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Research Paper

Meteorological Drought Analysis Over Northwest Region of Bangladesh and Its Socioeconomic Impact

Md. Mahfuj Alam[1], Md. Jubair Ahmed[2]*, Umme Habiba Siddiqua[3], Suzana Niaz[4]

ABSTRACT

Droughts are significant long-term disasters that affect large areas and result in severe human and economic impacts, being the most costly natural disaster worldwide. This research focuses on Bangladesh's northwest, where persistent droughts are monitored using the Standardized Precipitation Index (SPI). By assessing historical precipitation data from nine stations, the study identifies drought duration and severity. Findings indicate that while mild droughts are more frequent, severe droughts also occur, particularly in various areas. The analysis revealed that the longest severe drought lasted 37 months between June 1956 and July 1959 in Rangpur. The results aim to enhance water resource management and drought forecasting for the region.

Keywords: *Water Resources, Agricultural Impact, Socioeconomic Effects, Groundwater Depletion, Drought Monitoring, Drought Indexing, Hydrological Drought, Agricultural Drought, Drought Mitigation Strategies, Climate Change, Early Warning System*

Drought is a major global hazard that leads to significant water shortages, adversely affecting economies and human life, costing $6 to $8 billion annually. Bangladesh faces severe droughts, particularly in its northern regions, where poverty and agricultural reliance exacerbate the situation. The country has experienced nearly twenty major droughts in the past fifty years. Unlike more immediate natural disasters, drought is complex and challenging to predict, impacting regions differently. In Bangladesh, both major and local droughts frequently hinder crop production, especially during monsoon failures, which can lead to famine and drastically reduce yields. [1] [2] [3]

Drought is commonly classified into three types:

1. Meteorological Drought: This occurs when there is significant precipitation shortfall over time, varying by region's typical rainfall.

[1]Department of Civil Engineering, Faculty of Engineering, Ahsanullah University of Science and Technology, Dhaka, Bangladesh
[2]Master's of civil Engineering by Research, Universiti Tenaga Nasional, Malaysia
[3]Department of Civil Engineering, Faculty of Engineering, Ahsanullah University of Science and Technology, Dhaka, Bangladesh
[4]Department of Civil Engineering, Faculty of Engineering, Ahsanullah University of Science and Technology, Dhaka, Bangladesh
*Corresponding Author

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2. Hydrological Drought: Characterized by low water levels in streams and reservoirs, often exacerbated by human activity.
3. Agricultural Drought: Results from decreased atmospheric moisture affecting soil, leading to reduced agricultural output and food supply challenges.

Bangladesh's northwest region frequently experiences meteorological droughts, impacting crop yields, water access, and exacerbating health risks like mosquito-borne diseases. Drought indices, beginning with the standardized precipitation index (SPI), effectively measure drought severity by analyzing climatic and meteorological factors, particularly precipitation levels.[4] [5]

STUDY AREA

The northwest region of Bangladesh, situated between 24.5° N to 26.5° N and 88.5° E to 89.5° E, includes areas like the Padma River, Rajshahi's mango orchards, and cultural sites such as the Puthia Temple Complex and Mahasthangarh. It covers several districts, including Rajshahi, Rangpur, and Bogura, with a combined population of over 40 million. This region is crucial for agriculture, benefiting from annual rainfall between 1,200 to 3,000 mm, which supports its fertile plains and river basins, making it a significant contributor to Bangladesh's economy. [6]

