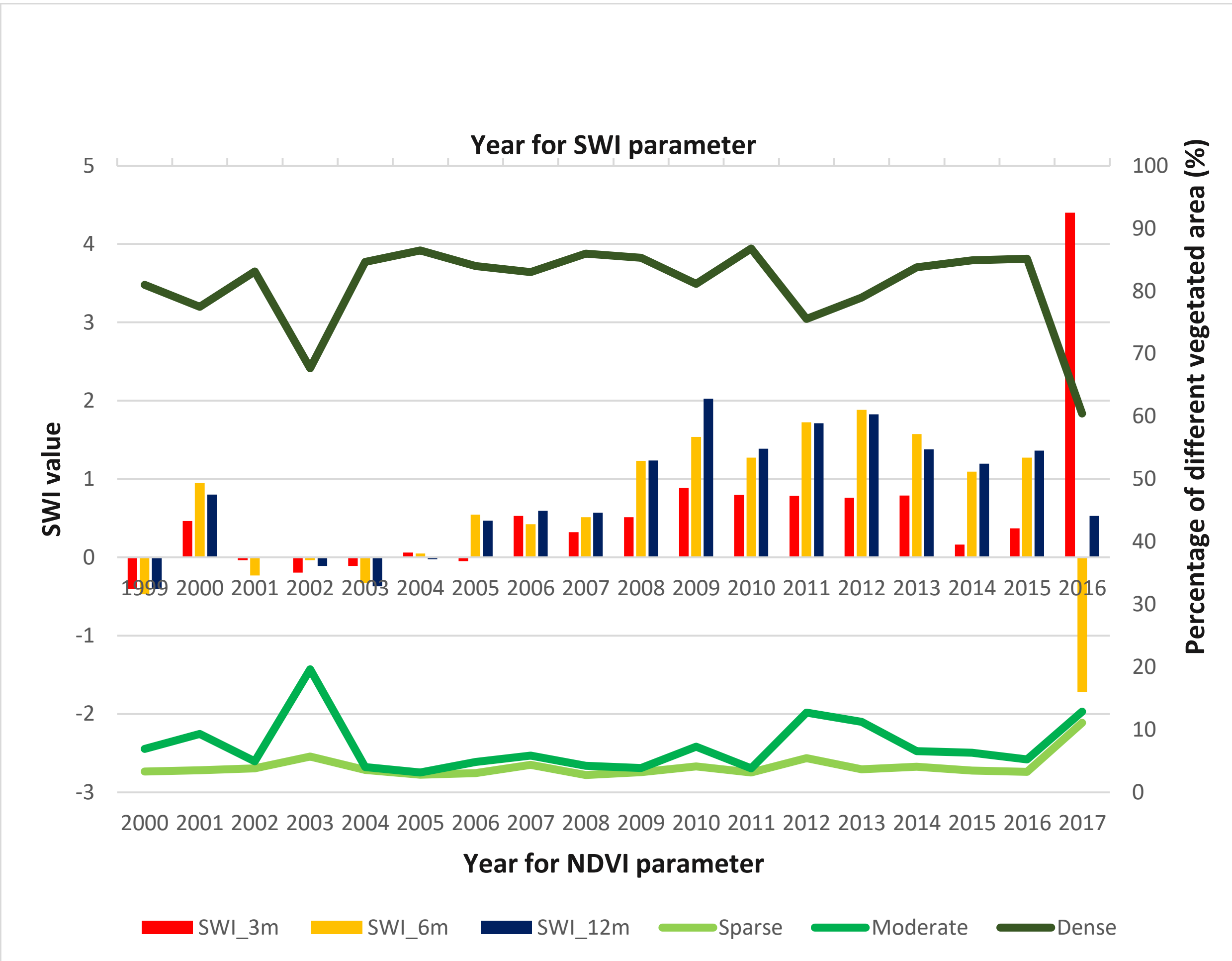


Figure 6.16: Variation of SWI (of previous year) and NDVI parameters for Bogra District

Dinajpur District

The figure 6.17 indicates that there was also a hydrological drought conditions from 2005 to 2016 in Dinajpur district. This had a great impact on sparse vegetation as it decreased greatly over the time. This decrease could be the result of hydrological drought conditions for a long term. The sparse vegetation have greater impact because pastures and shrubs mostly fall under this category, which however, depends on soil moisture where the water gets recharged from atmospheric rainfalls and nearby canals etc. The prolonged hydrological drought conditions coupling with the meteorological drought condition as seen above could have an impact on moderate vegetation also as it has a decreasing trend. On the other hand, the dense vegetation has an increasing trend over the time period proving the theory that hydrological drought has little or no effect on them.

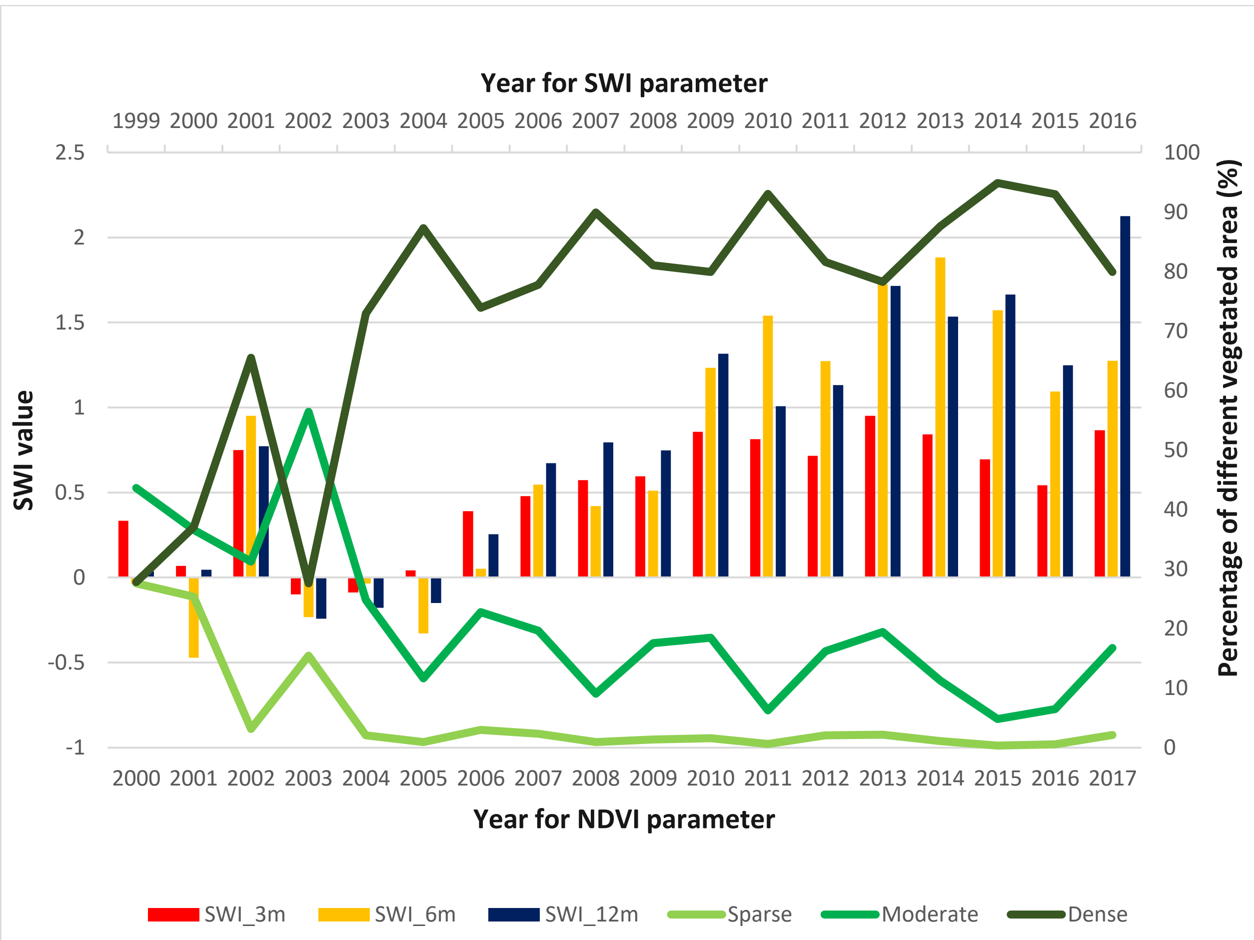


Figure 6.17: Variation of SWI (of previous year) and NDVI parameters for Dinajpur District

Pabna District

Pabna district experienced hydrological drought conditions from 2006 to 2016 and has an impact on sparse vegetation. The district had highest amount of sparse vegetation (34%) compared to other regions. The sparse vegetation started to decrease from 2008 and although it keep fluctuating, but had a marked decreasing trend until then.

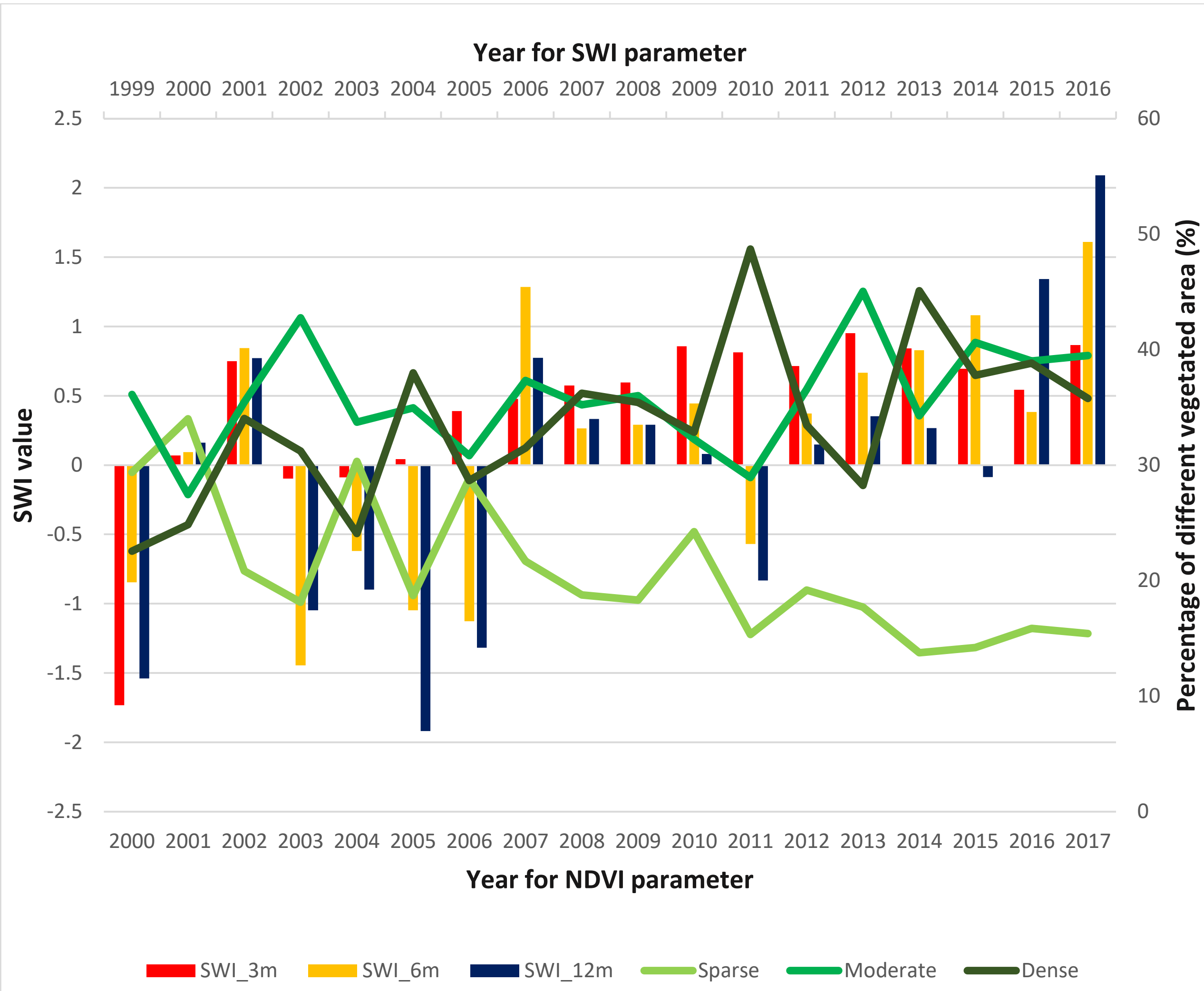


Figure 6.18: Variation of SWI (of previous year) and NDVI parameters for Pabna District

From above, it has been seen that Pabna had also experienced prolonged meteorological drought within that time period which could be one of the reason why the impact of drought is so high on sparsely vegetated area, since the recharge of soil moisture from precipitation was low. However, the rise of the percentage of sparse vegetation in 2012 as shown in the figure 6.18 could be due to the increase of amount of precipitation in 2011. The percentage of moderate and dense vegetation shows an increasing trend as the amount of sparse vegetation decrease. The reasons suggested above about decrease of sparse vegetation and increase of moderate and dense vegetation might not be true as it is just an assumption. Because there could be several other underlying reasons such as change of vegetation pattern or shrubs growing into large trees thereby increasing the density of the vegetation, improvement in the irrigation system which in turn resulted in a more healthy vegetation etc.

Rajshahi District

All the regions showed hydrological drought conditions from 2006 to 2016. Similarly, Rajshahi district had also experienced drought in that period. The percentage of moderate and sparse vegetation shows a decreasing trend over that period. The SWI value for Rajshahi district is greater than other regions and the figure shows that it has more intense hydrological drought conditions. As seen above that no pattern or correlation was found between SPI and vegetated area for this region, therefore we can assume that the decrease of vegetation could be the result of the hydrological drought only.

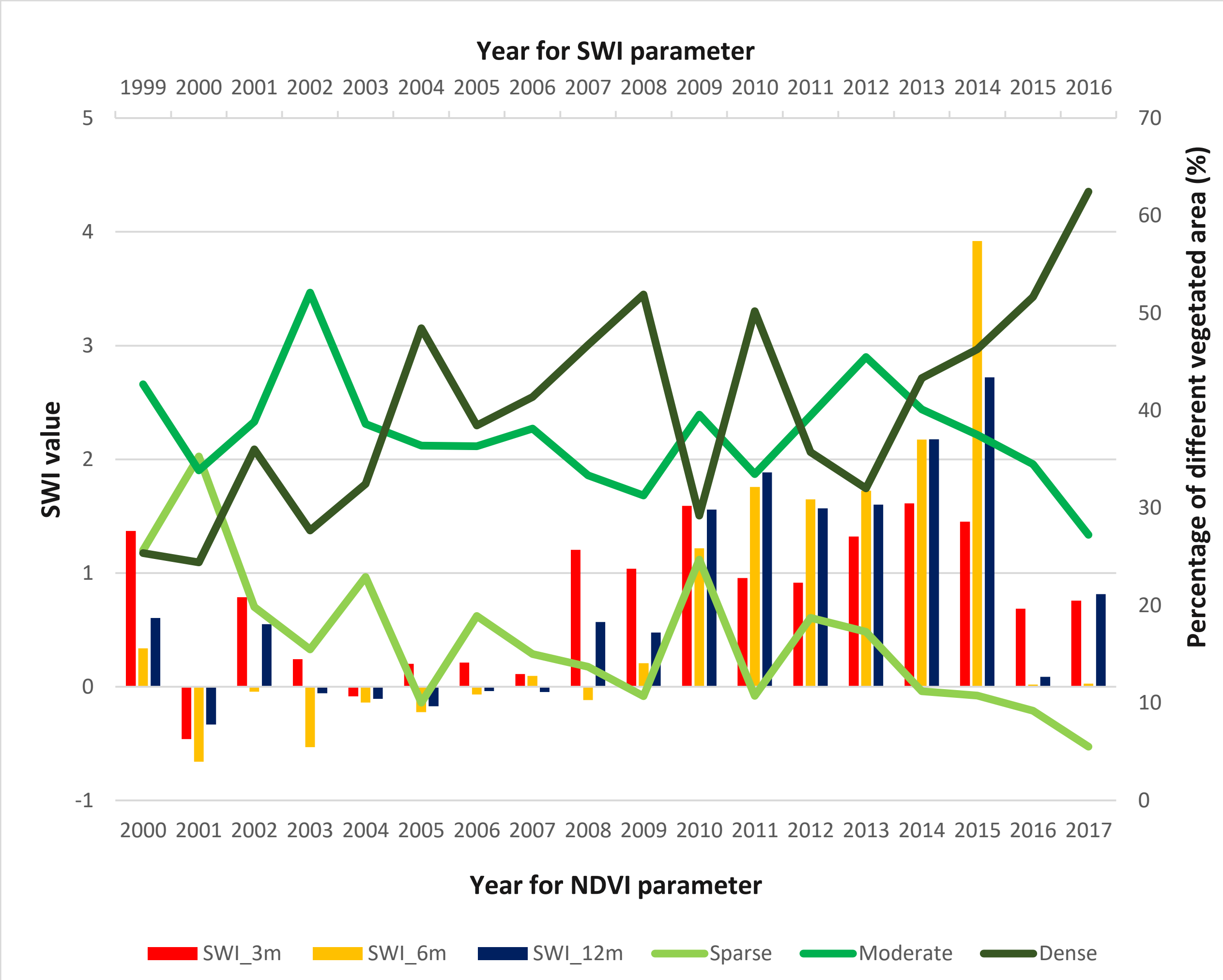


Figure 6.19: Variation of SWI (of previous year) and NDVI parameters for Rajshahi District

Rangpur District

The Rangpur district experienced hydrological drought from 2006 to 2016, like all other districts. The moderate and sparse vegetation shows a decreasing trend whereas the dense vegetation shows an increasing trend.

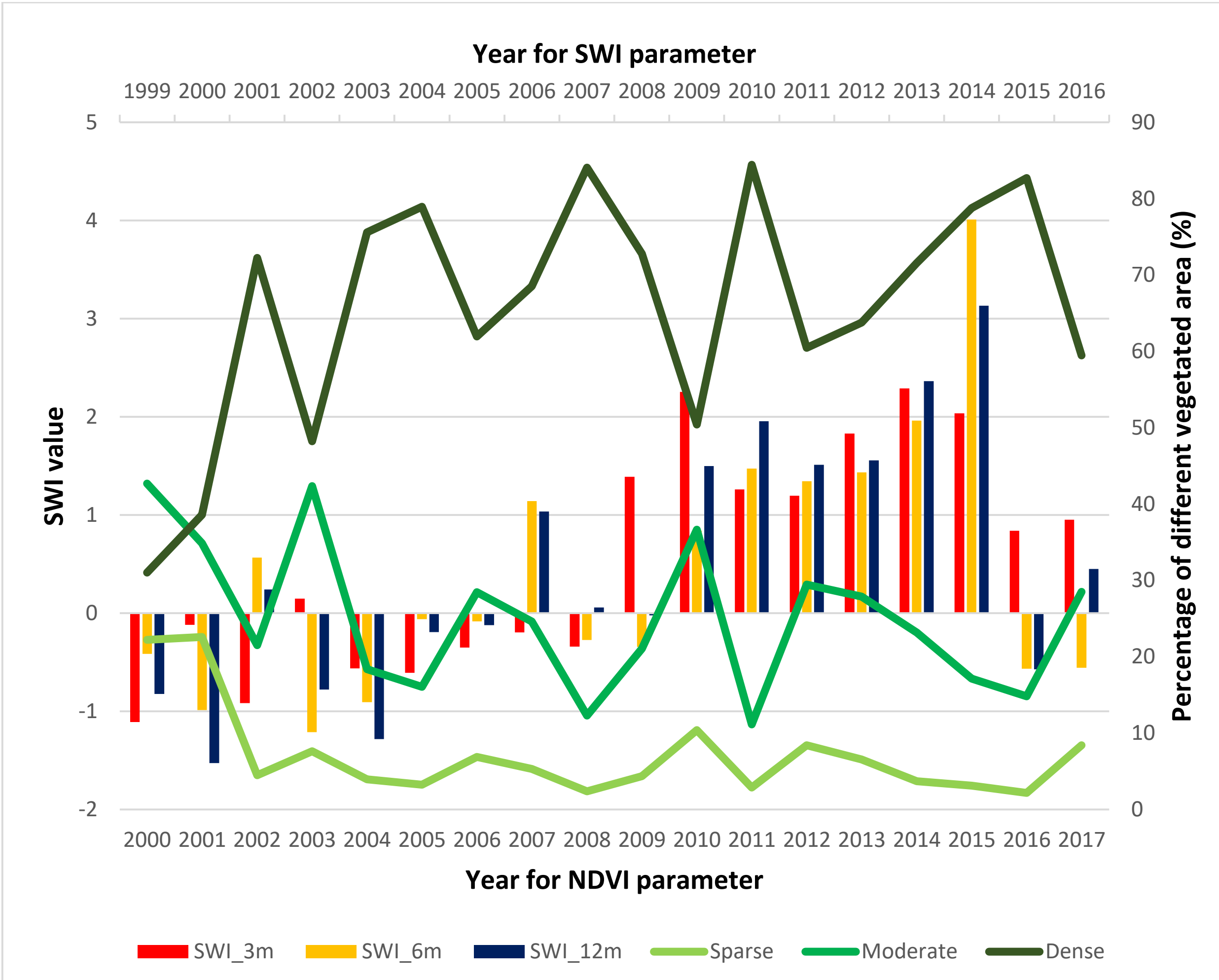


Figure 6.20: Variation of SWI (of previous year) and NDVI parameters for Rangpur District

6.6 Conclusions

The analysis has been carried out to monitor the agricultural drought conditions in north-western part of Bangladesh and compare that with meteorological and hydrological drought. Bogra, Dinajpur, Pabna, Rajshahi and Rangpur were selected as the study area. Although, all the districts lies in almost same geographical location, so there should be little or no difference in the hydro-meteorological conditions between them but the results of the analysis in many cases shows great variations and opposite scenarios. It has also been stated in many study that the meteorological drought results in hydrological droughts because of lack of rainfall, which in turn affected the recharge of small water bodies and affect the amount of soil moisture in the study area. In the analysis, it has been seen that prolonged meteorological drought conditions where the SPI value was negative for consecutive years resulted in a prolonged hydrological drought where SWI value is positive. However, a different result has been seen in many cases also, where there was hydrological drought conditions despite of the increase of amount of precipitation (when SPI value is positive).

The results also shows that sparsely vegetated areas get highly affected by both the meteorological and hydrological drought conditions than other type of vegetation. It is assumed that moderate and dense vegetation type has access to irrigation system or have longer roots so they do not have to depend on the soil moisture content like the sparsely vegetated areas, so the impact of drought on them is lower compared to sparse vegetation. However, in many cases it has also been seen that the amount of dense vegetation had decreased due to the drought conditions (as per the SPI and SWI values), this could be either due to prolonged drought conditions or some other underlying reasons. It is not necessary the changes in the vegetation was solely influenced by the meteorological and hydrological drought but there could be other possible reasons such as changes in the vegetation pattern, changes in the irrigation system, use of fertilizers , attack from pest or due to some other natural hazards or anthropogenic activities. This indicates that detailed investigations should be carried out to conclude.

Chapter Seven

Variability in Drought Characteristics

7.1 Introduction

In this chapter, drought onset timing was assessed through Standardized Precipitation Evapotranspiration Index (SPEI). Also, in order to make more accounting on drought variability United Nations Environment Program (UNEP) Aridity Index were calculated and the spatial and seasonal drought variability were assessed. Again, drought severity was assessed using Stochastic Component Time Series (SCTS) technique. *The detailed methodology of calculating SPEI, AI and SCTS is given in Chapter Three (Methodology).*

7.2 Drought Onset Assessment: SPEI Approach

The Standardized Precipitation Evapotranspiration Index (SPEI) was used to identify the drought characteristics. The SPEI's main advantage lies in its ability to detect the onset drought consistently; it is suggested for operational drought monitoring studies worldwide. Four step procedure as described in the methodology chapter was applied to calculate SPEI. The updated version of the R SPEI package was used to estimate the monthly SPEI in the study. The SPEI was computed at monthly time scale and the smaller negative SPEI means the most serious drought events tend to occur.

7.2.1 Variations in SPEI

The plot below shows twelve months SPEI for the district of Bogura. It was mentioned earlier that the smaller negative SPEI means the most serious drought events tend to occur. The negative SPEIs are related to the dry condition; a drought event is defined when the SPEI is continuously negative and reaches a value of "−1.0" or less. Hence, it is evident from the plot that extreme droughts are prevalent in all months, and in most of the months, the indices have downward trend, indicating a trend toward more intense drought. Drought is most intense in January, February, and March. However, the rest months are also highly dry. The droughts have increasing trends only in January and February months.

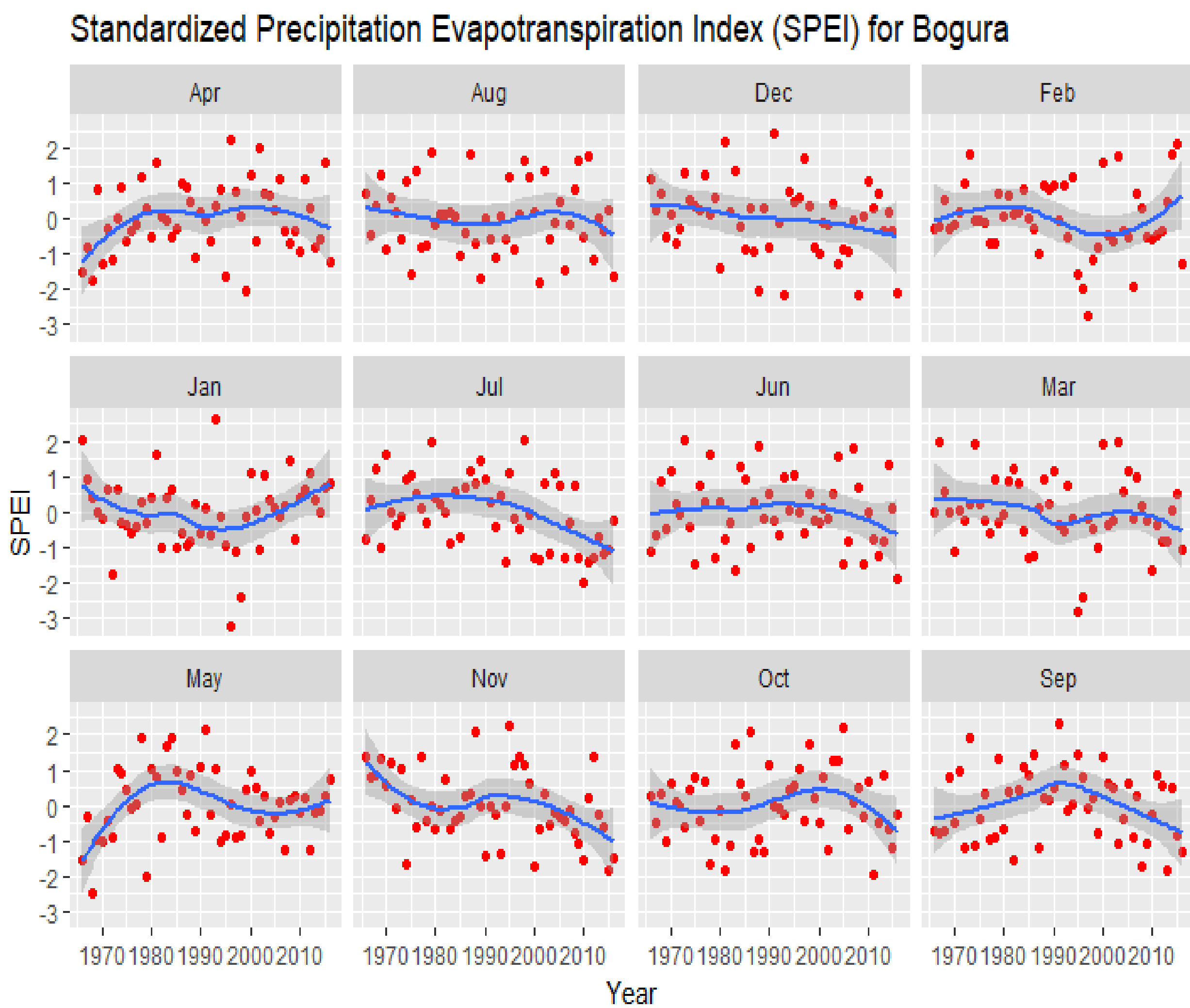


Figure 7.1: SPEI for Bogura

The indices for Dinajpur district show that the values are, for many years, well below 0 and consistently equal to below -1, indicating dry periods. None of the twelve months has an increasing trend in the value of the SPEI index. The severest downward trend is seen in the month of June, the closest being April, July, and October. The months of February, April, and July have the most consistent dry periods.

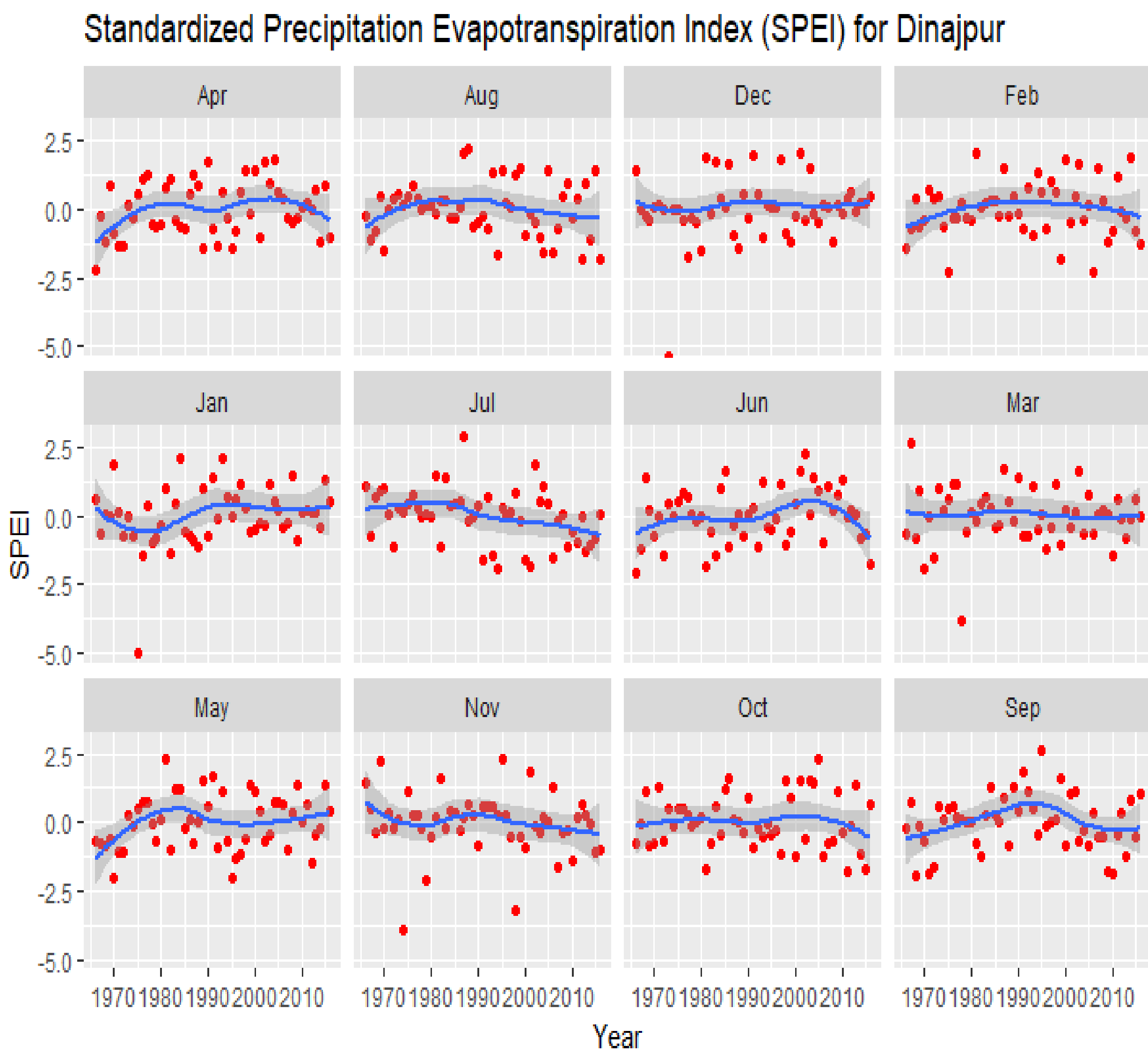


Figure 7.2: SPEI for Dinajpur

The SPEI indices for the region of Ishwardi show that most of the months have downward trend in the values of the index. The indices are with upward only for the months of December, February, and January. In most of the remaining months, there exist constant droughts. Of them, the month of March has the severest drought, followed by September and October. Moreover, the months with upward indices also have, for some years, constant dry periods.

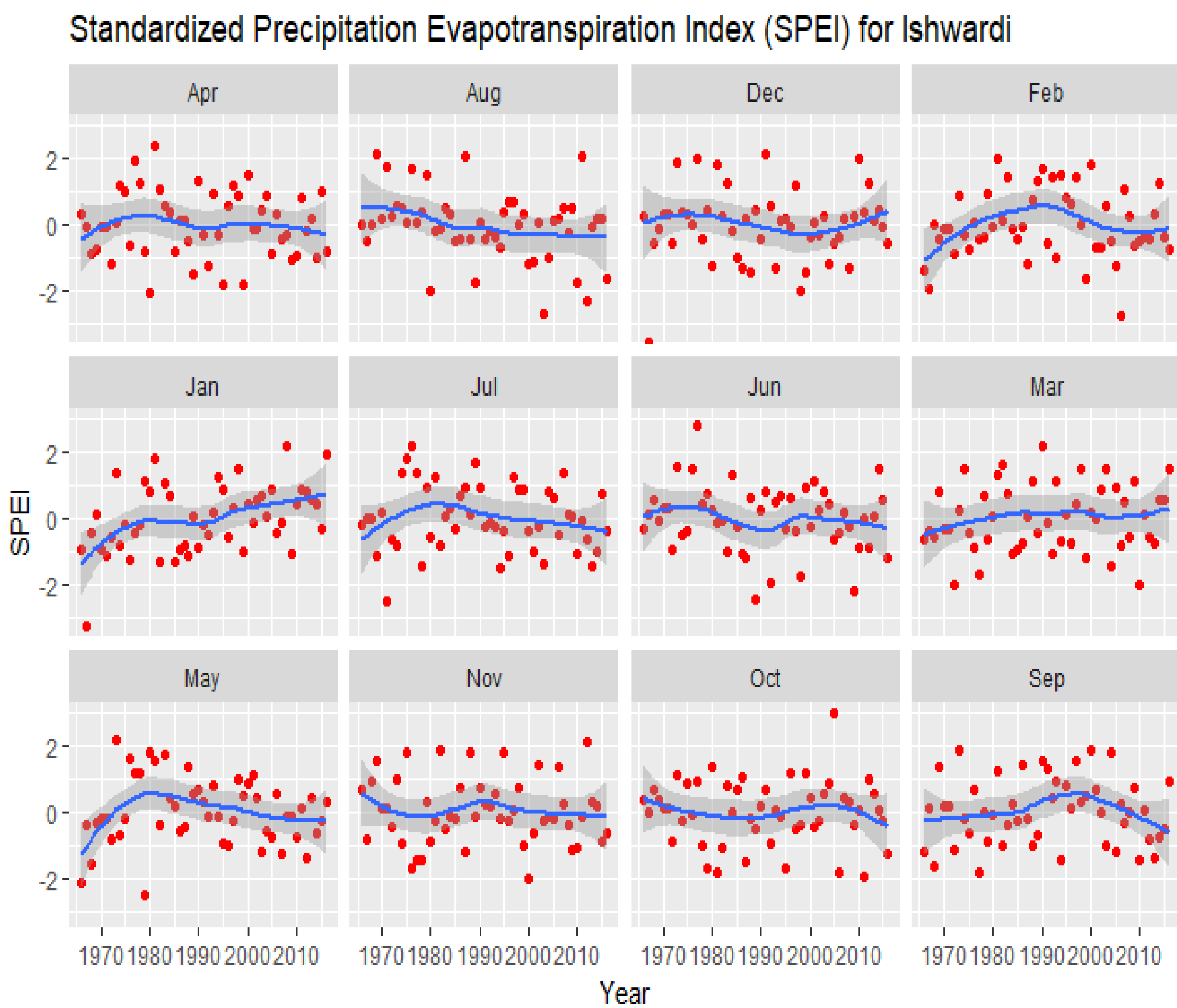


Figure 7.3: SPEI for Ishwardi

In Rajshahi, only April and January months are showing upward trend in Standardized Precipitation Evapotranspiration Index (SPEI), while both months a significant portion of years experiencing severe drought since the values equal to or below -1 are very common. Downward trends are severest in September and October months, both also having a consistent period of drought. In most months, values below zero are more common, providing evidence in favor of intensity toward dryness.

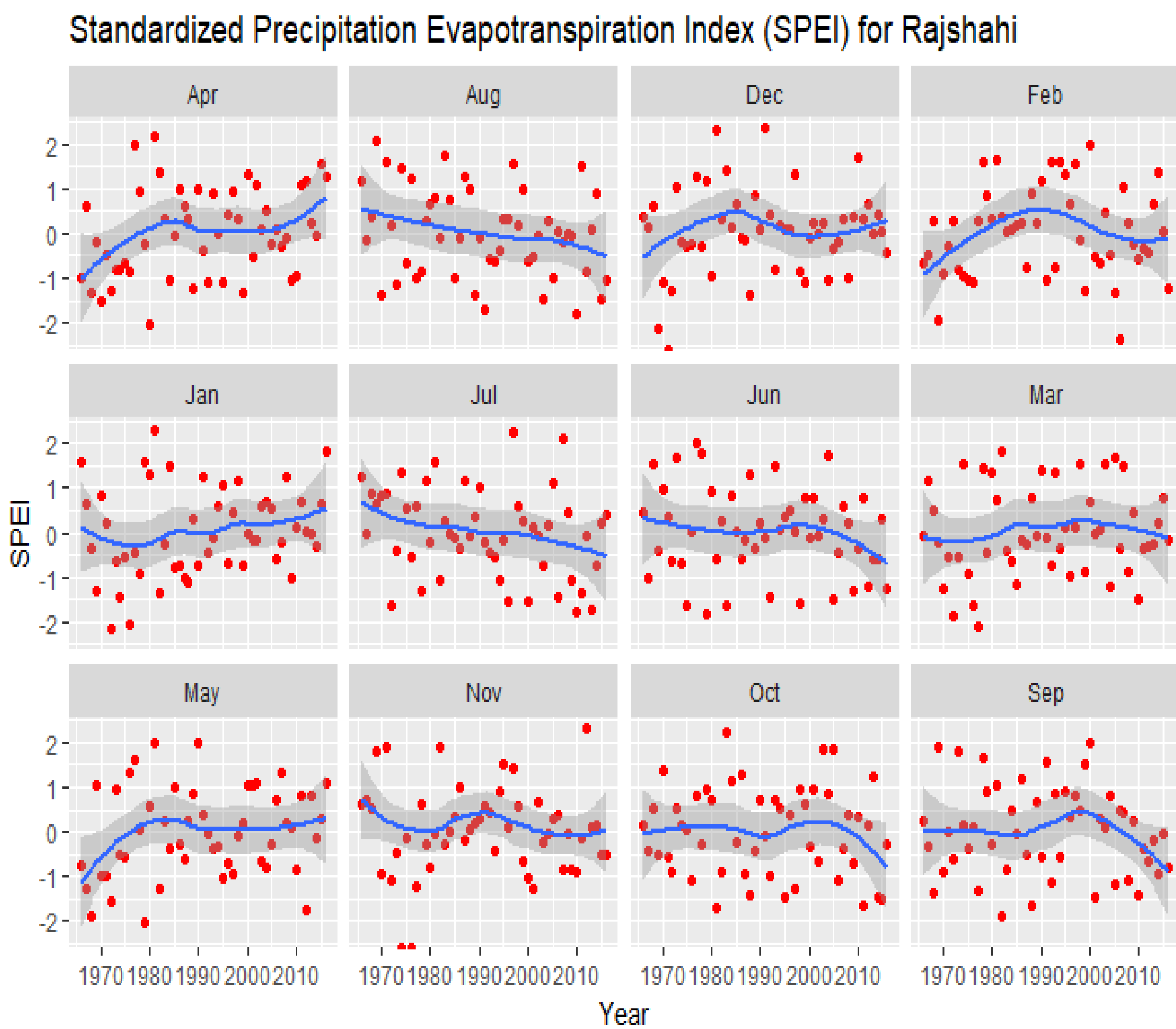


Figure 7.4: SPEI for Rajshahi

The Standardized Precipitation Evapotranspiration Index (SPEI) for Rangpur shows that in the month of May, there are several dry periods. The same is true in the case of April, June, July, October, December, while other months also experienced occasional dry periods.

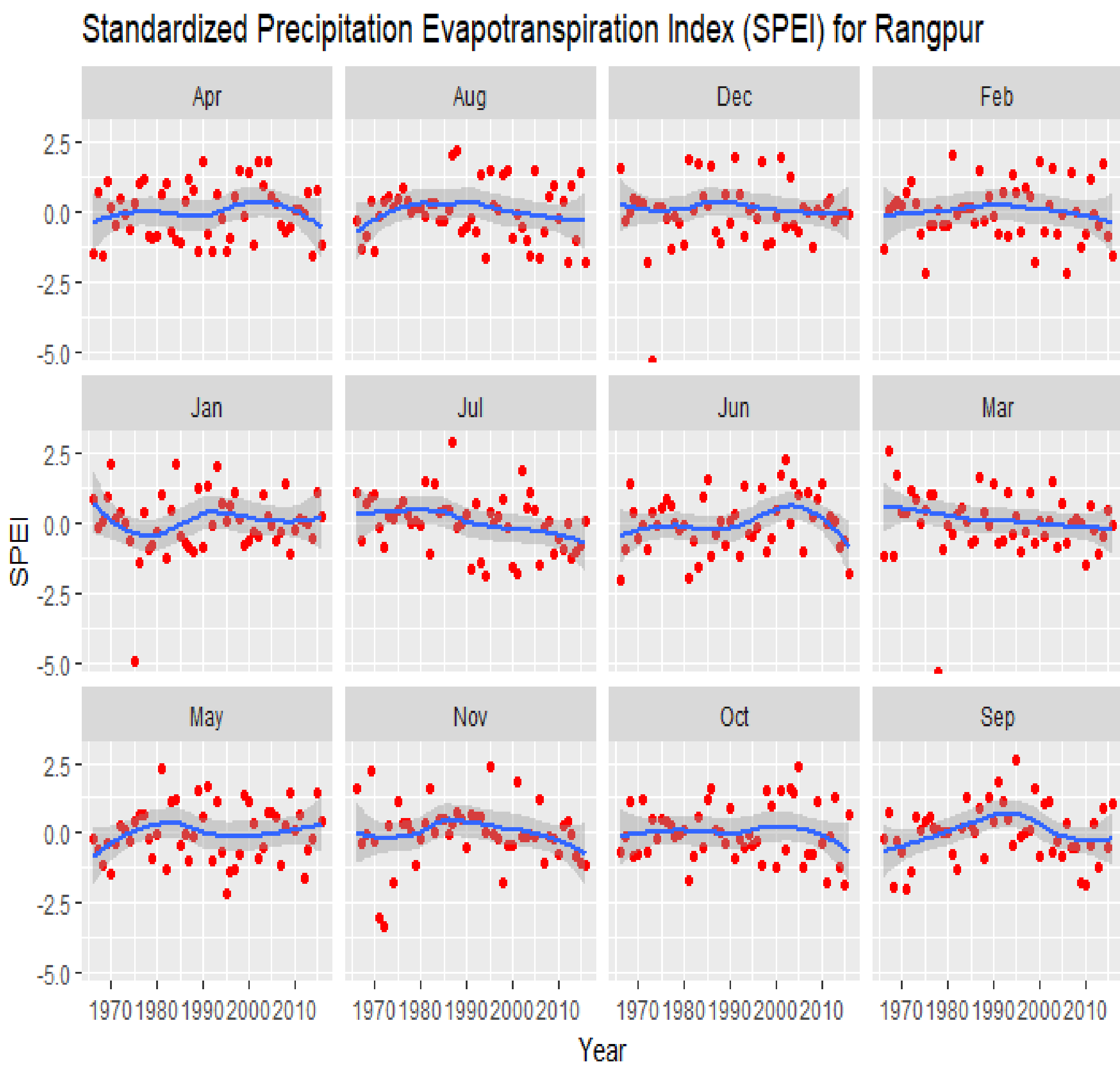


Figure 7.5: SPEI for Rangpur

The box plot of SPEI's suggest that drought is most severe in the regions of Dinajpur and Rangpur, where the index drops as low as almost -5, while only -1 is enough to be classified as a dry region. In both regions, there are a number of indices below interquartile range, which indicates they are atypical outcomes. Apart from this, the distributions of the index in the five regions are alike, the mean remaining close to zero, which implies, when considered with the fact that there are some extreme negative values, the regions are more tended to drought than wetness.