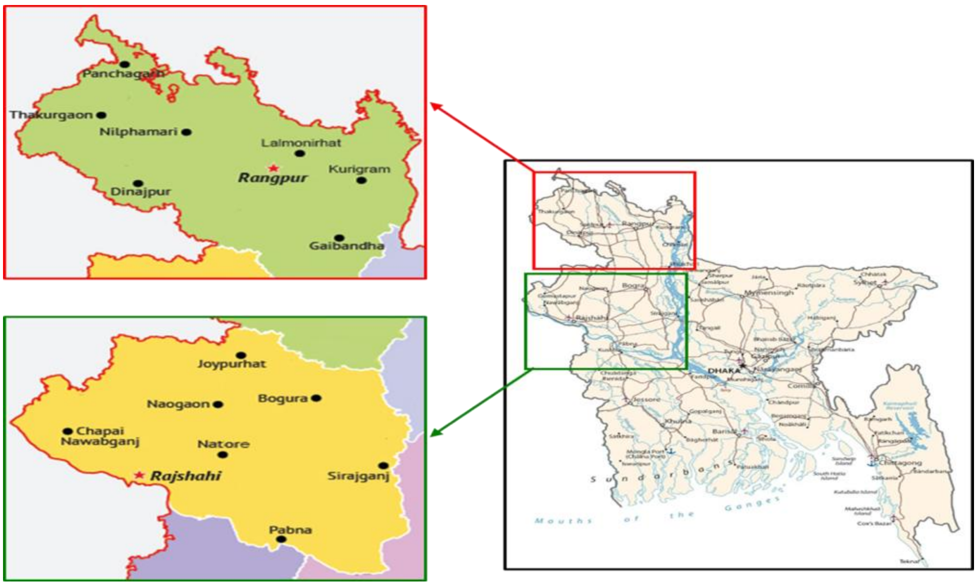


Fig 1: Map of Northwestern Bangladesh.

Data were collected from nine meteorological stations in northwestern Bangladesh, including Rajshahi, Bogra, and Rangpur. This subtropical region is studied for its significant climate changes and the environmental factors affecting temperature variations**.**

Table 1: Description of the Meteorological Stations in The Study Area

Station No.	Station Name	Latitude (N)	Longitude (E)	Data Period
1	Rajshahi	24° 22’ 26.40”	88° 36’ 4.10”	1964-2023
2	Bogra	24° 51’ 3.53”	89° 22’ 15.89”	1948-2023
3	Ishwardi	24° 7’ 42.89”	89° 3’ 56.63”	1961-2023
4	Tarash	24° 25’ 59.88”	89° 22’ 30”	2018-2023
5	Rangpur	25° 44’ 47.90’	89° 15’ 5.98”	1954-2023
6	Dinajpur	25° 37’ 38.82”	88° 38’ 16.04”	1948-2023
7	Dimla	26° 9’ 23.26”	88° 55’ 30.08”	2018-2023
8	Rajarhat	25° 48’ 0.0”	89° 32’ 60”	2018-2023
9	Saidpur	25° 46’ 39.68”	88° 53’ 30.08”	1991-2023

LITERATURE REVIEW

Drought

Drought is a prolonged dry spell that leads to significant issues like crop damage and water shortages. While many attribute drought mainly to low rainfall, it’s also influenced by factors like overpopulation and misuse of water. Defining drought can be tricky, necessitating various interpretations for different contexts. Meteorological drought refers to a lack of rainfall, while hydrological drought affects water sources. Agricultural drought impacts soil moisture, critical for crop growth. Understanding these definitions is vital for effective drought management. [7] [8]

DROUGHT AND CLIMATE CHANGE

Climate change intensifies droughts through a self-reinforcing cycle. Increased greenhouse gas emissions raise temperatures, causing hot air to absorb moisture and reduce rainfall. This cycle dries up lakes and rivers, killing plants that usually retain soil moisture. When rain finally occurs, it runs off due to lack of vegetation, leading to larger floods and more frequent wildfires. In Australia, unprecedented heat and drought are linked to climate change, and projections indicate that drought-prone areas will face variable rainfall, particularly in the west during seasonal farming periods. Over-extraction of freshwater for irrigation further compounds the problem, risking groundwater depletion and environmental issues like salinity and heavy metal contamination. [9]

IMPACT OF DROUGHT

Bangladesh faces significant drought challenges every five years, alongside frequent local droughts that disrupt crop cycles. The kharif period (June to October) experiences droughts affecting t.aman rice yields, while the rabi and pre-kharif periods (January to May) see dry conditions harming Rabi crops like Boro and wheat. Severe droughts can damage over 40%

of certain crops and impact millions of hectares annually. Historically, droughts have affected nearly half of the country and its population, leading to decreased food production, asset loss, and heightened food insecurity, particularly for vegetables and pulses. [7]

TYPES OF DROUGHT

Droughts are classified into four categories. Meteorological droughts are characterized by a shortfall in precipitation relative to the expected average for a region. Hydrological droughts occur when water levels in streams and reservoirs decline, often exacerbated by human activities. Agricultural droughts arise from reduced atmospheric moisture that negatively impacts soil moisture and crop yields. Lastly, socioeconomic droughts result from imbalances between the demand and supply of goods, driven by factors like population growth and decreased rainfall. [10]

CHARACTERISTICS OF DROUGHT

Droughts are characterized by severity, duration, spatial distribution, and additional features like frequency and intensity. Duration can range from a week to several years, with regions experiencing both dry and wet spells simultaneously. Magnitude refers to the accumulated water deficit, while intensity is the ratio of magnitude to duration. Severity can indicate the degree of precipitation deficit or its impacts. Geographic extent measures the area affected, which can vary during the event. Finally, frequency (or return period) defines the average time between droughts of a specified severity. Understanding these parameters is essential for effective drought monitoring and analysis.[11]

DROUGHT INDEX

Drought severity is measured using a drought index, which considers factors like precipitation, temperature, and water availability. This index is crucial for forecasting droughts, helping to reduce associated hazards. However, no single method is universally superior; the most effective measurement depends on the region and the type of drought being assessed, such as meteorological or agricultural droughts.[12]

Some of the indices that are widely used are described below:
Meteorological drought indices are crucial for assessing drought conditions, with the Standardized Precipitation Index (SPI) being a key tool based solely on precipitation data compared to multiyear averages. The Standardized Precipitation Evapotranspiration Index (SPEI) extends SPI by factoring in both precipitation and potential evapotranspiration (PET), addressing temperature impacts on water demand, and can be computed over various timescales. The Drought Reconnaissance Index (DRI) uses a simplified water balance approach, yielding three outputs analogous to SPI. The Streamflow Drought Index (SDI) assesses both wet and dry periods using monthly streamflow data, while the Palmer Drought Severity Index (PDSI) focuses on water supply and demand through a comprehensive water balance equation involving precipitation, temperature, and soil water content to gauge moisture deficiencies.[13] [14] [15]

The text describes various indices for measuring drought severity. The EDI (Evaporative Demand Index) designates ranges for drought conditions: extreme drought (-2 or lower), severe drought (-2 to -1.5), moderate drought (-1.5 to -1.0), and near normal (-1 to 1.0). The CHINA-Z Index (CZI) uses a specific statistical transformation based on precipitation data, while the Modified CZI (MCZI) utilizes the median precipitation instead of the mean. The Z-Score Index (ZSI) is similar to the CZI but does not require fitting data to specific distributions; higher values indicate more severe drought conditions, calculated using mean monthly precipitation and its standard deviation.[16]

DROUGHT CHARACTERIZATION UAING DROUGHT INDICES

The use of an index for drought characterizations serves several operational purposes: it aids in detecting drought and real-time monitoring, marks the start and end of drought periods, helps drought managers implement response measures, evaluates drought conditions, and represents regional drought concepts. Additionally, it correlates with quantitative impacts across various geographies and timeframes while facilitating communication about drought conditions among stakeholders.[17]

CONSIDERATION OF DROUGHT INDICATORS

The text discusses the importance of understanding water demands, supplies, and drought vulnerabilities in context. It raises questions about the availability, reliability, and consistency of data used for drought indicators, emphasizing that many drought plans rely on collects data subject to quality control. Results must be clear, valid, and scientifically sound. Additionally, indicators must reflect specific time periods and spatial contexts, as the implication of drought can vary by region and time.[18]

METHODS FOR DROUGHT ANALYSIS

Drought forecasting is critical for managing water resources, utilizing historical correlations and numerical methods based on physical equations. Models like ARIMA and SARIMA predict droughts, supported by specialized software. Additionally, drought indexing measures, such as the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI), reflect dry conditions and high evapotranspiration, calculated using simple numerical methods.[19]

TOOLS FOR DROUGHT ANALYSIS

Excel simplifies the calculation of the Standardized Precipitation Index (SPI) through both theoretical and empirical functions, also allowing for graphical results. Drought indices can be calculated manually or using dedicated software, with tools like Matlab and R often requiring advanced skills. To address this, a software called Drinc was developed at the National Technical University of Athens for easier index calculation. The software allows for importing various input data from MS Excel, whether monthly or annual, and supports both real and synthetic data series, with options for transforming rainfall data.[20]

Drought indices calculation

The Standardized Precipitation Index (SPI) was designed by [13]to quantify the precipitation deficit for multiple time scales. These time scales reflect different water resources. These time scales reflect the soil moisture conditions (small time scale) or the underground waters, river flows and lake water levels (large time scales).