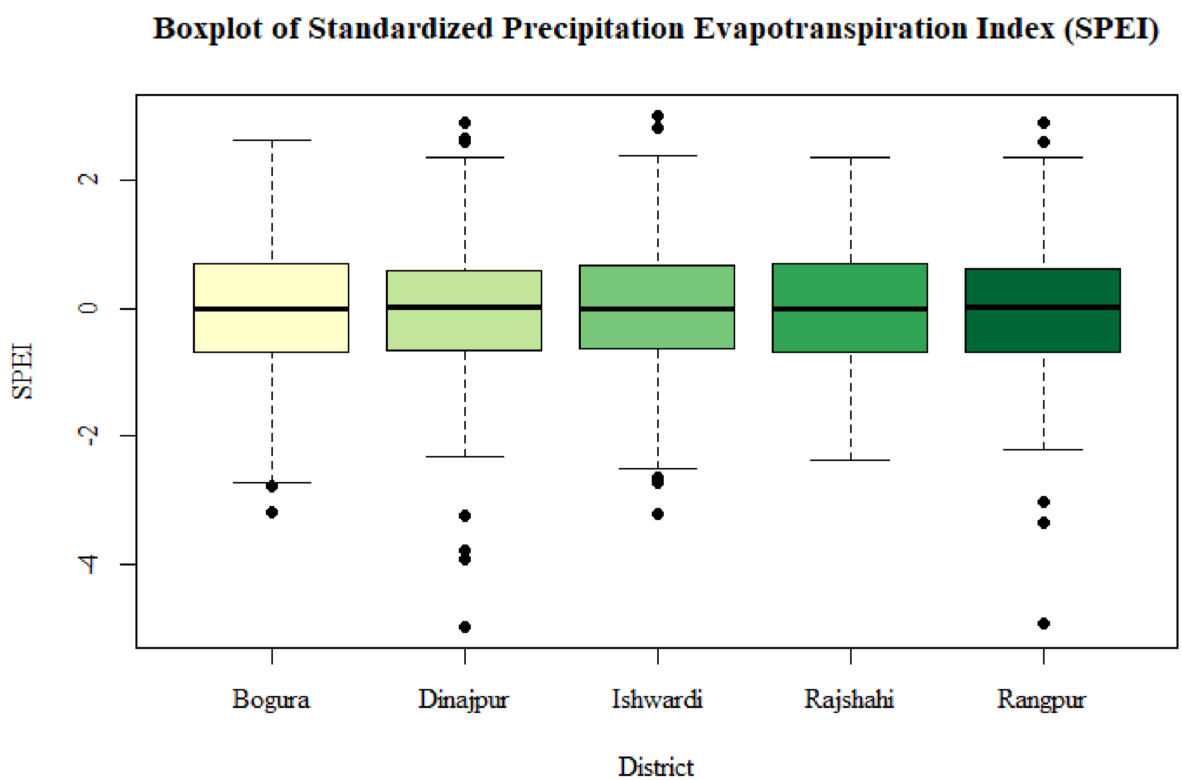


Figure 7.6: Box Plot of SPEI for different stations

7.3 Spatio-temporal Changes in Drought: UNEP Aridity Index Approach

Aridity is a measure of degree of dryness which indicates lack of moisture, thus arid climate results in lack of vegetation. We employ the United Nations Environmental Program ((UNEP, 1994) formula for Aridity Index which is obtained as annual precipitation and potential evapotranspiration. In this case, the boundaries that define various degrees of aridity are provided in the table:

Table 7.1: Classification based on aridity index

Classification	Aridity Index	Global land area
Hyperarid	AI < 0.05	7.5%
Arid	0.05 < AI < 0.20	12.1%
Semi-arid	0.20 < AI < 0.50	17.7%
Dry subhumid	0.50 < AI < 0.65	9.9%

Potential evaporation (PE) or potential evapotranspiration (PET) is the amount of evaporation that would occur if a sufficient water source were available. To estimate potential evapotranspiration, we obtained data from www.timeanddate.com for each region separately. We took the day lengths and then calculated mean day length (in hour). Heat index and alphas (α's) were subsequently calculated to finally attain PET and aridity index.

7.3.2 Spatial variation in Aridity Index

Results of the Aridity Index analysis are summarized in Table 7.2, which reveals that the district of Dinajpur experienced maximum aridity index (0.39), followed by Rangpur (0.38). Thus, Rangpur district is sometimes hyperarid, based on climate classification by

UNEP, shown at table 7.1, (since there are values less than 0.05), while at other times it produced a semi-arid climate (since maximum value was 0.38). However, mean value is 0.07, indicating a generally arid region.

Table 7.2: Summary of Aridity index for the five regions

Regions	Minimum AI	Maximum AI	Mean AI
Rajshahi	0.000329	0.251237	0.046569
Bogra	0.01247	0. 33964	0. 05244
Ishwardi	0.0002938	0.2763700	0.0491244
Rangpur	0.01603	0.38262	0.07269
Dinajpur	0.01310	0.39132	0.06783

Whereas Rajshahi region has aridity index as low as almost zero, indication a hyperarid climate, while at other times being semi-arid (being 0.25). The mean value, however, being 0.05, indicates that the area is generally arid. The situation is almost same in the case of Ishwardi region. It may be deduced that they are same for being two regions having latitudes similar, where the intensity of sunlight and hence of temperature is fairly same.

For the same reason, we deduce, that the climate condition in Bogra is similar to Rajshahi and Ishwardi regions. Our assumption is strengthened by the fact that the climate condition in Rangpur and Dinajpur districts are similar. Like that in Rangpur, the climate of Dinajpur is as intense as hyperarid and as modest as semi-arid. As a whole, these two regions are less arid than Rajshahi, Bogra, and Ishwardi, a finding justified by the fact that the latter regions are geographically located southern, where the sun shines more directly than the former two districts. Thus, it is evident that the regions which are exposed to more sunlight are ultimately more prone to be arid although all of our study regions are at some time point hyperarid, the most extreme climatic condition based on aridity index. Based on mean aridity index, it can be assumed that all regions are generally hyper-arid.

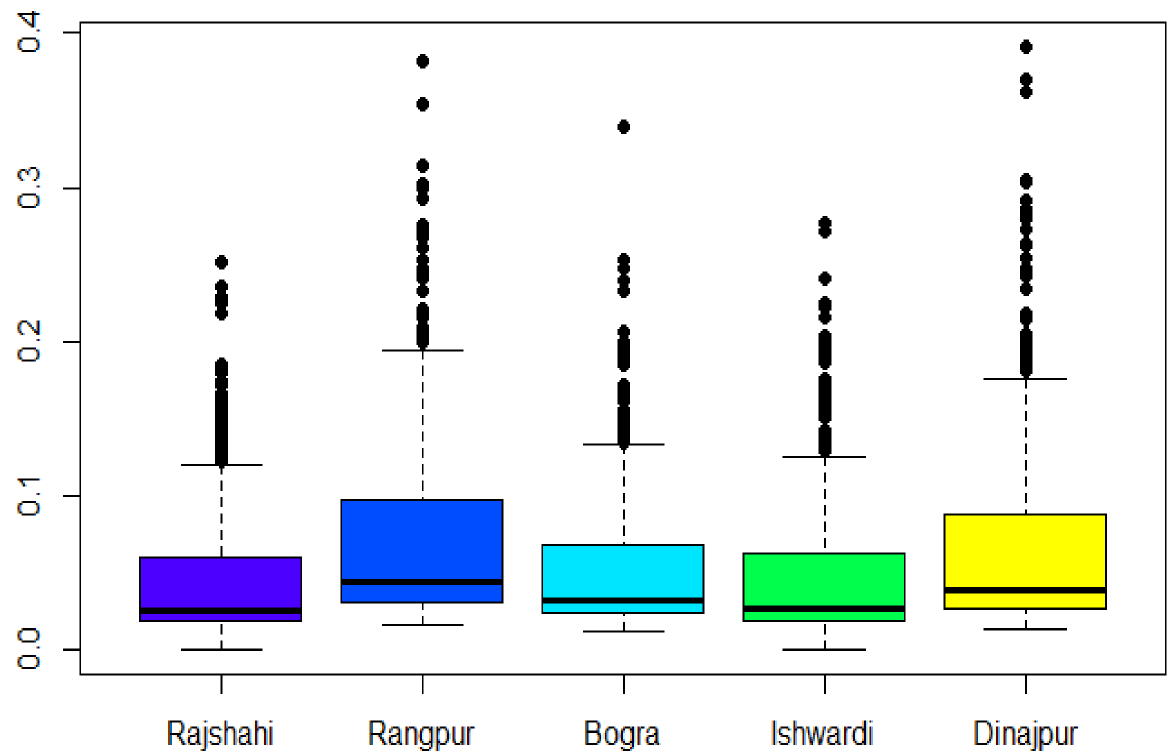


Figure 7.7: Fluctuation in Aridity indices in the five target regions.

The variation of aridity indices of the five regions are shown in Figure 7.7 (Box Plot). The figure shows that the distribution in five regions has a common outcome— that in all five regions there are some outliers above the general interval, a fact which indicates that although the regions tend to be hyperarid and arid, they are a number of semi-arid and atypical months.

The Figure 7.8 (histogram) reveals that in Rajshahi, most months are hyperarid (having the frequencies of values less than 0.05, indicative of hyperaridity) and fewer arid months.

The first point is also true for the other regions. As we saw earlier, there are some months in Rangpur and Dinajpur regions which are semi-arid. Now it is revealed from this histogram that there are not many such month as the frequency of semi-arid months are small.

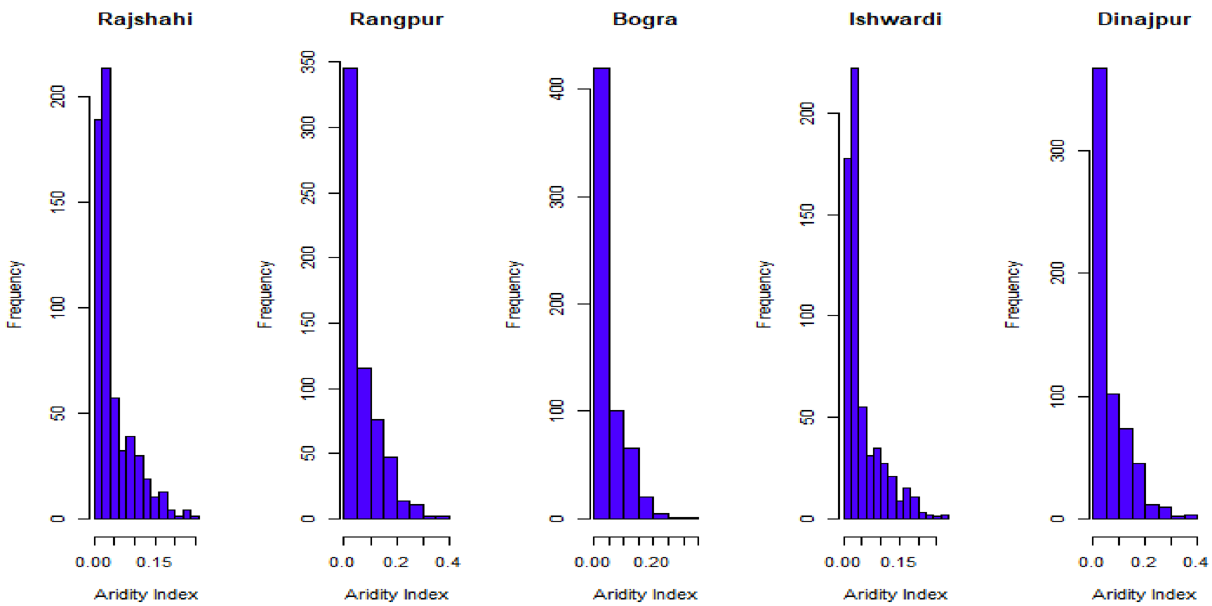


Figure 7.8: Histogram of Aridity indices in five different regions.

There is a common pattern of aridity in all five regions. They all have relatively higher number of months with smaller aridity indices and very fewer months with higher aridity indices. The fact is indicative of the fact that most months in all regions tend to be arid or hyper-arid.

7.3.3 Seasonal variation in Aridity Index

It is found that generally winter seasons are arid and summer and rainy seasons are mostly hyperarid. The climatic conditions based on aridity indices are almost same in summer and winter season.

Table 7.3: Climatic condition based on mean aridity index in three different seasons.

Season	Minimum AI	Maximum AI	Mean AI
Winter	0.07498	0.17847	0.11602
Summer	0.02095	0.04680	0.03268
Rainy	0.01730	0.04046	0.02613

The Table 7.3 and Figure 7.9 & 7.10 reveals that winter seasons are mostly 'arid', a fact justified from all three values- minimum, maximum, and mean values, and summer and rainy seasons are mainly hyperarid. Note that, the smaller values of aridity indices indicate more extreme arid climate, thus a season with a value of aridity index of 0.2 is less arid than a region with aridity index 0.04.

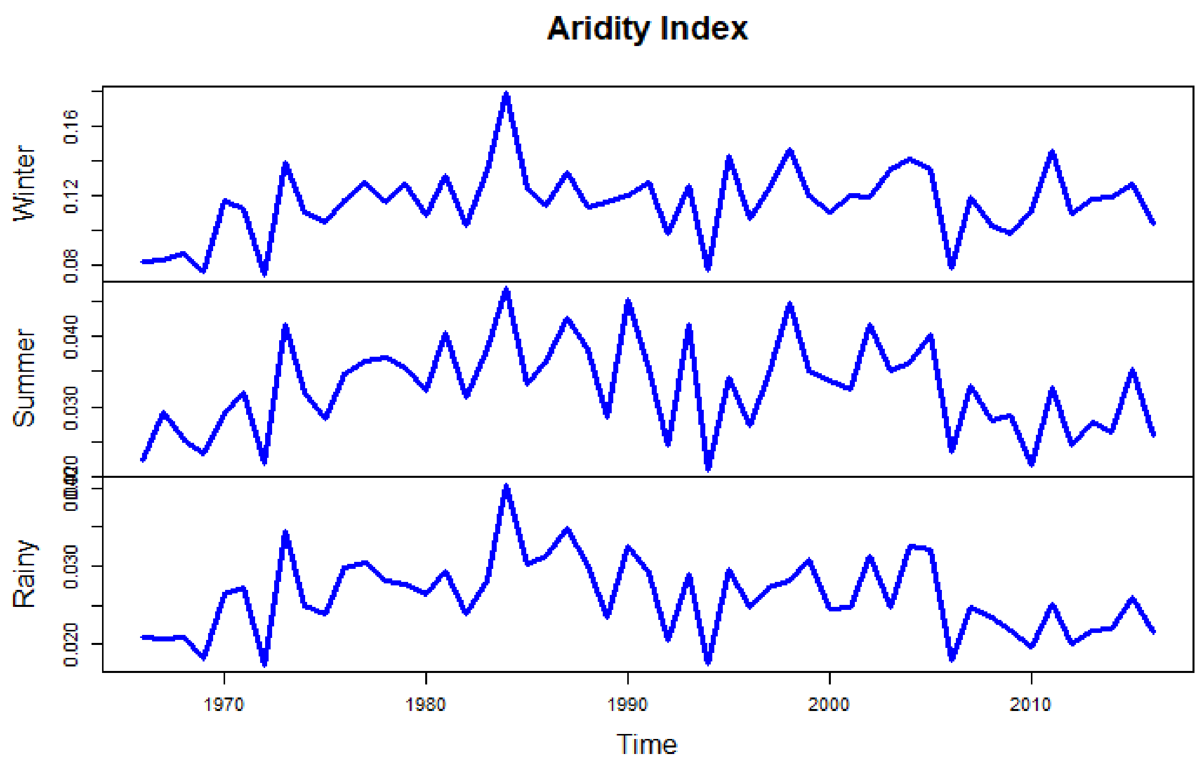


Figure 7.9: Fluctuation in Aridity indices over time (1966-2016).

However, in the case of winter season, there are relatively many more years with comparatively moderate values of aridity indices than smaller and higher values, albeit all values are indicative of an ‘arid’ season since they fall in the category 0.05 < AI < 0.20. Also, rainy season aridity indices shows a pattern fairly similar to that of summer season. There are equal number of years with hyper-arid rainy years, arid rainy years and semi-arid rainy years. In case of summer season, although no values are higher enough to consider indicative of less intensive than arid or semi-arid seasons. Hence, there are equal number of years with hyper-arid summers, arid summers and semi-arid summers.

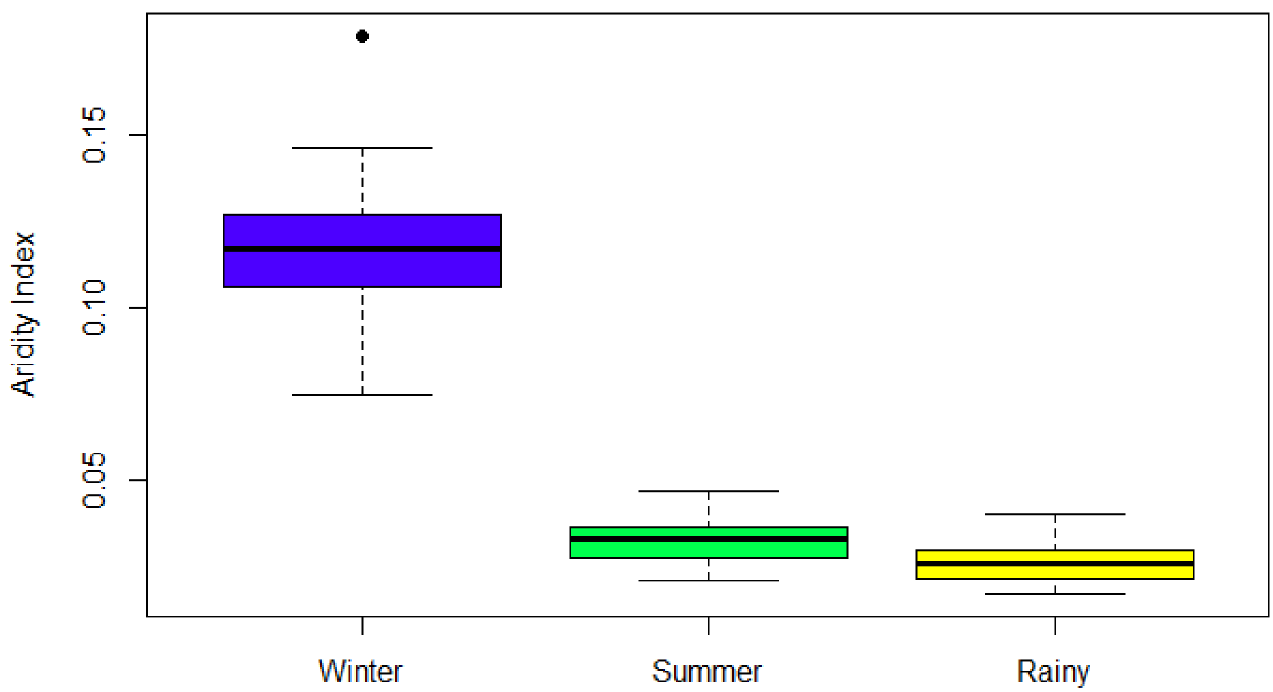


Figure 7.10: Fluctuation in Aridity indices in three different seasons.

The study also employed De Martonne (De Martonne, 1925) Aridity Indices and high variability in aridity was observed like as UNEP aridity indices. The graphs on De Martonne Aridity Indices are given in the Appendix.

7.4 Drought Severity Assessment: SCTS Technique

Drought potential can be assessed using the Stochastic Component Time Series (SCTS) Technique. Stochastic Component Time Series value for each year is calculated by dividing the difference between total and mean annual rainfall by the standard deviation of rainfall for each year. For each station, there is a minimum value of SCTS and also a maximum value of SCTS. ***The difference between the maximum and minimum value has been divided by three to get the probability of four drought classes as Low, Moderate, High and Very High drought.*** The probable drought classes for the considered stations are given in Table 7.4. The values of Stochastic Component Time series are given in **Appendix A.**

Table 7.4 : Stochastic Component Time Series values for probable drought severity classes

Station	Maxima	Minima	SCTS for Drought Severity Classes*			
			Very High	High	Moderate	Low
Bogura	13.235 (2003)	7.206 (1989)	7.206	9.215667	11.22533	13.235
Dinajpur	11.442 (1990)	7.392 (1995)	7.392	8.742000	10.09200	11.442
Ishwardi	13.671 (1982)	6.468 (1989)	6.468	8.869000	11.27000	13.671
Rajshahi	12.153 (1994)	7.857 (1997)	7.857	9.289000	10.72100	12.153
Rangpur	12.947 (1990)	7.566 (1989)	7.566	9.359667	11.15333	12.947

**Note: The value for Drought Severity classification varies from district to district, based on the maximum and minimum values of the district, since the difference between the maximum and minimum value of a district has been divided by three to get the probability of four drought classes as Low, Moderate, High and Very High drought, for that district.*

Analyzing the values of the SCTS (given in appendix), we found that SCTS for Bogura district showed new cyclic trend in every new decade. The trends, however, tend to be neutralized, regressing back to close to the mean value, which is around 10, implying a probable high drought condition. The Stochastic Component Time Series (SCTS) for Dinajpur district does not show any significant trend, remaining constant, close to the mean value (9.375), which falls in the range of very high to high probable drought. The Stochastic Component Time Series (SCTS) for Ishwardi also showed a fairly constant sequence, remaining very close to the mean observation (10.11), which implies moderate to high probable drought exists in the area. The Stochastic Component Time Series (SCTS) for Rajshahi district shows that the components have high values at the start of almost each decade, decreasing thereafter. Yet, the values are fairly wandering about the mean value (9.731), which, for Rajshahi district, implies moderate to high probable drought. The Stochastic Component Time Series (SCTS) for Rangpur district have irregular trends, but the values does not wander much from the mean value (9.723), implying high to moderate probable drought.

Chapter Eight

Volatility, Instability and Predictability of Drought Proneness

8.1 Introduction

Previous studies attempted to analyze the trend in rainfall in the North western part of Bangladesh, but no previous study attempted to assess the volatility dynamics of the rainfall data in North West Bangladesh. But it is important to assess volatility dynamics and transition pattern of rainfall for predictability of drought. The following study aims to assess the volatility dynamics and time-varying jumps in rainfall by the application of GARCH-jump model. Also to understand the transition pattern of rainfall, Markov chain of different steps is conducted to visualize the dependency relationship of rainfall, that is dependency of current rainfall upon the rainfall of previous time periods, which provides one realization of the weather process. The detailed methodology of GARCH-jump model and Markov Chain are provided in Chapter Three (Methodology). *Anomaly in the rainfall and less predictivity of drought scenario was revealed in previous chapters, in this chapter we shall verify this by assessing rainfall volatility, jumping behavior and transition pattern.*

8.2 Volatility in Rainfall and Instability in Drought Condition

To verify the less predictivity of droughts revealed in the previous chapters, volatility and jumping behaviour of rainfall was estimated using GARCH-jump model. The assessment was conducted for pre-monsoon and monsoon rainfall and the results are presented in

Table 8.1. The results revealed that jump parameters are significant for both pre-monsoon and monsoon (out of 8 parameters 6 parameters are significant at 5% level of significance and 2 parameters are significant at 1% level of significance), suggesting the existence of major jumps during these two periods. This is expected as the country experiences more rains during these two seasons.

Table 8.1 shows that parameters, ω, α, β and θ are significant for both the seasons. This indicates significant volatility in time series (ω). The significant value of α indicates the volatility is due to a random variability of rainfall. The significant value of β indicates the volatility will persist with time and therefore, rainfall variability is unpredictable for the study area. A significant jump in rainfall series (θ) was also noticed which indicates a shift of rainfall regime from wet to dry or vice versa can occur at any time.

Table 8.1: Estimated parameters of GARCH-jump models for pre-monsoon and monsoon rainfall over the study area

Parameters	Meaning of the Parameter	Pre-monsoon	Monsoon
π	Dependence of current value on previous values	**0 .0146**	**0.0200**
μ	Expected returns based on past information	0.0047	0 .0016
ω	Squared volatility	*0.0418*	**0.0668**
α	Influence of random deviations on volatility	**0.1100**	**0.0989**
β	Persistence of volatility over time	**0.9051**	**0.8188**
θ	Mean of jump size	*-0.1589*	*-0.1558*
d^2	Variance of jump size	**0.5199**	**0 .6001**
λ_0	Conditional jump intensity parameter	**0.0480**	**0.0965**

Bold number indicates significance at 1%; Italic numbers indicate significance at 5%

The results further reveal that the jump intensity parameter λ_0 is also statistically significant for both pre-monsoon and monsoon, implying that the jump intensity varies over time. Moreover, since $\lambda_0 > 0$, it can be confirmed that the GARCH-jump model is correctly chosen for describing the jump behaviour of rainfall. These findings reconfirm the fact that dry and wet condition in northwest Bangladesh fluctuates due to the volatile nature of rainfall.

8.3 Erratic Transition in Rainfall & Rapid Fluctuation in Drought Proneness

Finally, to verify the less predictability of drought scenario (as revealed in previous chapters) a Markov Chain model was developed to evaluate transition behaviour of rainfall and develop drought proneness index. The model was developed considering weekly rainfall less than 5 mm as the dry week and more than 5 mm as the wet week. The transition counts for the Markov model wetness/dryness condition of the present week compared to the previous week was estimated based on this threshold. In the same way, the transition probabilities for the next step was computed based on the dependency of present week condition on the rain status of two weeks before.

Similarly, higher-order transition probabilities (up to 10th step) were calculated which were finally used for the calculation of DI. The changes in DI values over the transition steps for different stations are presented in Figure 8.1. The figure shows that DI gradually become stable with time. For example, the DI values at Bogra was 0.179 for the first step, which indicates severe drought. It became moderate drought with DI value of 0.232 in the second step and mild drought with DI value of 0.257 at the third step. The DI value gradually increases and become stable at 0.267 after the 9th step. Similar changes were noticed at other stations. The results revealed that DI values change significantly within a short period. This again proves that variability of rainfall has made the drought condition rapidly varying with time. Large variability in rainfall has made the droughts unpredictable in the study area.

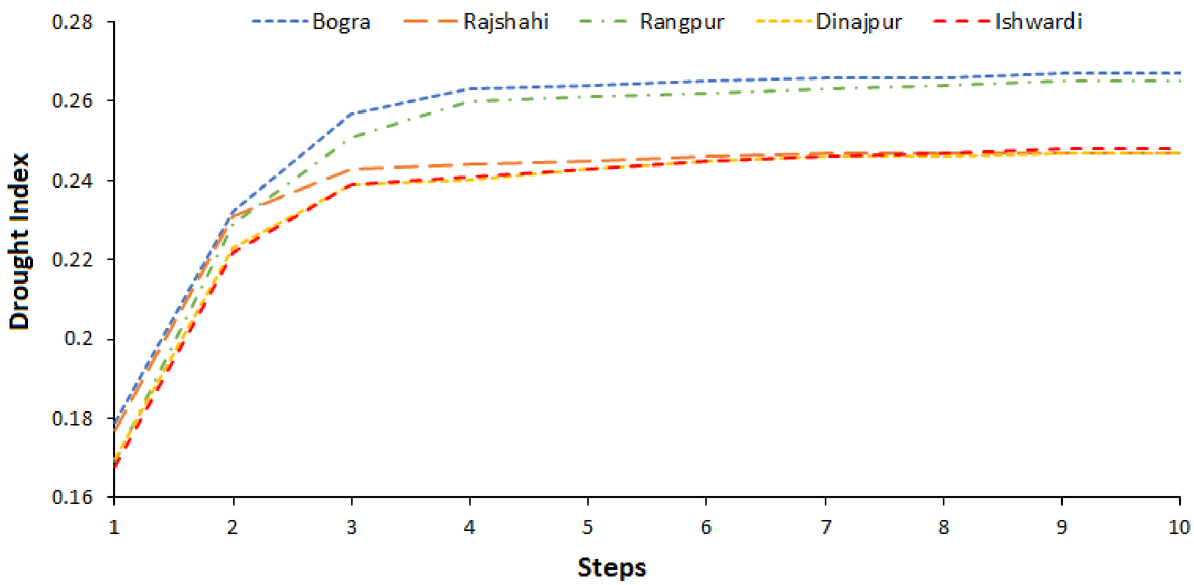


Figure 8.1: Drought Index in different steps obtained using transition probability matrix

8.4 Developing Drought Index From Transition Probability Matrix

The detailed methodology of measuring drought by application of Markov chain probability model is described in the Methodology chapter. Here we recall that from transition probability matrix, an index of drought proneness is defined as:

$$DI = P11 \times P01$$

This index of drought proneness is bounded by zero and one. Higher the value of DI, lower will be the degree of drought proneness.

Table 8.2: Degree of Drought Proneness based on Drought Index

Criteria	Degree of Drought proneness
0.000<DI<0.125	Chronic
0.0125<DI<0.180	Severe
0.180<DI<0.235	Moderate
0.235<DI<0.310	Mild
0.310<DI<1.00	Occasional

In the present study Markov chain model have been used to observe drought event during the period 1966-2016. For meteorological drought rainfall from March to May considered as summer season (Pre-monsoon season), June to October was considered as rainy season (monsoon season) and November to February was considered as winter season. On the other hand Markov chain model is a threshold based model, for present study average weekly 5 mm rainfall was considered as threshold value. The transition counts for the Markov model were obtained by considering today's and yesterday's rain status of the previous mentioned stations where (≥5 mm) rain is considered as wet day and (<5 mm) rain is considered as dry day. The Table 8.3 shows the frequencies of the first step transitions considering today's wet and dry day followed by yesterday's wet and dry day.

Table 8.3: Frequency distribution of first step transition counts for weekly rainfall data at Bogra station.

Yesterday state of rain	Today state of rain		Total
	Dry (0)	Wet(1)	
Dry (0)	985	295	1280
Wet (1)	296	1082	1378

Table 8.3 gives the maximum likelihood estimates of transition probabilities for a first step Markov chain obtained directly by using transition counts by the formula:

$P_{ij} = \frac{n_{ij}}{n_i}$, $n_i = \sum_j n_{ij}$ and , P_{ij} = P(X_1= j| X_0= i)

Table 8.4:The maximum likelihood estimates of transition probabilities of the first step model for weekly rainfall data at Bogra station.

Transition Probabilities	P_{00}	P_{01}	P_{10}	P_{11}
Maximum likelihood estimates	0.770	0.230	0.214	0.786

From the above table, we see that the highest proportion (0.786) belongs to transition of the form wet day to wet day and the lowest proportion (0.214) belongs to transition from wet day to dry day. It is to be noted that proportion of transition to the wet is higher than the proportion of transition to the dry. The following table 8.5 shows the frequencies of the second step transitions considering today's wet and dry day followed by two days before wet and dry day.

Table 8.5:Frequency distribution of second step transition counts for weekly rainfall data at Bogra station.

Yesterday state of rain	Today state of rain		Total
	Dry (0)	Wet(1)	
Dry (0)	474	161	635
Wet (1)	162	531	693

Table 8.6:The maximum likelihood estimates of transition probabilities of the second step model for weekly rainfall data at Bogra station.

Transition Probabilities	P_{00}	P_{01}	P_{10}	P_{11}
Maximum likelihood estimates	0.746	0.254	0.234	0.766

From the above table 8.6, we see that the highest proportion (0.766) belongs to transition of the form wet day to wet day and the lowest proportion (0.234) belongs to transition from wet day to dry day. It is to be noted that proportion of transition to the wet is higher than the proportion of transition to the dry. When the higher transition probability matrix became stable, then we estimate the Drought Index (DI) of that stable transition probability matrix. After all this we can make a comparison between these Drought Index. The sensitivity of crop damage without rain depends on soil moisture holding capacity as well as duration of drought proneness. In the similar manner, we computed the higher order transition probabilities (upto 10^{th} step) and calculated the Drought Index (DI) for all five stations, which are provided in **Table 8.7.**

Table 8.7: Drought Index (DI) in different steps/sequence using higher transition Probability matrix (with 5mm threshold value for 7 days) in 5 meteorological stations.

Sequence/ Step	**Drought Index (DI)**				
	Bogura	Rajshahi	Rangpur	Dinajpur	Ishwardi (Pabna)
1	0.179	0.177	0.169	0.170	0.168
2	0.232	0.231	0.229	0.223	0.222
3	0.257	0.243	0.251	0.239	0.239

4	0.263	0.244	0.260	0.240	0.241
5	0.264	0.245	0.261	0.243	0.243
6	0.265	0.246	0.262	0.245	0.245
7	0.266	0.247	0.263	0.246	0.246
8	0.266	0.247	0.264	0.246	0.247
9	0.267	0.247	0.265	0.247	0.248
10	0.267	0.247	0.265	0.247	0.248

8.5 Exploring Rapid Fluctuation in the Drought Condition

8.5.1 Rapid Fluctuation in Annual Drought Scenario

From the table 8.7 we observe that in Bogura, the first step of Drought Index is 0.179 which indicates severe drought. At the 2nd step Drought Index =0.232 which is now moderate drought. After 3 steps, Drought Index is 0.257 which is mild drought. The value of Drought Index varies until 8th transition and becomes stable at 9th step, finally the stable value of Drought Index is 0.267. Hence it is evident that due to the eratic behaviour of rainfall pattern, drought proneness scenario fluctuate in Bogura. Thus instability of rainfall distorts the predictibility of future variation in drought in Bogura.

In Rajshahi, the first step of Drought Index is 0.177 which indicates severe drought. At the 2nd step, Drought Index =0.231 which indicates moderate drought. After 3 steps, Drought Index is 0.243 which is mild drought. After 4 steps, Drought Index is 0.244 and the Drought Index varies until 6th step. At the 7th step, Drought Index become stable with value 0.247. Hence it is evident that due to the eratic behaviour of rainfall pattern, drought proneness scenario fluctuate in Rajshahi. Thus instability of rainfall distorts the predictibility of future variation in drought in Rajshahi.

In Rangpur, the first step of Drought Index is 0.169 which indicates severe drought. At the 2nd step, Drought Index =0.229 which is now moderate drought. After 3 steps, Drought Index is 0.251 which is mild drought. After 4 steps, Drought Index is 0.260, at the 9th step Drought Index become stable with value 0.265. Hence it is evident that due to the eratic behaviour of rainfall pattern, drought proneness scenario fluctuate in Rangpur. Thus instability of rainfall distorts the predictibility of future variation in drought in Rangpur.

In Dinajpur, the first step of Drought Index is 0.170 which indicates severe drought. At the 2nd step, Drought Index =0.223 which is now moderate drought. After 3 steps, Drought Index is 0.239 which is mild drought. After 4 steps, Drought Index is 0.240, at the 9th step Drought Index become stable with value 0.247. Hence it is evident that due to the eratic behaviour of rainfall pattern, drought proneness scenario fluctuate in Rangpur. Thus instability of rainfall distorts the predictibility of future variation in drought in Rangpur.

In Ishwardi (Pabna), the first step of Drought Index is 0.168 which indicates severe drought. At the 2nd step, Drought Index =0.222 which is now moderate drought. After 3 steps, Drought Index is 0.239 which is mild drought. After 4 steps, Drought Index is 0.241 and the Drought Index varies until 8th step. At the 9th step, Drought Index become stable with value 0.248. Hence it is evident that due to the erratic behaviour of rainfall pattern, drought proneness scenario fluctuate in Pabna. Thus instability of rainfall distorts the predictibility of future variation in drought in Pabna.

Thus it is seen that due to erratic transition in the rainfall the drought scenario fluctuate rapidly in the region.

8.5.2 Rapid Fluctuation in Seasonal Drought Scenario

Bogra

The figure 8.2 show that the first step of Drought Index in winter is 0.010 which indicates chronic drought. Next higher transition probability matrix indicates, Drought Index =0.011 which is also chronic drought. Here transition probability matrix is stable. Finally the Drought Index is 0.011 which indicates chronic drought. In summer, the first step of Drought Index is 0.238 which indicates mild drought. Next higher transition probability matrix indicates, Drought Index =0.254 which is also mild drought. Similarly at 5th step, transition probability matrix is stable. Finally the Drought Index is 0.257 which indicates mild drought. The first step of Drought Index in rainy season is 0.581 which indicates occasional drought. Next higher transition probability matrix indicates, Drought Index =0.698 which is also occasional drought. Similarly at 5th step, transition probability matrix is stable. Finally the Drought Index is 0.732 which indicates occasional drought. So, there was an eratic behaviour of rainfall pattern indicating drought proneness scenario fluctuate which form severe, moderate and mild drought.

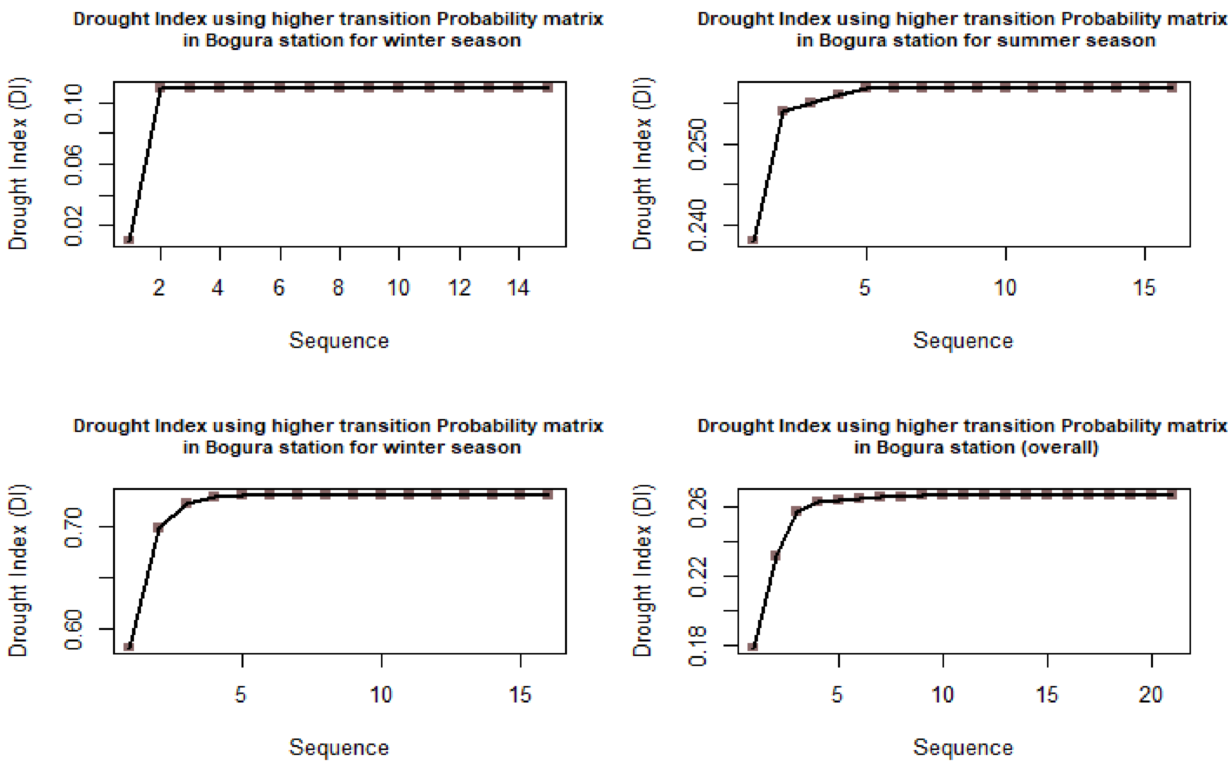


Figure 8.2: Higher transition scenario of Drought Index for 7 days with 5mm threshold value at Bogra station.

Dinajpur

Figure 8.3 shows that the first step of Drought Index in winter is 0.0073 which indicates chronic drought. Next higher transition probability matrix indicates, Drought Index =0.0072 which is also chronic drought. Here transition probability matrix is stable. Finally the Drought Index is 0.0072 which indicates chronic drought. For summer, the first step of Drought Index is 0.236 which indicates mild drought. Next higher transition probability matrix indicates, Drought Index =0.237 which is also mild drought. Here the transition probability matrix is stable. Finally the Drought Index is 0.237 which indicates mild drought.The first step of Drought in rainy season Index is 0.549 which indicates occasional drought. Next higher transition probability matrix indicates, Drought Index =0.656 which is also occasional drought. Similarly at 5th step, transition probability matrix is stable. Finally the Drought Index is 0.687 which indicates occasional drought. There was an eratic behaviour of rainfall pattern indicating drought proneness scenario fluctuate which form severe, moderate and mild drought process occurs respectively at Dinajpur station.

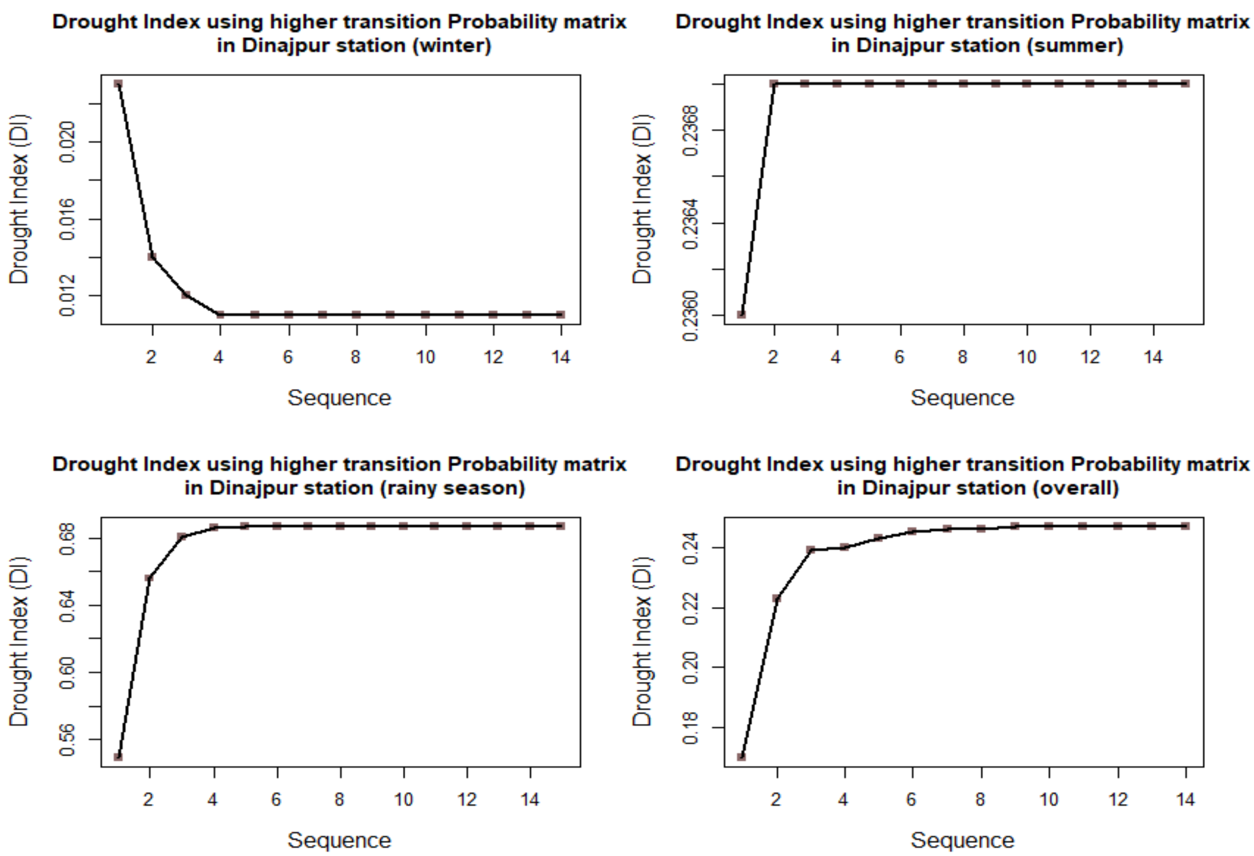


Figure 8.3 : Higher transition scenario of Drought Index for 7 days with 5mm threshold value at Dinajpur station.

Ishwardi (Pabna)

The figure 8.4 show that the first step of Drought Index in winter is 0.023 which indicates chronic drought. Next higher transition probability matrix indicates, Drought Index =0.014 which is also chronic drought. Similarly at 4th step, transition probability matrix is stable. Finally the Drought Index is 0.011 which indicates chronic drought. In summer, the first step of Drought Index is 0.222 which indicates moderate drought. Next higher transition probability matrix indicates, Drought Index =0.246 which is mild drought. Similarly at 4th step, transition probability matrix is stable. Finally the Drought Index is 0.248 which indicates mild drought. In rainy season, the first step of Drought Index is 0.456 which indicates occasional drought. Next higher transition probability matrix indicates, Drought Index =0.578 which is also occasional drought. Similarly at 5th step, transition probability matrix is stable. Finally the Drought Index is 0.634 which indicates occasional drought. So, there is fluctuation of drought proneness in all season at Ishwardi station.

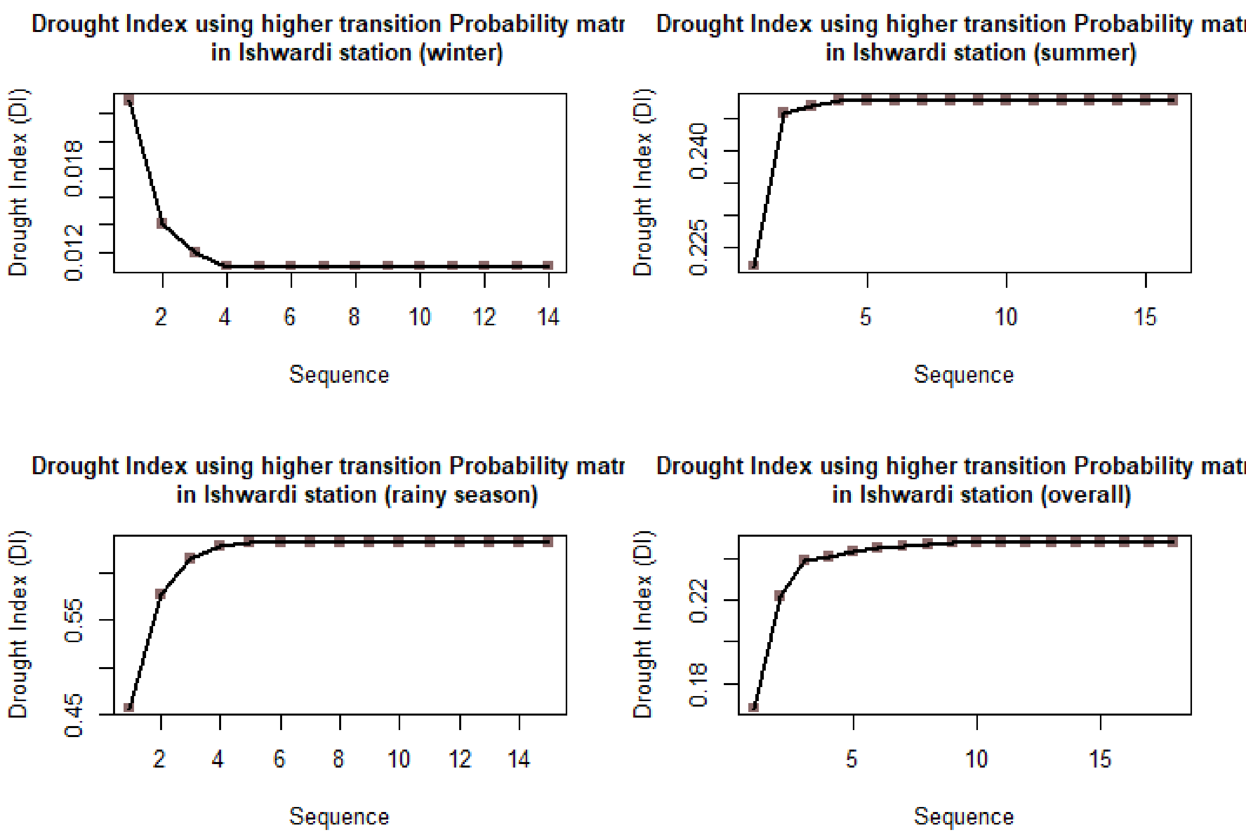


Figure 8.4: Higher transition scenario of Drought Index for 7 days with 5mm threshold value at Ishwardi station.