The SPI is defined for each of the above time scales as the difference between monthly precipitation on (3- months, 6- months, or 12-months) time scale (xi) and the mean value ($\bar{x}$), divided by the standard deviation (s),

$$SPI=\frac{xi-\bar{x}}{s}$$

Where xi is the monthly rainfall amount and $\bar{x}$ and s are the mean and standard deviation of rainfall calculated from the whole time series of monthly values.

Procedure and Formulas for Computation of SPI

1. The transformation of the precipitation value in to standardized precipitation index (SPI) has the purpose of

a. Transforming the mean of the precipitation value adjusted to 0;
b. Standard deviation of the precipitation is adjusted to 1.0; and
c. Skewness of the existing data has to be readjusted to zero.

When these goals have been achieved the standardized precipitation index can be interpreted as mean 0 and standard deviation of 1.

2. Mean= X $=\frac{\sum X}{N}$

Where N is the number of precipitation observations.

In EXCEL the mean is computed as Mean = Average (first:last)

3. The standard deviation for the precipitation is computed as:

$s=\sqrt{\frac{\sum(X-\bar{X})^2}{N}}$

In EXCEL the standard deviation is computed as s =st dev (first:last)

4. The skewness of the given precipitation is computed as:

$$\text{Skew}=\frac{N}{(N-1)}(N-2)^{\sum\left(\frac{x-\bar{x}}{s}\right)^3}$$

5. The precipitation is converted to lognormal values and the statistics U, shape and scale parameters of gamma distribution are computed:

Log mean = $\bar{x}_{ln} = \ln(\bar{x})$

$U=\bar{x}_{ln} - \sum \ln(x) \times \frac{1}{N}$

Shape parameter=$\beta = \frac{1+\sqrt{1+\frac{4U}{3}}}{4U}$

Scale parameter= $\alpha = \frac{\overline{X}}{\beta}$

6.The gamma transformed values were again transformed,

t transform= $t = \sqrt{\ln\left[\frac{1}{x_g}\right]}$

Where $x_g \leq .5$

Or, t transform=$t = \sqrt{\ln\left[\frac{1}{1-x_g}\right]}$

Where $x_g \leq 1.0$

Employing the approximate conversion provided by [21]

$\text{SPI}=-\left[t - \frac{c_0+c_1t+c_2t^2}{1+d_0+d_1t+d_2t^2+d_3t^3}\right]$

Where $x_g \leq .5$

$\text{SPI}=+\left[t - \frac{c_0+c_1t+c_2t^2}{1+d_0+d_1t+d_2t^2+d_3t^3}\right]$

Where, $x_g \leq 1.0$

Where, c_0 =2.515517, c_1 =0.802583, c_2 =0.010328, d_1 =1.432788, d_2 =0.189269, d_3=0.001308 constants values.

Table 2: Classification of Drought According to SPI. [13]

SPI Values	Classification
2.0+	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

Drought event occurs any time the SPI is continuously negative and reaches an intensity of -1.00 or less. The event ends when the SPI becomes positive.

METHODOLOGY

Introduction

To Calculate drought using SPI_SL_6 program typically follows a Statistical Method known as the Standardized Precipitation Index (SPI).In this method, three-month, six-month, twelve-month and twenty-four-month time scales (SPI3, SPI6, SPI12 and SPI24) are chosen to represent short- and long-term droughts. The latest SPI program (SPI_SL_6) from the National Drought Mitigation Centre is used to compute SPI for each station at different time scale. [5]

In this study, the latest SPI program (SPI_SL_6) from the National Drought Mitigation Centre (Program to Calculate Standardized Precipitation Index, 2016) is used to compute SPI for each station at different time scales. [22]

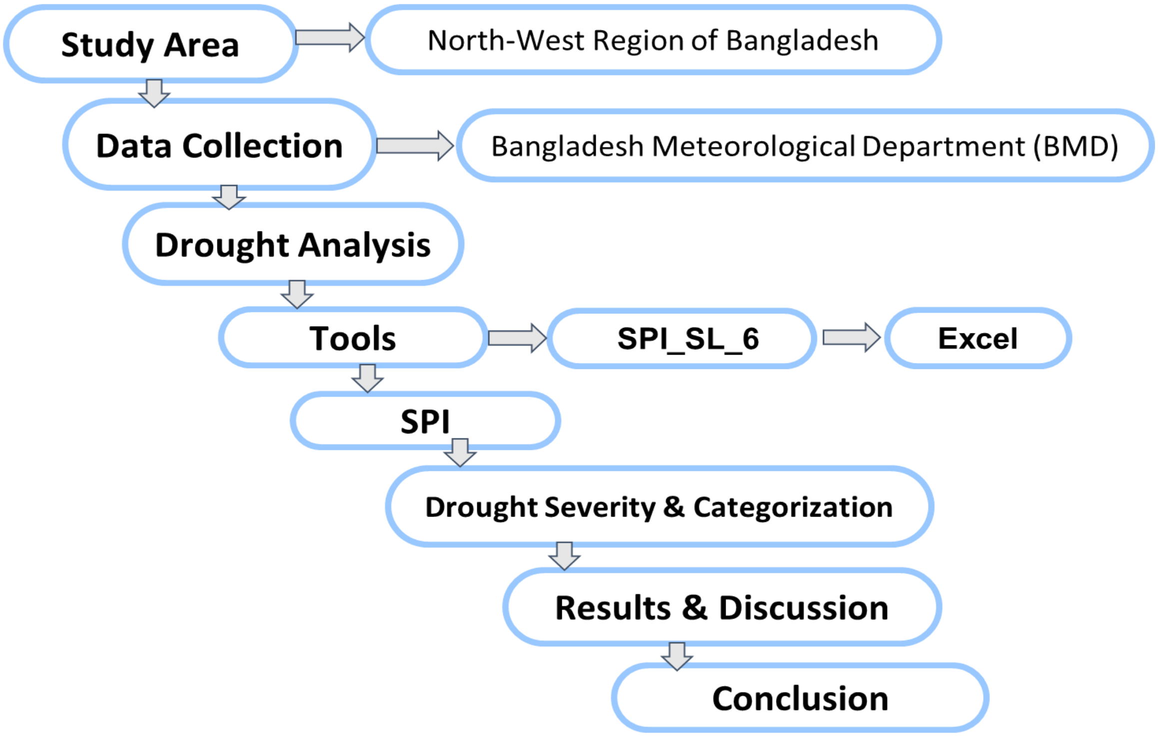


Fig 2: Flow chart of the Methodology of the Study

DATA COLLECTION

Data collecting is essential to the completion of any climatological investigation. There are 25 types of atmospheric monitoring networks that are operated and coordinated by the BMD (BMD). The major data required for the analysis are monthly minimum and maximum temperature, rainfall, humidity, wind speed and sun hours. Sixty-two (1948-2010) years of climatic data was obtained from Bangladesh Meteorological Department(BMD). The same has been utilized to derive SPI. These data are collected from 1948 to 2010 for this study. [23]

Spi Calculation

This program presents some inconveniences: input data must be presented in "notepad" format, where rainfall must be submitted on 3 columns, the first for years, the second for months and third with monthly rainfall.

Input File

This program presents some inconveniences: input data must be presented in "notepad" format, where rainfall must be submitted on 3 columns, the first for years, the second for months and third with monthly rainfall.

Fig 3: Input File

Program Execution

SPI_SL_6.exe was used to execute the program. The number of SPI monthly intervals (up to six at one time) were entered to run the program. The SPI monthly intervals (i.e. 3,6,9,12,24-months) were entered. The input and output file names were entered.