Rajshahi

The figure 8.5 show that the first step of Drought Index in winter is 0.020 which indicates chronic drought in winter. Next higher transition probability matrix indicates, Drought Index =0.013 which is also chronic drought. Similarly at 3rd step, transition probability matrix is stable. Finally the Drought Index is 0.011 which indicates chronic drought. In summer, the first step of Drought Index is 0.222 which indicates moderate drought. Next higher transition probability matrix indicates, Drought Index =0.224 which is also moderate drought. Similarly at 4th step, transition probability matrix is stable. Finally the Drought Index is 0.228 which indicates moderate drought. The first step of Drought Index in rainy season is 0.576 which indicates occasional drought. Next higher transition probability matrix indicates, Drought Index =0.669 which is also occasional drought. Similarly at 4th step, transition probability matrix is stable. Finally the Drought Index is 0.691, which indicates occasional drought. So, there is fluctuation of drought proneness in all season at Rajshahi station.

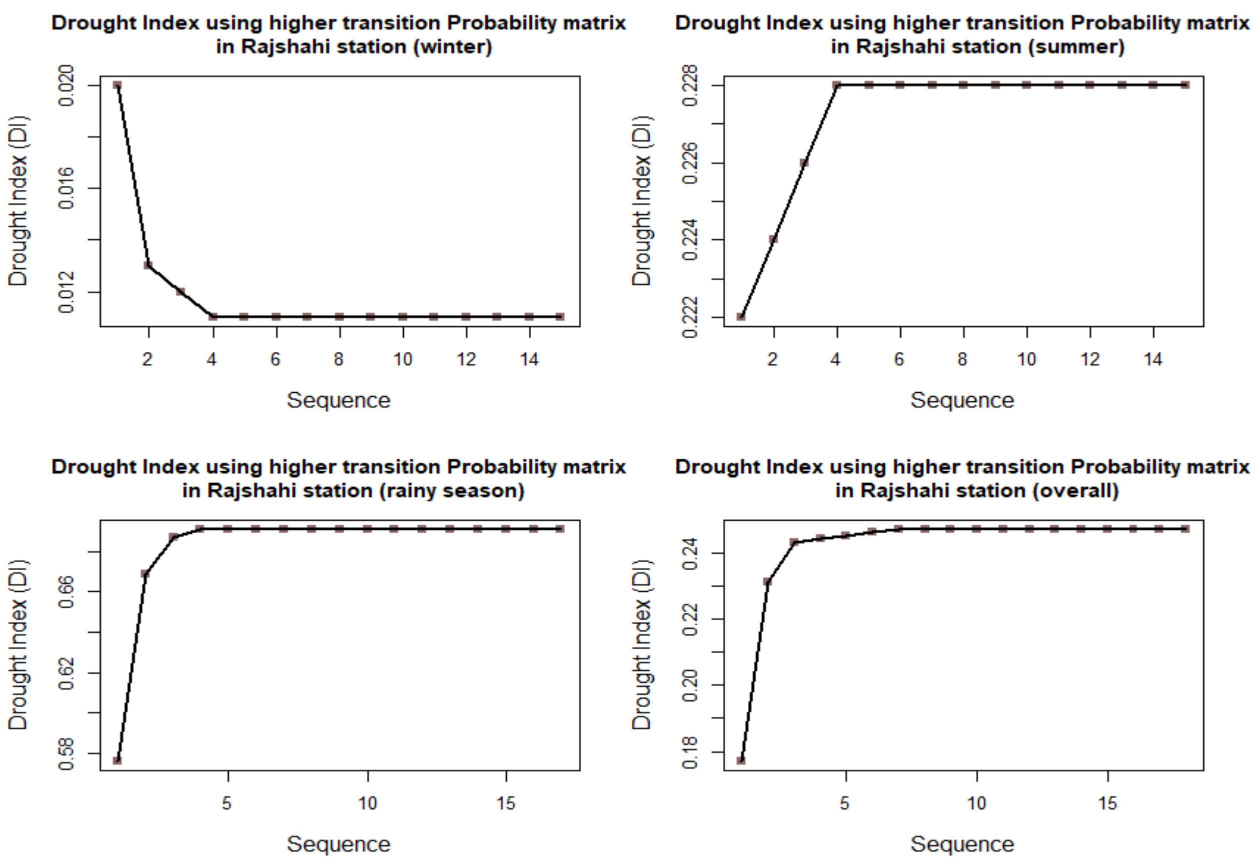


Figure 8.5 : Higher transition scenario of Drought Index for 7 days with 5mm threshold value at Rajshahi station.

Rangpur Station

The figure 8.6 show that the first step of Drought Index in winter is 0.010 which indicates chronic drought. Next higher transition probability matrix indicates, Drought Index =0.0091 which is also chronic drought. Similarly at 3rd step, transition probability matrix is stable. Finally the Drought Index is 0.009 which indicates chronic drought. In summer, the first step of Drought Index is 0.269 which indicates mild drought. Next higher transition probability matrix indicates, Drought Index =0.312 which is occasional drought. Similarly at 5th step, transition probability matrix is stable. Finally the Drought Index is 0.324 which indicates occasional drought. The first step of Drought Index in rainy season is 0.583 which indicates occasional drought. Next higher transition probability matrix indicates, Drought Index =0.682 which is also occasional drought. Similarly at 5^{th} step, transition probability matrix is stable. Finally the Drought Index is 0.707 which indicates occasional drought. So, there is fluctuation of drought proneness in the summer and winter seasons at Rangpur station.

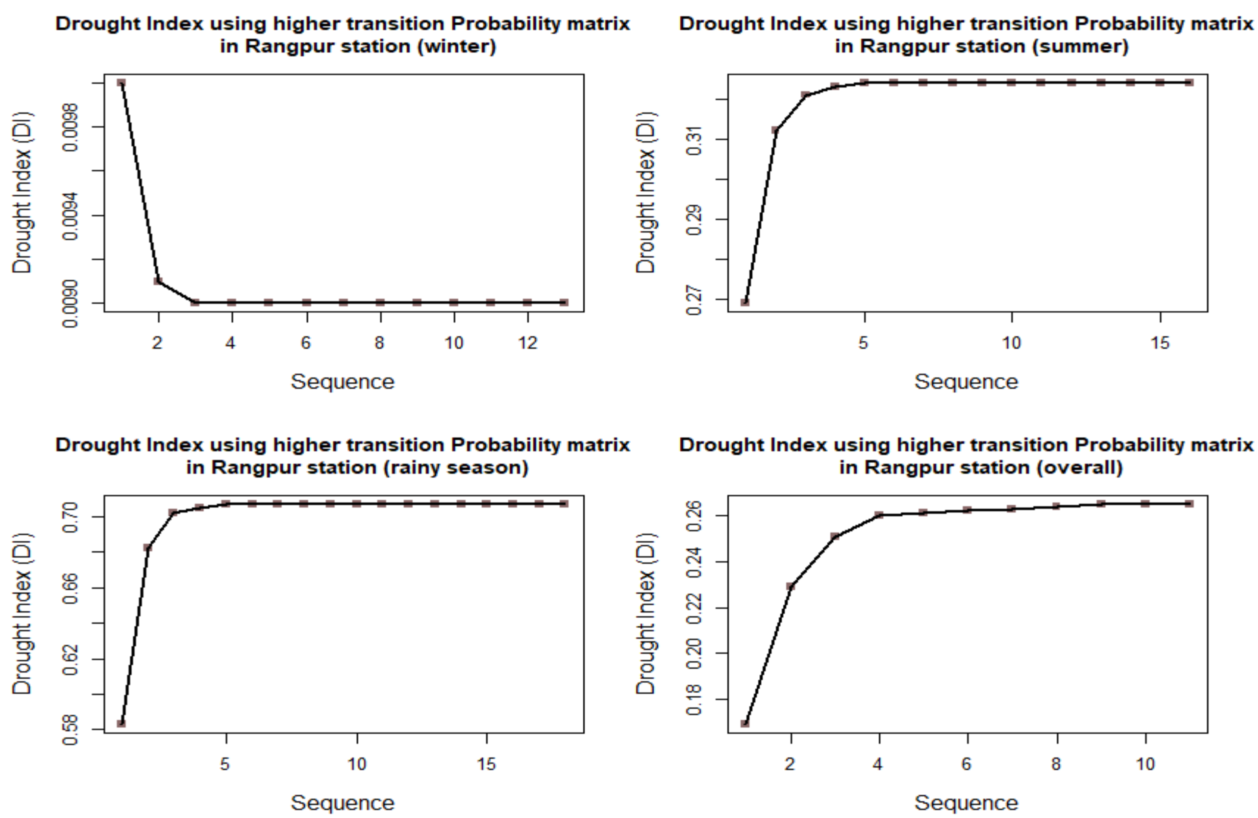


Figure 8.6 : Higher transition scenario of Drought Index for 7 days with 5mm threshold value at Rangpur station.

8.6 Predictability of Drought Proneness

The study attempted to assess variability, trends, anomaly, volatility and transition in rainfall in the drought-prone northwest region of Bangladesh to have a better insight on the causes of its occurrence, the possibility of the persistence of present trends in droughts and scope of its predictability. The ITA results revealed a fluctuation of trends in different parts of the study period. Analysis of rainfall anomaly also revealed a rapid shift in rainfall regime from wet to dry or dry to wet in a short period. This was also validated by GARCH-jump model and Markov Chain analysis. The results indicate that the present trend of declining droughts may not persist. Large volatility and rapid shifting nature of rainfall have made the predictability of droughts high uncertain in the region. The rainfall region can rapidly shift from present wet longer wet or near wet phase to a severe dry phase and trigger droughts in the region. The study indicates that droughts in the study area is highly random and therefore can occur any time.

Due to large volatility and rapid shifting nature of drought it is not possible to predict future drought condition using usual prediction models, hence Random Forest Algorithm method was applied to assess the predictability of drought proneness. Random Forest Algorithm is a supervised machine learning algorithm which can be used for both classification and regression tasks . Supervised learning is a learning function that matches some inputs (one or many features or independent variables) to an output based comparable input-output pairs. It learns from a training data set and applies its learning to a test set, paving the way for prediction (Samuel, 1959). As it can already be seen from its name, random forest algorithm builds multiple decision trees and merges them together to get a more accurate and stable prediction. In the study, in order to test, the entire data set was divided into train set and test set, then the models were generated for five different districts. But due to volatility and rapid fluctuation in rainfall data the prediction process failed, it did not provide realistic result. Since, the prediction process failed, we left the initiative and discard the detailed discussion on the process and its results.

Although, this study could not produce a prediction model for drought due to high volatility and rapid fluctuation of drought scenario, it identified the scope for further analysis. This study will open the door of research in this particular direction. In future, the available rainfall records of other locations in the study area can be used for replication of the study to individual locations to understand the spatial variability of drought predictability. It can be hoped that researchers, planners and policy makers will make headway in their fields using the findings of this study and contribute to the welfare of the country.

8.7 Supplementary tables

Table-8.8: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of winter season at Bogra Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.100	.143	.010	Chronic
.104	.106	.011	Chronic
.104	.104	.011	Chronic
.104	.104	.011	Chronic

Table-8.9: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of summer season at Bogra Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.372	.639	.238	Mild
.468	.542	.254	Mild
.493	.517	.255	Mild
.501	.510	.256	Mild

.506	.508	.257	Mild
.507	.507	.257	Mild

Table-8.10: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of rainy season at Bogra Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.654	.889	.581	Occasional
.808	.864	.698	Occasional
.844	.857	.723	Occasional
.853	.856	.730	Occasional
.855	.856	.732	Occasional
.855	.856	.732	Occasional

Table-8.11: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days at Bogra Station (overall).

P_{01}	P_{11}	DI	Degree of drought proneness
.230	.779	.179	Severe
.351	.662	.232	Moderate
.429	.599	.257	Mild
.468	.563	.263	Mild
.486	.543	.264	Mild
.498	.532	.265	Mild
.506	.525	.266	Mild
.509	.522	.266	Mild
.515	.519	.267	Mild
.516	.518	.267	Mild
.517	.517	.267	Mild

Table-8.12: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of winter season at Dinajpur Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.085	.086	.0073	Chronic
.085	.085	.0072	Chronic
.085	.085	.0072	Chronic

Table-8.13: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of summer season at Dinajpur Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.457	.517	.236	Mild

.479	.494	.237	Mild
.485	.488	.237	Mild
.486	.487	.237	Mild

Table-8.14: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of rainy season at Dinajpur Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.631	.870	.549	Occasional
.782	.839	.656	Occasional
.818	.832	.681	Occasional
.827	.829	.686	Occasional
.829	.829	.687	Occasional
.829	.829	.687	Occasional

Table-8.15: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days at Dinajpur Station. (Overall)

P_{01}	P_{11}	DI	Degree of drought proneness
.219	.777	.170	Severe
.342	.653	.223	Moderate
.410	.584	.239	Mild
.441	.545	.240	Mild
.464	.524	.243	Mild
.479	.512	.245	Mild
.488	.505	.246	Mild
.492	.501	.246	Mild
.494	.499	.247	Mild
.495	.498	.247	Mild
.496	.497	.247	Mild

Table-8.16: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of winter season at Ishurdi Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.088	.258	.023	Chronic
.103	.132	.014	Chronic
.106	.111	.012	Chronic
.106	.107	.011	Chronic
.106	.106	.011	Chronic

Table-8.17: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of summer season at Ishurdi Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.335	.663	.222	Moderate
.478	.552	.246	Mild
.493	.516	.247	Mild
.496	.504	.248	Mild
.498	.500	.248	Mild

Table-8.18: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of rainy season at Ishurdi Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.527	.866	.456	Occasional
.705	.821	.578	Occasional
.766	.805	.616	Occasional
.787	.800	.629	Occasional
.794	.798	.634	Occasional
.796	.797	.634	Occasional

Table-8.19: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days at Ishwardi Station (overall).

P_{01}	P_{11}	DI	Degree of drought proneness
.216	.782	.168	Severe
.338	.658	.222	Moderate
.407	.588	.239	Mild
.439	.549	.241	Mild
.461	.527	.243	Mild
.475	.514	.245	Mild
.485	.507	.246	Mild
.491	.503	.247	Mild
.495	.501	.248	Mild
.496	.499	.248	Mild

Table-8.20: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of winter season at Rajshahi Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.093	.219	.020	Chronic
.105	.121	.013	Chronic
.107	.109	.012	Chronic
.107	.107	.011	Chronic
.107	.107	.011	Chronic

Table-8.21: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of summer season at Rajshahi Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.379	.585	.222	Moderate
.448	.499	.224	Moderate
.470	.482	.226	Moderate
.477	.478	.228	Moderate
.477	.478	.228	Moderate

Table-8.22: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of rainy season at Rajshahi Station.

P_{01}	P_{11}	DI	Degree of drought proneness
.666	.865	.576	Occasional
.799	.838	.669	Occasional
.825	.833	.687	Occasional
.830	.832	.691	Occasional
.831	.831	.691	Occasional

Table-8.23: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days at Rajshahi Station. (overall)

P_{01}	P_{11}	DI	Degree of drought proneness
.245	.722	.177	Severe
.369	.627	.231	Moderate
.433	.563	.243	Mild
.463	.531	.244	Mild
.476	.514	.245	Mild
.489	.504	.246	Mild
.493	.502	.247	Mild
.495	.500	.247	Mild
.497	.498	.247	Mild
.497	.498	.247	Mild

Table-8.24: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of winter season at Rangpur Station.

P_{01}	P_{11}	DI	Degree of drought
.093	.111	.0100	Chronic
.095	.096	.0091	Chronic
.095	.095	.0090	Chronic
.095	.095	.0090	Chronic

Table- 8.25: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of summer season at Rangpur Station.

P_{01}	P_{11}	DI	Degree of drought
.377	.715	.269	Mild
.505	.618	.312	Occasional
.548	.586	.321	Occasional
.562	.575	.323	Occasional
.567	.572	.324	Occasional
.569	.571	.324	Occasional

Table-8.26: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days of rainy season at Rangpur Station.

P_{01}	P_{11}	DI	Degree of drought
.668	.873	.583	Occasional
.805	.847	.682	Occasional
.834	.842	.702	Occasional
.839	.841	.705	Occasional
.841	.841	.707	Occasional
.841	.841	.707	Occasional

Table-8.27: Drought Index (DI) using higher transition Probability matrix with 5mm threshold value for 7 days at Rangpur Station. (overall)

P_{01}	P_{11}	DI	Degree of drought
.221	.801	.169	Severe
.335	.684	.229	Moderate
.409	.615	.251	Mild
.453	.574	.260	Mild
.475	.549	.261	Mild
.488	.536	.262	Mild
.499	.527	.263	Mild
.505	.522	.264	Mild
.511	.519	.265	Mild
.512	.517	.265	Mild
.514	.517	.265	Mild

Chapter Nine

Comparison of Study Findings with West Bengal

9.1 Introduction

West Bengal is adjacent to our study area and it has three distinct meteorological seasons, viz., summer (March-May), rainy season (June-October) and winter (November-February). Also in our study we followed the same meteorological seasons, hence our findings is comparable to with that of West Bengal. It should be noted here that West Bengal has two meteorological sub-divisions- the Sub-Himalayan West Bengal (SHWB) and Gangetic West Bengal (GWB), hence our analysis & discussion will be in accordance with these two divisions.

9.2 Comparison of rainfall trend with West Bengal

First of all we consider the trend in rainfall, in that case from the figure below it is evident that in the Sub-Himalayan West Bengal (SHWB), during the the last century there was a increase in rainfall from 1930 to 1970, but thereafter there is decrease in rainfall (Figure 9.1). But the rainfall scenario in the Gangetic West Bengal (GWB) was different in this time, there was decrease in rainfall from 1930 to 1980 (Figure 9.2). Now let us observe the seasonal and annual variation in rainfall, in that case the GWB experienced more annual and monsoon rainfall during 1981-2000. The SHWB recorded more rainfall than the GWB (*Nandargi S.S. and Barman K., 2018.).* This is indicative that the Sub-Himalayan West Bengal (SHWB) and Gangetic West Bengal (GWB) have different rainfall climatology due to the different geographic characteristics, one being hilly and other being riverine.

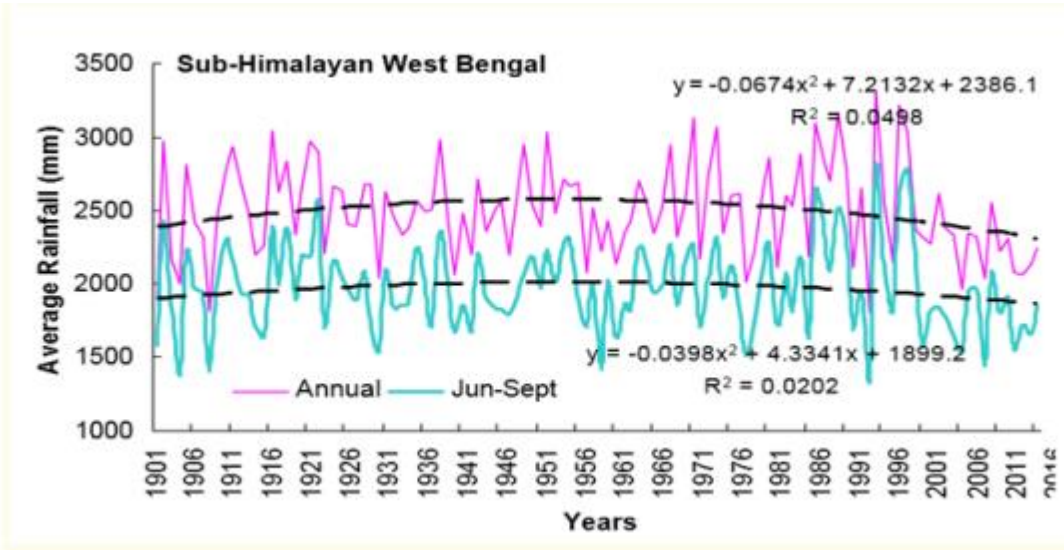


Figure 9.1 : Average Rainfall Trend in the Sub-Himalayan West Bengal (SHWB)

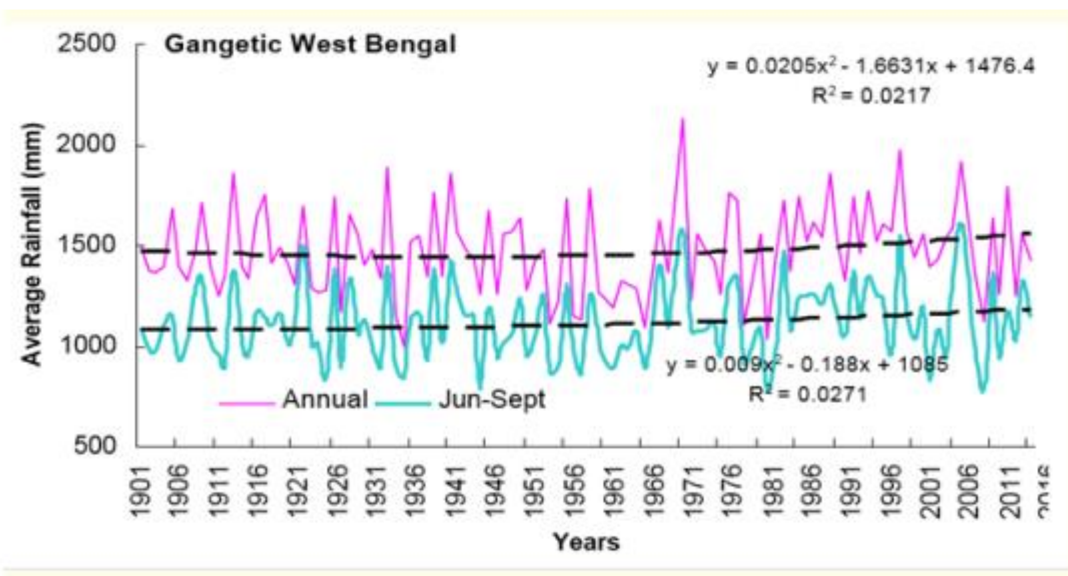


Figure 9.2 : Average Rainfall Trend in the Gangetic West Bengal (GWB)

The annual rainfall trend of North-west region of Bangladesh showed similar trend as Sub-Himalayan West Bengal, both of them showed instability and rapid fluctuation in rainfall (Figure 9.1 & Figure 9.3).

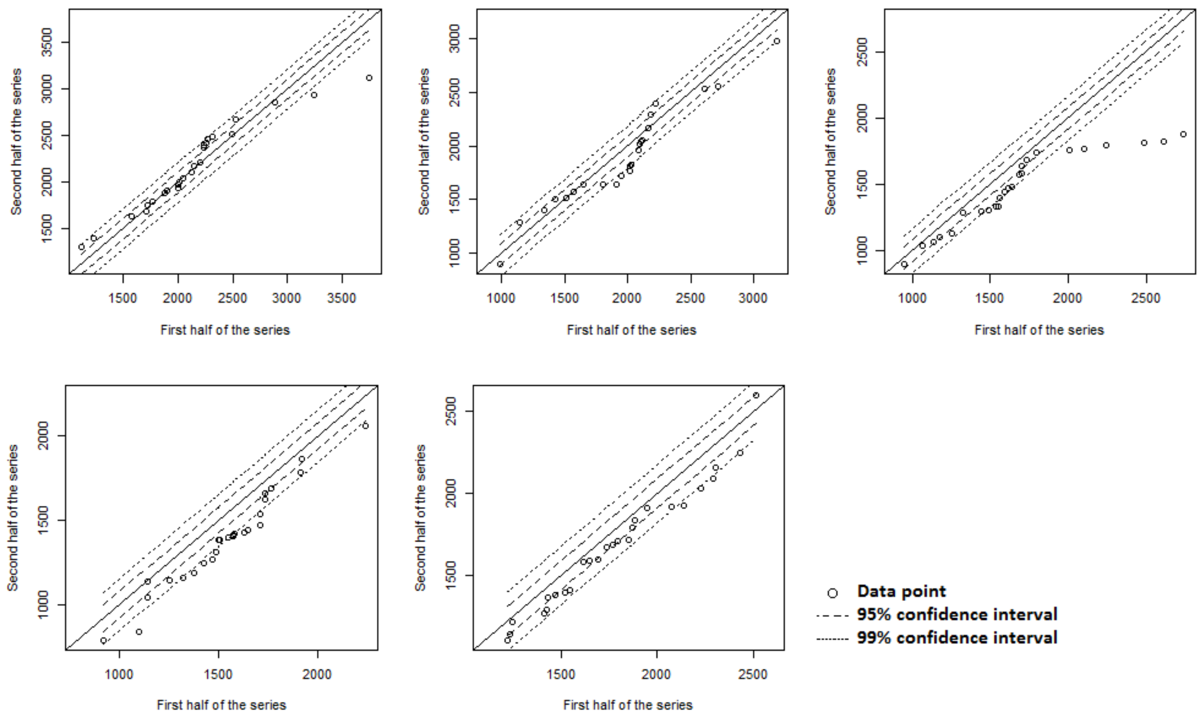


Figure 9.3 : Innovative trend analysis of annual rainfall for the period 1959-2018 in North-west region of Bangladesh

9.3 Comparison of rainfall anomaly with West Bengal

Standardized Rainfall Anomaly Index (SRAI)shows that the percentage of negative anomaly is less in the Sub-Himalayan West Bengal (SHWB) during monsoon season. But the scenario is reverse in Gangetic West Bengal (GWB), (Figure 9.4). Now let us explore the background reasons behind the diverse scenario. The Himalayan region experiences heavy rainfall during monsoon only, but Gangetic region faces rainfall in pre-moonsoon and post-moonsoon season also. The rainfall anomaly index also showed that numbers of dry years are increasing *(Nandargi S.S.and Barman K., 2018).*

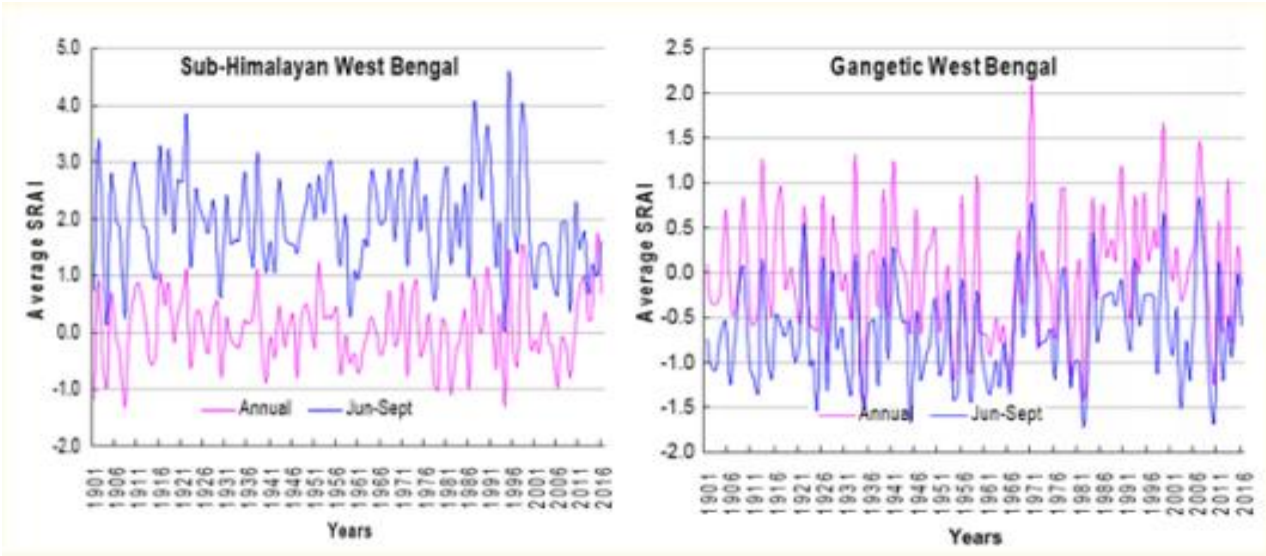


Figure 9.4 : Average Standardized Rainfall Anomaly Index (SRAI) trend in West Bengal

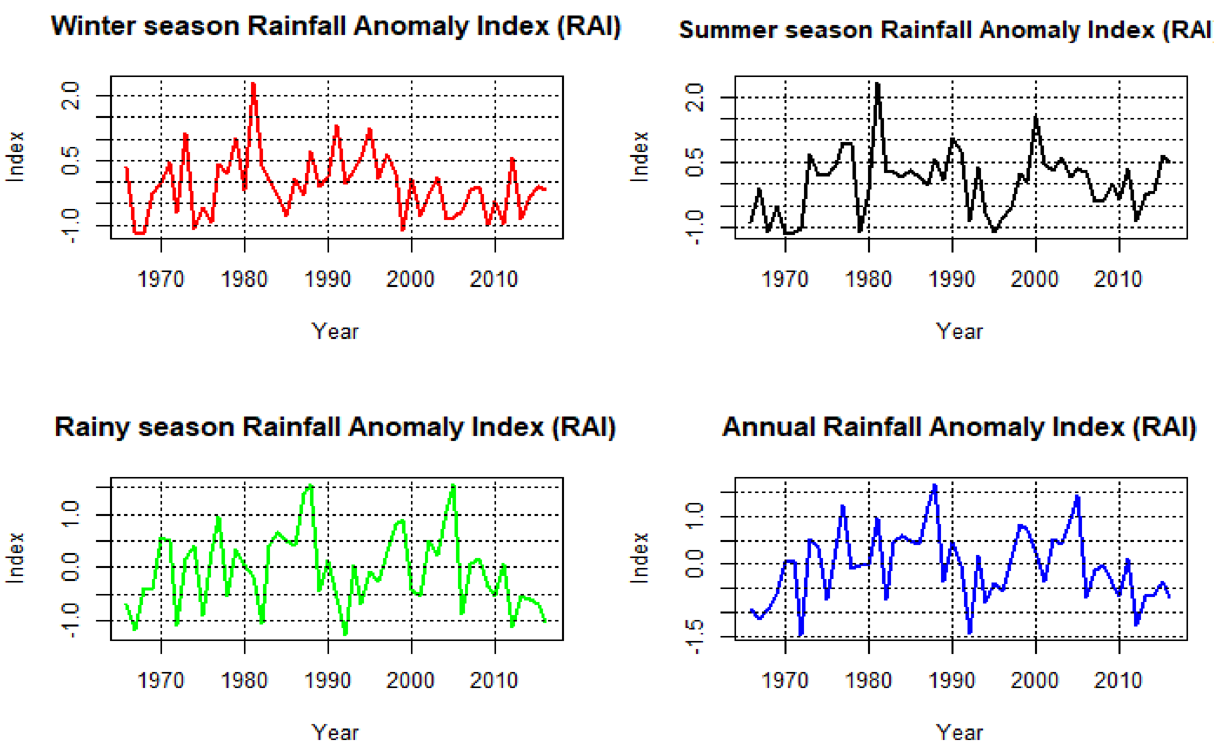


Figure 9.5: Seasonal and Annual Rainfall Anomaly Index (RAI) for 1966-2016 for North-west region of Bangladesh

In comparison of rainfall anomaly, the north-west region of Bangladesh shows similar trend with that of Sub-Himalayan West Bengal (SHWB), which is evident from comparison of Figure 9.4 and Figure 9.5. Both the region shows high anomaly in the rainfall trend.

9.4 Comparison of Meteorological Drought (SPI) with West Bengal

Drought's characteristics change with time lag. At the longer time scales, droughts become less frequent but their duration increases (*Krishna Gopal Gosh, 2019).* The change of SPI over years reveals a remarkable pattern related to climate change in West Bengal (Figure 9.6).

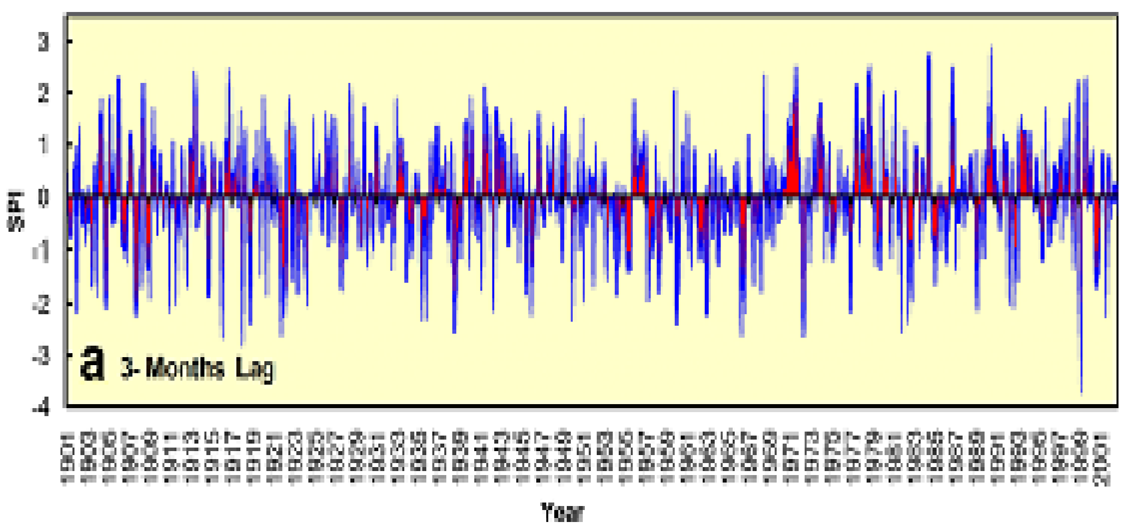


Figure 9.6: Standardized Precipitation Index (SPI) for 3-months, for West Bengal.

The SPI values for North-west region of Bangladesh is given in figure 9.7. Comparing figure 9.6 and figure 9.7 we observe that drought scenario fluctuate rapidly in both west Bengal and north-west region of Bangladesh. This instability in drought condition distorts its predictability.

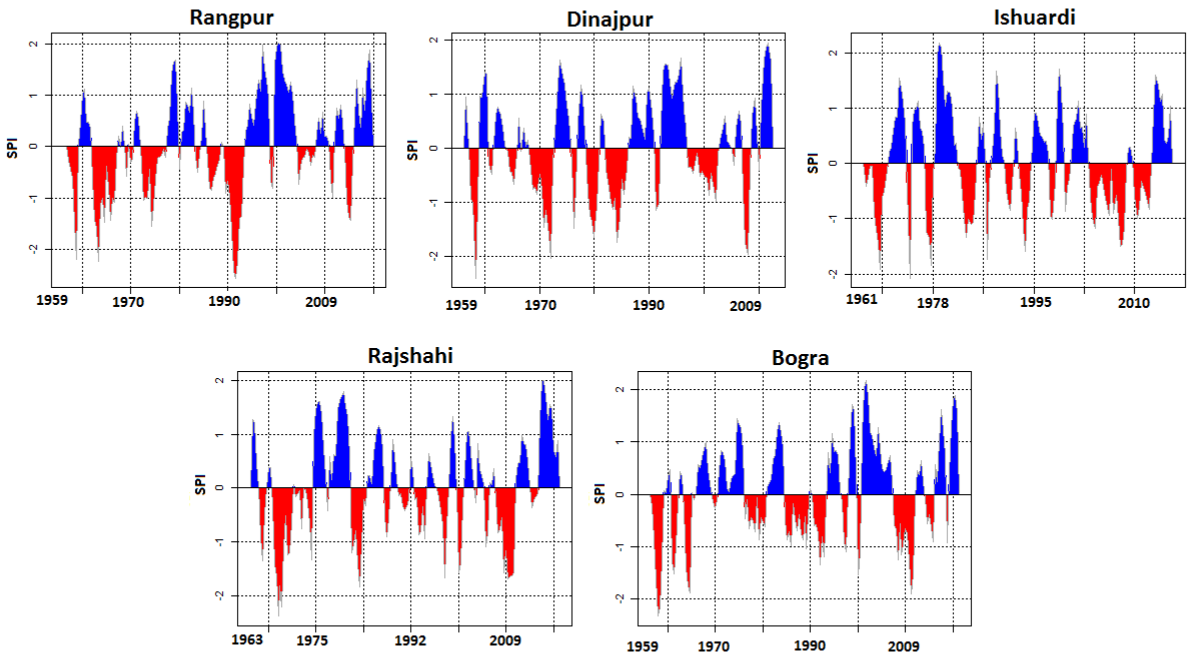


Figure 9.7: Standardized precipitation index for a time scale of four months at different locations of the North-west Bangladesh.

Chapter Ten

Conclusion and Recommendations

10.1 Introduction

The study attempted to assess variability, trends, anomaly, volatility and transition in rainfall in the drought-prone northwest region of Bangladesh to have a better insight on the causes of its occurrence, the possibility of the persistence of present trends in droughts and scope of its predictability. The ITA results revealed a fluctuation of trends in different parts of the study period. Analysis of rainfall anomaly also revealed a rapid shift in rainfall regime from wet to dry or dry to wet in a short period. This was also validated by GARCH-jump model and Markov Chain analysis. The results indicate that the present trend of declining droughts may not persist. The rainfall region can rapidly shift from present wet longer wet or near wet phase to a severe dry phase and trigger droughts in the region. Large volatility and rapid shifting nature of rainfall have made the predictability of droughts high uncertain in the region.

10.2 Summary of Findings

Anomaly in the Rainfall

The discrete rainfall anomaly showed that seasonal and annual rainfall anomalies fluctuate frequently over time due to high variability in rainfall. To verify whether high anomaly in the rainfall creates droughts in the study, RAI values for different years were estimated. The RAI time series averaged for the study area is shown in Figure 4.2. It was observed that RAI fluctuate significantly over time like the rainfall. However, there is no consistency or apparent pattern in variation. The results indicate a sudden occurrence of droughts in the region or the droughts in the region is less predictable. The seasonal RAI values were also calculated, and similar random fluctuations were observed. *Therefore, it can be remarked that high variability of rainfall has made the droughts less predictable in northwest Bangladesh.*

Trends in the Rainfall

ITA was conducted to visual inspection of trends over the period and its significance. ITA of annual rainfall for the period 1959-2018 for five stations are presented in Figure 4.3. A decreasing trend in annual rainfall at a 95% confidence interval (5% level of significance) was noticed in recent years at most of the stations. The trends were significantly positive or insignificant in the early years. The results indicate a large decrease in rainfall in most of the stations have made the overall decrease in rainfall for the entire study period as detected by the MK test.

Decadal Change in the Rainfall Pattern

The analysis of monthly rainfall for the five decades shows (Figure 4.4) significant changes in rainfall pattern. Rainfall decreased in the month of June, July, September and October in the last decade (2006-2015) than previous decade (1996-2005). But interestingly, the rainfall increased in December, January and February in the last decade (2006-2015) than the previous decade (1996-2005). From all these findings there is a clear indication that rainfall pattern has been changing in recent years. Rainfall is decreasing in rainy season, but no such pattern is found for the summer season. But in recent years, summer season is facing less drought incidence than the previous years. One reason may be that the rainfall pattern is shifting its trend to backward months, more specifically, rainy season is now starting earlier from April. That is why the winter season rainfall is increasing.

Variability in Meteorological Drought

The variability in pre-monsoon rainfall was noticed to decrease at three locations include the station where drought is increasing. Therefore, it can be remarked that changes in mean monsoon rainfall may be linked to the changes in droughts in the study area. The increase or decrease in mean pre-monsoon rainfall in recent years has influenced the calculation of rainfall deficit for recent years. This resulted in higher or lower values of SPI in later periods and an increasing or decreasing trend in SPI. A similar interpretation can be made for monsoon droughts as the droughts were found to increase at the stations where monsoon rainfall was found to decrease. However, the results were not consistent for all the stations (Figure 5.2, Figure 5.3 and Table 5.3). The results indicate that analysis of variability and trends are not enough for a complete understanding of the cause of change in droughts. Besides, such analyses are not enough to understand whether the decreasing trend in droughts will persist in the near future or there will be a rainfall regime shift which would alter drought trends.

Impact of Meteorological Drought on Ground Water Level

The correlation matrix of SPI of five different districts and their respective minimum ground water levels shows that SPI's are fairly moderately correlated to one another, and the same can be claimed concerning the level of ground water of the regions. The SPI's and ground water level of each district are not, however, positively correlated, rather, they are negatively correlated, maximum correlation being -0.47. This implies, SPI and minimum ground water level do not have similar trend (Table 5.4).

Variability in Hydrological Drought

The analysis of ground water level shows that all the districts have an increasing trend of standardized water level index. We have considered the years since 1977 until 2017, a total of 41 years. Of these 23 years are identified as having drought. However, only ten of those years correspond to the years before 2000, and 13 of them are after 2000. Thus, out of just 18 recent years, 13 are identified as having drought, while out of 23 former years, only 10 years experienced drought condition. The scenario for six month SWI is like that of trimonthly output, the values show an increasing trend. The only difference is that in this case, the drought condition is more severe after the year 2005. In general, 63 percent of the years with drought are after 2005. Also eye-catching is the fact that out of those 14 years, 75% are with drought (Figure 5.5 & figure 5.6).

Change in Vegetation Cover

The Normalized Vegetation Index (NDVI) of Rajshahi, Rangpur, Bogra, Pabna and Dinajpur districts were carried out to see the land cover changes over the time from 2000 to 2020. The NDVI values which ranges from – 1 to +1 has been classified in to five different classes according to a reference given above in the methodology. The different classes are water, and sparse, medium and thick vegetation. However, the increase of dense vegetation over time is a general trend seen in every area. . However, during 2003 and 2017 the dense vegetation class had seen a drastic decrease in Bogra, it came as low as 60%. The notable fact here is the moderate vegetation class sees an up rise whenever the dense vegetation lowers. In Dinajpur, the fluctuation in the early years has been drastic as moderate vegetation was over 40% and dense and sparse vegetation has been little above 25%. This fluctuation shows a trend as well, in no less than three years the dense vegetation spikes. In Pabna, after 2017, the dense vegetation has seen an increase and has remained over 60% to date. The sparse vegetation has been gradually decreasing over the years and moderate vegetation has decreased drastically (below 20%) after 2017. The trend in Rajshahi district is like district Pabna where initial years have no dominant vegetation class. However, in 2003, 2010 and 2013, the moderate vegetation class had toppled the dense vegetation class. The sparse vegetation class has been minimally present in Rangpur as well as the water class (Figure 6.6, Figure 6.7, Figure 6.8, Figure 6.9 & Figure 6.10).

Impact of Meteorological Drought on Agricultural Drought

Agricultural drought is related to meteorological drought, since the vegetation pattern greatly varies according to the SPI value of the previous year. SPI value has been used to assess the meteorological drought and NDVI value for agricultural or vegetative drought. The figure 5.11 shows that the percentage of different vegetated areas decreased greatly in the drought years in Bogra. There is a major decrease in sparse and moderate vegetation in the year 2002, 2004, 2011 and 2015 and the SPI value of previous years shows drought conditions. The decrease in vegetation is greater when there was a drought for more than 2 years, which thereby affects the vegetation growth for the next years. The percentage of sparse and moderate vegetation for 2011, 2014 and 2016 are the examples when the amount of vegetation decreased greatly as the region was experiencing mild to severe droughts for a long time as shown by the SPI values of the previous years. However, the figure also shows that dense vegetation gets affected when drought conditions prolonged for consecutive years. Similar relationship between meteorological drought and agricultural drought were observed in other districts.

Impact of Hydrological Drought on Agricultural Drought

Agricultural drought is related to hydrological drought also, since the vegetation pattern greatly varies according to the ground water level. SWI value has been used to assess the hydrological drought and NDVI value for vegetative drought. SWI is a relative measure of soil wetness of the 1-m soil layer ranging between wilting level (0%) and field capacity (100%). Therefore, SWI values for previous years are considered during comparison with NDVI value. The figure 6.16 shows that Bogra district had experienced hydrological drought consecutively from 2005 to 2016. Therefore, this resulted in a major decrease in dense vegetation, which on the other hand, increases the percentage of moderate vegetation greatly and sparse vegetation to some extent in the study area. The figure 6.17 indicates that there was also a hydrological drought conditions from 2005 to 2016 in Dinajpur district. This had a great impact on sparse vegetation as it decreased greatly over the time. The prolonged hydrological drought conditions coupling with the meteorological drought condition have an impact on moderate vegetation also as it has a decreasing trend. Similar impact of hydrological drought on vegetation cover was observed in other districts.

Variation in Drought Characteristics

There is a common pattern of aridity in all five regions. They all have relatively higher number of months with smaller aridity indices and very fewer months with higher aridity indices. The fact is indicative of the fact that most months in all regions tend to be arid or hyper-arid. It is found that generally winter seasons are arid and summer and rainy seasons are mostly hyperarid. It was observed that different values of aridity indices are fairly evenly distributed in the case of summer season. It means that there are as many years with smaller aridity indices as with relatively higher and moderate aridity indices, although no values are higher enough to consider indicative of less intensive than arid or semi-arid seasons. In winter season, there are many more years with moderate values of aridity indices, albeit all values are indicative of an 'arid' season since they fall in the category 0.05 < AI < 0.20. The rainy season aridity indices shows a pattern fairly similar to that of summer season. There are equal number of years with hyper-arid rainy years, arid rainy years and semi-arid rainy years. (Figure 7.7, Figure 7.8 & Figure 7.9). The study also employed De Martonne Aridity Indices and high variability in aridity was observed like as UNEP aridity indices, no significant trend observed.