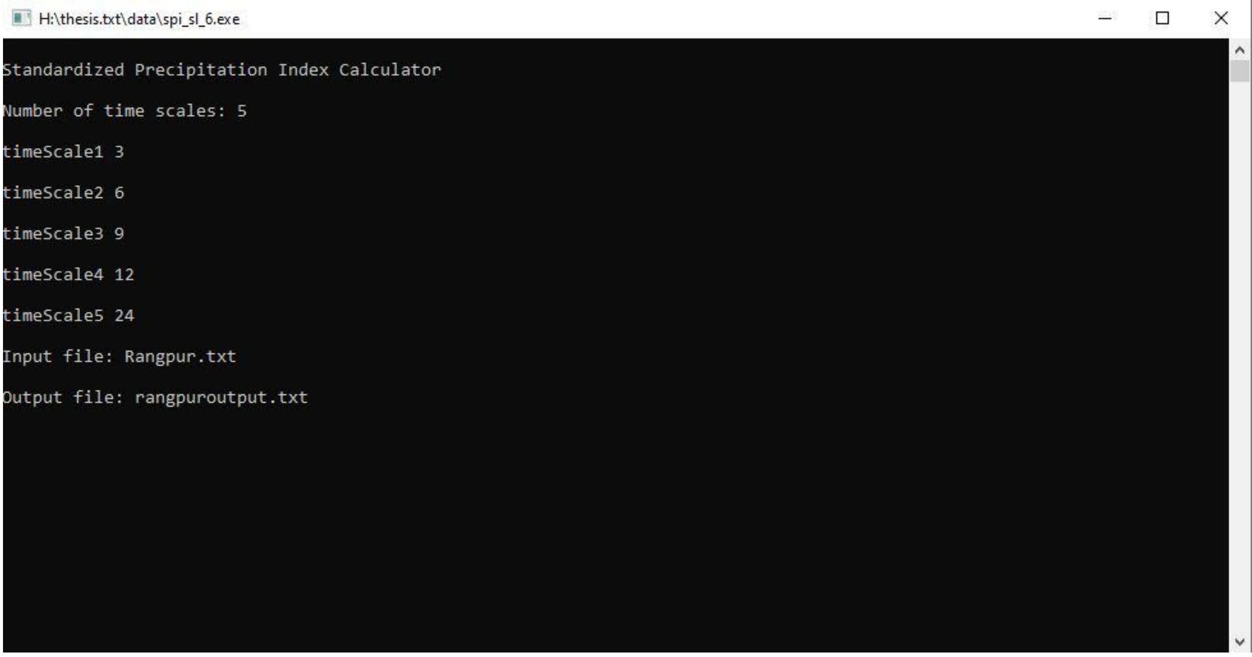
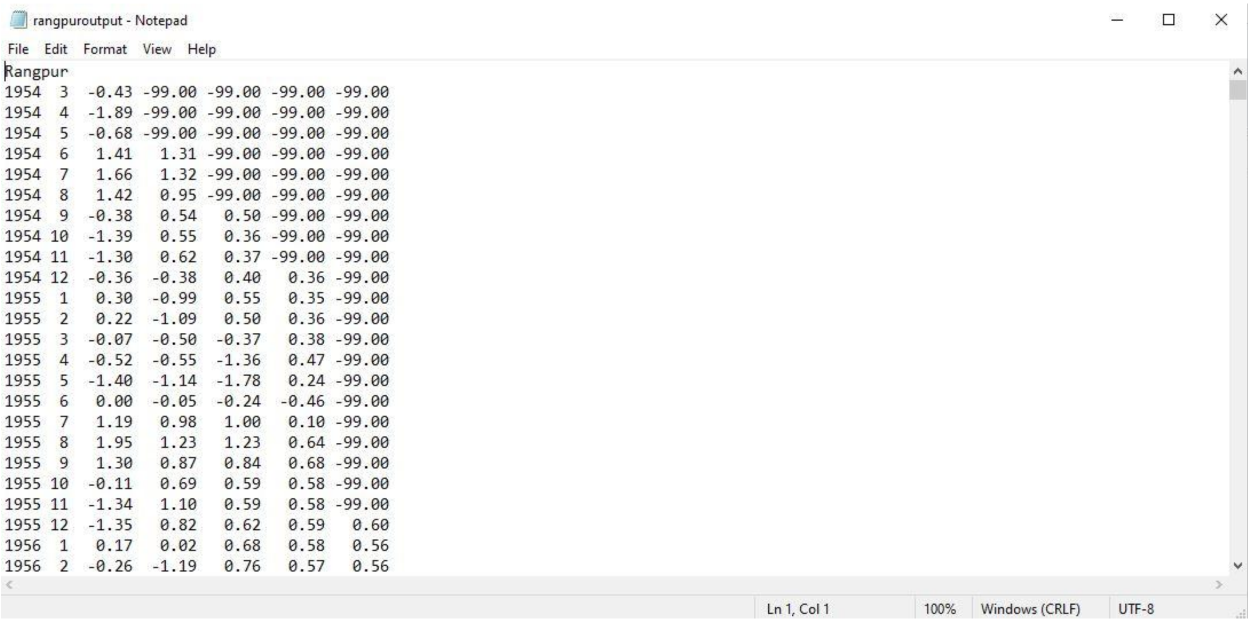


Fig 4: The input and output files used for SPI calculation with "SPI_SL_6.exe" software. [22]

Output File:

The output data file, they are divided into several columns, the first of which is the year and the two months. Number of the other columns is equal to the number of processed scales (3 months, 6 months, etc.) each column containing SPI values for 3 months, SPI values for 6 months, etc.