Drought Severity

Analyzing the values of the Stochastic Component Time Series (SCTS), we found that SCTS for Bogura district showed new cyclic trend in every new decade. The trends, however, tend to be neutralized, regressing back to close to the mean value, which is around 10, implying a probable high drought condition. The SCTS for Dinajpur district does not show any significant trend, remaining constant, close to the mean value (9.375), which falls in the range of very high to high probable drought. The SCTS for Rajshahi district shows that the components have high values at the start of almost each decade, decreasing thereafter. Yet, the values are fairly wandering about the mean value (9.731), which, for Rajshahi district, implies moderate to high probable drought. The SCTS for Rangpur district have irregular trends, but the values does not wander much from the mean value (9.723), implying high to moderate probable drought.

Volatility in Rainfall and Instability in Drought Proneness

To verify the less predictivity of droughts revealed in the previous chapters, volatility and jumping behaviour of rainfall was estimated using GARCH-jump model. The assessment was conducted for pre-monsoon and monsoon rainfall and the results are presented in Table 8.1. Table 8.1 shows that parameters, ω, α, β and θ are significant for both the seasons. This indicates significant volatility in time series (ω). The significant value of α

indicates the volatility is due to a random variability of rainfall. The significant value of β indicates the volatility will persist with time and therefore, rainfall variability is unpredictable for the study area. A significant jump in rainfall series (θ) was also noticed which indicates a shift of rainfall regime from wet to dry or vice versa can occur at any time. The results further reveal that the jump intensity parameter λ_0 is also statistically significant for both pre-monsoon and monsoon, implying that the jump intensity varies over time. Moreover, since $\lambda_0 > 0$, it can be confirmed that the GARCH-jump model is correctly chosen for describing the jump behaviour of rainfall. These findings reconfirm the fact that dry and wet condition in northwest Bangladesh fluctuates due to the volatile nature of rainfall.

Erratic Transition in Rainfall and Rapid Fluctuation in Drought Proneness

Finally, to verify the less predictability of drought scenario (as revealed in previous chapters) a Markov Chain model was developed to evaluate transition behaviour of rainfall and develop drought proneness index. Higher-order transition probabilities (up to 10^{th} step) were calculated which were finally used for the calculation of DI. The results revealed that DI values change significantly within a short period. When the higher transition probability matrix became stable, then we estimate the Drought Index (DI) of that stable transition probability matrix. After all this we can make a comparison between these Drought Index. From the table 8.7 we observe that in Bogura, the first step of Drought Index is 0.179 which indicates severe drought. At the 2^{nd} step Drought Index =0.232 which is now moderate drought. After 3 steps, Drought Index is 0.257 which is mild drought. The value of Drought Index varies until 8^{th} transition and becomes stable at 9^{th} step, finally the stable value of Drought Index is 0.267. Similar instability in drought scenario was observed in other districts. Hence it is evident that due to the eratic behaviour of rainfall pattern, drought proneness scenario fluctuate in north-west region of Bangladesh. Thus instability of rainfall distorts the predictibility of future variation in drought.

Predictability of Droughts

Large volatility and rapid shifting nature of rainfall have made the predictability of droughts high uncertain in the region. The rainfall region can rapidly shift from present wet longer wet or near wet phase to a severe dry phase and trigger droughts in the region. The study indicates that droughts in the study area is highly random having large volatility and rapid shifting nature. Due to large volatility and rapid shifting nature of drought it is not possible to predict future drought condition using usual prediction models, hence Random Forest Algorithm method was applied to assess the predictability of drought proneness. But due to volatility and rapid fluctuation in rainfall data the prediction process failed, it did not provide realistic result.

Comparison of Findings with West Bengal

The comparison of study findings with West Bengal (India) reveals similar pattern in rainfall and drought. The annual rainfall trend of North-west region of Bangladesh showed similar trend as Sub-Himalayan West Bengal, both of them showed instability and rapid fluctuation in rainfall. The comparison of RAI values of Bangladesh & West Bengal showed that in both the region there is high anomaly in the rainfall. The comparison of SPI values of Bangladesh & West Bengal showed that in both the region there is high instability in the drought proneness.

10.3 Recommendations

This study might not address all aspects of drought assessment but has made some attempts to give the direction of research on drought in Bangladesh by proposing some methods and mechanism. Verification of these methods will be beneficial for future research on this phenomenon. The results of the study indicate that the recent submission of droughts in Bangladesh is a temporary submission and the country may be affected by droughts again in the near future. The finding of the study can help disaster risk mitigation policy planning.

The general conception that droughts occur twice in a decade in Bangladesh is found not applicable through analysis of climate data for the last two decades. However, it is often argued that the recent submission of droughts is a temporal phenomenon which does not indicate a reduction of drought frequency in Bangladesh. The existing uncertainty in drought trend emphasizes the need for further analysis of rainfall pattern to make a factual conclusion.

The study reveals that the dryness pattern has become variable in the North-West region of Bangladesh, though in different scales in different locations. Hence, climate change adaptation strategies needs to be developed and applied urgently before it becomes too late. Comparison can be delineated among existing drought indices (developed in climatic conditions different from Bangladesh) and developed drought indices in this study. Analysis can be performed to identify whether there is any specific drought movement path/locus over the country, i.e., to identify the case where drought is initiated in a station in a specific month and then it moves to another station in the next month. The trend of drought movement path can be used as important information for drought warning system in the country.

Our empirical analysis suggests that the rainfall data are characterized by both volatility dynamics and time-varying jumps. Such findings indicate that the average amount of rainfall in different districts of Bangladesh are not stable. Application of GARCH-jump model confirm that in future, there might be a volatile level of rainfall and therefore, amount of rainfall could either decrease or increase. These results thus indicate the instability in future drought scenario. To this end, uncertainties in rainfall intensity could emerge as a major obstacle in the entire production process. To overcome such hurdle, the government of Bangladesh should adopt effective adaptation strategies.

It is not necessary the changes in the vegetation was solely influenced by the meteorological and hydrological drought but there could be other possible reasons such as changes in the vegetation pattern, changes in the irrigation system, use of fertilizers , attack from pest or due to some other natural hazards or anthropogenic activities. This indicates that detailed investigations should be carried out to conclude.

Although, this study could not produce an efficient prediction model for drought due to high volatility and rapid fluctuation of drought scenario, it identified the scope for further analysis. This study will open the door of research in this particular direction. In future, the available rainfall records of other locations in the study area can be used for replication of the study to individual locations to understand the spatial variability of drought predictability. The procedure used in this study for systematic analysis of rainfall data with robust statistical methods can be replicated for analysis of predictivity of any other climatic phenomena in Bangladesh and any other regions. It can be hoped that researchers, planners and policy makers will make headway in their fields using the findings of this study and contribute to the welfare of the country.

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Appendix A (Additional Tables)

TableA1 : Descriptive statistics of annual rainfall for the period of 1966-2016 (Rajshahi Division)

	Avg.	Min	Max	Std	CV
Dhunot	1838	969	2632	427	23
Khetlal	1827	1017	2624	439	24
Nandigram	1630	768	2518	427	26
Nawkhila	1626	953	2454	375	23
Shibganj	1829	1098	2973	438	24
Sirajganj	1781	924	2667	403	23
Ullapara	1731	949	2469	375	22
Gurudaspur	1773	915	3426	533	30
Joari	1597	798	2555	396	25
Lalpur	1445	677	2895	407	28
Natore	1578	720	2208	316	20
Singra	1731	890	2584	455	26
Atghoria	1692	1183	2365	340	20
Faridpur	1725	929	3051	435	25
Pabna	1592	1019	2513	312	20
Sujanagar	1648	748	2995	440	27
Tanore	1500	752	2625	354	24
Godagari	1346	701	2179	287	21
Puthia	1492	619	2031	364	24
Sardah	1430	663	2284	377	26
Bholahat	1494	752	3152	472	32
Nawabganj	1317	600	2126	344	26
Nachole	1435	764	2808	402	28
Rohanpur	1388	748	2434	323	23
Shibganj	1524	718	3564	537	35
Atrai	1536	699	3095	473	31
Badalgachi	1581	648	2594	419	27
Manda	1420	757	2268	326	23
Mohadebpur	1576	852	2267	368	23
Naogaon	1507	888	2302	327	22
Nazipur	1476	658	2209	384	26
Sapahar	1442	843	2152	311	22
BograMS	1724	1081	2601	381	22
IshwardiMS	1536	894	2742	399	26
RajshahiMS	1486	792	2352	331	22
Studyarea	1579	1127	2041	257	16

Table A2: Descriptive statistics of winter season rainfall for the period of 1966-2016 (Rajshahi Division)

	Avg.	Min	Max	Std	CV
Dhunot	41	0	147	41	100
Khetlal	34	0	129	30	89
Nandigram	26	0	136	29	111
Nawkhila	37	0	126	32	88
Shibganj	36	0	240	39	109
Sirajganj	51	0	147	41	81
Ullapara	49	0	166	40	81
Gurudaspur	55	0	359	65	117
Joari	39	0	109	32	82
Lalpur	43	0	178	40	92
Natore	48	0	296	47	98
Singra	49	0	224	48	97
Atghoria	55	0	172	44	80
Faridpur	52	0	193	49	93
Pabna	57	0	166	44	76
Sujanagar	53	0	148	40	76
Tanore	39	0	180	41	107
Godagari	40	0	147	36	90
Puthia	38	0	134	34	89
Sardah	41	0	139	35	85
Bholahat	46	0	195	49	107
Nawabganj	35	0	134	34	97
Nachole	38	0	172	42	110
Rohanpur	37	0	155	33	90
Shibganj	38	0	160	37	98
Atrai	30	0	115	30	102
Badalgachi	34	0	181	34	101
Manda	35	0	105	28	82
Mohadebpur	38	0	144	31	82
Naogaon	39	0	150	32	83
Nazipur	29	0	105	27	95
Sapahar	28	0	125	29	105
BograMS	40	0	126	31	77
IshwardiMS	46	0	128	36	77
RajshahiMS	45	0	125	36	79
Studyarea	41	0	124	27	64

TableA3 : Descriptive statistics of summer season rainfall for the period of 1966-2016 (Rajshahi Division)

	Avg.	Min	Max	Std	CV
Dhunot	364	28	670	164	45
Khetlal	296	38	628	143	48
Nandigram	262	20	578	136	52
Nawkhila	313	20	590	120	38
Shibganj	322	74	754	158	49
Sirajganj	376	83	910	161	43
Ullapara	328	90	641	137	42
Gurudaspur	272	0	928	170	62
Joari	280	61	626	139	50
Lalpur	248	20	591	147	59
Natore	255	42	614	126	49
Singra	290	81	1060	177	61
Atghoria	300	13	727	127	42
Faridpur	352	58	873	173	49
Pabna	285	37	546	115	40
Sujanagar	310	75	717	164	53
Tanore	219	50	648	118	54
Godagari	202	57	482	106	52
Puthia	225	37	515	122	54
Sardah	218	42	654	106	48
Bholahat	203	0	1251	182	89
Nawabganj	189	25	456	88	47
Nachole	216	12	710	143	66
Rohanpur	188	63	498	90	48
Shibganj	203	7	714	127	62
Atrai	230	50	647	134	58
Badalgachi	234	6	610	119	51
Manda	209	38	663	115	55
Mohadebpur	253	30	1095	196	78
Naogaon	250	27	811	156	62
Nazipur	213	5	708	140	66
Sapahar	199	25	605	113	56
BograMS	292	54	592	122	42
IshwardiMS	280	27	747	142	51
RajshahiMS	221	50	556	103	46
Studyarea	260	85	519	89	34

Table A4: Descriptive statistics of rainy season rainfall for the period of 1966-2016 (Rajshahi Division)

	Avg.	Min	Max	Std	CV
Dhunot	1426	652	2173	353	25
Khetlal	1498	798	2455	383	26
Nandigram	1342	625	2254	381	28
Nawkhila	1270	674	2058	323	25
Shibganj	1312	720	2434	367	28
Sirajganj	1355	633	2081	321	24
Ullapara	1353	692	2089	313	23
Gurudaspur	1446	628	2545	436	30
Joari	1277	644	2185	343	27
Lalpur	1141	420	2304	346	30
Natore	1274	564	1849	268	21
Singra	1392	772	2206	360	26
Atghoria	1336	796	1958	313	23
Faridpur	1300	612	2205	378	29
Pabna	1250	678	2130	314	25
Sujanagar	1280	195	2303	393	31
Tanore	1242	557	2188	284	23
Godagari	1105	598	1681	241	22
Puthia	1226	455	1796	310	25
Sardah	1171	449	2040	345	29
Bholahat	1244	540	2303	407	33
Nawabganj	1093	446	1964	299	27
Nachole	1180	625	2414	336	28
Rohanpur	1164	626	2077	275	24
Shibganj	1278	561	3033	469	37
Atrai	1276	556	2891	436	34
Badalgachi	1314	537	2126	373	28
Manda	1177	668	1848	270	23
Mohadebpur	1280	743	2136	314	25
Naogaon	1212	755	1822	256	21
Nazipur	1227	503	1903	307	25
Sapahar	1208	728	1875	254	21
BograMS	1393	757	2315	350	25
IshwardiMS	1209	678	2206	321	27
RajshahiMS	1221	634	1920	293	24
Studyarea	1271	879	1666	211	17

Table A5: Z statistic of MK/MMK test, Sen's Slope of annual rainfall for the period of 1966-2016 (Rajshahi Division)

	Annual Rainfall_MK/MMK Test Result			
	MK/MMK Z	P	Tau	Sen Slope
Dhunot	-2.06	0.04	-0.20	-8.15
Khetlal	-0.68	0.50	-0.07	-3.71
Nandigram	-0.88	0.38	-0.09	-5.10
Nawkhila	-1.21	0.23	-0.12	-4.34
Shibganj	-1.89	0.06	-0.18	-8.00
Sirajganj	-0.99	0.32	-0.10	-4.64
Ullapara	0.45	0.65	0.04	1.20
Gurudaspur	1.25	0.21	0.12	4.00
Joari	-1.10	0.27	-0.11	-3.82
Lalpur	-2.40	0.02	-0.23	-7.94
Natore	-0.01	0.99	0.00	-0.23
Singra	-1.38	0.17	-0.18	-10.70
Atghoria	-1.97	0.05	-0.16	-5.31
Faridpur	-1.37	0.17	-0.13	-6.25
Pabna	0.20	0.84	0.02	0.19
Sujanagar	0.20	0.84	0.02	0.29
Tanore	0.09	0.93	0.01	0.41
Godagari	-0.15	0.88	-0.01	-0.65
Puthia	-2.00	0.05	-0.19	-6.44
Sardah	0.91	0.36	0.09	3.84
Bholahat	0.09	0.93	0.01	0.00
Nawabganj	1.64	0.10	0.16	6.15
Nachole	-0.93	0.35	-0.09	-2.91
Rohanpur	-1.01	0.31	-0.10	-3.42
Shibganj	0.58	0.56	0.06	1.97
Atrai	-2.10	0.04	-0.20	-9.71
Badalgachi	-3.27	0.00	-0.32	-11.44
Manda	1.64	0.10	0.16	5.33
Mohadebpur	-1.08	0.28	-0.11	-4.26
Naogaon	-0.88	0.38	-0.09	-2.95
Nazipur	-1.41	0.16	-0.14	-4.91
Sapahar	-0.06	0.95	-0.01	0.00
BograMS	-0.88	0.38	-0.09	-3.19
IshwardiMS	-0.91	0.36	-0.09	-4.36
RajshahiMS	-2.36	0.02	-0.23	-7.31
Studayarea	-1.07	0.28	-0.10	-3.27

Table A6: Z statistic of MK/MMK test, Sen's Slope of winter rainfall for the period of 1966-2016 (Rajshahi Division)

	MK Z	P	Tau	Sen Slope
Dhunot	-2.64	0.01	-0.25	-0.67
Khetlal	1.13	0.26	0.11	0.25
Nandigram	-1.76	0.08	-0.17	-0.40
Nawkhila	-0.67	0.50	-0.07	-0.10
Shibganj	-1.63	0.10	-0.16	-0.37
Sirajganj	-0.83	0.41	-0.08	-0.40
Ullapara	-0.54	0.59	-0.05	-0.18
Gurudaspur	-0.14	0.89	-0.01	0.00
Joari	-2.22	0.03	-0.21	-0.71
Lalpur	-1.38	0.17	-0.13	-0.30
Natore	-1.08	0.28	-0.11	-0.41
Singra	-0.11	0.91	-0.01	0.00
Atghoria	-0.81	0.42	-0.08	-0.33
Faridpur	-0.18	0.86	-0.02	0.00
Pabna	-1.26	0.21	-0.12	-0.43
Sujanagar	0.27	0.79	0.03	0.14
Tanore	0.50	0.62	0.05	0.13
Godagari	-1.27	0.20	-0.12	-0.30
Puthia	-0.35	0.73	-0.03	-0.05
Sardah	-0.22	0.83	-0.02	0.00
Bholahat	0.00	1.00	0.00	0.00
Nawabganj	-0.72	0.47	-0.07	-0.14
Nachole	-0.11	0.92	-0.01	0.00
Rohanpur	-0.41	0.68	-0.04	-0.05
Shibganj	0.90	0.37	0.09	0.24
Atrai	-1.38	0.17	-0.13	-0.33
Badalgachi	-1.22	0.22	-0.12	-0.22
Manda	0.28	0.78	0.03	0.07
Mohadebpur	-1.76	0.08	-0.17	-0.46
Naogaon	-0.85	0.39	-0.08	-0.17
Nazipur	-2.21	0.03	-0.21	-0.32
Sapahar	-0.79	0.43	-0.08	-0.13
BograMS	-0.93	0.35	-0.09	-0.20
IshwardiMS	-0.12	0.90	-0.01	-0.09
RajshahiMS	-1.27	0.20	-0.12	-0.41
Studayarea	-0.67	0.50	-0.07	-0.14

Table A7: Z statistic of MK/MMK test, Sen's Slope of summer rainfall for the period of 1966-2016 (Rajshahi Division)

	MK Z	P	Tau	Sen Slope
Dhunot	-0.94	0.35	-0.09	-1.93
Khetlal	-0.32	0.75	-0.03	-1.12
Nandigram	-0.65	0.52	-0.06	-1.31
Nawkhila	-1.21	0.23	-0.12	-1.48
Shibganj	-0.40	0.69	-0.04	-0.83
Sirajganj	-0.36	0.72	-0.04	-1.18
Ullapara	0.00	1.00	0.00	0.70
Gurudaspur	1.39	0.16	0.13	2.30
Joari	0.72	0.47	0.07	0.62
Lalpur	-1.37	0.17	-0.13	-1.94
Natore	0.76	0.45	0.07	0.60
Singra	-1.06	0.29	-0.10	-1.96
Atghoria	-0.46	0.64	-0.05	-0.83
Faridpur	-0.74	0.46	-0.07	-1.29
Pabna	-1.02	0.31	-0.10	-1.37
Sujanagar	-0.44	0.66	-0.04	-1.07
Tanore	0.38	0.70	0.04	0.14
Godagari	0.25	0.80	0.03	0.20
Puthia	-0.38	0.70	-0.04	-0.77
Sardah	1.85	0.06	0.18	1.51
Bholahat	1.07	0.28	0.10	1.44
Nawabganj	1.84	0.07	0.18	1.41
Nachole	-0.87	0.38	-0.08	-1.00
Rohanpur	1.22	0.22	0.12	0.92
Shibganj	1.27	0.21	0.12	1.51
Atrai	-0.36	0.72	-0.04	-0.55
Badalgachi	-0.51	0.61	-0.05	-0.57
Manda	1.32	0.19	0.13	1.20
Mohadebpur	0.29	0.77	0.03	0.29
Naogaon	0.76	0.45	0.07	0.77
Nazipur	-0.93	0.35	-0.09	-1.11
Sapahar	0.50	0.61	0.05	0.48
BograMS	0.47	0.64	0.05	0.33
IshwardiMS	-0.97	0.33	-0.09	-1.60
RajshahiMS	1.29	0.20	0.13	0.77
Studayarea	-0.16	0.87	-0.02	-0.38

Table A8: Z statistic of MK/MMK test, Sen's Slope of rainy season rainfall for the period of 1966-2016 (Rajshahi Division)

	MK Z	P	Tau	Sen Slope
Dhunot	-1.71	0.09	-0.17	-5.63
Khetlal	-0.63	0.53	-0.06	-3.28
Nandigram	-1.13	0.26	-0.11	-4.69
Nawkhila	-1.27	0.21	-0.12	-3.25
Shibganj	-2.23	0.03	-0.22	-7.25
Sirajganj	-0.80	0.42	-0.08	-3.00
Ullapara	0.00	1.00	0.00	0.70
Gurudaspur	0.78	0.44	0.08	1.60
Joari	-0.98	0.33	-0.12	-6.05
Lalpur	-1.86	0.06	-0.18	-6.37
Natore	-0.14	0.89	-0.01	-0.39
Singra	-1.92	0.05	-0.23	-8.91
Atghoria	-1.73	0.08	-0.13	-4.96
Faridpur	-1.39	0.16	-0.13	-6.00
Pabna	0.79	0.43	0.08	2.22
Sujanagar	0.03	0.97	0.00	0.11
Tanore	0.03	0.98	0.00	0.06
Godagari	-0.28	0.78	-0.03	-0.68
Puthia	-2.03	0.04	-0.20	-5.78
Sardah	0.32	0.75	0.03	2.04
Bholahat	-0.34	0.73	-0.03	-3.20
Nawabganj	1.61	0.11	0.16	4.62
Nachole	-1.11	0.27	-0.11	-2.70
Rohanpur	-1.48	0.14	-0.14	-4.69
Shibganj	0.02	0.99	0.00	0.00
Atrai	-2.34	0.02	-0.23	-8.78
Badalgachi	-4.78	0.00	-0.35	-11.00
Manda	1.43	0.15	0.14	3.65
Mohadebpur	-1.99	0.05	-0.19	-6.14
Naogaon	-1.50	0.13	-0.15	-4.21
Nazipur	-1.45	0.15	-0.14	-4.94
Sapahar	-0.19	0.85	-0.02	-0.50
BograMS	-0.97	0.33	-0.09	-3.78
IshwardiMS	-0.81	0.42	-0.08	-3.09
RajshahiMS	-3.09	0.00	-0.30	-8.93
Studayarea	-1.66	0.10	-0.16	-3.00

TableA9: Descriptive statistics of annual rainfall for the period of 1966-2016 (Rangpur Division)

Station name	Average	Max	Min	Standard deviation	CV
latu	306	532	178	67	22
Badarganj	188	338	98	53	28
Gaibandha	171	361	68	57	33
Bhithargarh	260	456	32	76	29
Bhurangamari	268	371	139	59	22
Boda	207	342	22	58	28
Ghoraghat	168	458	28	92	55
Debiganj	188	316	1	61	32
Dimla	249	510	65	85	34
Gobindaganj	151	259	85	36	24
Hatibandha	221	391	70	73	33
Hilli	161	289	81	43	27
Kaunia	199	350	64	58	29
Khansama	194	299	115	44	23
Kantanagar	186	801	93	110	59
kurigram	205	299	137	44	21
Lalmanirhat	207	328	50	76	36
Nawabganj	160	269	76	43	27
Panchagarh	221	363	32	64	29
Patgram	118	278	0	84	71
Saidpur	229	917	26	146	64
Thakurgaon	195	395	32	56	29
Phulbari	182	334	81	66	36
Setabganj	184	621	69	76	41
Tentulia	253	449	55	70	28
Ulipur	187	279	105	41	22
Rangpur MS	181	312	103	38	21
Dinajpur MS	157	267	95	34	22

Table A10: Descriptive statistics of winter season rainfall for the period of 1966-2016 (Rangpur Division)

Station name	Average	Max	Min	Standard deviation	CV
latu	101	3303	205	649	60
Badarganj	103	989	0	193	186
Gaibandha	107	931	0	199	186
Bhithargarh	105	761	0	199	189
Bhurangamari	135	848	0	238	177
Boda	133	803	0	209	157
Ghoraghat	79	547	0	142	179
Debiganj	38	499	0	74	196
Dimla	212	1661	0	346	163
Gobindaganj	67	502	0	111	166
Hatibandha	212	1150	0	298	140
Hilli	74	544	0	123	165
Kaunia	34	281	0	52	153
Khansama	57	385	0	78	137
Kantanagar	40	172	0	39	98
kurigram	41	353	0	56	136
Lalmanirhat	375	1033	0	351	94
Nawabganj	66	305	0	78	119
Panchagarh	85	655	0	148	175
Patgram	18	179	0	853	73
Saidpur	148	1658	0	311	210
Thakurgaon	82	643	0	134	165
Phulbari	243	835	0	272	112
Setabganj	100	1006	0	198	198
Tentulia	91	711	0	175	191
Ulipur	54	1296	0	79	146
Rangpur MS	33.8	118	0	26	77
Dinajpur MS	31	123	0	28	88

Table A11: Descriptive statistics of summer season rainfall for the period of 1966-2016 (Rangpur Division)

Station name	Average	Max	Min	Standard deviation	CV
latu	1075	3303	205	648	60
Badarganj	431	1069	116	209	48
Gaibandha	440	1949	14	366	83
Bhithargarh	446	1634	48	284	64
Bhurangamari	608	1583	13	350	57
Boda	378	911	0	192	51
Ghoraghat	383	2637	0	444.6	116
Debiganj	331	1225	0	281	85
Dimla	530	2147	0	431	81
Gobindaganj	340	1021	9	220	65
Hatibandha	490	1623	0	366	75
Hilli	342	1239	20	266	78
Kaunia	484	1554	46	330	68
Khansama	372	1398	0	261	70
Kantanagar	476	2874	57	455	95
kurigram	509	1265	16	266	52
Lalmanirhat	448	1123	0	335	75
Nawabganj	296	1005	0	231	78
Panchagarh	338	1227	0	269	79
Patgram	218	845	0	230	106
Saidpur	479	3314	0	574	120
Thakurgaon	378	1292	0	292	77
Phulbari	419	1102	0	310	74
Setabganj	338	1384	0	292	87
Tentulia	417	1947	0	402	96
Ulipur	463	1297	0	271	58
Rangpur MS	392	1022	2	203	52
Dinajpur MS	279	909	54	172	62

Table A12: Descriptive statistics of rainy season rainfall for the period of 1966-2016 (Rangpur Division)

Station name	Average	Max	Min	Standard deviation	CV
latu	2494	4672	906	645	26
Badarganj	1714	3047	569	527	31
Gaibandha	1514	4983	212	896	59
Bhithargarh	2570	4620	0	819	32
Bhurangamari	2470	5614	424	1157	47
Boda	1978	3445	0	607	31
Ghoraghat	1567	6226	14	1221	78
Debiganj	1889	3218	0	641	34
Dimla	2243	6464	183	1207	57
Gobindaganj	1409	2258	658	338	24
Hatibandha	1950	3761	466	651	33
Hilli	1516	2909	771	434	29
Kaunia	1867	3189	551	613	33
Khansama	1902	3061	1013	469	25
Kantanagar	1713	8994	854	1179	69
kurigram	1910	2815	1054	500	26
Lalmanirhat	1694	2630	506	515	30
Nawabganj	1555	2891	623	447	29
Panchagarh	2229	4027	277	710	32
Patgram	1175	2932	0	853	73
Saidpur	2125	9915	259	1491	70
Thakurgaon	1884	3575	39	629	33
Phulbari	1517	2661	471	502	33
Setabganj	1772	7110	806	843	48
Tentulia	2527	4403	489	728	29
Ulipur	1730	2930	872	441	25
Rangpur MS	1747	3033	909	417	24
Dinajpur MS	1573	2840	901	380	24

Table A13: Z statistic of MK/MMK test, Sen's Slope of annual rainfall for the period of 1966-2016 (Rangpur Division)

Station name	Z	tau	p	sen's slope
latu	2.4	0.228	0.0185	20.9667
Badarganj	0.3	0.029	0.76998	1.8846
Gaibandha(Bhawaniganj)	-1.4	-0.134	0.16735	-4.0126
Bhithargarh	-3.1	-0.298	0.002081	-25.4
Bhurangamari	-3.1	-0.304	0.00167	-23.3422
Boda	-0.4	-0.035	0.72081	-3.0383
Ghoraghat	-4.2	-0.402	0.000032	-32.3417
Debiganj	-1.3	-0.125	0.19938	-8.29
Dimla	0	-0.001	1	-0.205
Gobindaganj	-0.9	-0.084	0.38926	-3.3375
Hatibandha	-4.2	-0.402	0.000032	-32.34
Hilli	-1.8	-0.175	0.071368	-9.06
Kaunia	-0.4	-0.044	0.65507	-3.1871
Khansama	0	-0.005	0.96113	-0.6578
Kantanagar	-0.7	-0.065	0.5054	-4.5884
kurigram	0.3	0.026	0.79493	2.4473
Lalmanirhat	-1.9	-0.183	0.059517	-18.3625
Nawabganj	-0.3	-0.031	0.75759	-1.3143
Panchagarh	0.3	0.029	0.76998	3.2158
Patgram	-3.7	-0.362	0.000177	-43.24
Saidpur	1	0.095	0.32973	8.52
Thakurgaon	-0.2	-0.022	0.82641	0.9733
Phulbari	-2.3	-0.225	0.020182	-16.9256
Setabganj	0	0.002	0.98704	0.4211
Tentulia	0.9	0.084	0.38926	7.0525
Ulipur	-2.5	-0.243	0.012078	-12.3
Rangpur MS	1.2	0.117	0.2293	5.5
Dinajpur MS	1	0.1	0.30507	3.52

***MS means meteorological station such Rajshahi MS means Rajshahi meteorological station**

Table A14: Z statistic of MK/MMK test, Sen's Slope of winter rainfall for the period of 1966-2016 (Rangpur Division)

Station name	Z	tau	p	sen's slope
latu	0	0.005	0.96759	0
Badarganj	-0.8	-0.082	0.40267	-0.26
Gaibandha(Bhawaniganj)	-1.4	-0.133	0.1724	-6.6053
Bhithargarh	1.2	0.115	0.23558	0.376
Bhurangamari	-1.5	-0.144	0.13893	-0.4525
Boda	0	-0.001	1	0
Ghoraghat	-3.7	-0.349	0.000222	-0.5812
Debiganj	-0.4	-0.037	0.70672	0
Dimla	1.6	0.159	0.10077	0.8476
Gobindaganj	0	0.003	0.98053	0
Hatibandha	-3.7	-0.349	0.000222	-0.5812
Hilli	-1.7	-0.159	0.09847	-0.4925
Kaunia	-1.9	-0.187	0.053142	-0.2591
Khansama	0.5	0.049	0.6145	0.125
Kantanagar	-1	-0.097	0.3175	0.2556
kurigram	-0.6	-0.058	0.55265	-0.155
Lalmanirhat	0.7	0.07	0.47433	0.3333
Nawabganj	0.7	0.67	0.4912	0.0258
Panchagarh	2.1	0.204	0.035008	0.6419
Patgram	-0.6	-0.053	0.57557	0
Saidpur	-0.2	-0.016	0.87723	-0.0083
Thakurgaon	0.8	0.078	0.42597	0.2
Phulbari	-1.1	-0.107	0.26829	-0.2467
Setabganj	1.2	0.115	0.23876	0.2889
Tentulia	-1.1	-0.109	0.26035	-0.2435
Ulipur	0	0	1	0
Rangpur MS	-0.5	-0.048	0.6257	-0.0909

Dinajpur MS	0.8	0.081	0.406	0.0714
Study area	-0.3785	-0.0135	0.429297	-0.24324

Table A15: Z statistic of MK/MMK test, Sen's Slope of summer rainfall for the period of 1966-2016 (Rangpur Division)

Station name	Z	tau	p	sen's slope
latu	3.1	0.3	0.0019	10.19
Badarganj	0.1	0.013	0.897	0.257
Gaibandha(Bhawaniganj)	-1.2	-0.112	0.249	-2.805
Bhithargarh	0.8	0.082	0.402	1.45
Bhurangamari	-0.1	-0.014	0.89	-0.45
Boda	1.4	0.137	0.158	2.4
Ghoraghat	-1.7	-0.161	0.098	-3.91
Debiganj	-1.6	-0.155	0.1114	-2.285
Dimla	0.9	0.092	0.346	2.75
Gobindaganj	-0.7	-0.065	0.505	-0.969
Hatibandha	-0.8	-0.078	0.426	-1.96
Hilli	-0.4	-0.038	0.697	-0.838
Kaunia	-1	-0.094	0.329	-2.219
Khansama	0.1	0.007	0.948	0.091
Kantanagar	-2.3	-0.225	0.0201	-5.55
kurigram	0.3	0.031	0.757	0.78
Lalmanirhat	-0.9	-0.084	0.389	-2.26
Nawabganj	-0.6	-0.063	0.521	-1.181
Panchagarh	2.1	0.202	0.0376	3.42
Patgram	-3.5	-0.338	0.00043	-6.43
Saidpur	0.7	0.073	0.455	2.28
Thakurgaon	2	0.193	0.047	2.57
Phulbari	-0.7	-0.065	0.505	-1.99
Setabganj	1.7	0.162	0.094293	3.5944
Tentulia	1.5	0.147	0.131	2.66
Ulipur	-1.2	-0.12	0.22	-1.92
Rangpur MS	1.4	0.134	0.167	1.98

Dinajpur MS	1.8	0.169	0.08	1.49
Study area	0.042857	0.004643	0.338669	0.040907

Table A16: Z statistic of MK/MMK test, Sen's Slope of rainy season rainfall for the period of 1966-2016 (Rangpur Division)

Station name	Z	tau	p	sen's slope
latu	1.1	0.107	0.269	6.44
Badarganj	0.2	0.023	0.82	1.65
Gaibandha	-1	-0.095	0.33	-2.98
Bhithargarh	-4	-0.387	0.00007	-29.27
Bhurangamari	-3.5	-0.334	0.00055	-15.87
Boda	-1	-0.095	0.33	-4.95
Ghoraghat	-3.7	-0.357	0.00022	-24.88
Debiganj	-1.5	-0.141	0.146	-9.23
Dimla	-1.1	-0.103	0.291	-5.13
Gobindaganj	-1.1	-0.111	0.255	-3.15
Hatibandha	-3.3	-0.321	0.00092	-19.96
Hilli	-2.3	-0.22	0.0193	-9.18
Kaunia	-0.8	-0.082	0.403	-5.089
Khansama	-0.4	-0.037	0.709	-1.998
Kantanagar	0.6	0.06	0.537	2.804
kurigram	0.2	0.018	0.858	0.825
Lalmanirhat	-3.4	-0.33	0.000646	-17.02
Nawabganj	-0.4	-0.038	0.697	-1.83
Panchagarh	2	0.018	0.858	0.827
Patgram	-3.2	-0.311	0.0013	-33.12
Saidpur	0.6	0.059	0.548	4.11
Thakurgaon	-0.6	-0.055	0.575	-3.698
Phulbari	-3.1	-0.299	0.002	-14.3
Setabganj	-0.8	-0.079	0.417	-3.12
Tentulia	0.6	0.057	0.559	3.58
Ulipur	-1.9	-0.187	0.053	-9.14
Rangpur MS	0.8	0.077	0.043	3.24

Dinajpur MS	0.5	0.053	0.585	1.17
Study area	-1.08929	-0.11107	0.332429	-6.759607143

Table A17: Stochastic Component Time Series (SCTS) for 5 Districts

year	Bogura	Dinajpur	Ishwardi	Rajshahi	Rangpur
1966	10.37884	7.662625	9.884466	8.955922	8.950541
1967	10.32459	10.66473	10.86285	10.66661	10.61953
1968	8.019546	8.618161	8.684792	7.99421	10.3665
1969	9.530669	9.782686	8.298691	9.441868	9.966602
1970	7.768894	7.684567	11.00604	9.051888	8.756131
1971	10.74478	9.749592	8.058206	9.76383	8.553469
1972	9.723115	9.023992	9.706014	9.462567	10.58105
1973	8.795878	9.782828	11.077	8.87457	8.321211
1974	10.48858	9.782828	9.947885	8.891043	10.3665
1975	9.047171	9.782828	9.514578	9.204735	9.490252
1976	9.399133	9.782828	8.897097	9.282028	9.048415
1977	11.23075	9.782828	7.515256	10.22681	9.967896
1978	8.514144	9.782828	10.75977	8.773276	9.59444
1979	7.703679	9.782828	7.801145	8.530453	8.52079
1980	10.1757	9.782828	9.903337	10.93075	9.44138
1981	11.85591	8.028411	11.84325	11.22567	9.900895
1982	9.244741	9.906311	13.67089	11.42851	8.692275
1983	10.68736	8.931393	12.48999	8.508227	10.32144
1984	10.3306	9.661936	10.16921	10.04371	9.571589
1985	9.687053	9.439364	11.17511	10.93459	10.5319
1986	10.45776	10.35956	9.224996	10.7224	10.82779

1987	8.559354	7.858574	7.616969	8.572874	7.624294
1988	8.905993	8.178819	11.76698	8.855448	10.18283
1989	7.206049	9.20274	6.468106	9.06229	7.566247
1990	10.7536	11.44162	12.23745	11.14649	12.94693
1991	9.284699	8.651844	10.85993	9.098767	9.434414
1992	9.165705	7.893951	9.12738	9.387133	10.0121
1993	10.29621	9.821741	11.7254	9.825443	9.658825
1994	11.64348	10.52602	9.936402	12.15265	9.588092
1995	9.457961	7.391594	9.6843	9.329858	8.296417
1996	11.63789	8.88898	11.00215	10.02401	10.04503
1997	10.91478	8.725344	9.897081	7.85729	9.778415
1998	9.574394	10.37202	11.41602	10.3921	11.60364
1999	9.549902	10.01947	9.851901	9.23014	10.41791
2000	11.6243	9.995299	10.51289	8.587192	9.64112
2001	9.91816	10.02423	9.51116	9.573405	10.4019
2002	9.627173	8.359547	11.88689	10.91713	10.14363
2003	13.23529	11.09378	10.33301	11.12141	10.3395
2004	9.259171	10.01133	9.223462	9.322109	10.70365
2005	9.929006	10.00417	8.328977	8.943024	10.78943
2006	11.83602	9.667968	10.27446	9.521411	9.631096
2007	8.124528	8.678376	8.965254	8.576572	9.085715
2008	9.395898	9.516562	10.91224	9.706224	11.14581
2009	7.903637	9.813723	9.177979	9.316115	8.391371
2010	10.47442	8.82883	12.75791	11.20873	9.618074
2011	8.374099	9.871227	8.180711	8.67148	8.906182
2012	10.20824	8.468892	12.71697	10.95884	10.02045
2013	10.01969	10.14246	10.99128	11.26511	11.61737
2014	8.783607	8.719888	8.635218	9.177368	7.922063

2015	12.21678	9.190657	10.54826	10.40862	9.085777
2016	9.196218	9.009285	10.55266	11.17955	8.893724

TableA18 : Discrete rainfall anomalies

Year	Winter	Summer	Rainy	Annual
1966	13.90196	-118.475	-180.716	-285.289
1967	-33.098	-11.0745	-300.156	-344.329
1968	-34.098	-148.075	-102.316	-284.489
1969	-7.89804	-69.2745	-108.076	-185.249
1970	-1.09804	-149.275	167.2839	16.91137
1971	18.10196	-146.675	152.9639	24.39137
1972	-20.698	-139.075	-282.076	-441.849
1973	43.10196	79.32549	50.80392	173.2314
1974	-31.698	22.12549	126.0039	116.4314
1975	-17.498	24.12549	-230.956	-224.329
1976	-27.098	49.52549	85.80392	108.2314
1977	16.70196	112.3255	292.7239	421.7514
1978	7.901961	107.7255	-140.676	-25.0486
1979	39.90196	-146.875	103.0839	-3.88863
1980	-5.69804	-18.0745	15.48392	-8.28863
1981	89.30196	278.5255	-47.2361	320.5914
1982	14.10196	34.32549	-270.556	-222.129
1983	1.701961	33.92549	119.1239	154.7514
1984	-8.29804	19.92549	192.8839	204.5114
1985	-23.098	38.12549	154.9239	169.9514
1986	3.501961	16.92549	126.9239	147.3514
1987	-8.69804	-4.47451	420.9639	407.7914

1988	27.30196	65.72549	478.6039	571.6314
1989	-3.09804	8.92549	-115.636	-109.809
1990	4.501961	124.7255	42.04392	171.2714
1991	50.50196	90.72549	-146.516	-5.28863
1992	-1.29804	-111.475	-322.196	-434.969
1993	9.901961	43.52549	7.043922	60.47137
1994	22.30196	-88.2745	-173.796	-239.769
1995	48.30196	-147.875	-21.7161	-121.289
1996	2.901961	-102.875	-71.4361	-171.409
1997	24.30196	-72.0745	88.36392	40.59137
1998	7.501961	26.32549	246.9639	280.7914
1999	-32.498	7.32549	266.2839	241.1114
2000	2.501961	183.7255	-105.916	80.31137
2001	-22.498	56.52549	-142.236	-108.209
2002	-8.09804	36.32549	153.0039	181.2314
2003	4.501961	73.92549	69.84392	148.2714
2004	-25.098	18.12549	317.8039	310.8314
2005	-23.298	39.12549	471.0839	486.9114
2006	-19.698	33.92549	-220.916	-206.689
2007	-5.09804	-52.4745	20.32392	-37.2486
2008	-3.09804	-55.2745	50.32392	-8.04863
2009	-29.498	0.32549	-92.1161	-121.289
2010	-12.498	-50.0745	-142.116	-204.689
2011	-27.898	42.12549	21.52392	35.75137
2012	21.70196	-114.275	-288.996	-381.569
2013	-24.498	-31.4745	-141.356	-197.329
2014	-9.29804	-23.4745	-152.396	-185.169
2015	-2.89804	74.52549	-176.076	-104.449
2016	-5.09804	58.12549	-265.996	-212.969

Table A19: Cumulative Precipitation Anomalies

Year	Bogura	Dinajpur	Ishwardi	Rajshahi	Rangpur
1966	-532.824	-440.647	-444	191.2941	-969.059
1967	-87.8824	-90.6471	13.82353	-134.176	-176.471
1968	-240.882	-227.765	-685	-182.176	-409.824
1969	-235.824	82.35294	355	830.2941	112.9412
1970	278.1176	-237.647	88.82353	229.8235	97.52941
1971	-109.882	-364.765	-297	134.8235	-841.824
1972	-519.824	-745.647	-542	-600.706	-734.059
1973	1000.118	67.35294	1112.824	636.8235	337.5294
1974	-34.8824	-314.765	-157	76.82353	-409.824
1975	-334.824	-219.647	305	-377.706	-437.059
1976	366.1176	67.35294	1235.824	149.8235	-4.47059
1977	-409.882	-314.765	998	258.8235	-402.824
1978	117.1765	-219.647	-99	212.2941	-55.0588
1979	711.1176	67.35294	182.8235	270.8235	148.5294
1980	-272.882	-314.765	-288	-83.1765	-300.824
1981	-27.8235	169.3529	751	719.2941	-284.059
1982	-292.882	-318.647	-120.176	-174.176	301.5294
1983	-120.882	57.23529	-61	-30.1765	-182.824
1984	536.1765	217.3529	208	53.29412	1547.941
1985	177.1176	436.3529	-195.176	-25.1765	982.5294
1986	251.1176	-91.7647	-255	-149.176	-108.824
1987	247.1765	1258.353	181	33.29412	993.9412
1988	734.1176	560.3529	174.8235	164.8235	624.5294
1989	-475.882	-129.765	-501	-334.176	-542.824
1990	310.1765	133.3529	609	243.2941	286.9412

1991	775.1176	351.3529	322.8235	221.8235	563.5294
1992	-521.882	-393.765	-681	-820.176	-414.824
1993	141.1765	231.3529	111	89.29412	319.9412
1994	-173.882	-518.647	-313.176	-135.176	-598.471
1995	368.1176	570.2353	-462	-227.176	285.1765
1996	159.1765	-360.647	-62	-252.706	-196.059
1997	-214.882	148.3529	504.8235	784.8235	71.52941
1998	712.1176	348.2353	-108	-119.176	-55.8235
1999	-156.824	588.3529	262	340.2941	730.9412
2000	322.1176	-162.647	434.8235	392.8235	-154.471
2001	-495.882	183.2353	-266	-296.176	71.17647
2002	244.1765	601.3529	-93	-77.7059	387.9412
2003	176.1176	396.3529	-271.176	134.8235	502.5294
2004	268.1176	250.2353	45	126.8235	259.1765
2005	324.1765	1027.353	329	-116.706	652.9412
2006	-409.882	-375.647	-87.1765	-132.176	-217.471
2007	30.11765	-463.765	-171	358.8235	-383.824
2008	24.17647	-175.647	-186	-206.706	-293.059
2009	-105.882	364.3529	-81.1765	-234.176	317.5294
2010	-614.882	-401.765	-850	-867.176	-318.824
2011	-34.8235	-300.647	244	-80.7059	-273.059
2012	-375.882	-149.647	-311.176	-113.176	-22.4706
2013	-669.882	-215.765	-615	-411.176	-504.824
2014	-58.8235	-549.647	-50	-333.706	-565.059
2015	65.11765	304.3529	210.8235	143.8235	517.5294
2016	-807.882	-382.765	-428	-284.176	-255.824

TableA20 : 3 Months SWI

Year	Bogra	Dinajpur	Rangpur	Rajshahi	Ishwardi
1977	-1.88097	-1.09441	-0.07866	-1.40784	-0.37132
1978	-1.71305	-1.13257	-0.12008	-1.52867	-0.75505
1979	-0.72579	-0.7817	1.137956	-1.64083	-0.73969
1980	-1.36624	-1.22449	-0.49606	-1.33441	-0.30947
1981	-1.67874	-1.14723	-1.33573	-1.70295	-0.53211
1982	-0.95992	-0.76169	0.394208	-1.06911	-0.5484
1983	-0.68772	-0.75328	0.112052	-0.94435	-1.15836
1984	-0.94694	-0.92185	0.066127	-1.34573	-0.5144
1985	-0.82546	-0.62137	-0.17189	-0.97818	-0.27692
1986	-0.59487	-0.82193	0.195377	-0.85165	-0.41596
1987	-0.44403	-1.012	-0.07171	-0.82827	-0.42252
1988	-0.30034	-0.89842	-0.24832	-0.71528	-0.57884
1989	0.115738	-0.73221	2.257793	-0.15774	0.250339
1990	-0.09575	-0.96538	0.545039	-0.94916	-0.82352
1991	0.064112	-0.72528	0.717603	-0.58078	-0.47746
1992	0.1812	-0.38011	1.147166	-0.11322	-0.19767
1993	0.094601	-0.71005	-1.02482	0.196027	0.102433
1994	0.134473	-0.11943	1.424879	-0.09098	-0.82616
1995	0.765027	0.670099	1.432237	1.053512	-0.40685
1996	0.335321	0.226164	0.222163	0.172141	-0.77575

1997	0.1474	0.128554	-1.55458	-0.32653	-0.92924
1998	0.182687	0.06394	-2.14766	-0.11244	-1.16021
1999	0.147294	0.334412	-1.73318	1.369972	-1.11002
2000	-0.40204	0.068382	-0.12758	-0.46042	-0.11951
2001	0.462132	0.750369	0.946831	0.785329	-0.91877
2002	-0.03635	-0.09848	-0.57293	0.24178	0.147258
2003	-0.19592	-0.08799	-0.59919	-0.0849	-0.56378
2004	-0.10868	0.042148	-0.75874	0.20152	-0.60795
2005	0.061102	0.390376	-0.41776	0.210467	-0.35274
2006	-0.04794	0.478561	0.088787	0.110797	-0.19778
2007	0.529769	0.573343	0.452555	1.203645	-0.34277
2008	0.322855	0.596296	0.293811	1.037125	1.389227
2009	0.514492	0.857206	0.414106	1.590435	2.253249
2010	0.886937	0.814404	-0.38153	0.954196	1.25973
2011	0.796574	0.715712	0.314931	0.914102	1.197121
2012	0.785343	0.950861	0.082164	1.319616	1.830351
2013	0.760424	0.842074	0.024198	1.612681	2.287987
2014	0.789617	0.694623	-2.19802	1.451667	2.036555
2015	0.164084	0.54295	1.777654	0.684801	0.839056
2016	0.370112	0.866654	1.187708	0.756216	0.950574
2017	4.399453	4.382736	-1.19693	1.357398	1.889349

Table A21: 6 Months SWI

Year	Bogra	Dinajpur	Rangpur	Rajshahi	Ishwardi
1977	-1.81326	-1.81326	-0.32273	-0.87208	-0.96308
1978	-1.55055	-1.55055	-0.18007	-0.53649	-0.66109
1979	-0.33999	-0.33999	1.625202	-0.78382	-0.28739
1980	-1.45462	-1.45462	-0.82069	-0.86798	-0.61152
1981	-1.33117	-1.33117	-0.60674	-0.9489	-0.90881
1982	-0.25254	-0.25254	0.403365	-0.33449	-0.52488
1983	-0.18607	-0.18607	0.077394	-0.22042	-0.63681
1984	-1.41967	-1.41967	-1.74449	-0.97724	-0.84275
1985	-0.8019	-0.8019	-1.10277	-0.60904	-0.28878
1986	-0.46704	-0.46704	-0.53637	-0.52983	-0.30476
1987	-0.64769	-0.64769	-1.08791	-0.80016	-0.3782
1988	-0.96947	-0.96947	-0.83364	-0.88246	-0.58467
1989	-0.06098	-0.06098	1.340431	-0.57959	0.568268
1990	-0.65921	-0.65921	-0.76328	-0.86626	-0.69175
1991	-0.85474	-0.85474	-1.4962	-0.82112	-0.55203
1992	0.92985	0.92985	0.756975	-0.04848	0.877377
1993	-0.54262	-0.54262	-1.98517	-0.46339	0.327936
1994	0.857112	0.857112	1.673371	-0.06327	-0.14758
1995	0.294863	0.294863	1.244696	0.264075	0.306325
1996	0.16657	0.16657	0.503277	-0.16882	-0.01826
1997	0.405321	0.405321	-0.35852	-0.2856	0.061012

1998	-0.55761	-0.55761	1.347259	-0.08536	-0.67547
1999	-0.036	-0.036	-0.84501	0.338468	-0.41416
2000	-0.4712	-0.4712	0.093237	-0.66017	-0.98701
2001	0.951671	0.951671	0.845118	-0.04464	0.564235
2002	-0.23169	-0.23169	-1.44522	-0.53182	-1.21314
2003	-0.03585	-0.03585	-0.62015	-0.13953	-0.90629
2004	-0.3281	-0.3281	-1.04713	-0.224	-0.06134
2005	0.050778	0.050778	-1.12671	-0.06843	-0.08378
2006	0.546478	0.546478	1.284919	0.093339	1.139746
2007	0.421141	0.421141	0.264813	-0.11701	-0.27561
2008	0.511076	0.511076	0.290746	0.206999	-0.346
2009	1.233428	1.233428	0.443957	1.2161	0.838378
2010	1.53931	1.53931	-0.57003	1.755694	1.471696
2011	1.273708	1.273708	0.37288	1.646368	1.343381
2012	1.724627	1.724627	0.666013	1.724678	1.435294
2013	1.883318	1.883318	0.829273	2.172935	1.96141
2014	1.572674	1.572674	1.081435	3.919604	4.011467
2015	1.094605	1.094605	0.383035	0.018139	-0.56766
2016	1.274625	1.274625	1.609689	0.027739	-0.5564
2017	-1.71919	-1.71919	0.355722	0.146261	-0.41729

Table A22: 12 months SWI

Year	Bogra	Dinajpur	Rangpur	Rajshahi	Ishwardi
1977	-1.83534	-1.38263	-0.1968	-1.08872	-0.94379
1978	-1.62015	-1.13938	-0.05116	-1.03696	-0.58655
1979	-0.61198	-0.58225	2.060437	-1.21541	-0.20396
1980	-1.60315	-1.30967	1.141129	-1.21025	-0.39715
1981	-1.46211	-1.13141	-0.61859	-1.33472	-0.61514
1982	-0.53936	-0.56744	0.808667	-0.68274	-0.63818
1983	-0.54387	-0.60149	0.74013	-0.58605	-0.66886
1984	-1.45638	-1.17339	-0.76378	-1.20257	-0.77815
1985	-1.05554	-0.87289	-0.4257	-0.79569	-0.38412
1986	-0.83599	-0.92107	-0.03921	-0.97527	-0.35961
1987	-0.77503	-1.4657	-0.71484	-0.9364	-0.42619
1988	-0.76282	-0.9522	-0.46679	-0.69056	-0.67591
1989	-0.1722	-1.03462	1.775808	-0.48098	0.368907
1990	-0.63929	-1.11029	-0.21531	-0.95287	-0.73087
1991	-0.72855	-1.11163	-1.03811	-0.85538	-0.76898
1992	0.417876	-0.25394	0.277468	-0.14668	0.44492
1993	-0.51989	-1.01956	-1.94893	-0.2304	0.24627
1994	0.535133	0.484032	1.360079	-0.07827	-0.3543
1995	0.245747	0.409937	1.058276	0.481718	0.186543
1996	0.073361	0.101233	0.051943	-0.05597	-0.22879
1997	0.276892	0.371078	-1.17002	-0.29501	-0.18444

1998	-0.49222	-0.1911	-0.76753	-0.08839	-0.92809
1999	-0.0765	0.036067	-1.53974	0.605324	-0.82439
2000	-0.40256	0.046202	0.16106	-0.33179	-1.52915
2001	0.799298	0.772338	0.771739	0.549385	0.239957
2002	0.005705	-0.2412	-1.04844	-0.05926	-0.77772
2003	-0.11136	-0.17812	-0.89958	-0.10677	-1.28462
2004	-0.36903	-0.14916	-1.91952	-0.17129	-0.19428
2005	-0.02333	0.254438	-1.31846	-0.03851	-0.12365
2006	0.467467	0.673294	0.772967	-0.04616	1.03589
2007	0.591864	0.794845	0.33332	0.568719	0.058296
2008	0.569655	0.748359	0.292029	0.476337	-0.02443
2009	1.237824	1.316167	0.08041	1.558193	1.497118
2010	2.023732	1.007633	-0.83255	1.884375	1.95587
2011	1.387602	1.132681	0.148968	1.568425	1.51151
2012	1.711049	1.714183	0.352909	1.600208	1.55621
2013	1.827078	1.534112	0.267452	2.174815	2.364354
2014	1.380738	1.663686	-0.08648	2.719871	3.130936
2015	1.194617	1.248252	1.342353	0.085601	-0.57398
2016	1.361407	2.12541	2.091306	0.813408	0.449631
2017	0.529605	0.955191	0.173083	0.606684	0.15889

Appendix B

(Additional Graphs)

FigureB1 : Mean annual rainfall (mm) distribution for the period of 1966-2016 in the study area (Data Source: BMD and BWDB)

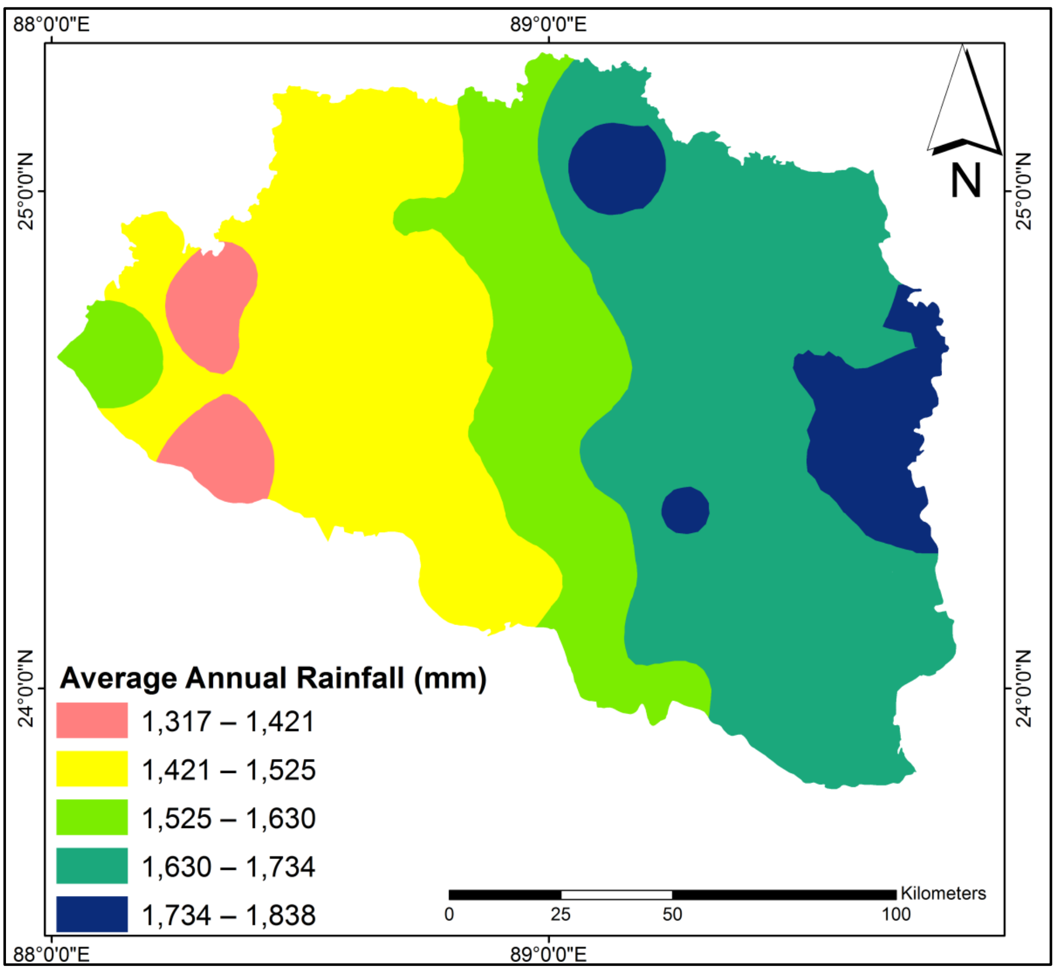
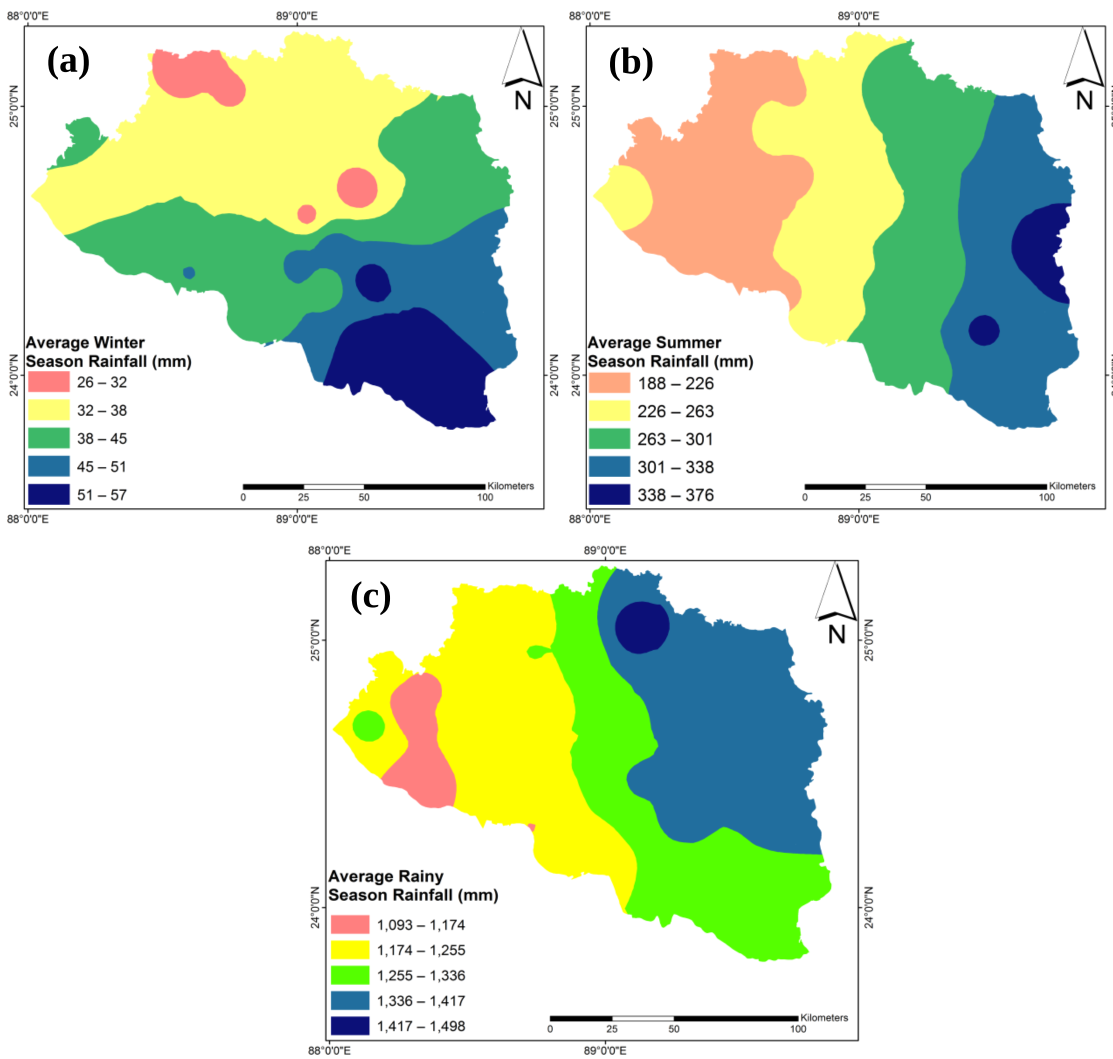


Figure B2: Mean seasonal rainfall (mm) for the period of 1966-2016 distribution in the study area a) winter season, b) summer season and c) rainy season ((Data Source: BMD and BWDB)



FigureB3 : Distribution of coefficient of variation (**CV** in %) of seasonal rainfall for the period of 1971-2011 over the study area (a) winter season, (b) summer season and (c) Rainy season (Rajshahi Division)

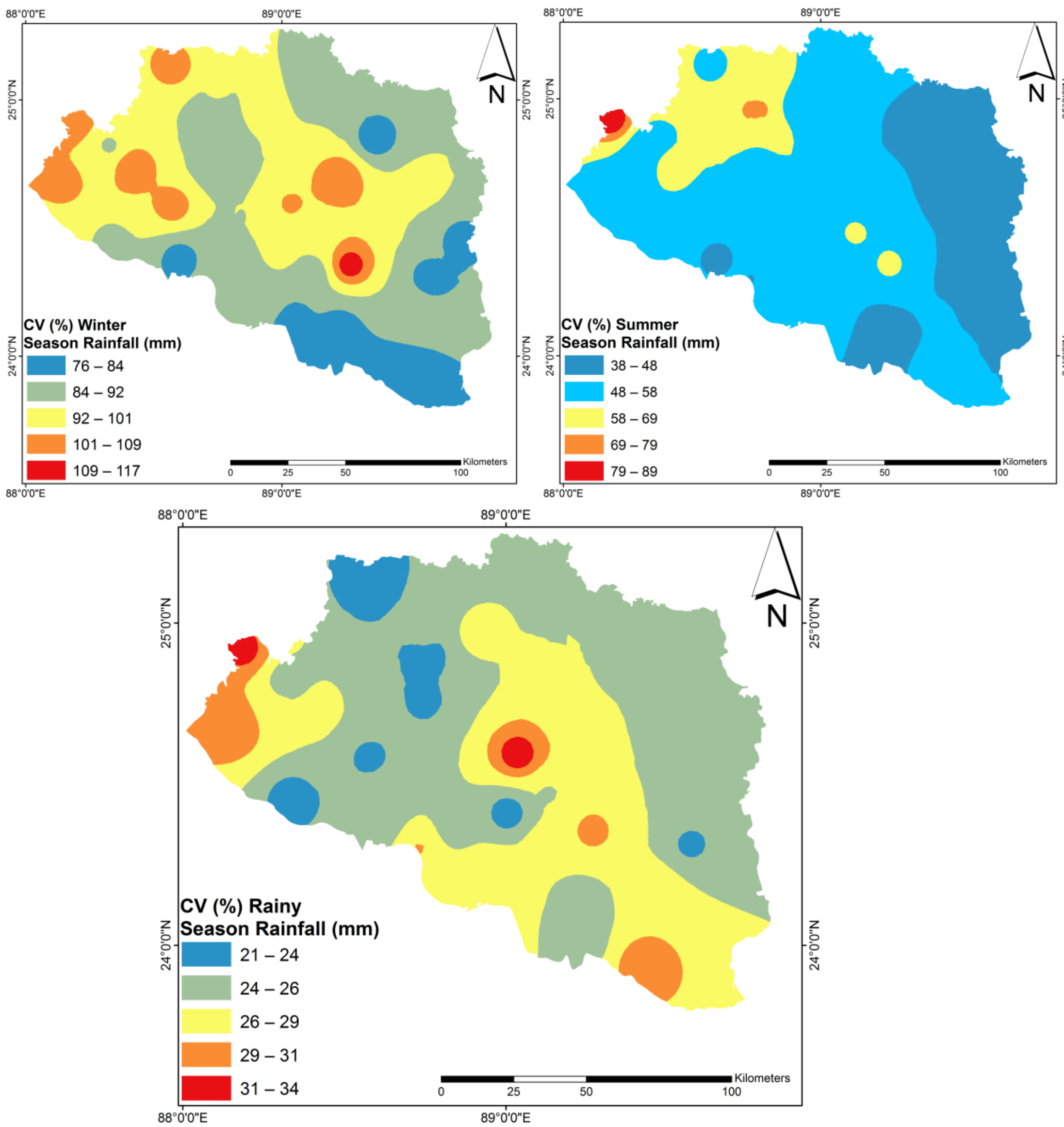
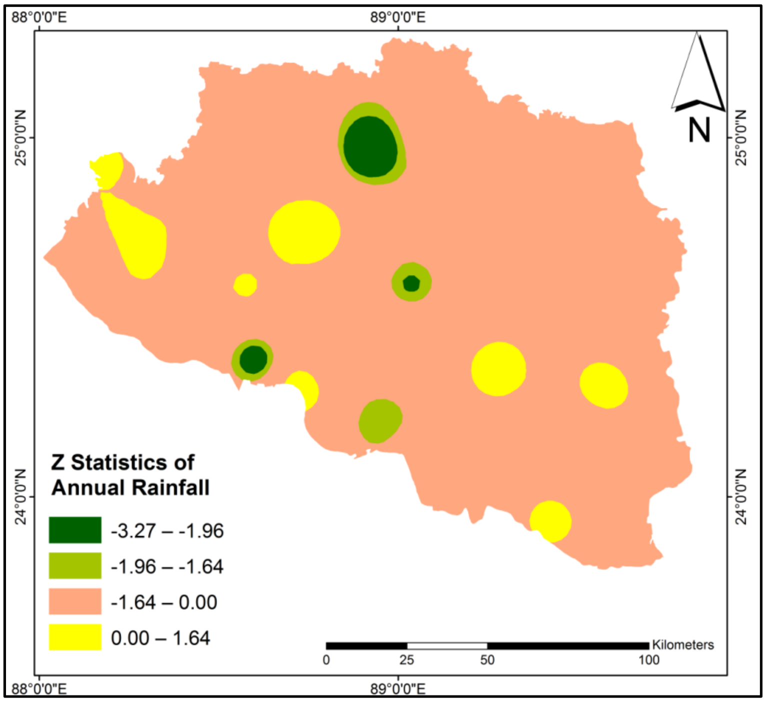


Figure B4. Distribution of Z statistic of MK test of annual rainfall for the period of 1966-2016 over Rajshahi division



FigureB5: Distribution of Z statistic of MK test of winter season rainfall for the period of 1966-2016 over Rajshahi division

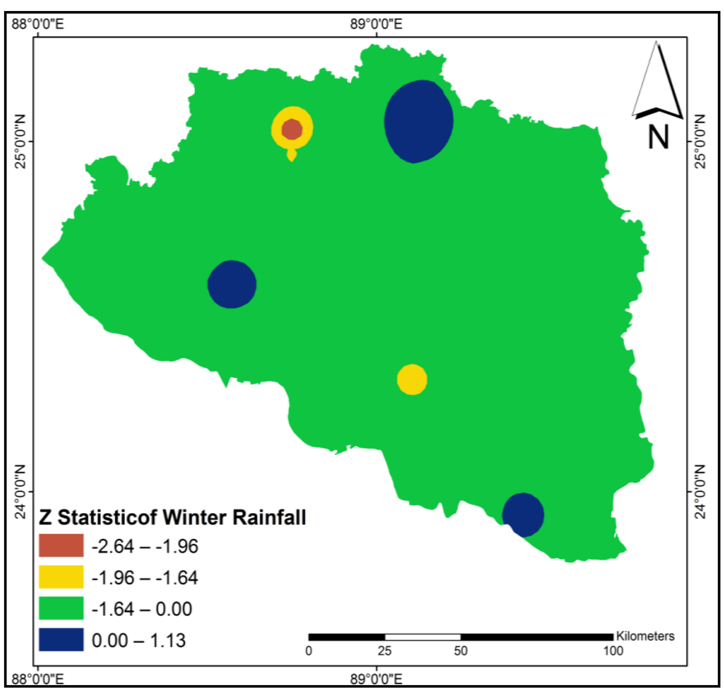


Figure B6: Distribution of Z statistic of MK test of summer season rainfall for the period of 1966-2016 over Rajshahi division

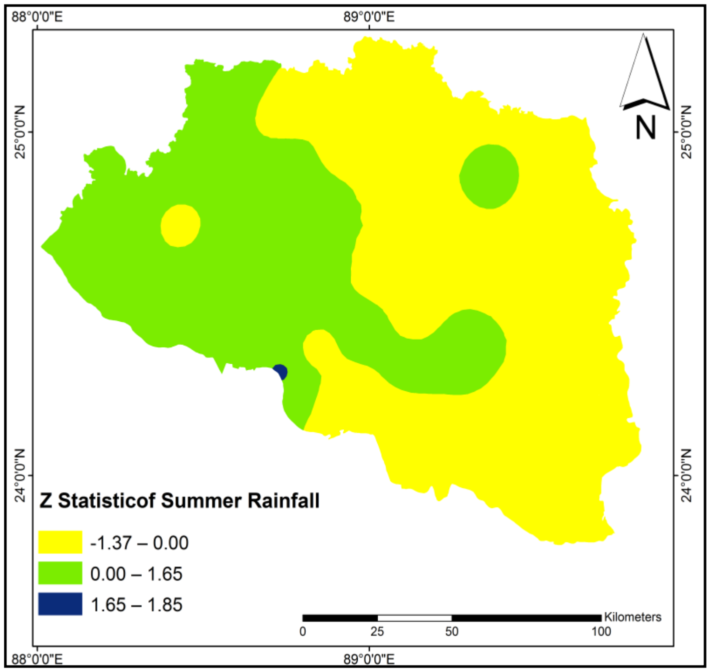


Figure B7: Distribution of Z statistic of MK test of rainy season rainfall for the period of 1966-2016 over Rajshahi division

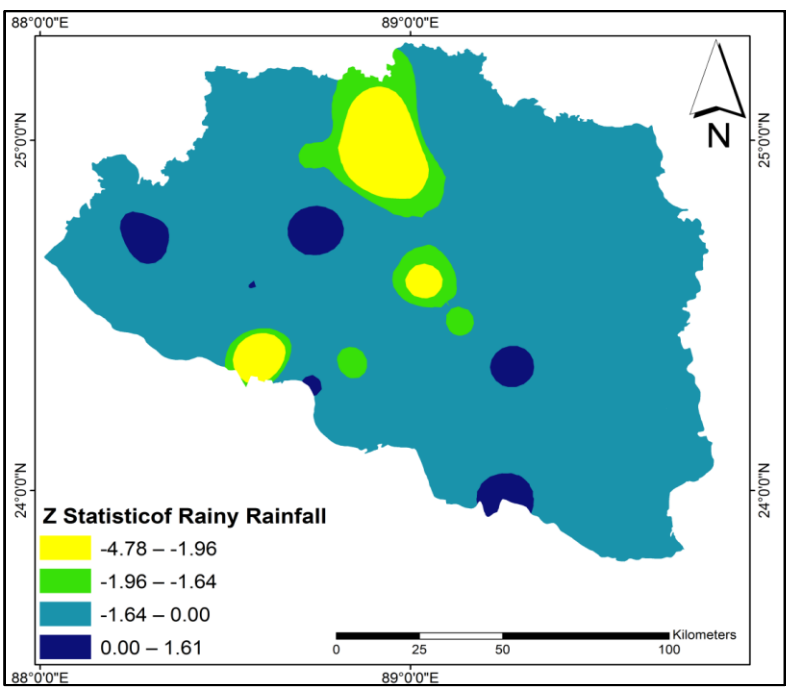


Figure B8: Average Winter Rainfall & CV (Rangpur Division)

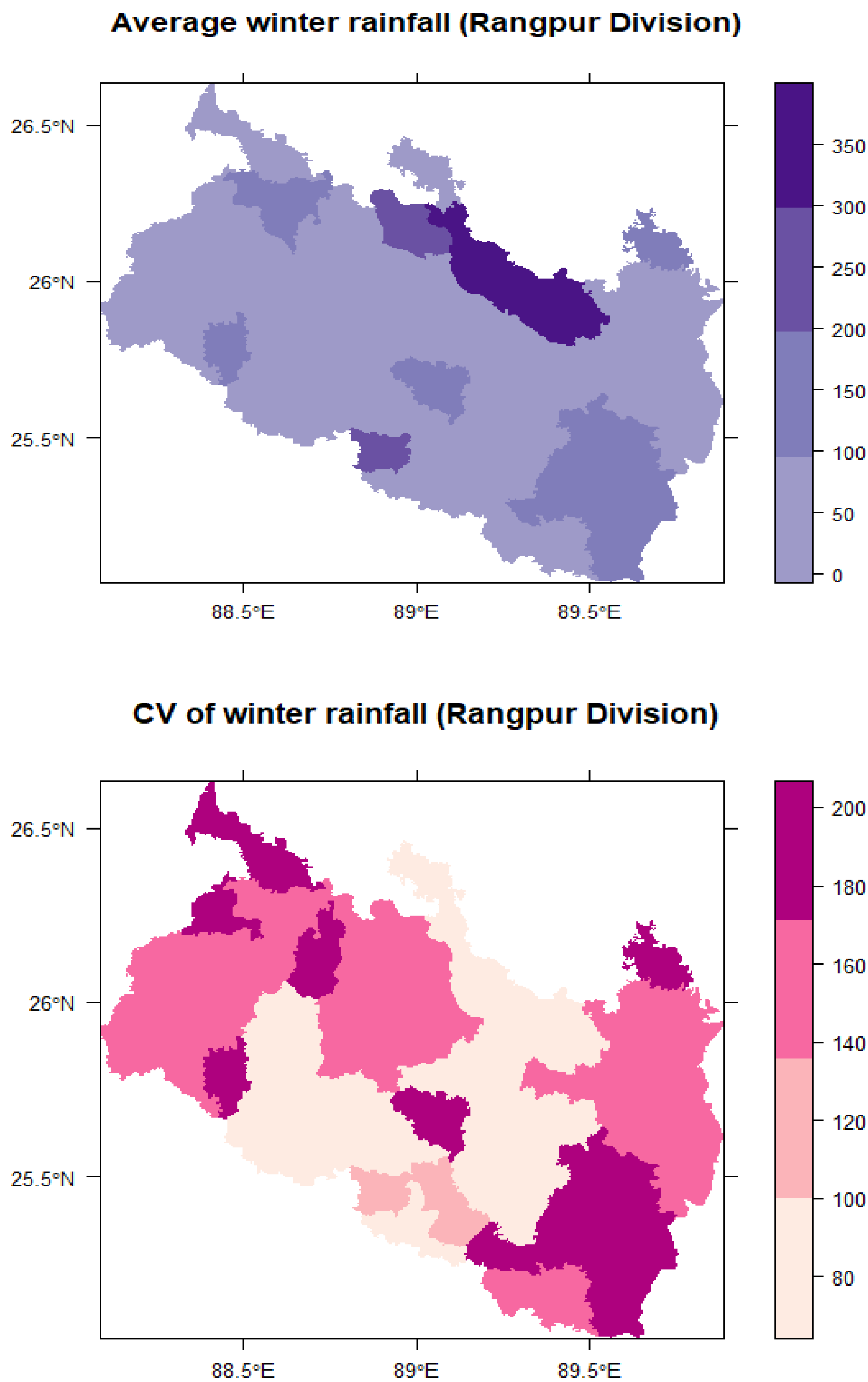
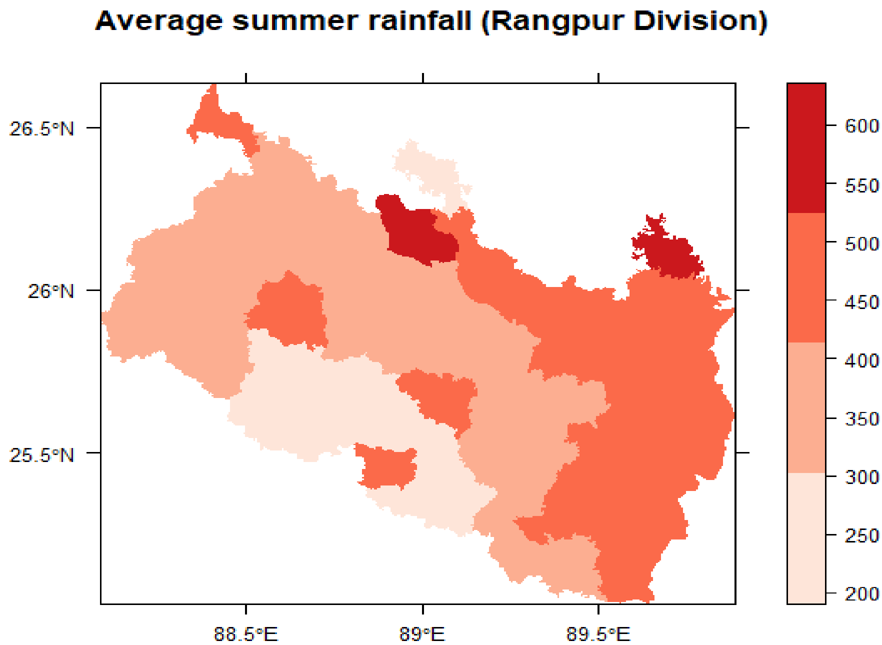


Figure B9: Average Summer Rainfall & CV (Rangpur Division)



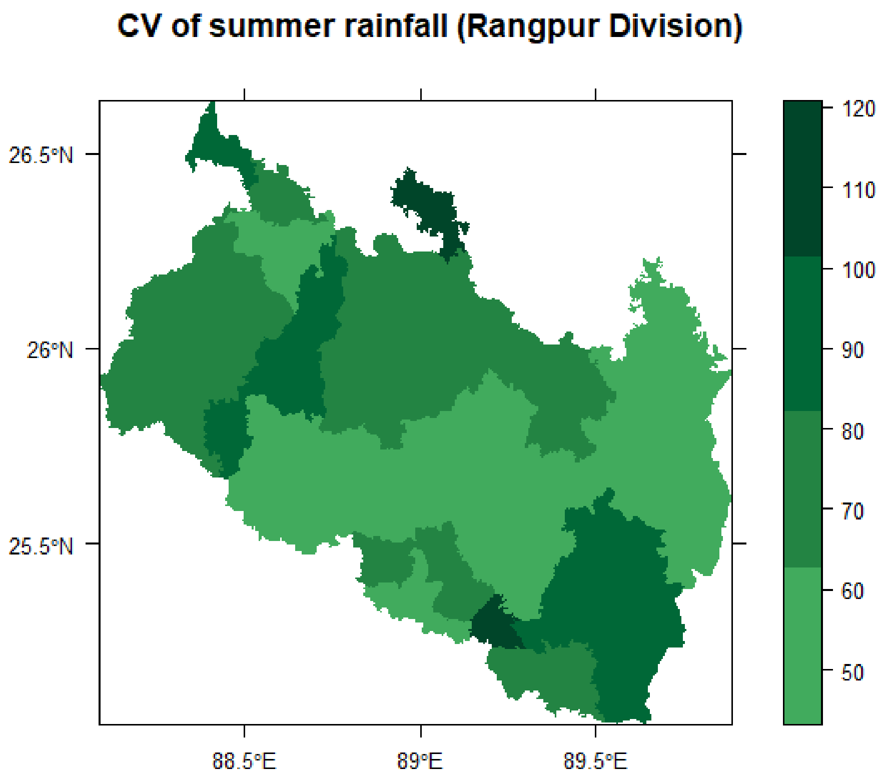
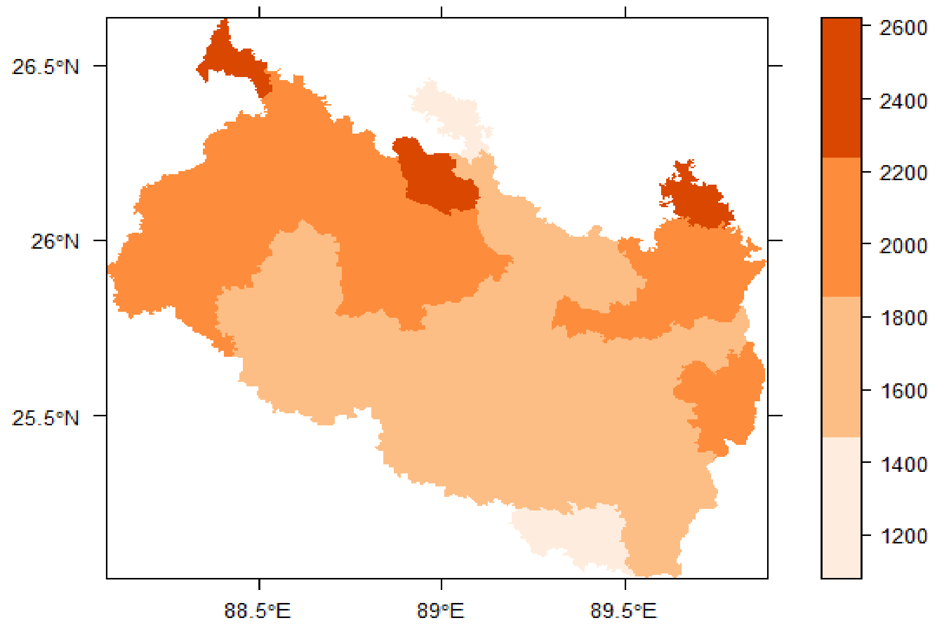


Figure B10: Average Rainy Season Rainfall & CV (Rangpur Division)

Average rainy rainfall (Rangpur Division)



CV of rainy rainfall (Rangpur Division)

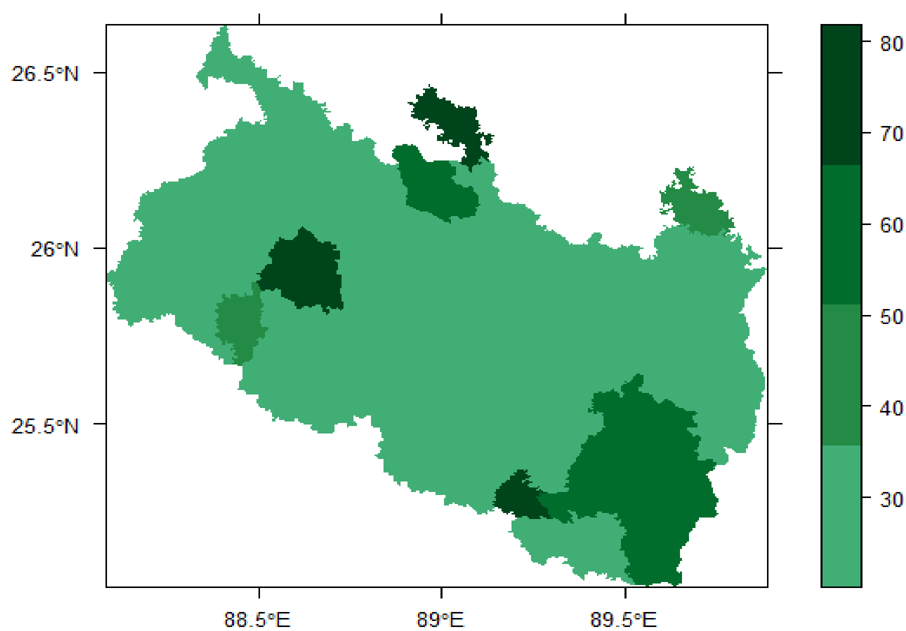


Figure B11: Annual Z statistic of rainfall (Rangpur Division)

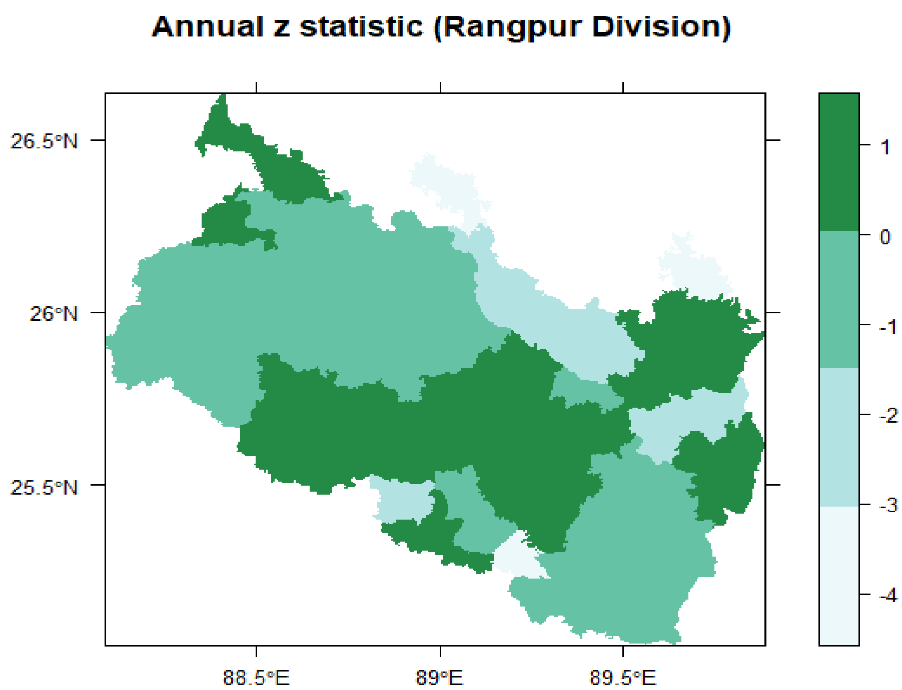


Figure B12: Winter season z statistic of rainfall (Rangpur Division)

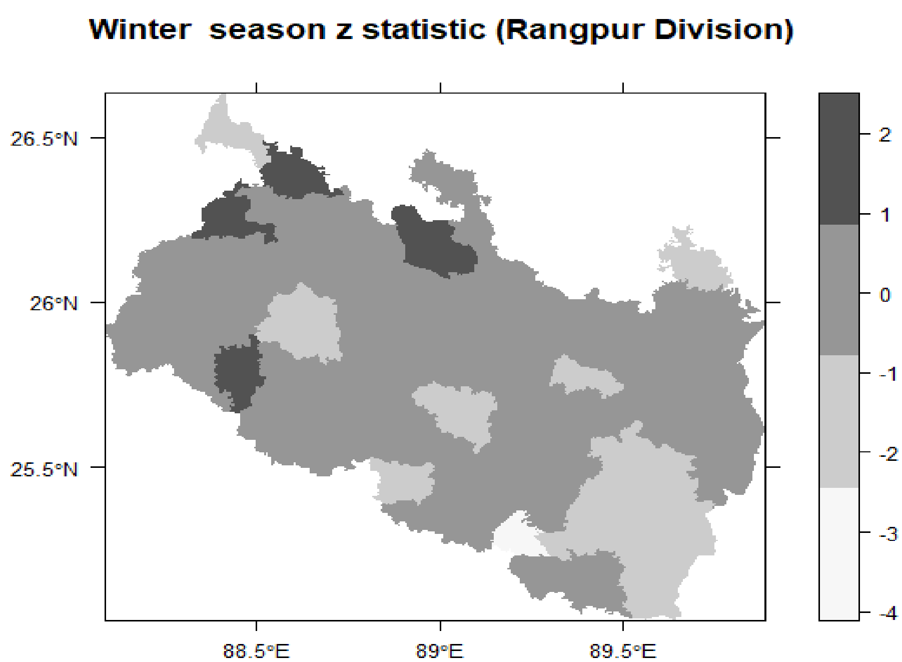


Figure B13: Summer season z statistic of rainfall (Rangpur Division)

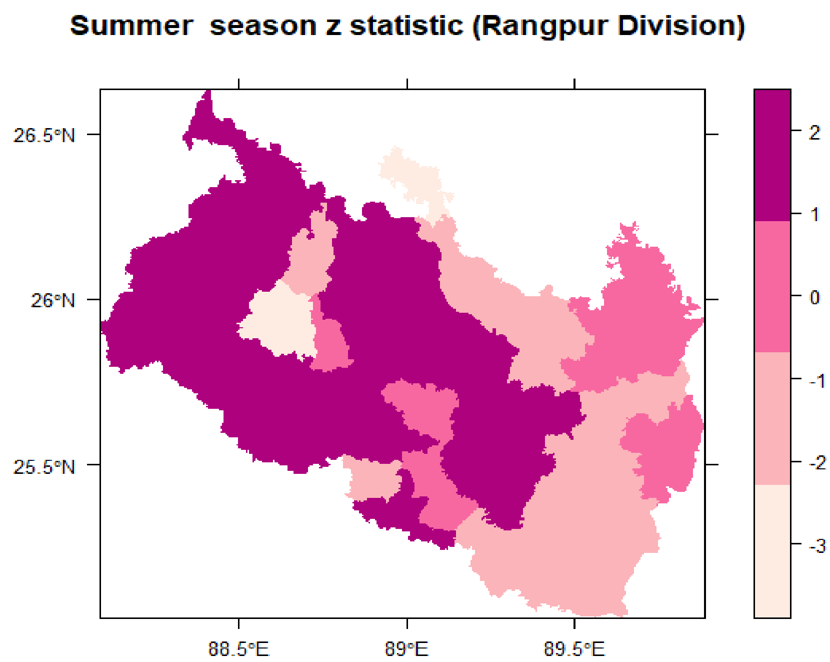


Figure B14: Rainy season z statistic of rainfall (Rangpur Division)