Rangpur

1954	3	-0.43	-99.00	-99.00	-99.00	-99.00
1954	4	-1.89	-99.00	-99.00	-99.00	-99.00
1954	5	-0.68	-99.00	-99.00	-99.00	-99.00
1954	6	1.41	1.31	-99.00	-99.00	-99.00
1954	7	1.66	1.32	-99.00	-99.00	-99.00
1954	8	1.42	0.95	-99.00	-99.00	-99.00
1954	9	-0.38	0.54	0.50	-99.00	-99.00
1954	10	-1.39	0.55	0.36	-99.00	-99.00
1954	11	-1.30	0.62	0.37	-99.00	-99.00
1954	12	-0.36	-0.38	0.40	0.36	-99.00
1955	1	0.30	-0.99	0.55	0.35	-99.00
1955	2	0.22	-1.09	0.50	0.36	-99.00
1955	3	-0.07	-0.50	-0.37	0.38	-99.00
1955	4	-0.52	-0.55	-1.36	0.47	-99.00
1955	5	-1.40	-1.14	-1.78	0.24	-99.00
1955	6	0.00	-0.05	-0.24	-0.46	-99.00
1955	7	1.19	0.98	1.00	0.10	-99.00
1955	8	1.95	1.23	1.23	0.64	-99.00
1955	9	1.30	0.87	0.84	0.68	-99.00
1955	10	-0.11	0.69	0.59	0.58	-99.00
1955	11	-1.34	1.10	0.59	0.58	-99.00
1955	12	-1.35	0.82	0.62	0.59	0.60
1956	1	0.17	0.02	0.68	0.58	0.56
1956	2	-0.26	-1.19	0.76	0.57	0.56

Fig 5: Output File

Manual Calculation of SPI for validation:

			X bar												
	Mean	173.421	173.835												
	SD	210.212													
	Sum	4201.07													
	n	822													
			Year	Month	Prcp	x	ln(X)	gamma	Spi 12	Manual calc	Programmed calc	Spi 3	Spi 6	Spi 9	Spi 12
A	0.04730995		1954	1	1										
alpha	5.448418776		1954	2	1										
Bita	31.90550452		1954	3	1							-0.45			
			1954	4	1							-1.9			
			1954	5	275							-0.7			
Scale	Desc		1954	6	944							1.36	1.26		
-5	Extrmely dry		1954	7	602							1.64	1.29		
-1.99	Severely dry		1954	8	211							1.43	0.94		
-1.5	Severely dry		1954	9	101							-0.39	0.52	0.48	
-1.49	Moderately dry		1954	10	90							-1.41	0.54	0.34	
-1	Moderately dry		1954	11	1							-1.32	0.59	0.34	
-0.99	near normal		1954	12	1	185.75	5.2244	0.61756	0.29908	near normal	near normal	-0.38	-0.4	0.38	0.34
0	near normal		1955	1	20	187.333	5.23289	0.62524	0.31926	near normal	near normal	0.29	-1.03	0.54	0.34
0.99	near normal		1955	2	3	187.5	5.23378	0.62604	0.32138	near normal	near normal	0.22	-1.13	0.49	0.34
1	Moderately wet		1955	3	8	188.083	5.23689	0.62884	0.32878	near normal	near normal	-0.09	-0.54	-0.39	0.37
1.49	Moderately wet		1955	4	55	192.583	5.26053	0.65003	0.38539	near normal	near normal	-0.52	-0.58	-1.41	0.45
1.5	Very wet		1955	5	124	180	5.19296	0.58893	0.2248	near normal	near normal	-1.43	-1.19	-1.82	0.21
1.99	Very wet		1955	6	566	148.5	5.00058	0.41562	-0.21312	near normal	near normal	-0.03	-0.08	-0.28	-0.33
2	extrmely wet		1955	7	892	172.667	5.15136	0.55082	0.12774	near normal	near normal	1.16	0.95	0.97	0.07
			1955	8	562	201.917	5.30786	0.69149	0.50008	near normal	near normal	1.96	1.23	1.24	0.62
			1955	9	160	206.833	5.33191	0.71195	0.55909	near normal	near normal	1.32	0.85	0.82	0.67
			1955	10	19	200.917	5.30289	0.68721	0.48796	near normal	near normal	-0.12	0.67	0.57	0.57
			1955	11	5	201.25	5.30455	0.68864	0.492	near normal	near normal	-1.36	1.07	0.57	0.57
			1955	12	1	201.25	5.30455	0.68864	0.492	near normal	near normal	-1.37	0.82	0.6	0.57
			1956	1	12	200.583	5.30123	0.68578	0.48391	near normal	near normal	0.15	0.01	0.67	0.56
			1956	2	1	200.417	5.3004	0.68506	0.48189	near normal	near normal	-0.28	-1.24	0.76	0.56