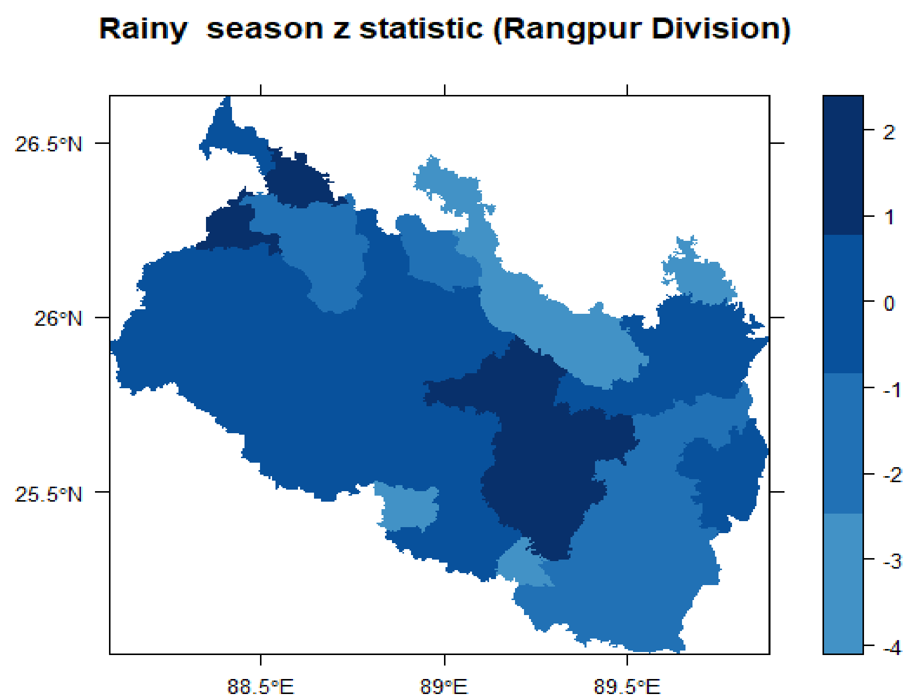


Figure B15: SPI plot for Bogura

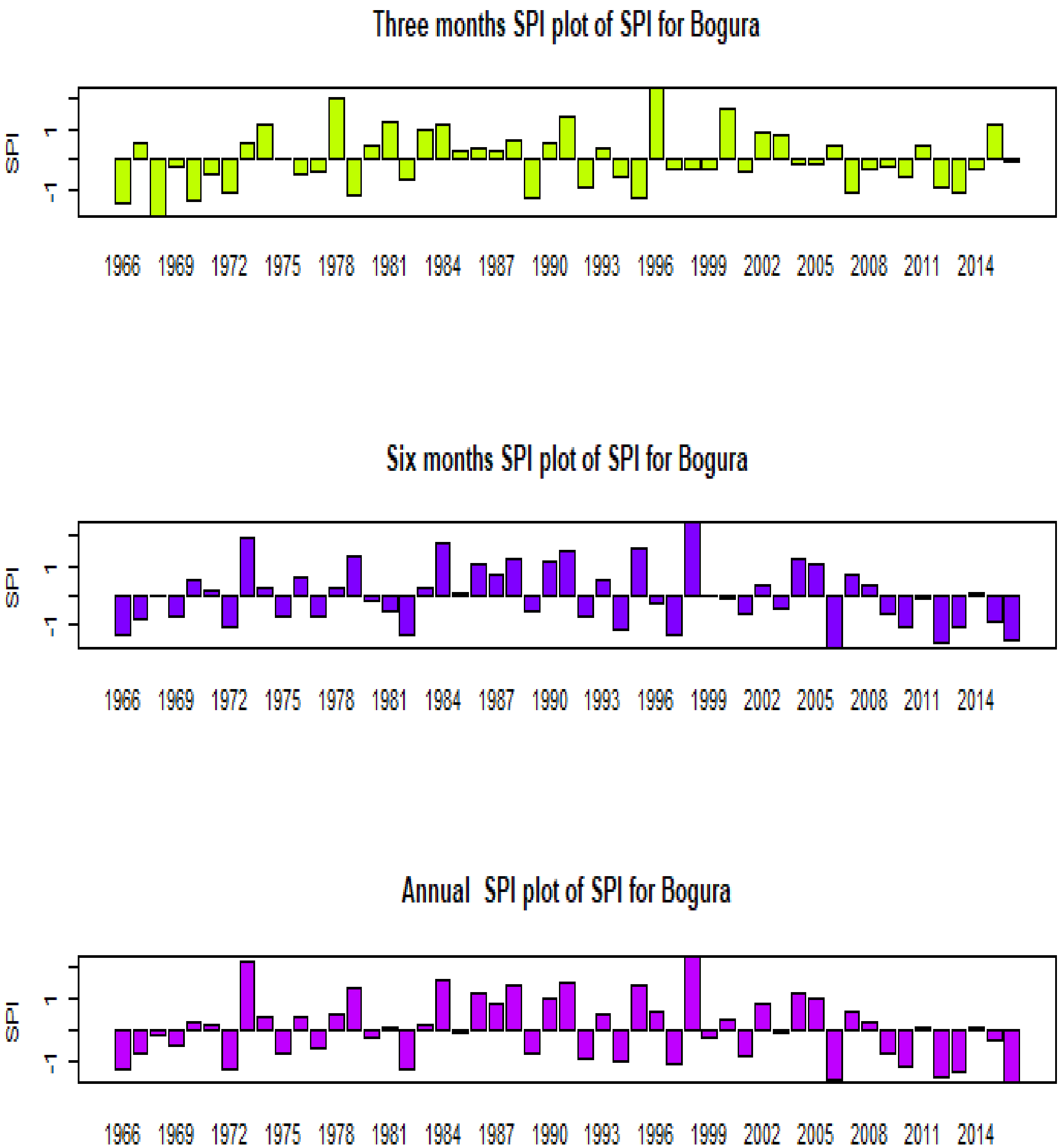
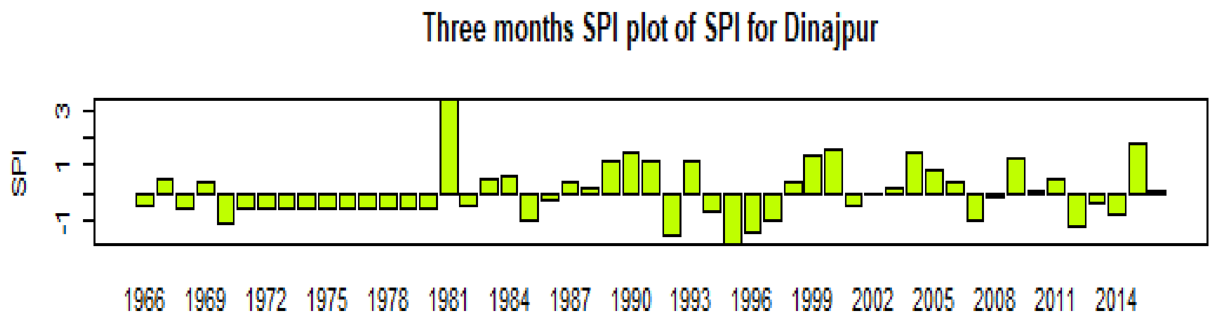
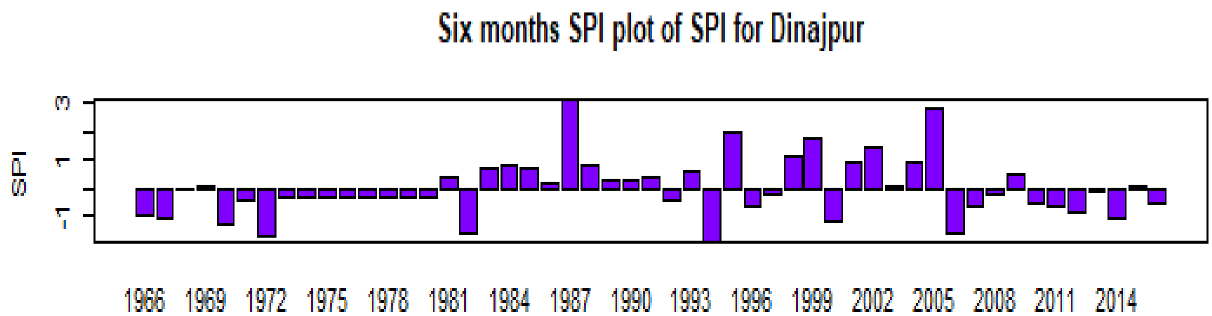


Figure B16: SPI Plot for Dinajpur





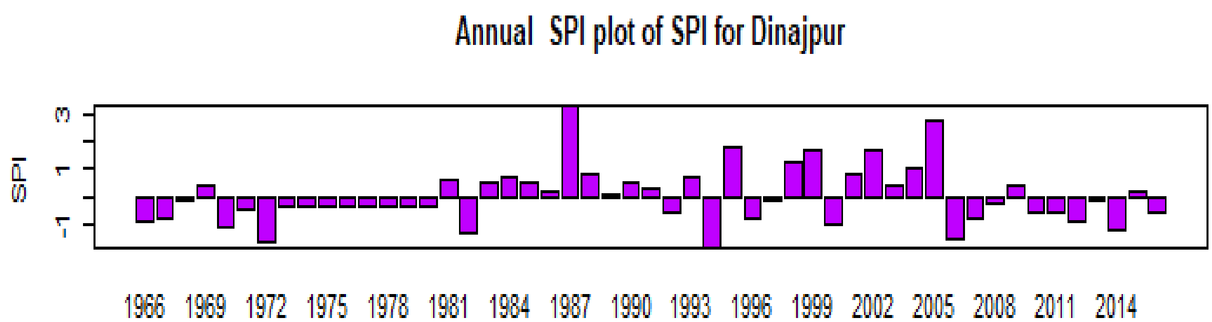
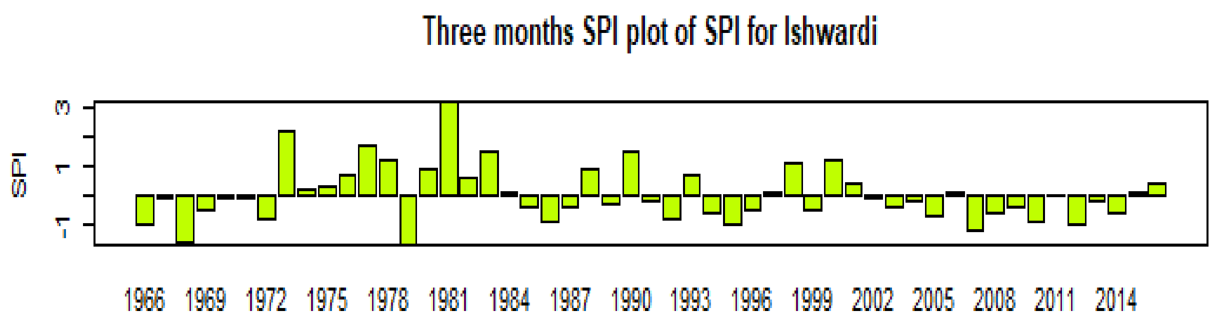
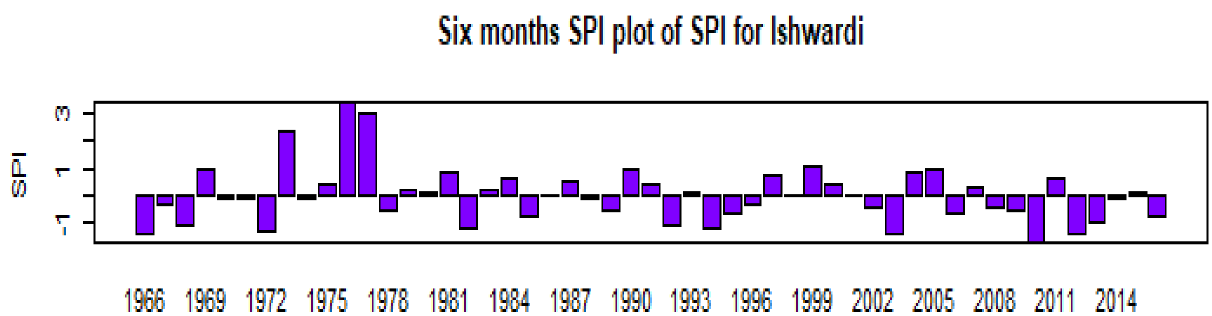


Figure B17: SPI Plot for Ishawardi





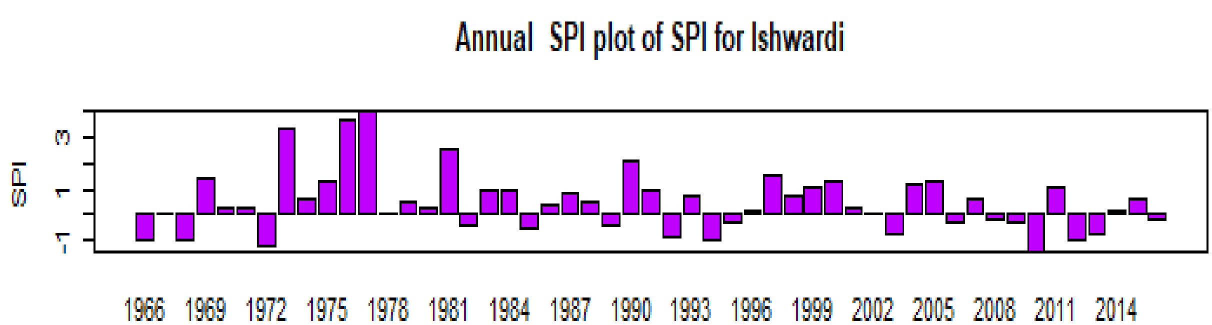
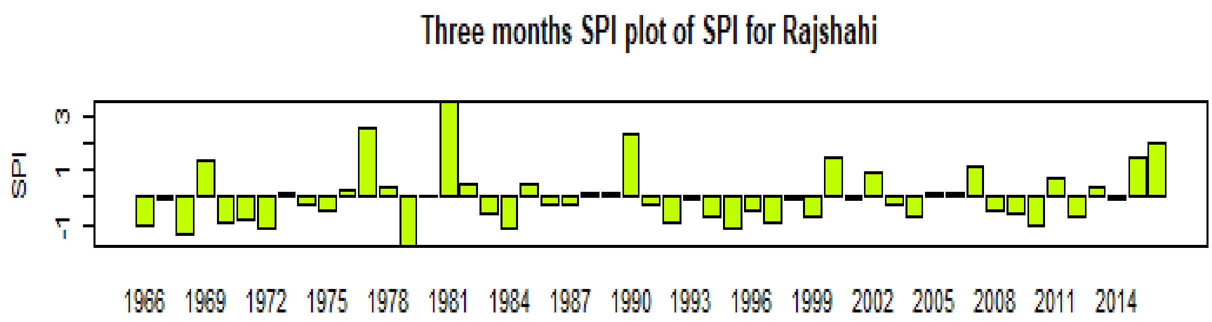
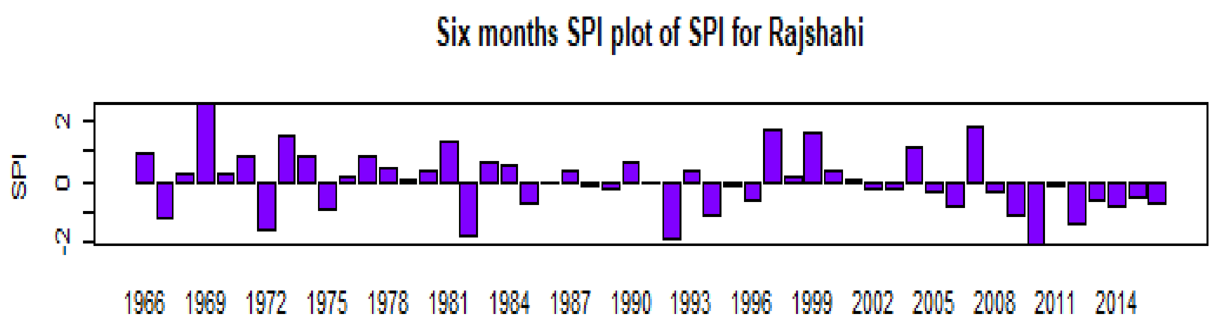


Figure B18: SPI Plot for Rajshahi





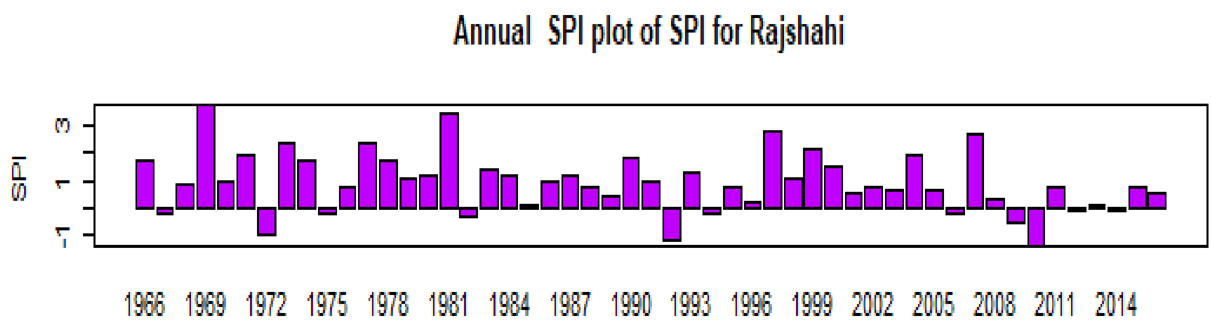


Figure B19: SPI Plot for Rangpur

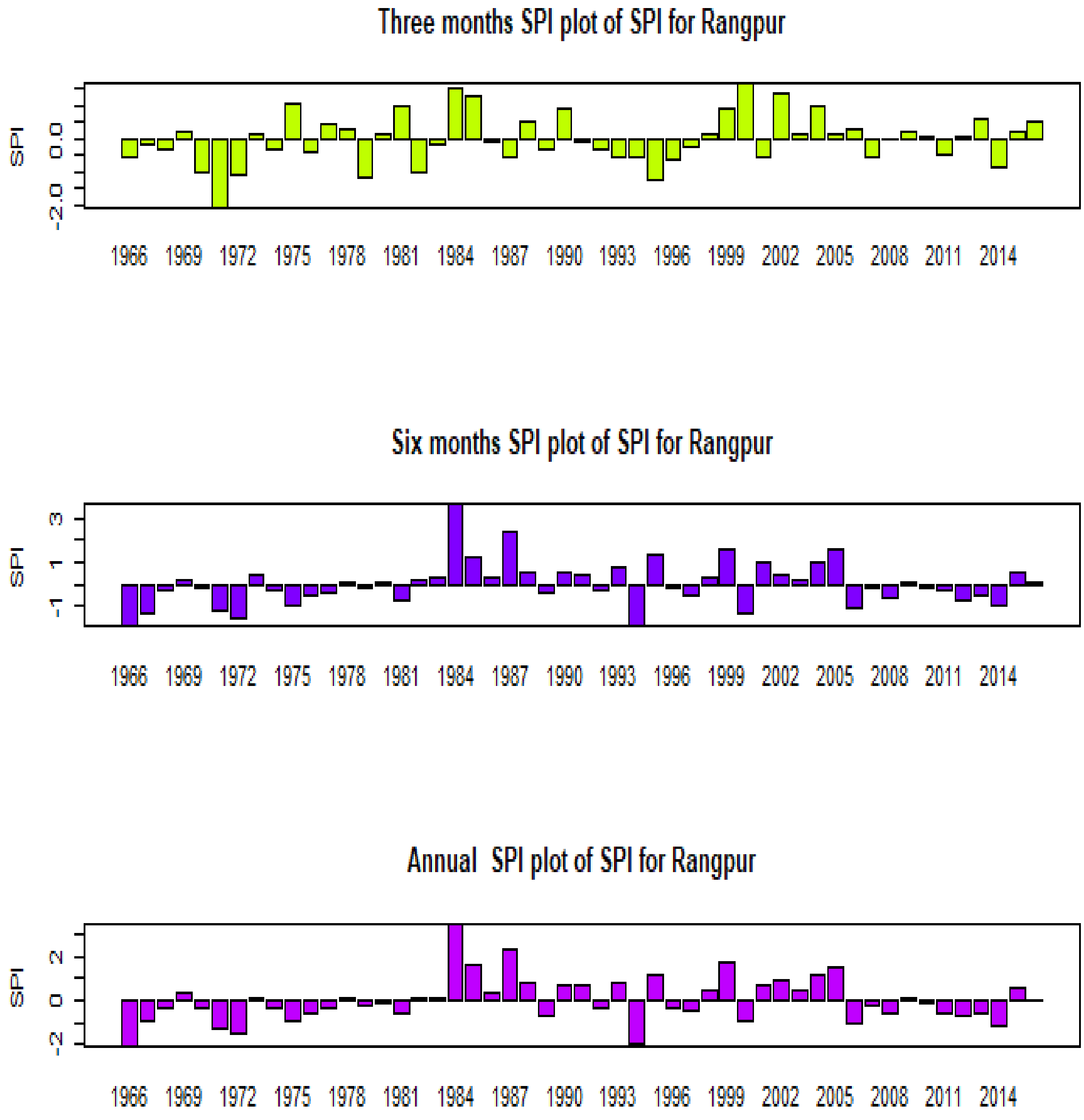


Figure B20: 12 months SWI for Bogura

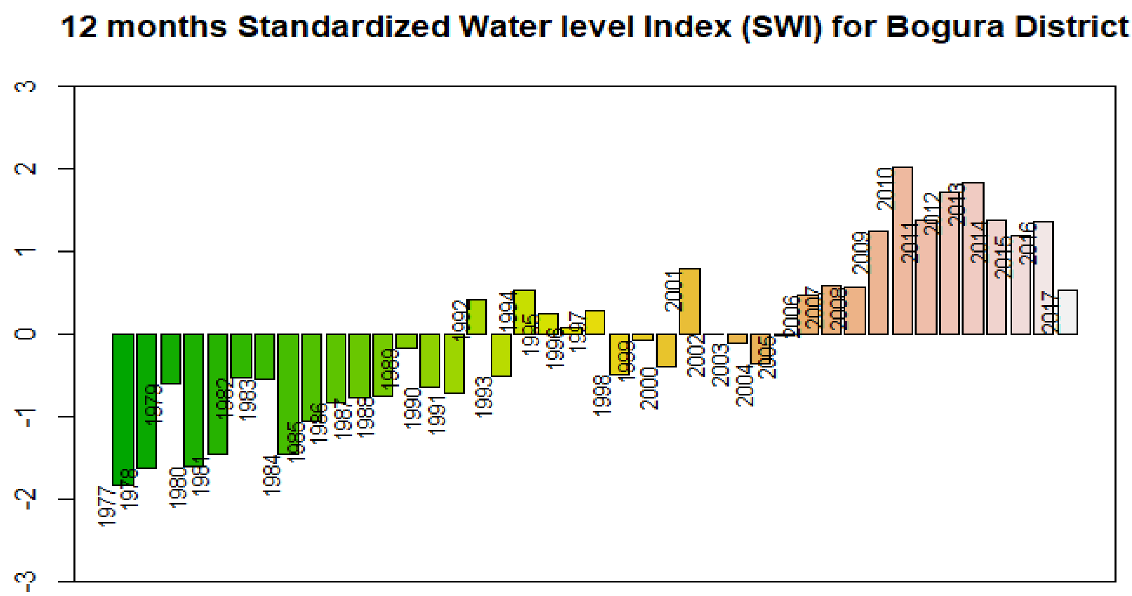


Figure B21: 12 months SWI for Rajshahi

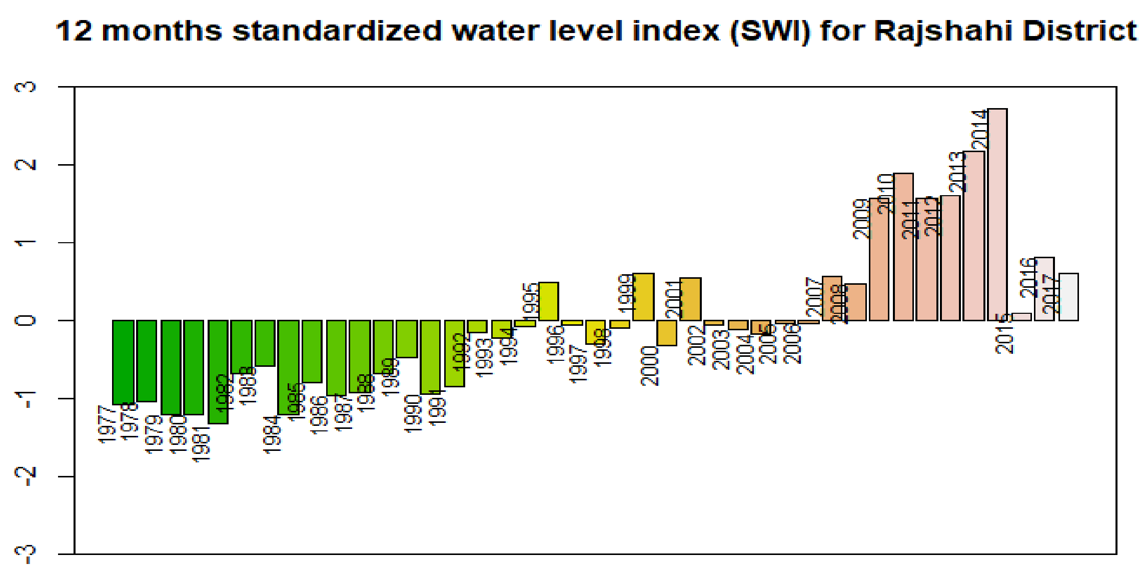


Figure B22: 12 months SWI for Ishawardi

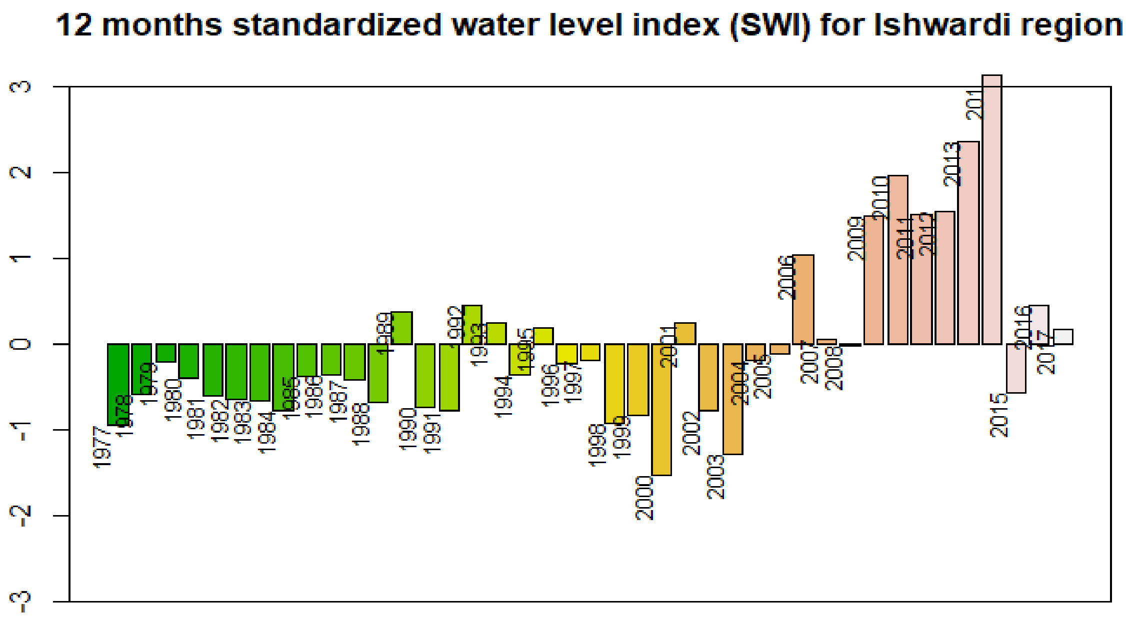


Figure B23: 12 months SWI for Rangpur

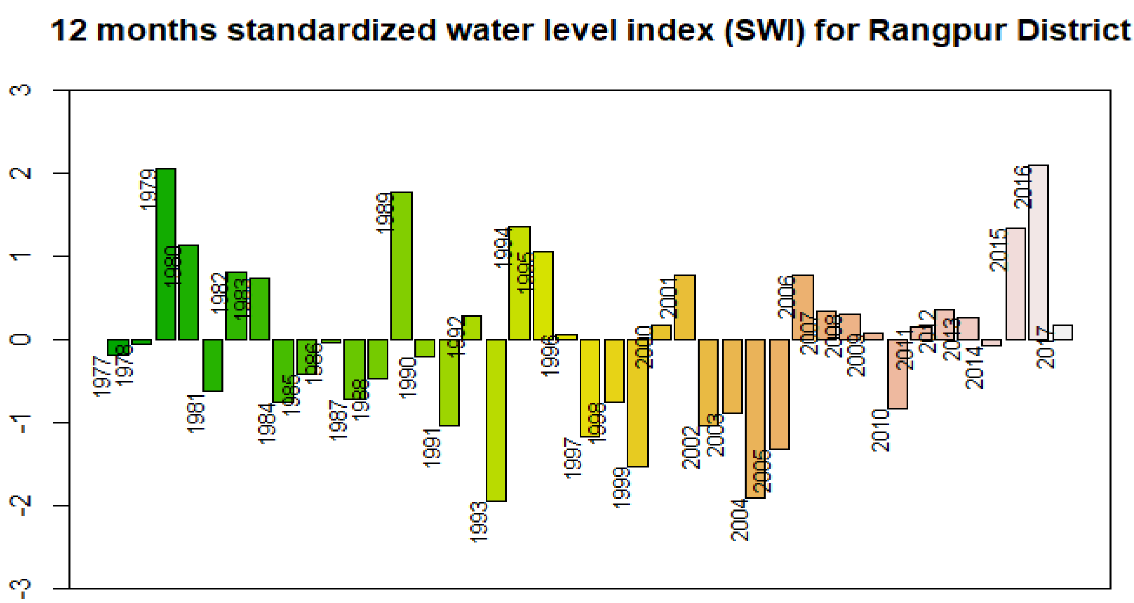


Figure B24: De Martonne Aridity Index for Bogura

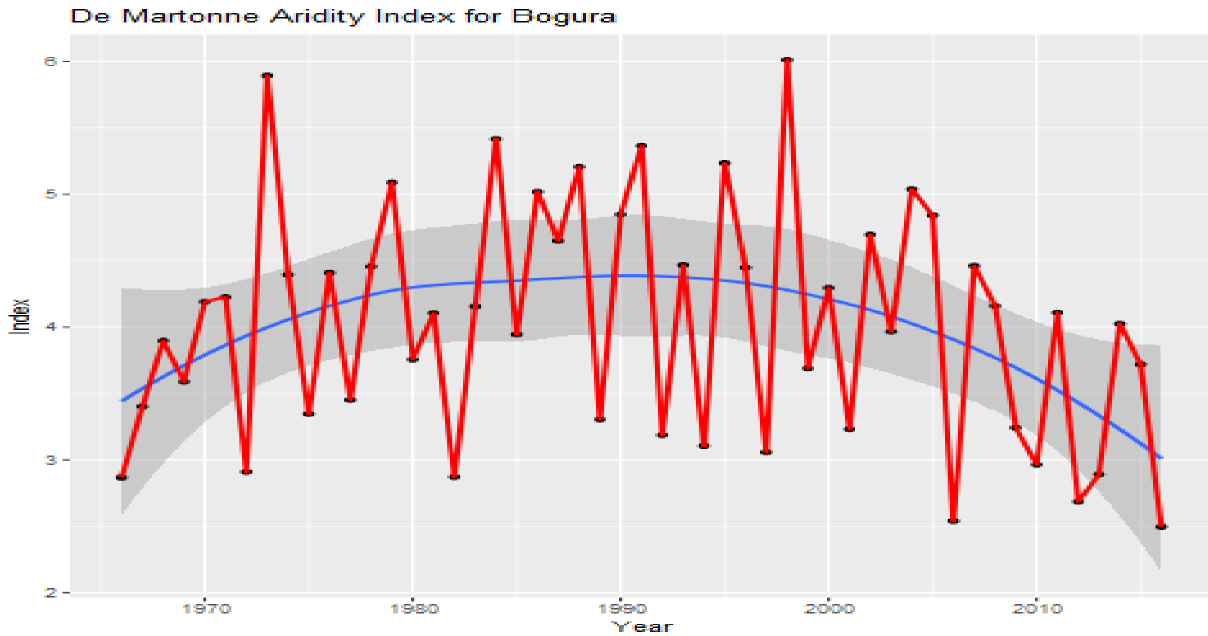


Figure B25: De Martonne Aridity Index for Rajshahi

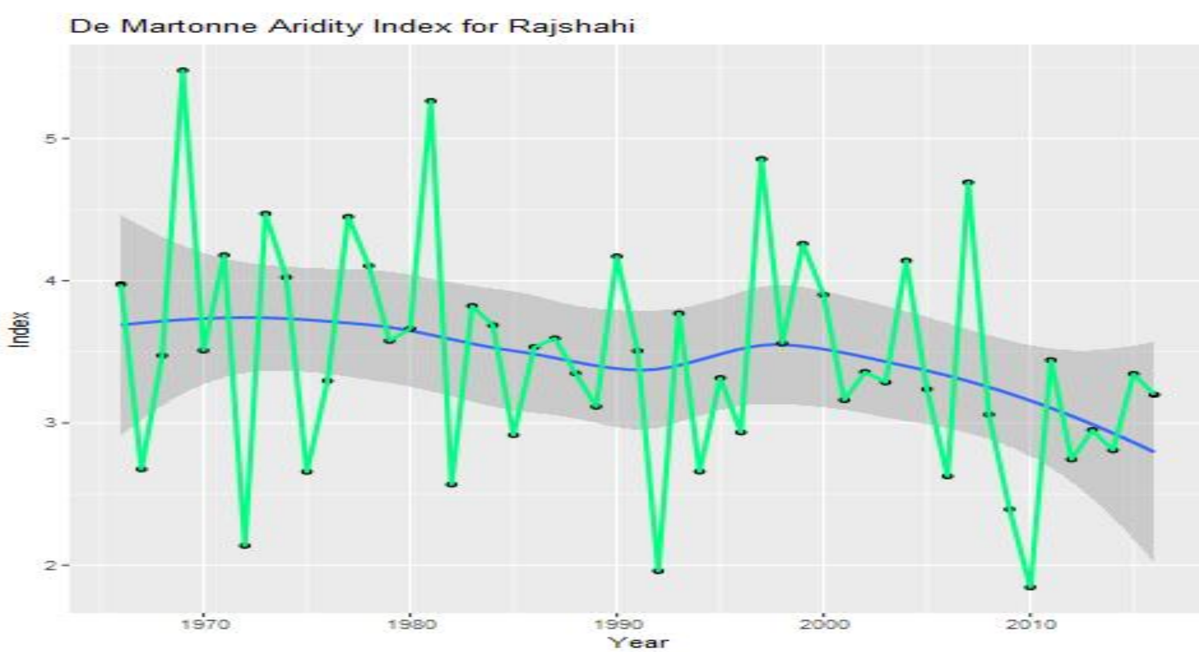


Figure B26: De Martonne Aridity Index for Dinajpur

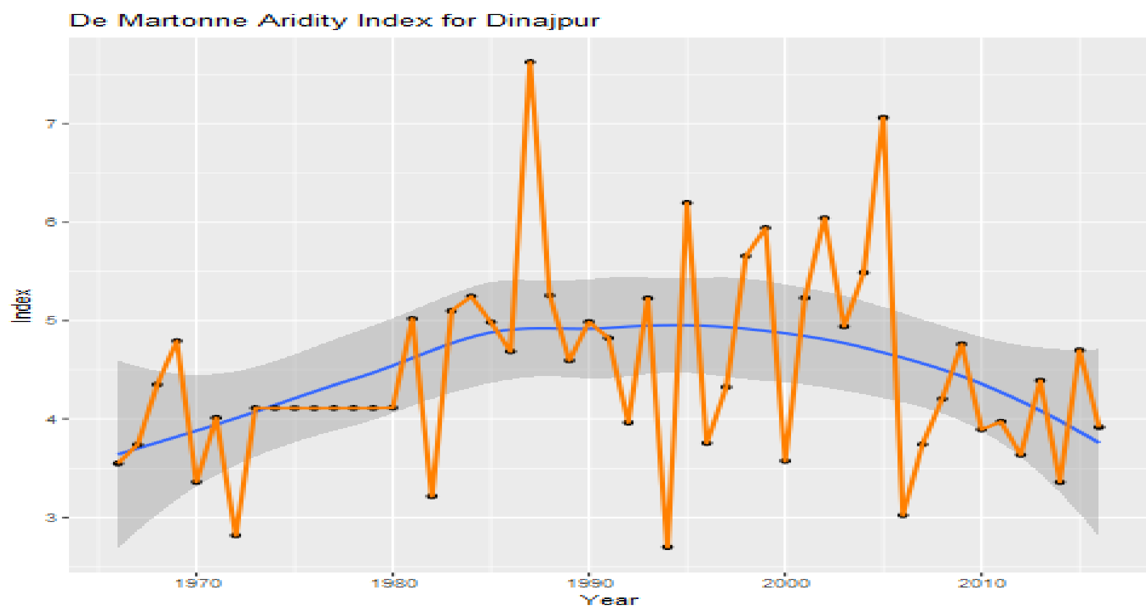


Figure B27: De Martonne Aridity Index for Rangpur

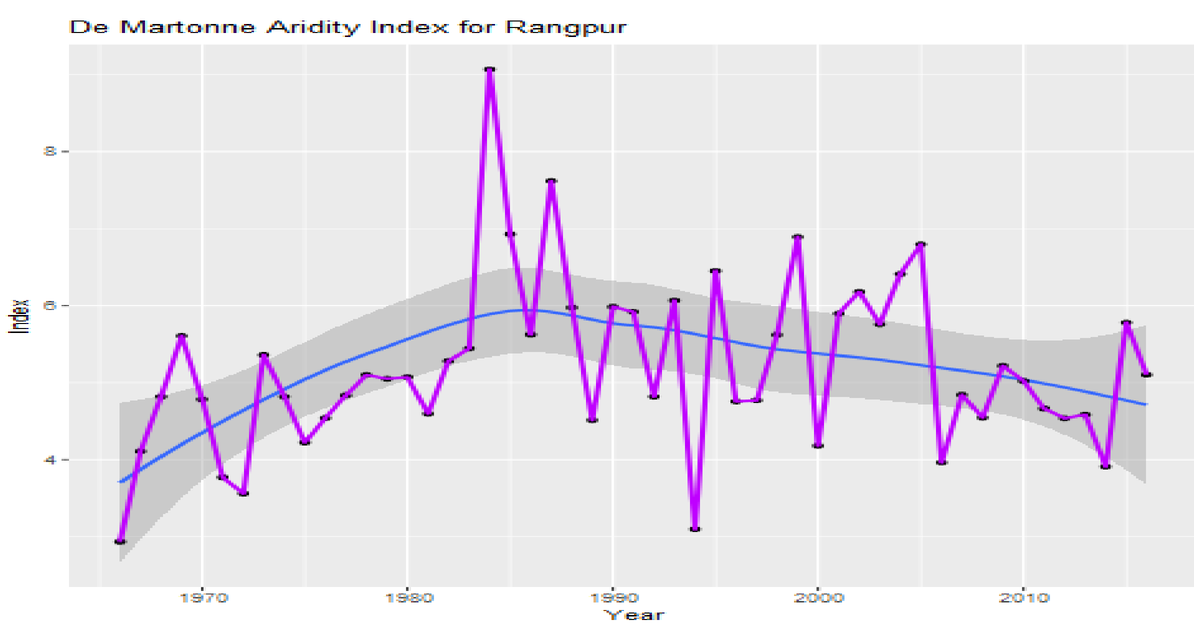
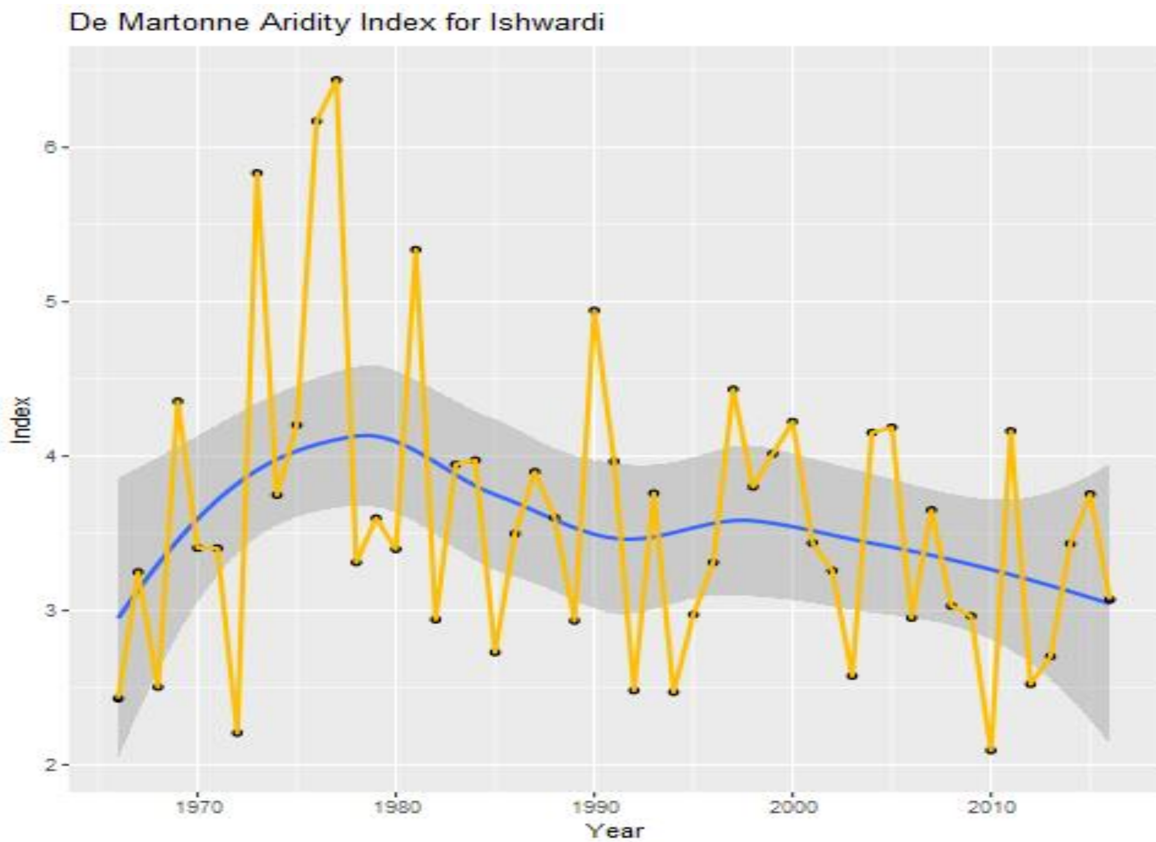
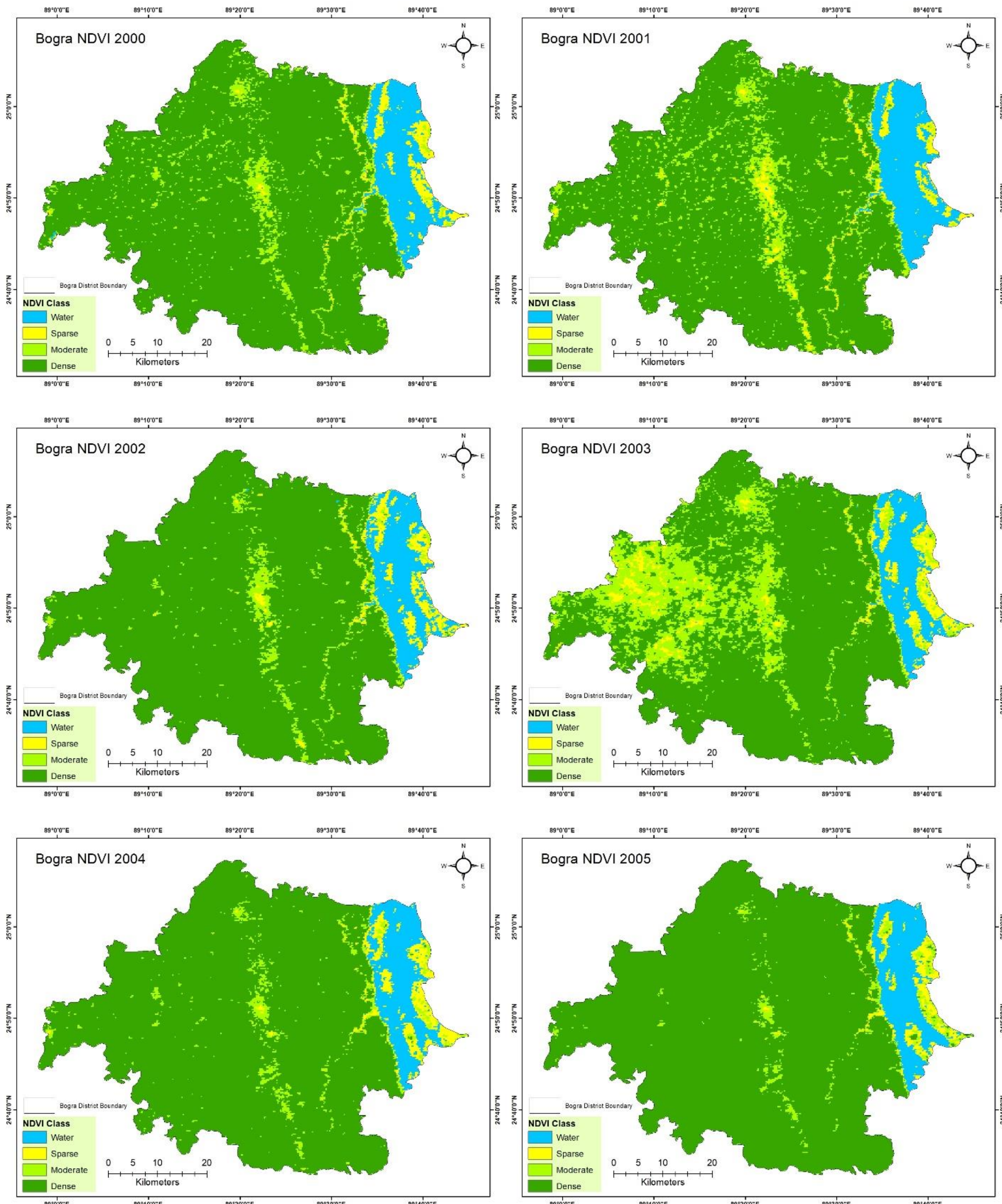


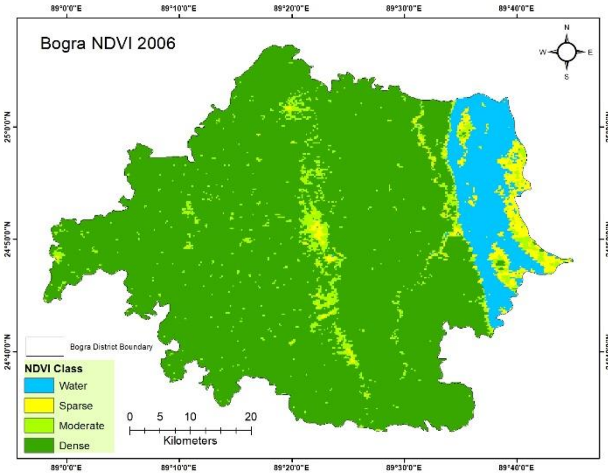
Figure B28: De Martonne Aridity Index for Ishwardi

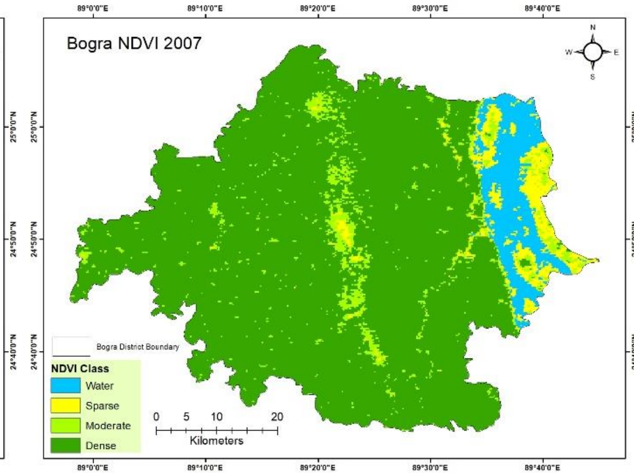


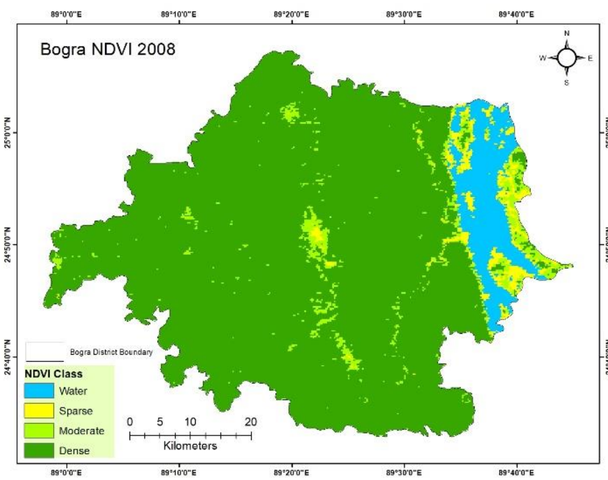
Appendix C: NDVI Maps

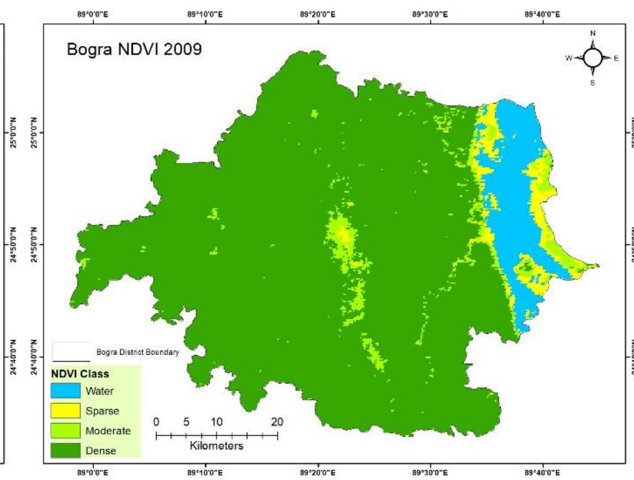
Figure C1: Time Series of NDVI for Bogura District

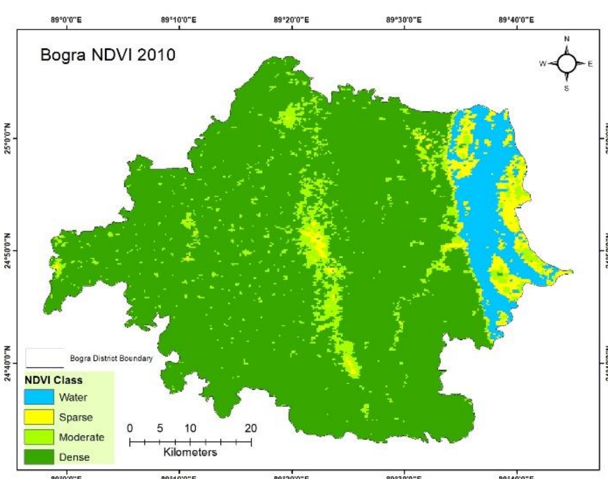


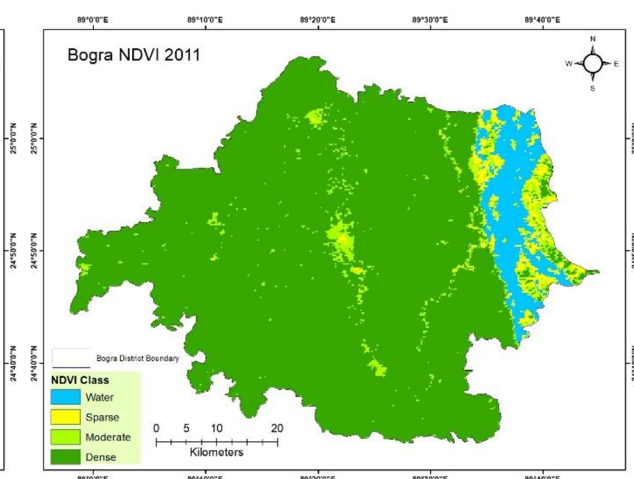

Bogra NDVI 2006
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°0'0"N
24°50'0"N
24°40'0"N
N
W
E
S
Bogra District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

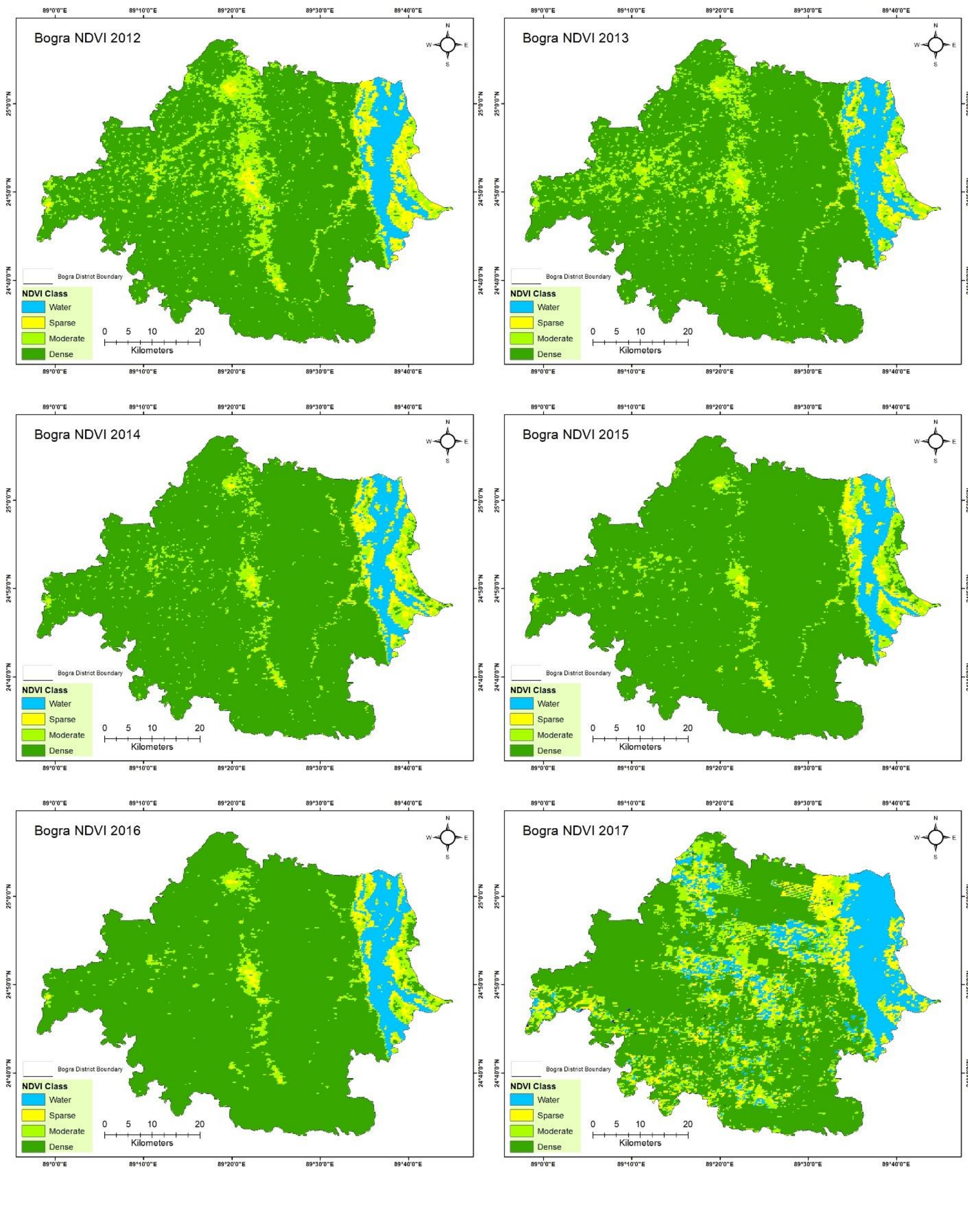

Bogra NDVI 2007
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°0'0"N
24°50'0"N
24°40'0"N
N
W
E
S
Bogra District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Bogra NDVI 2008
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°0'0"N
24°50'0"N
24°40'0"N
N
W
E
S
Bogra District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Bogra NDVI 2009
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°0'0"N
24°50'0"N
24°40'0"N
N
W
E
S
Bogra District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Bogra NDVI 2010
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°0'0"N
24°50'0"N
24°40'0"N
N
W
E
S
Bogra District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Bogra NDVI 2011
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°0'0"N
24°50'0"N
24°40'0"N
N
W
E
S
Bogra District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers



Bogra NDVI 2012
Bogra NDVI 2013
Bogra NDVI 2014
Bogra NDVI 2015
Bogra NDVI 2016
Bogra NDVI 2017
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°0'0"N
24°50'0"N
24°40'0"N
N
W
E
S
Bogra District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

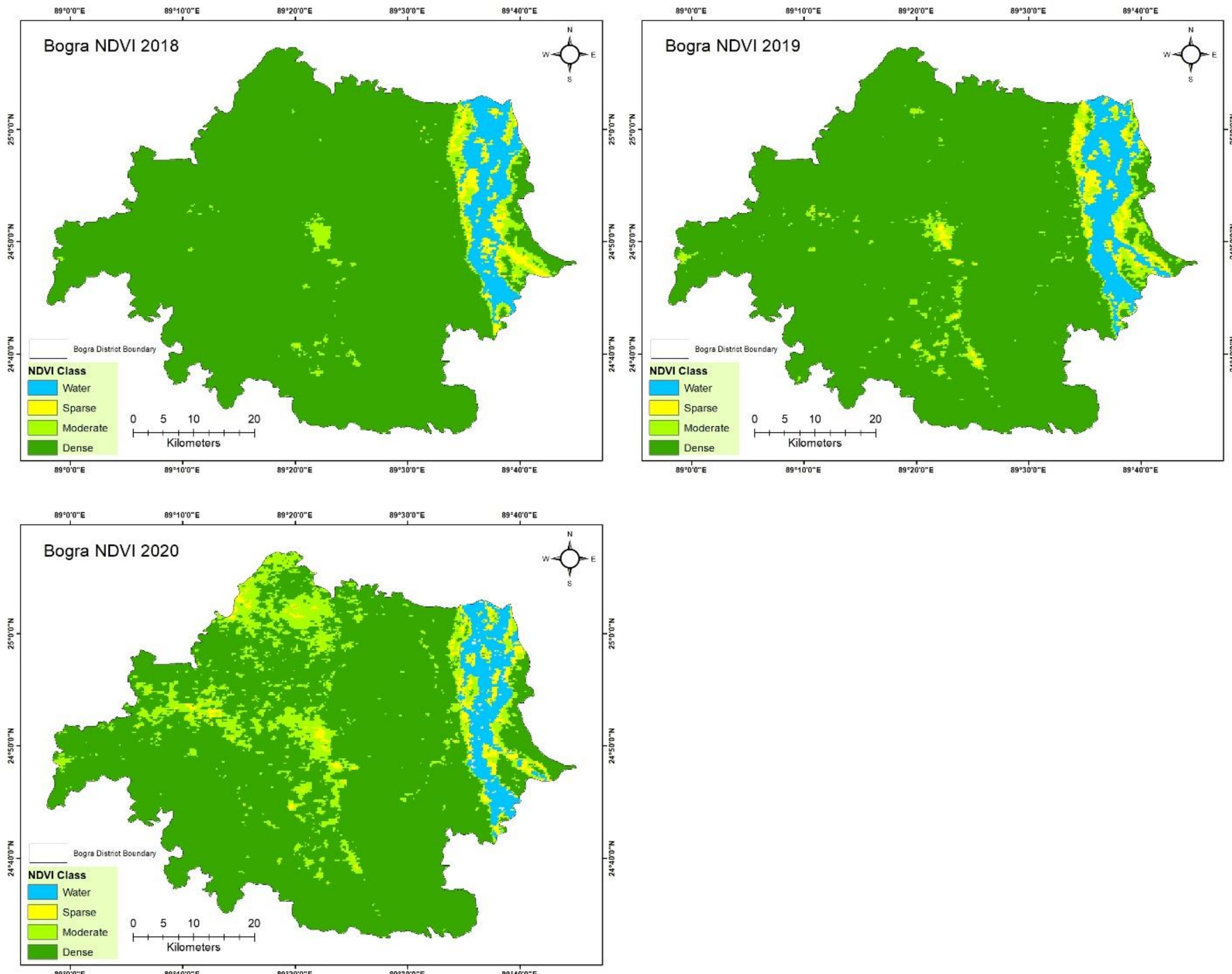
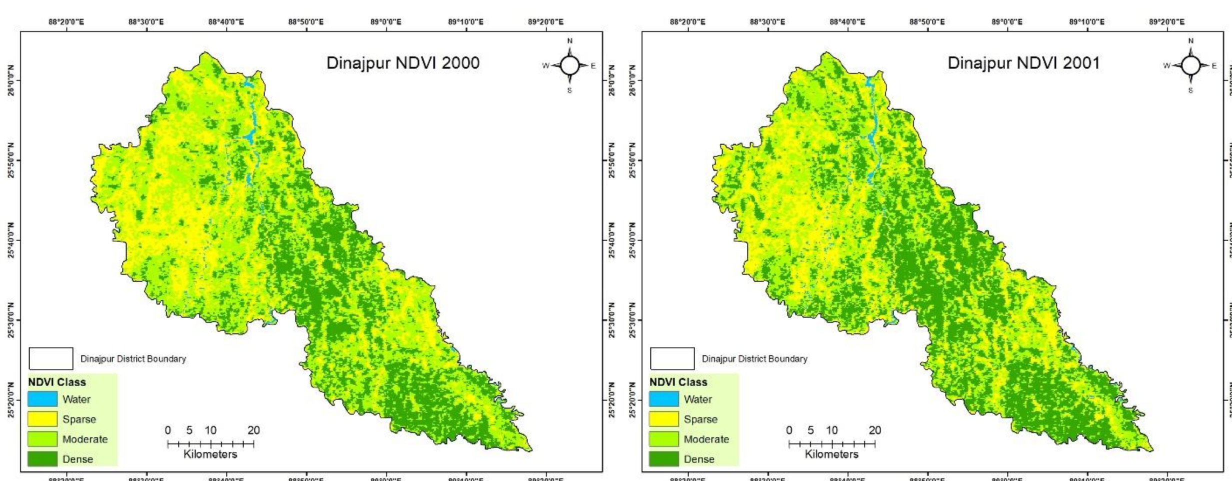
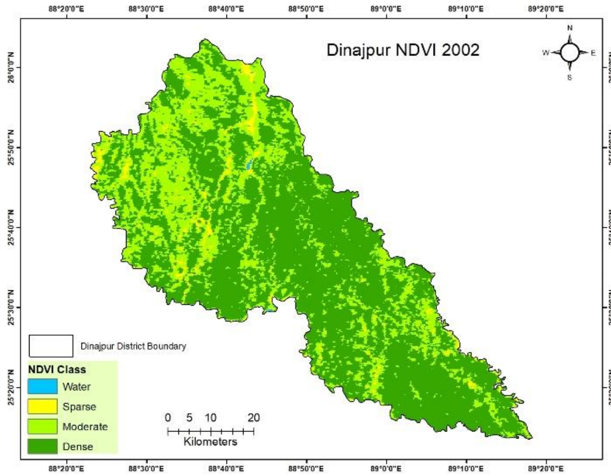
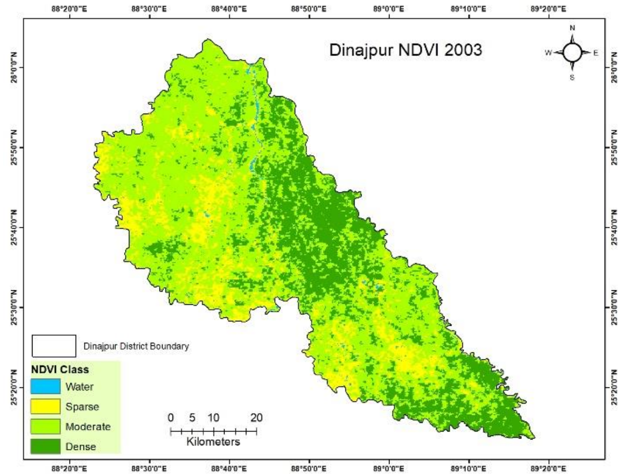
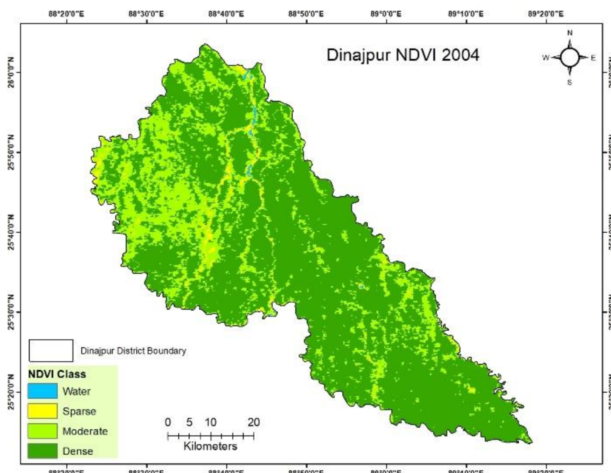


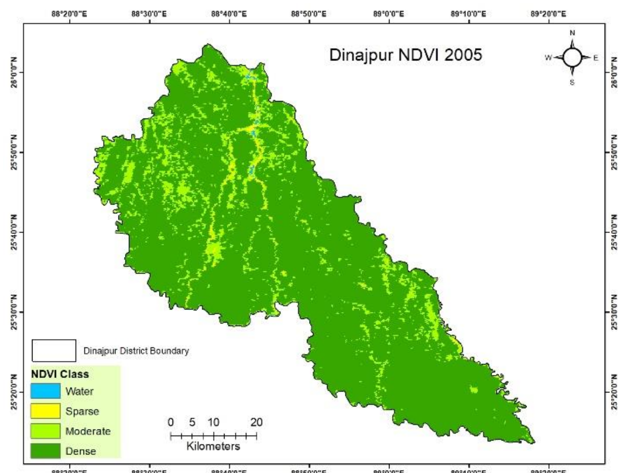
Figure C2 : Time Series of NDVI for Dinajpur District

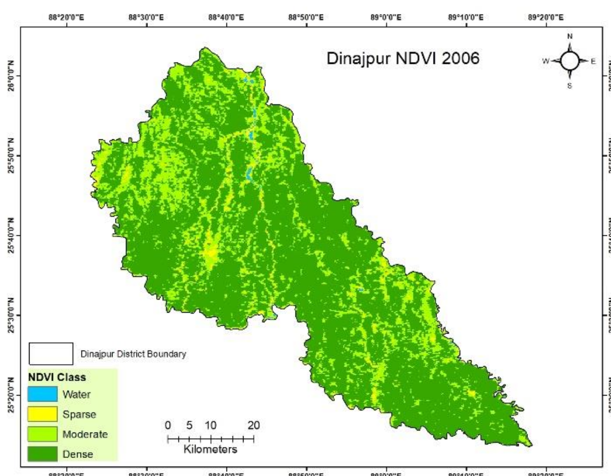


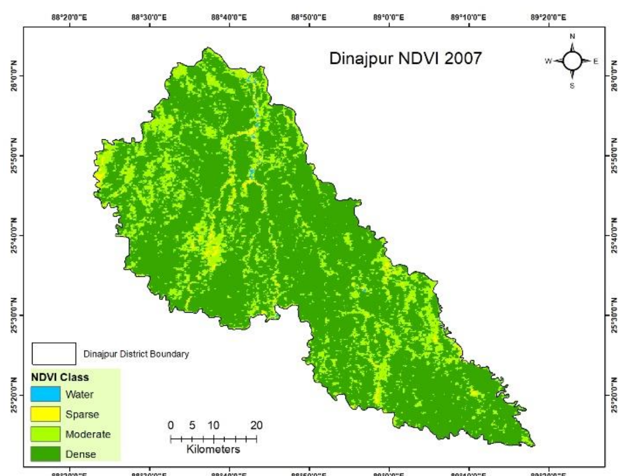

Dinajpur NDVI 2002
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

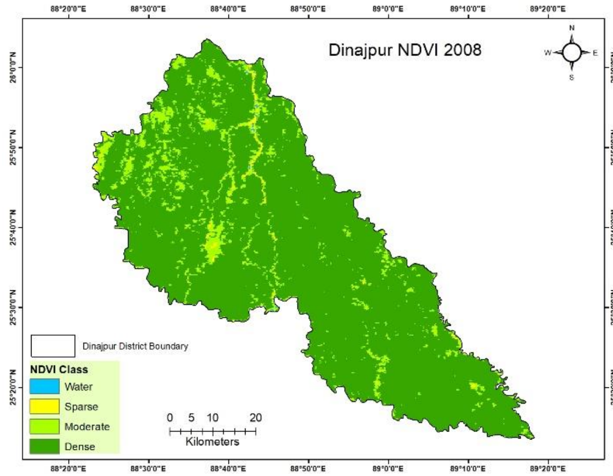

Dinajpur NDVI 2003
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

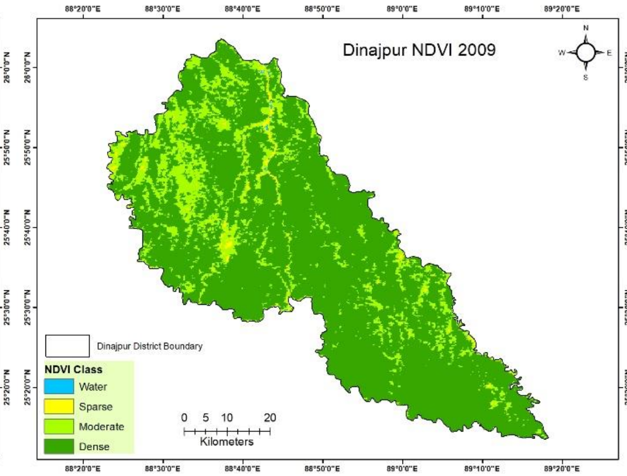

Dinajpur NDVI 2004
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

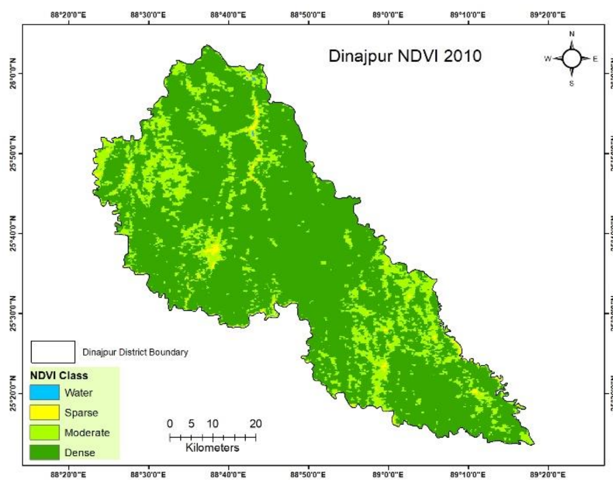

Dinajpur NDVI 2005
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

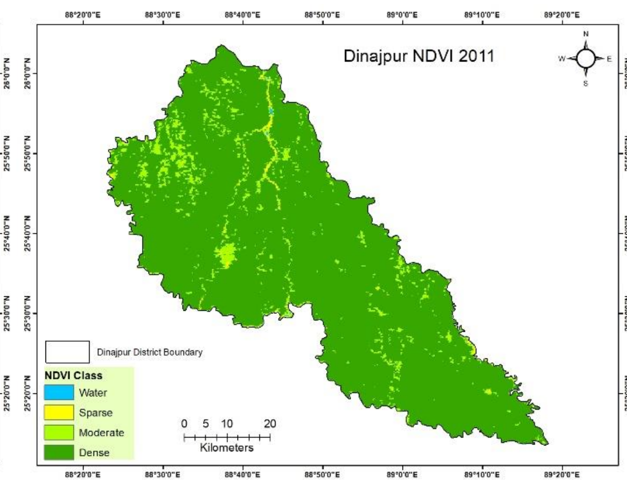

Dinajpur NDVI 2006
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

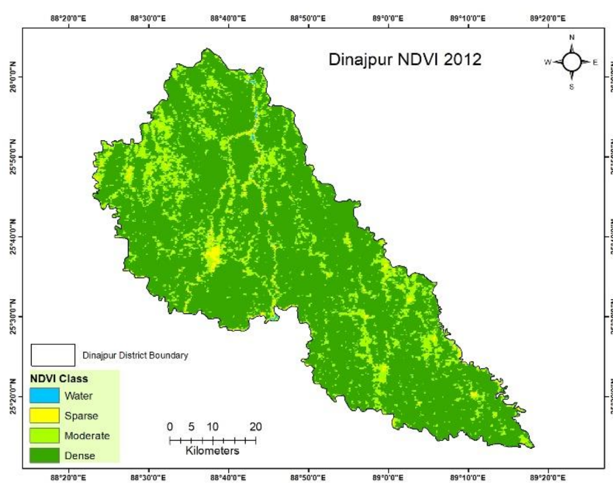

Dinajpur NDVI 2007
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

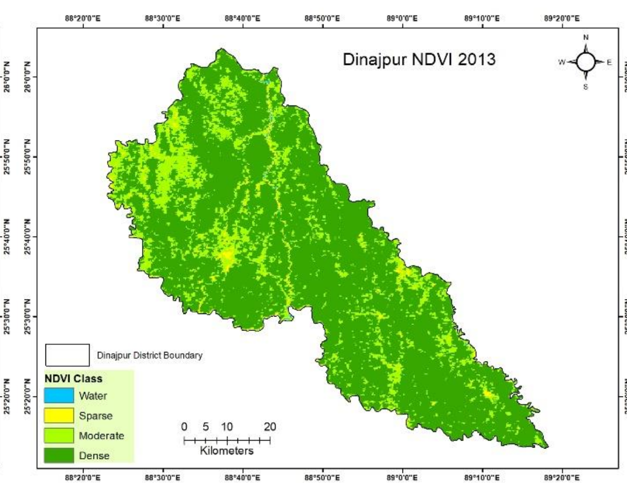

Dinajpur NDVI 2008
N
W
E
S
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

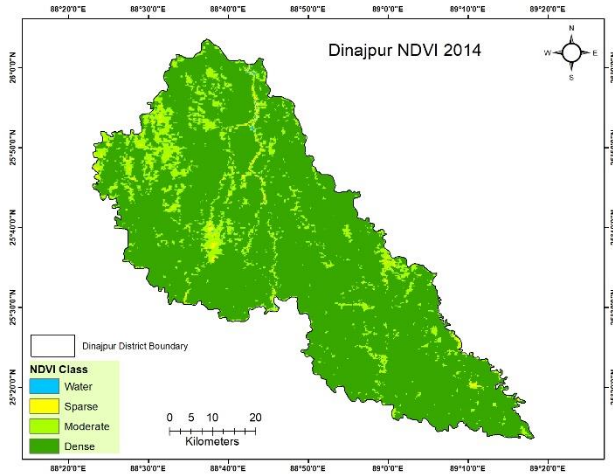

Dinajpur NDVI 2009
N
W
E
S
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

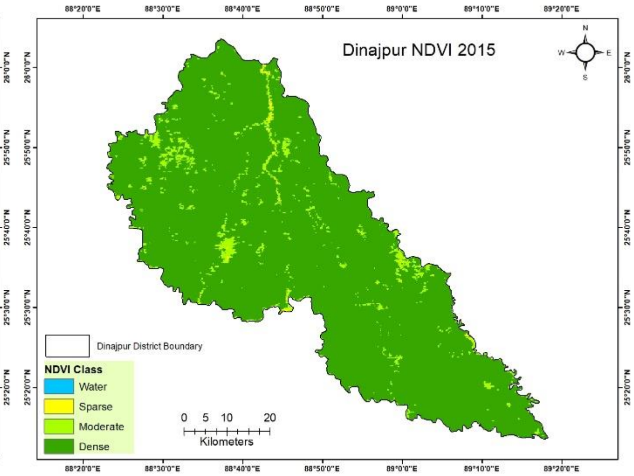

Dinajpur NDVI 2010
N
W
E
S
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

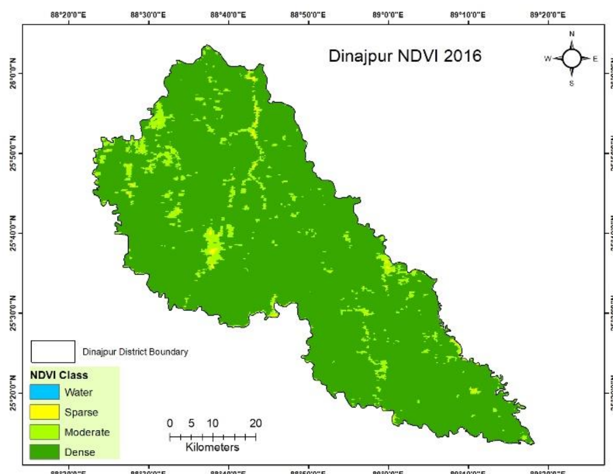

Dinajpur NDVI 2011
N
W
E
S
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

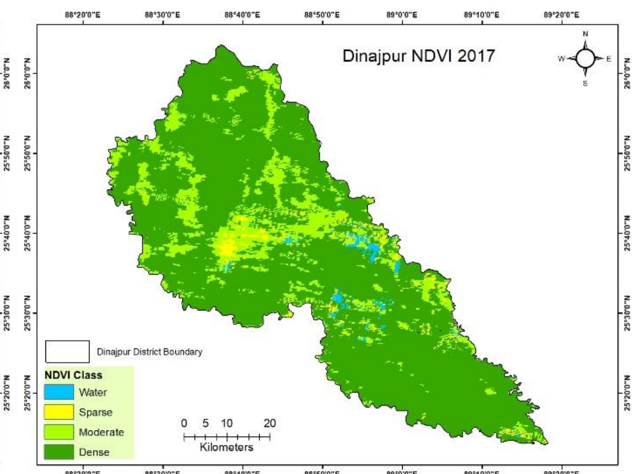

Dinajpur NDVI 2012
N
W
E
S
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

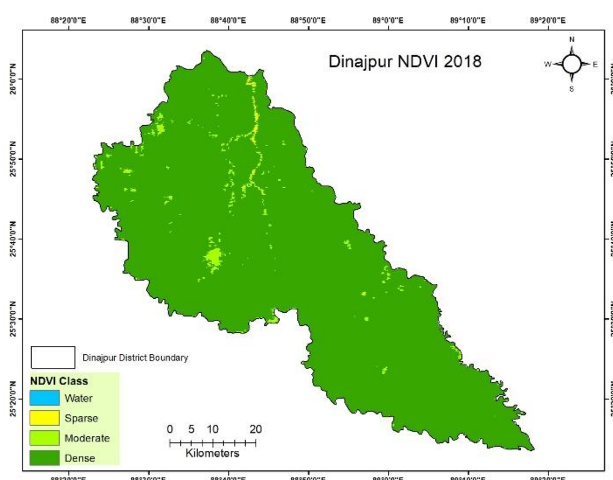

Dinajpur NDVI 2013
N
W
E
S
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

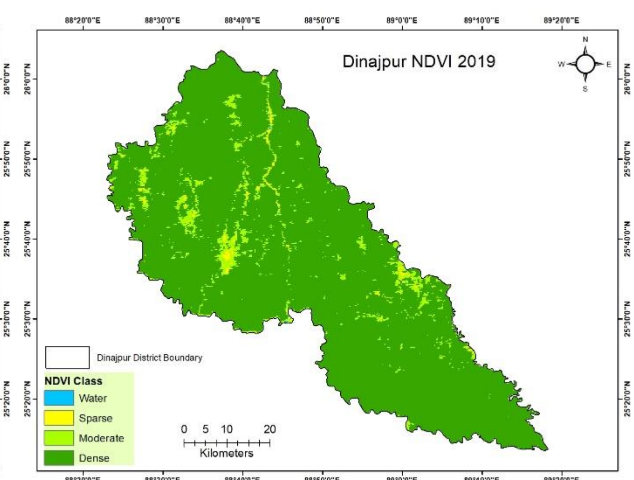

Dinajpur NDVI 2014
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N


Dinajpur NDVI 2015
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N


Dinajpur NDVI 2016
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N


Dinajpur NDVI 2017
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N


Dinajpur NDVI 2018
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N


Dinajpur NDVI 2019
N
W
E
S
Dinajpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
26°0'0"N
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N

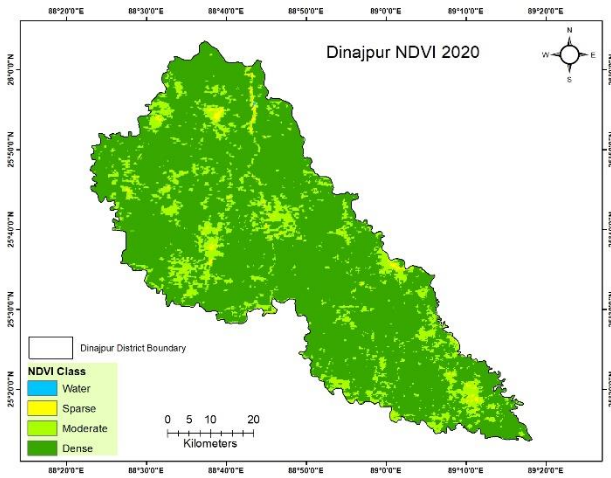
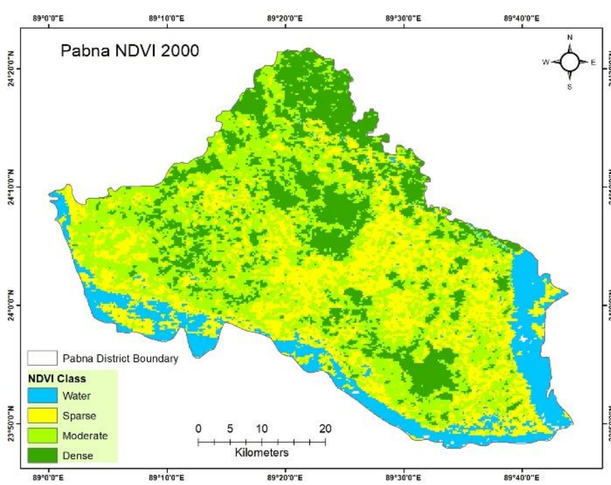
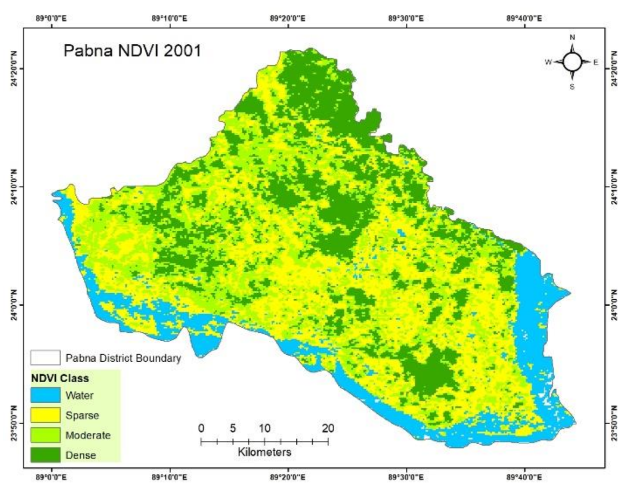
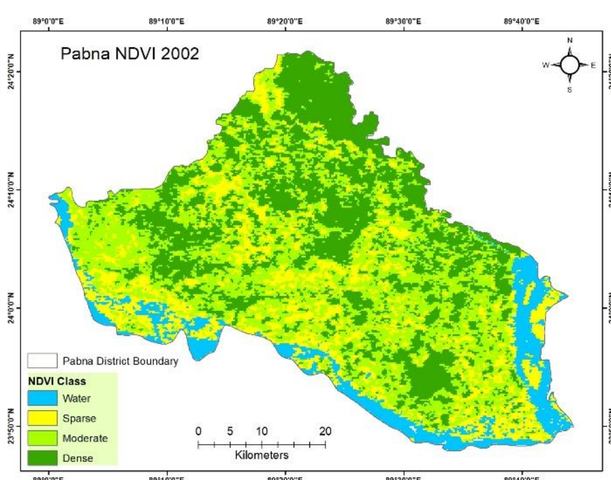
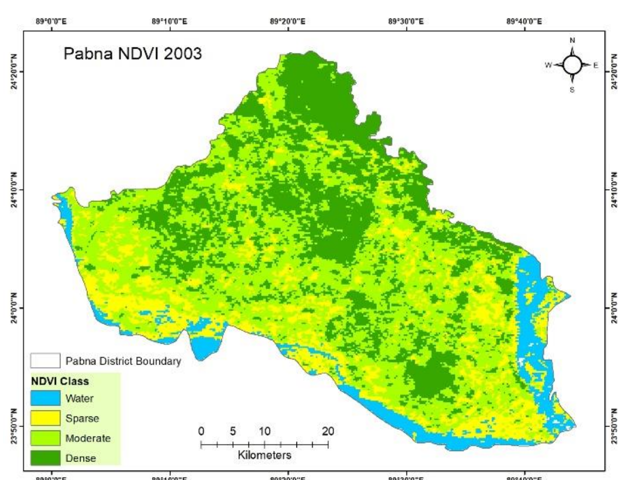


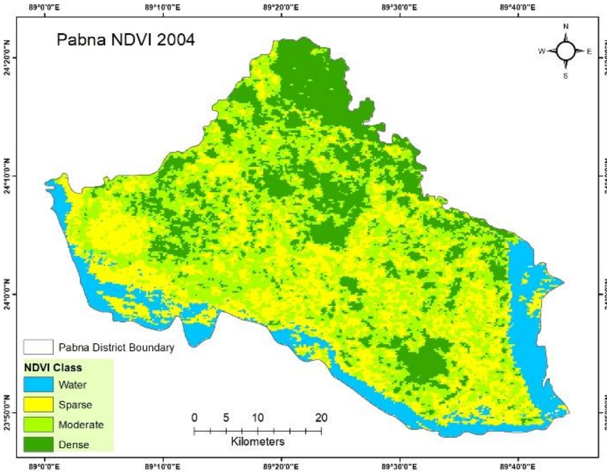
Figure C3: Time Series of NDVI for Pabna District

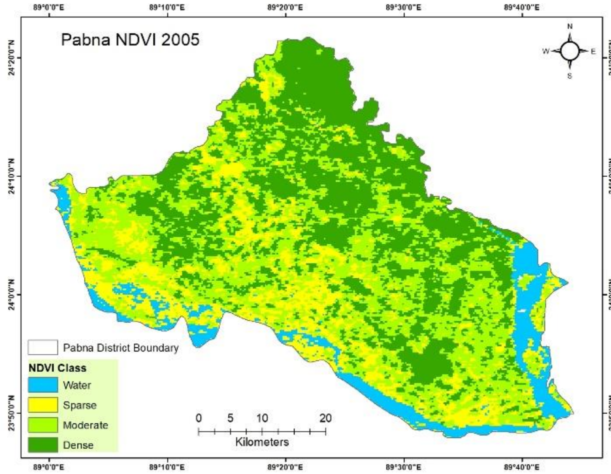


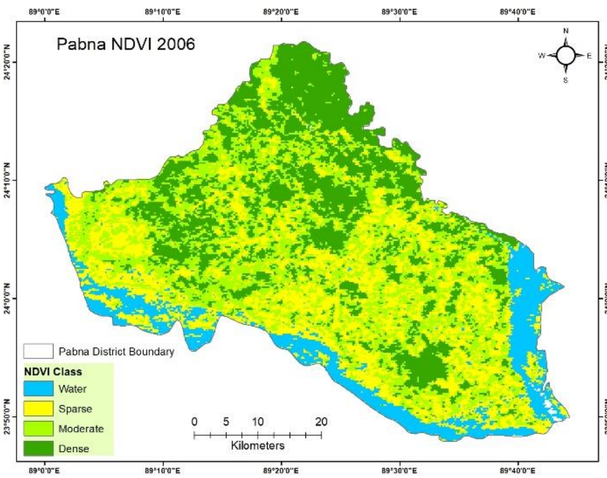


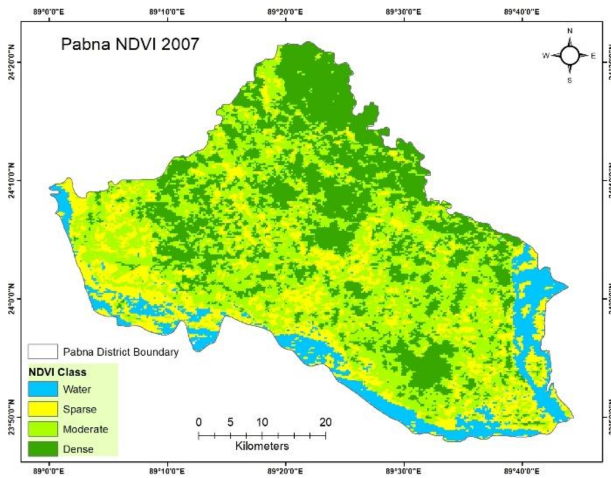


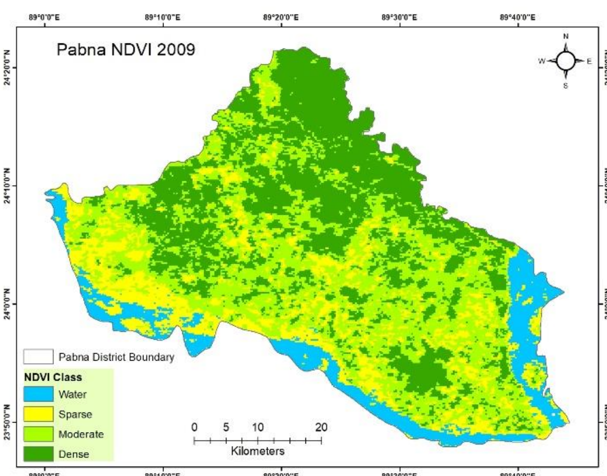


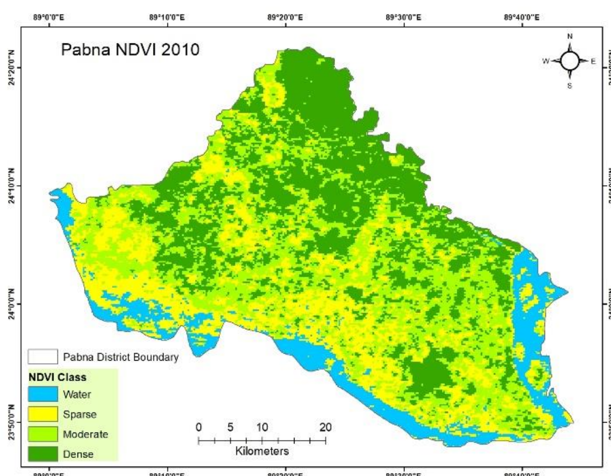

Pabna NDVI 2004
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

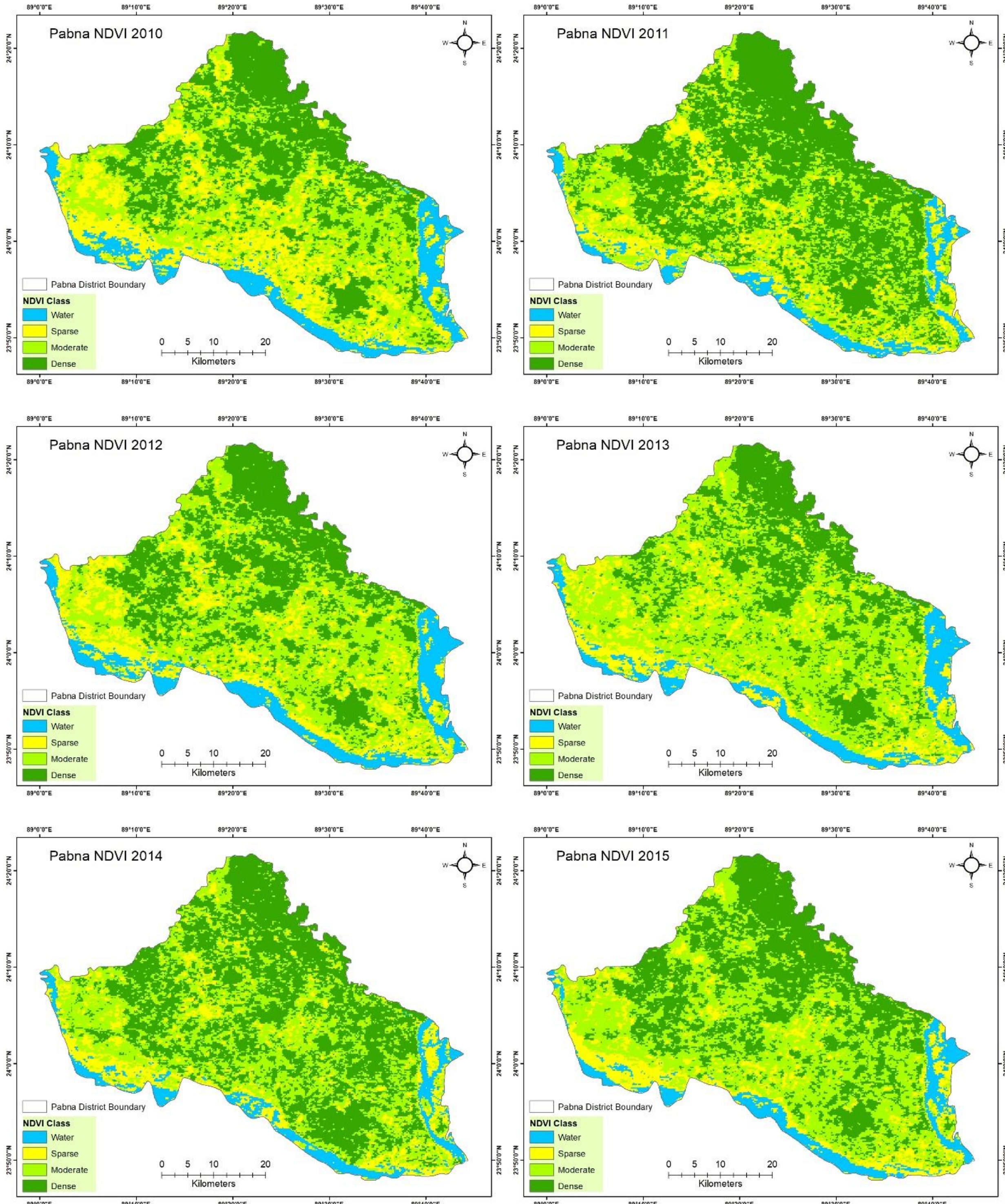

Pabna NDVI 2005
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

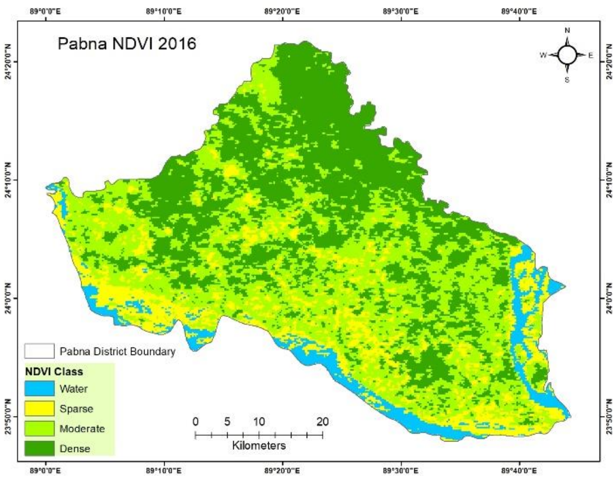

Pabna NDVI 2006
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

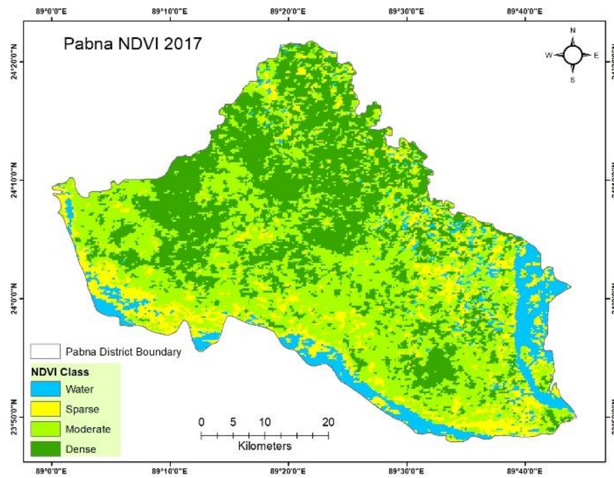

Pabna NDVI 2007
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

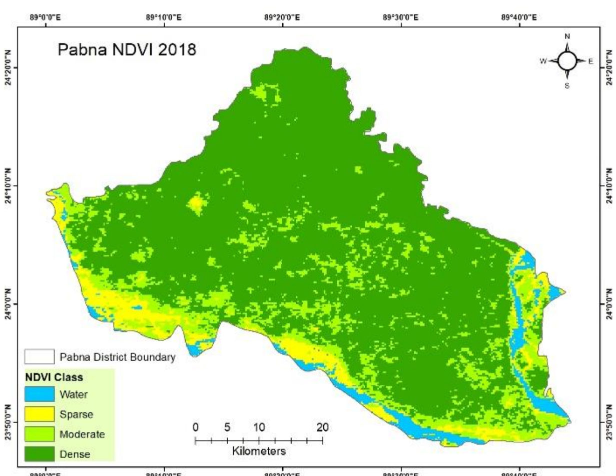

Pabna NDVI 2009
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

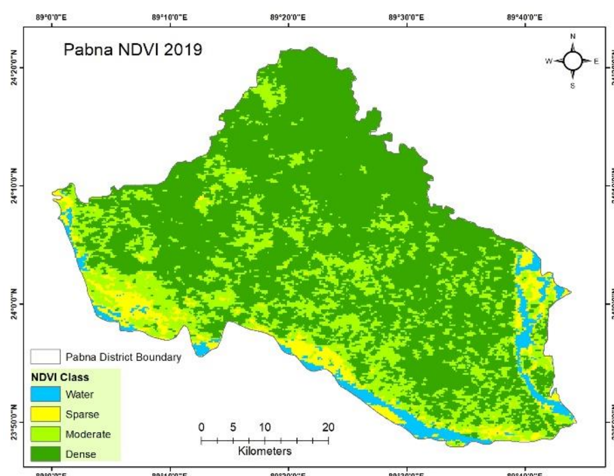

Pabna NDVI 2010
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Pabna NDVI 2010
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
Pabna NDVI 2011
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
Pabna NDVI 2012
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
Pabna NDVI 2013
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
Pabna NDVI 2014
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
Pabna NDVI 2015
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Pabna NDVI 2016
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
24°20'0"N
24°10'0"N
24°0'0"N
23°50'0"N


Pabna NDVI 2017
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
24°20'0"N
24°10'0"N
24°0'0"N
23°50'0"N


Pabna NDVI 2018
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
24°20'0"N
24°10'0"N
24°0'0"N
23°50'0"N


Pabna NDVI 2019
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
24°20'0"N
24°10'0"N
24°0'0"N
23°50'0"N

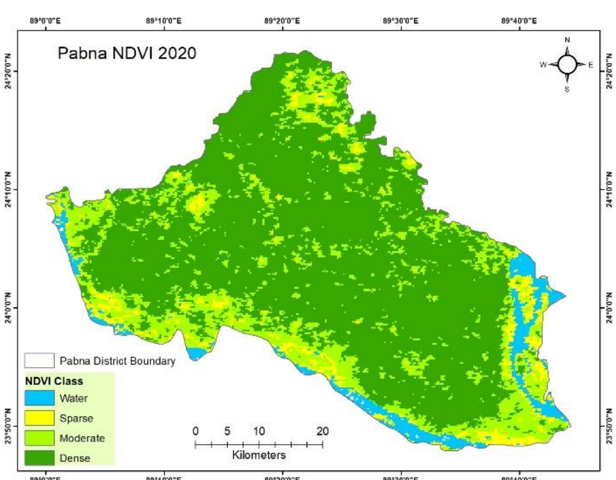
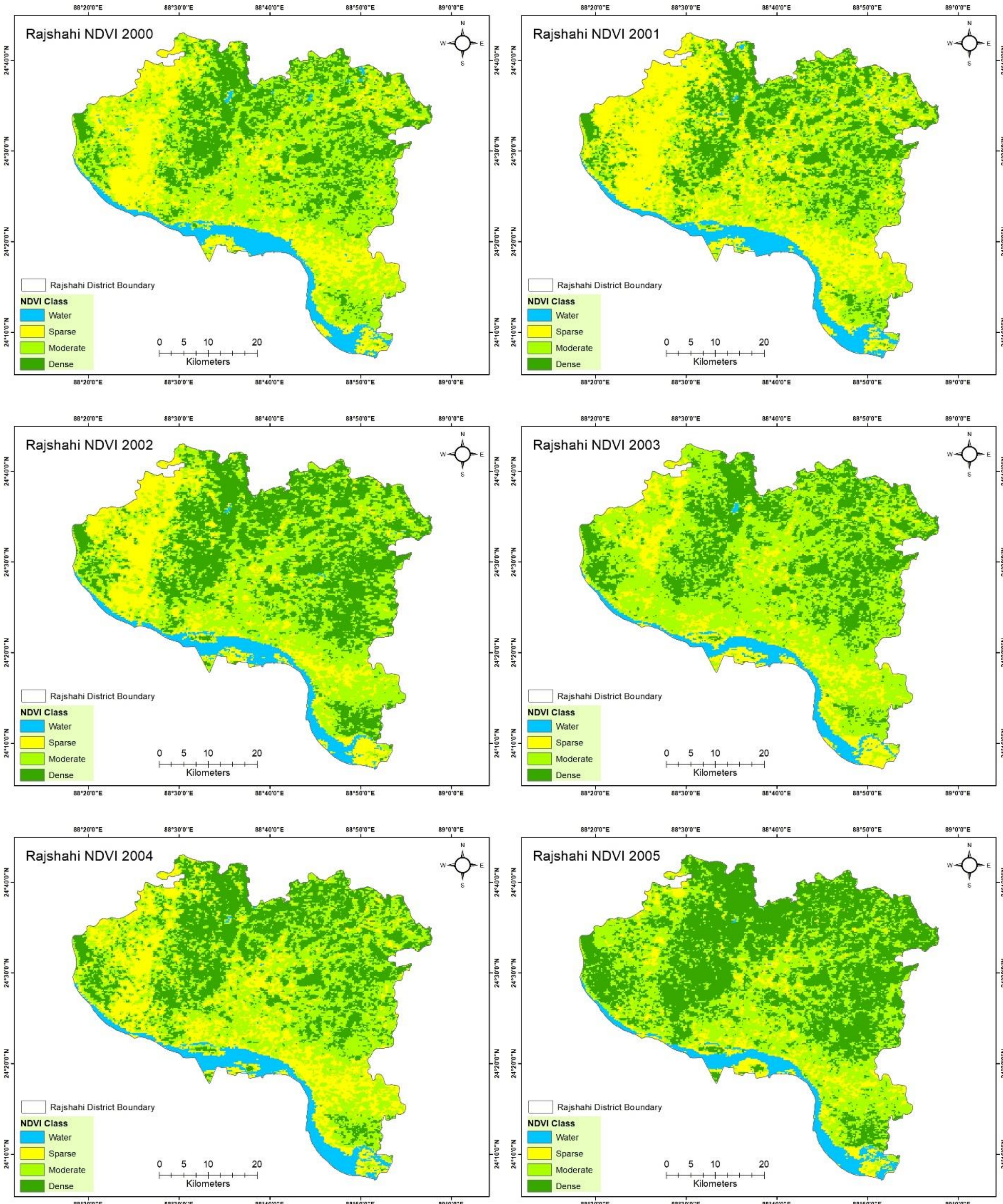
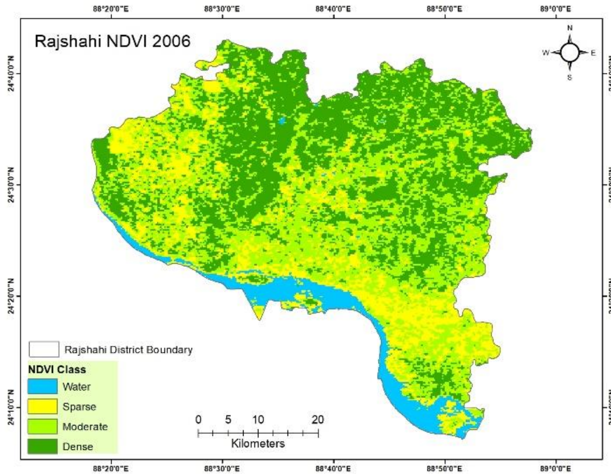
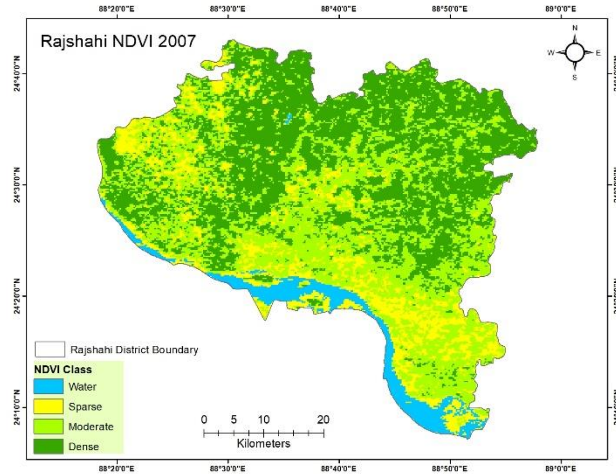
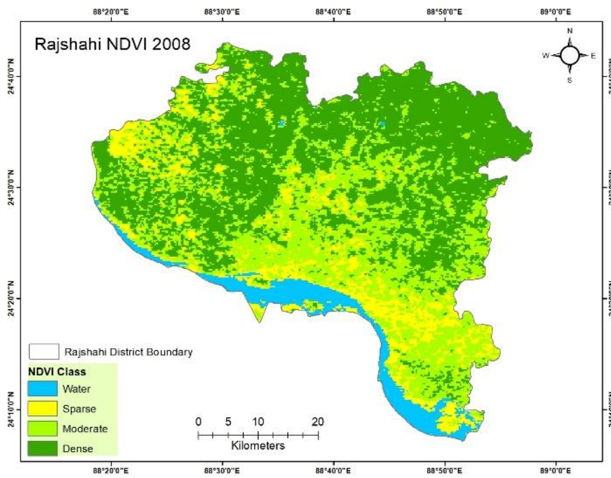

Pabna NDVI 2020
N
W
E
S
Pabna District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
24°20'0"N
24°10'0"N
24°0'0"N
23°50'0"N

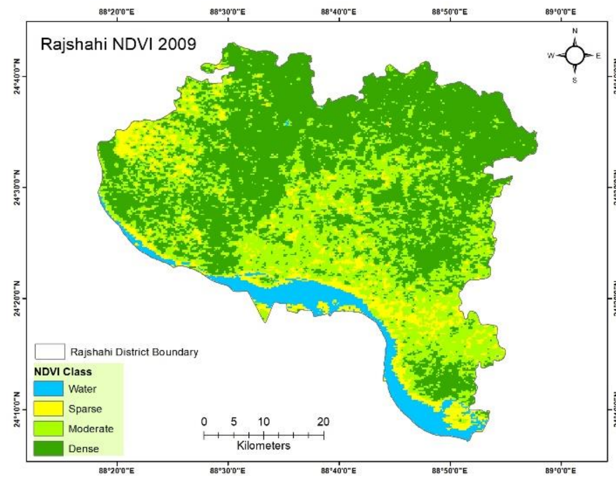
Figure C4: Time Series of NDVI for Rajshahi District

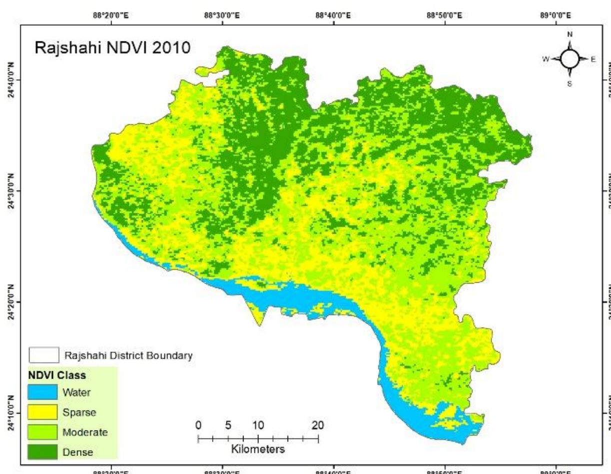


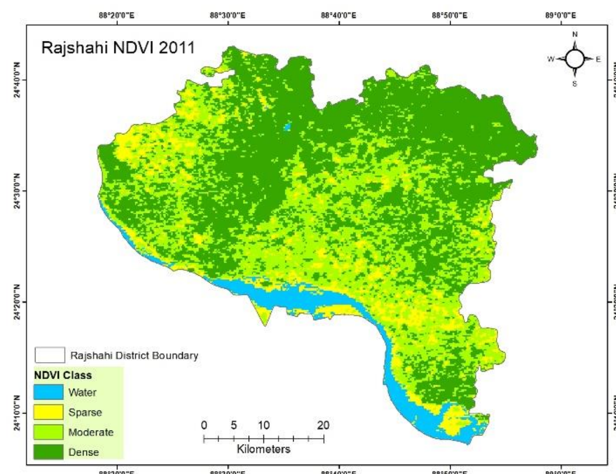

Rajshahi NDVI 2006
N
W
E
S
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
24°40'0"N
24°30'0"N
24°20'0"N
24°10'0"N

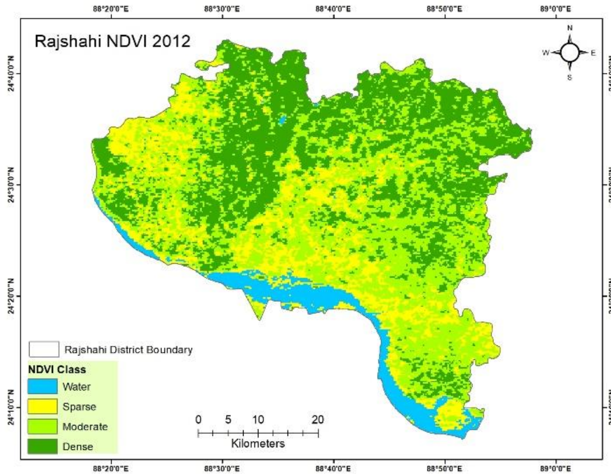

Rajshahi NDVI 2007
N
W
E
S
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
24°40'0"N
24°30'0"N
24°20'0"N
24°10'0"N

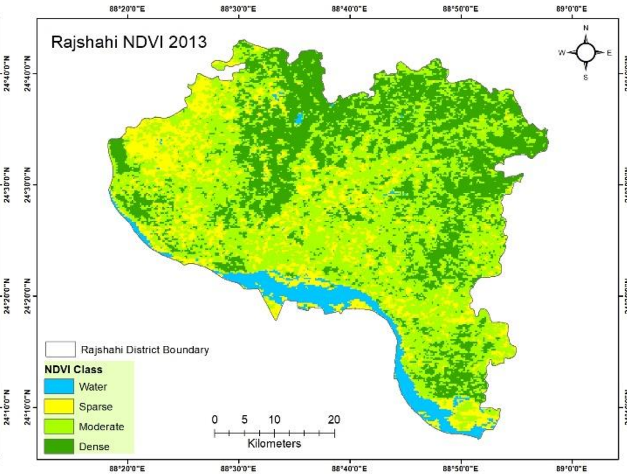

Rajshahi NDVI 2008
N
W
E
S
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
24°40'0"N
24°30'0"N
24°20'0"N
24°10'0"N

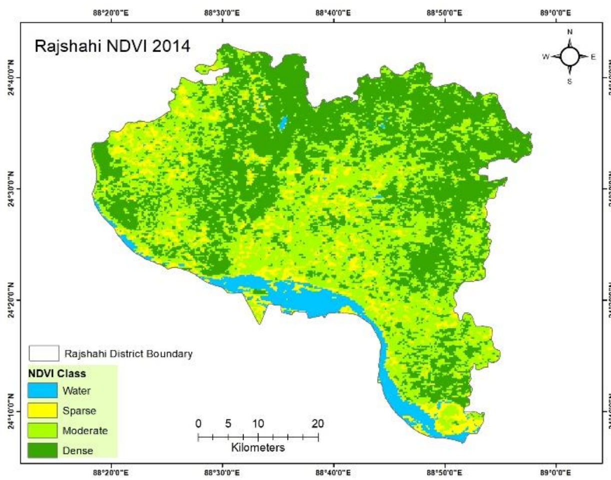

Rajshahi NDVI 2009
N
W
E
S
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
24°40'0"N
24°30'0"N
24°20'0"N
24°10'0"N

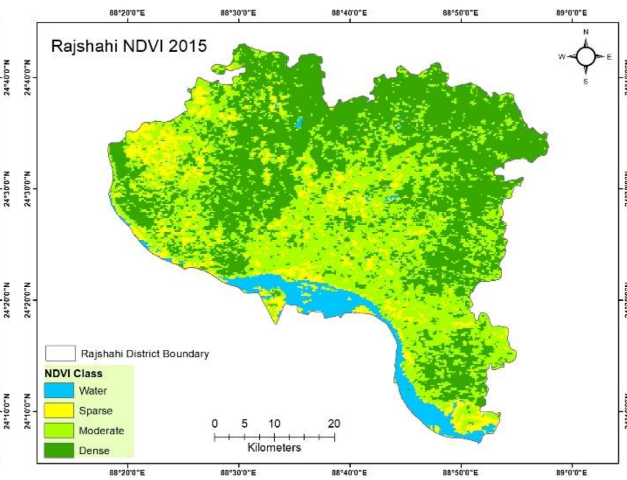

Rajshahi NDVI 2010
N
W
E
S
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
24°40'0"N
24°30'0"N
24°20'0"N
24°10'0"N

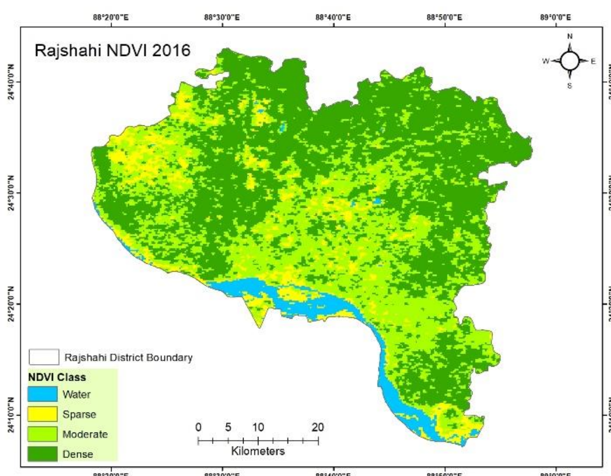

Rajshahi NDVI 2011
N
W
E
S
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°20'0"E
88°30'0"E
88°40'0"E
88°50'0"E
89°0'0"E
24°40'0"N
24°30'0"N
24°20'0"N
24°10'0"N

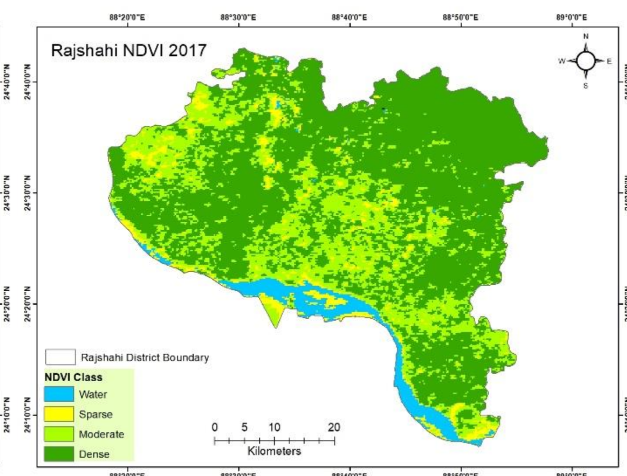

Rajshahi NDVI 2012
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Rajshahi NDVI 2013
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Rajshahi NDVI 2014
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Rajshahi NDVI 2015
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Rajshahi NDVI 2016
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers


Rajshahi NDVI 2017
Rajshahi District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

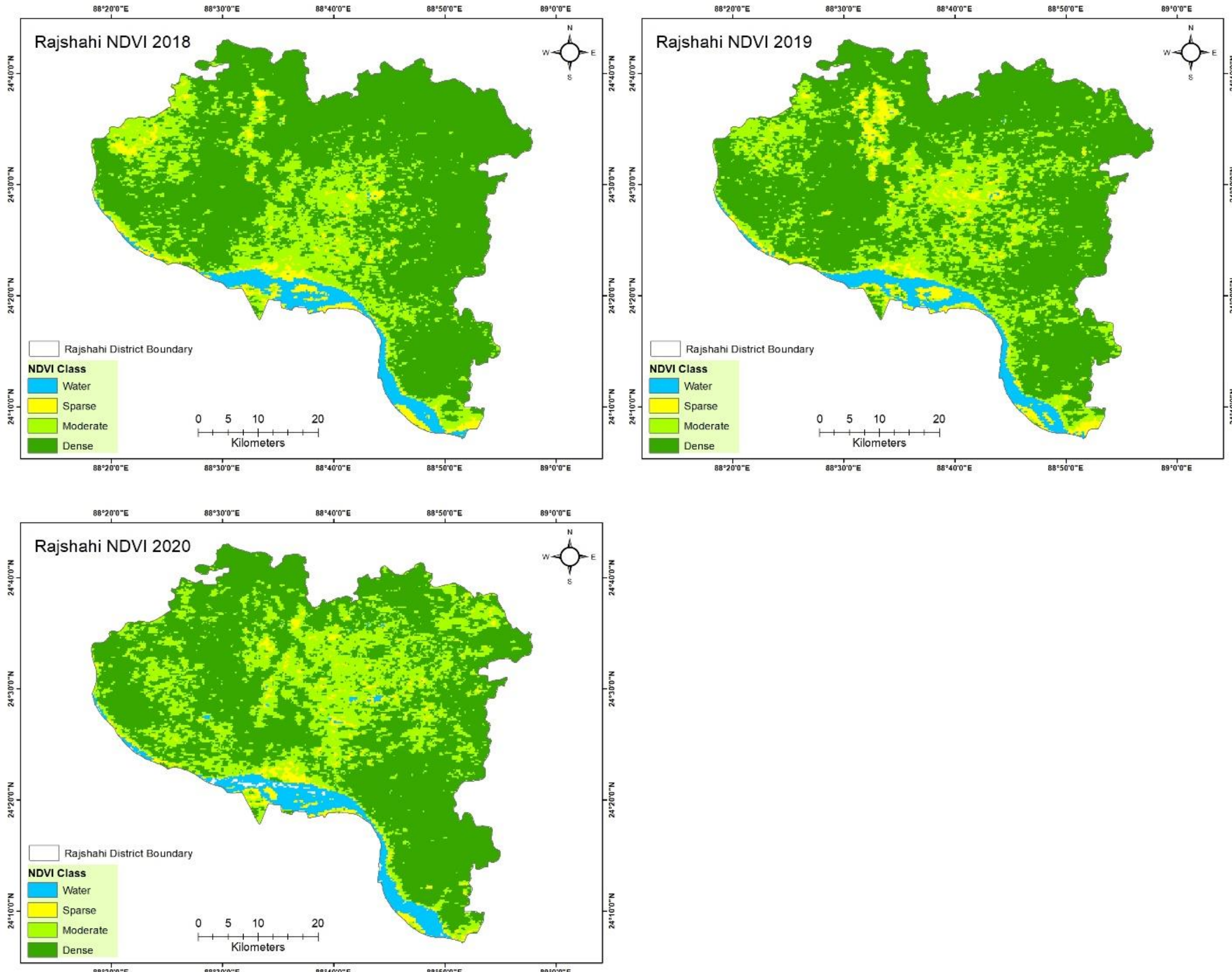
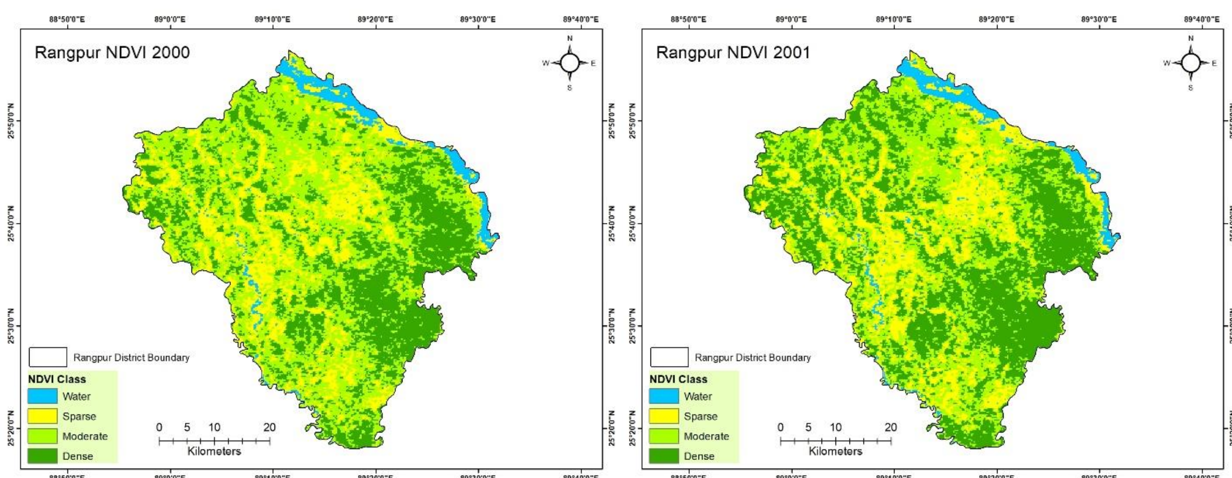
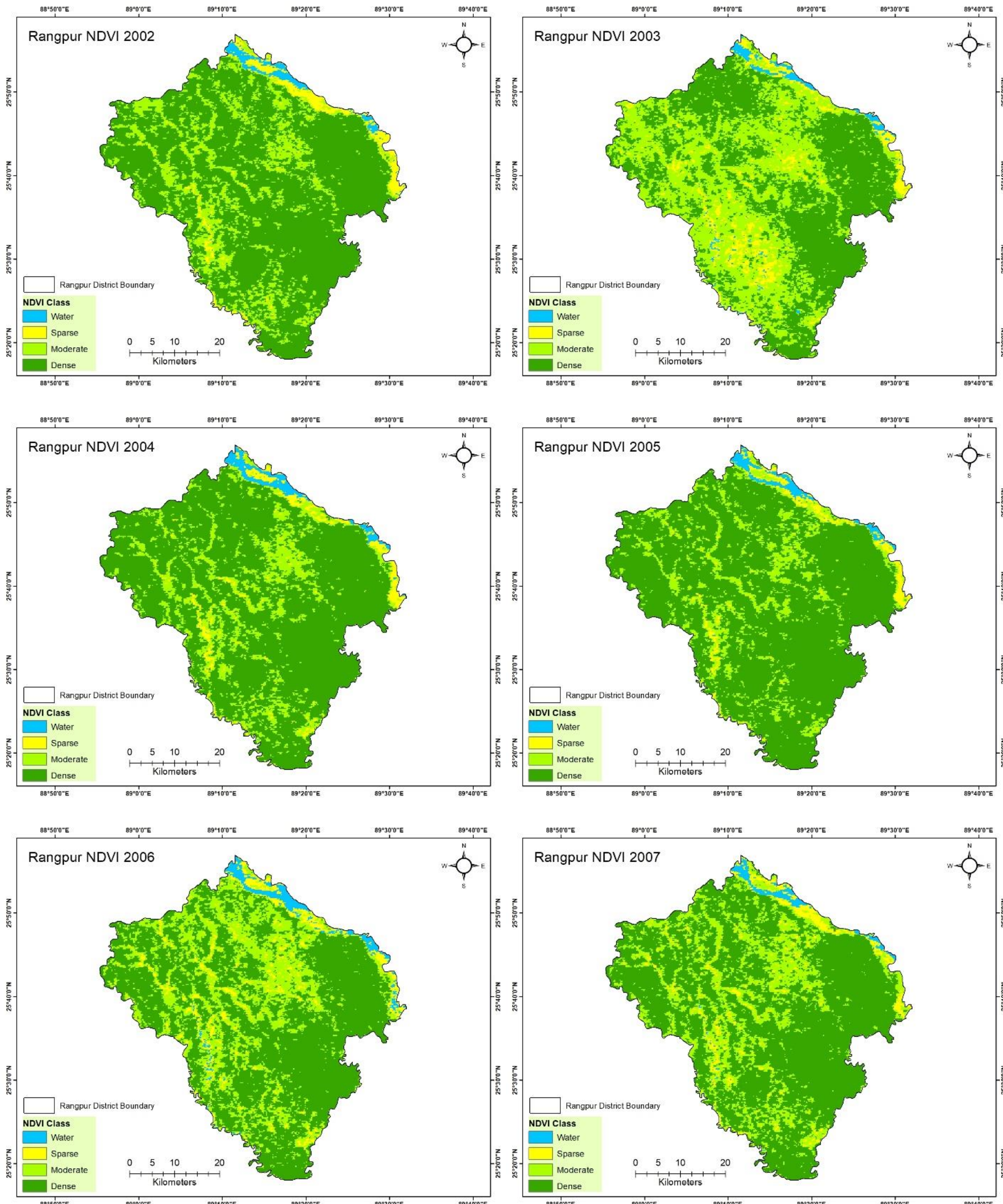
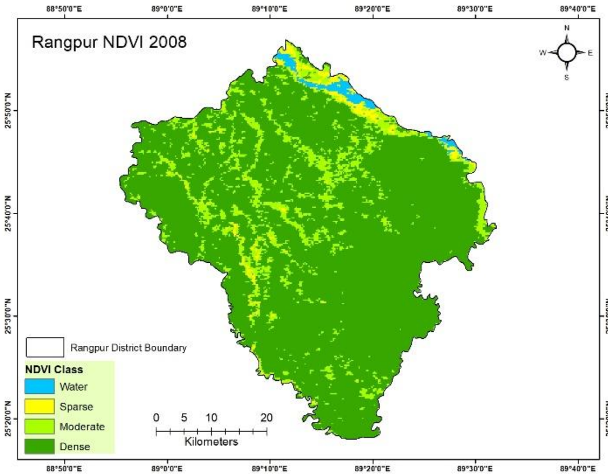
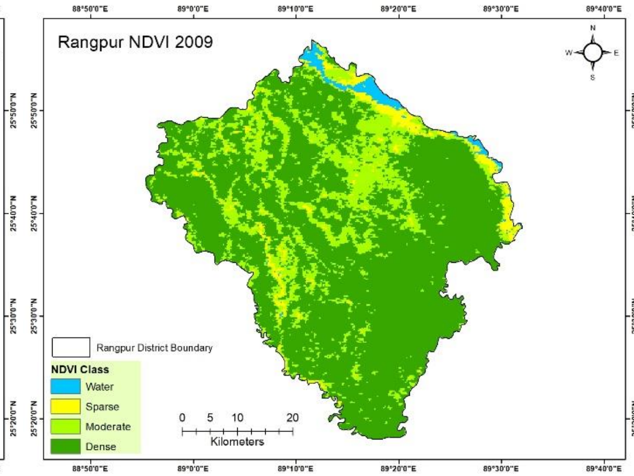


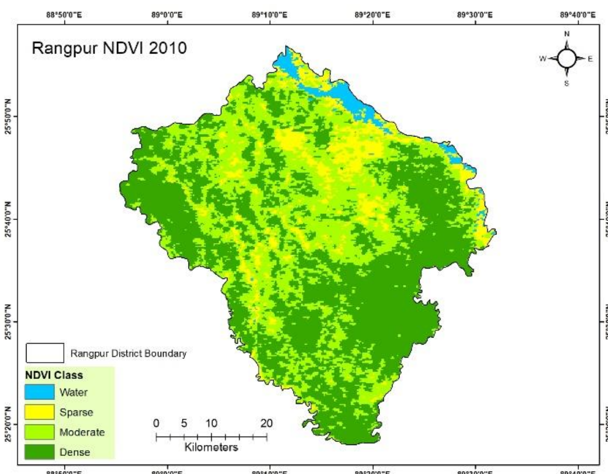
Figure C5: Time Series of NDVI for Rangpur District

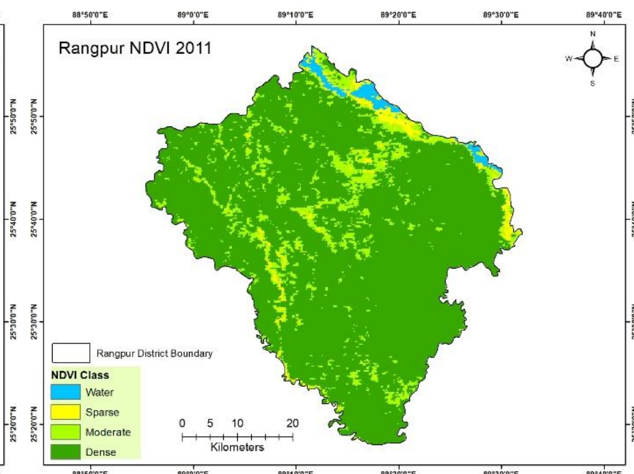


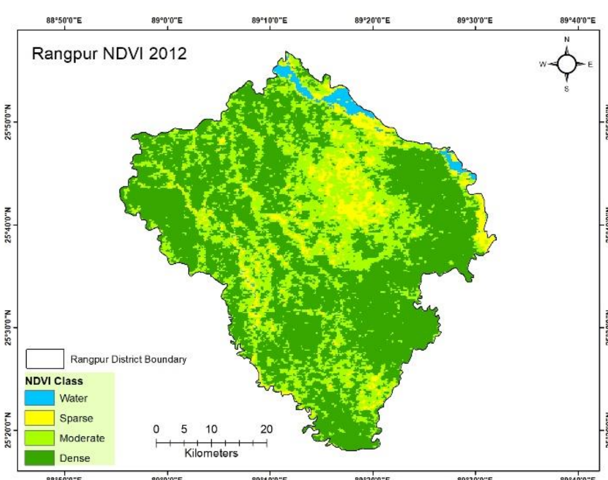

Rangpur NDVI 2002
Rangpur NDVI 2003
Rangpur NDVI 2004
Rangpur NDVI 2005
Rangpur NDVI 2006
Rangpur NDVI 2007
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers

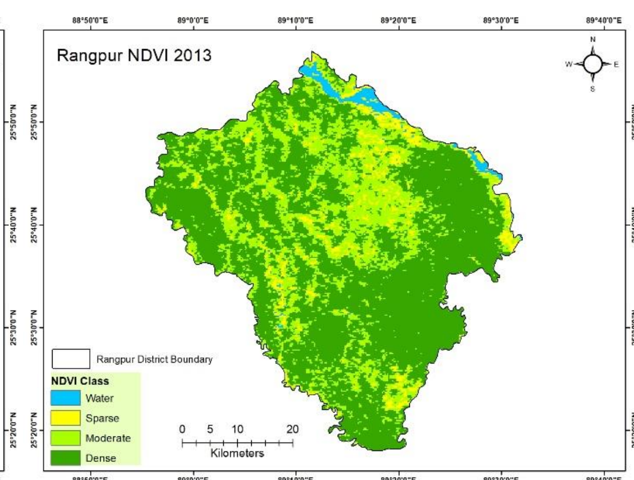

Rangpur NDVI 2008
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N

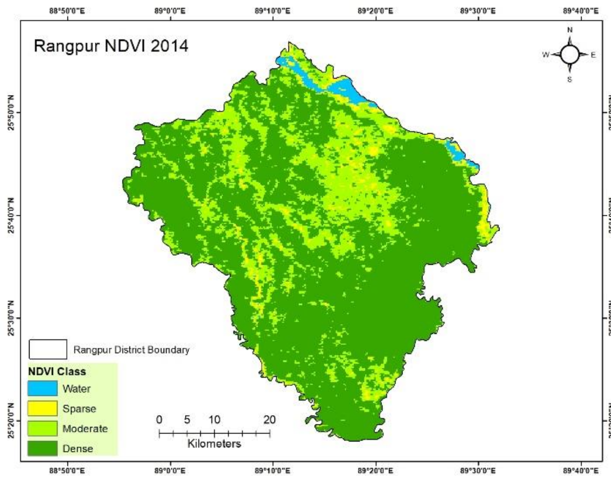

Rangpur NDVI 2009
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N

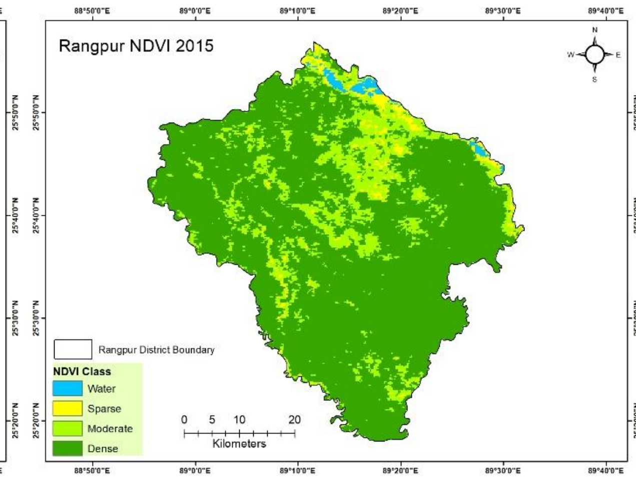

Rangpur NDVI 2010
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N

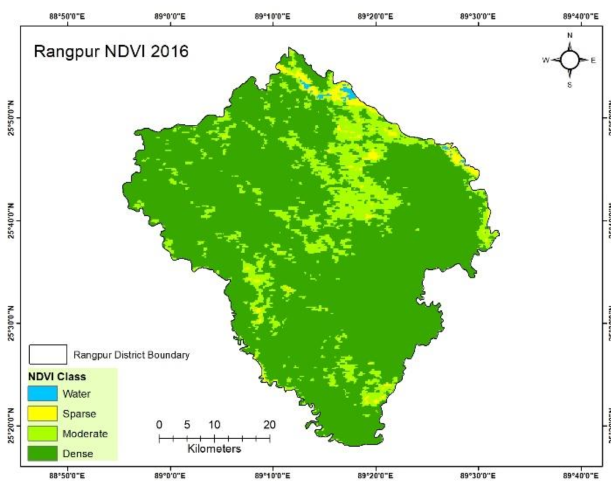

Rangpur NDVI 2011
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N

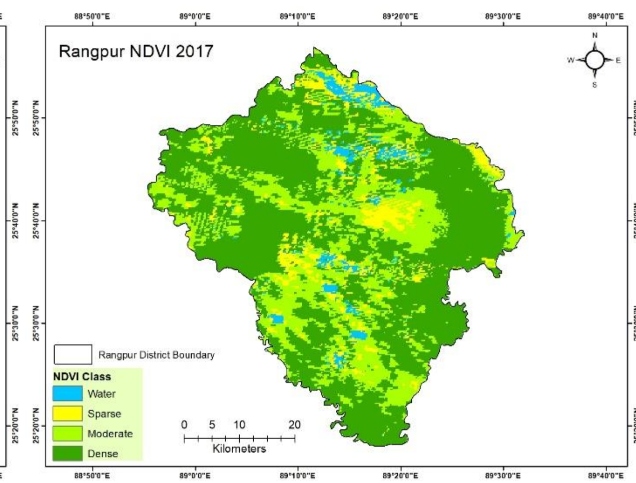

Rangpur NDVI 2012
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N

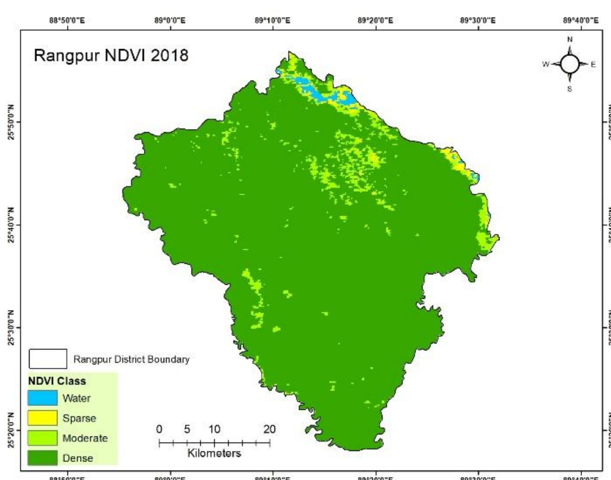

Rangpur NDVI 2013
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N

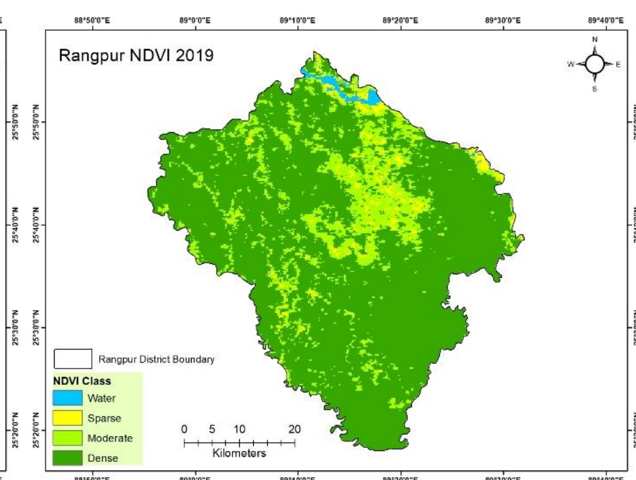

Rangpur NDVI 2014
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N

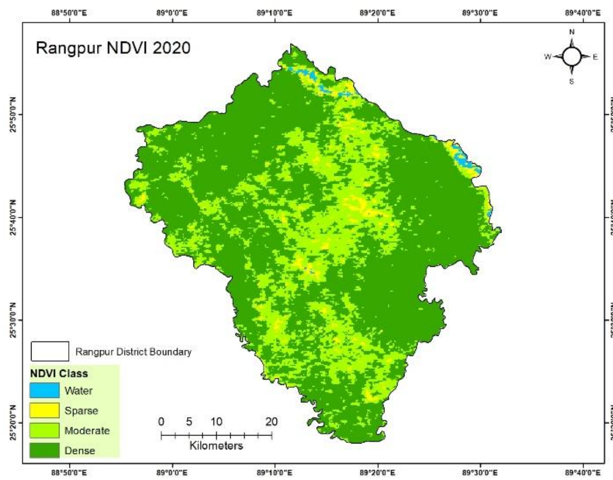

Rangpur NDVI 2015
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N


Rangpur NDVI 2016
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N


Rangpur NDVI 2017
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N


Rangpur NDVI 2018
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N


Rangpur NDVI 2019
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N


Rangpur NDVI 2020
88°50'0"E
89°0'0"E
89°10'0"E
89°20'0"E
89°30'0"E
89°40'0"E
25°50'0"N
25°40'0"N
25°30'0"N
25°20'0"N
N
W
E
S
Rangpur District Boundary
NDVI Class
Water
Sparse
Moderate
Dense
0 5 10 20
Kilometers