Fig 6: The calculations of SPI by MS Excel

RESULT AND ANALYSIS

SPI variation for Rangpur station:

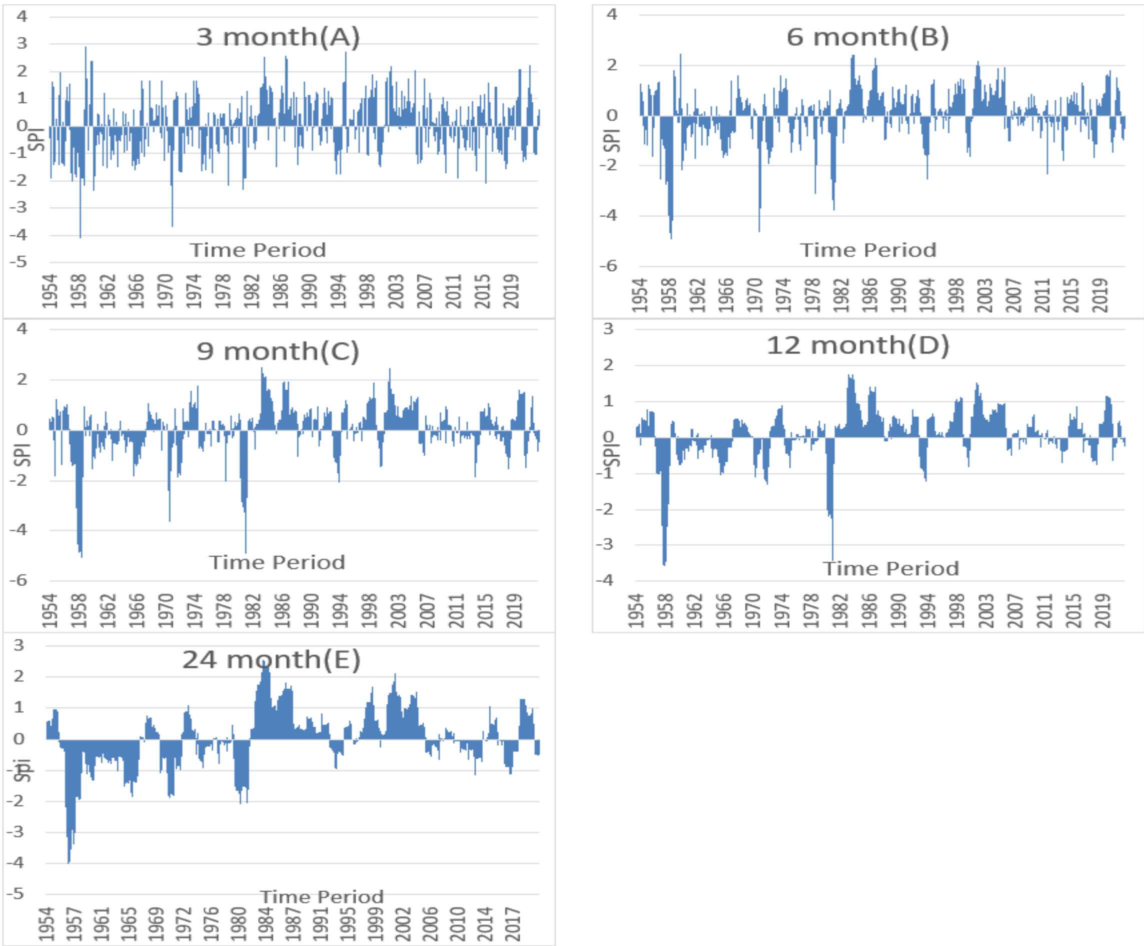


Fig 7: Variation of SPI (A, B, C, D, E) (calculated based on 3,6,9,12 and 24 months' time scale) for the whole period (1954-2023) at Rangpur Station.

SPI variation for Saidpur station:

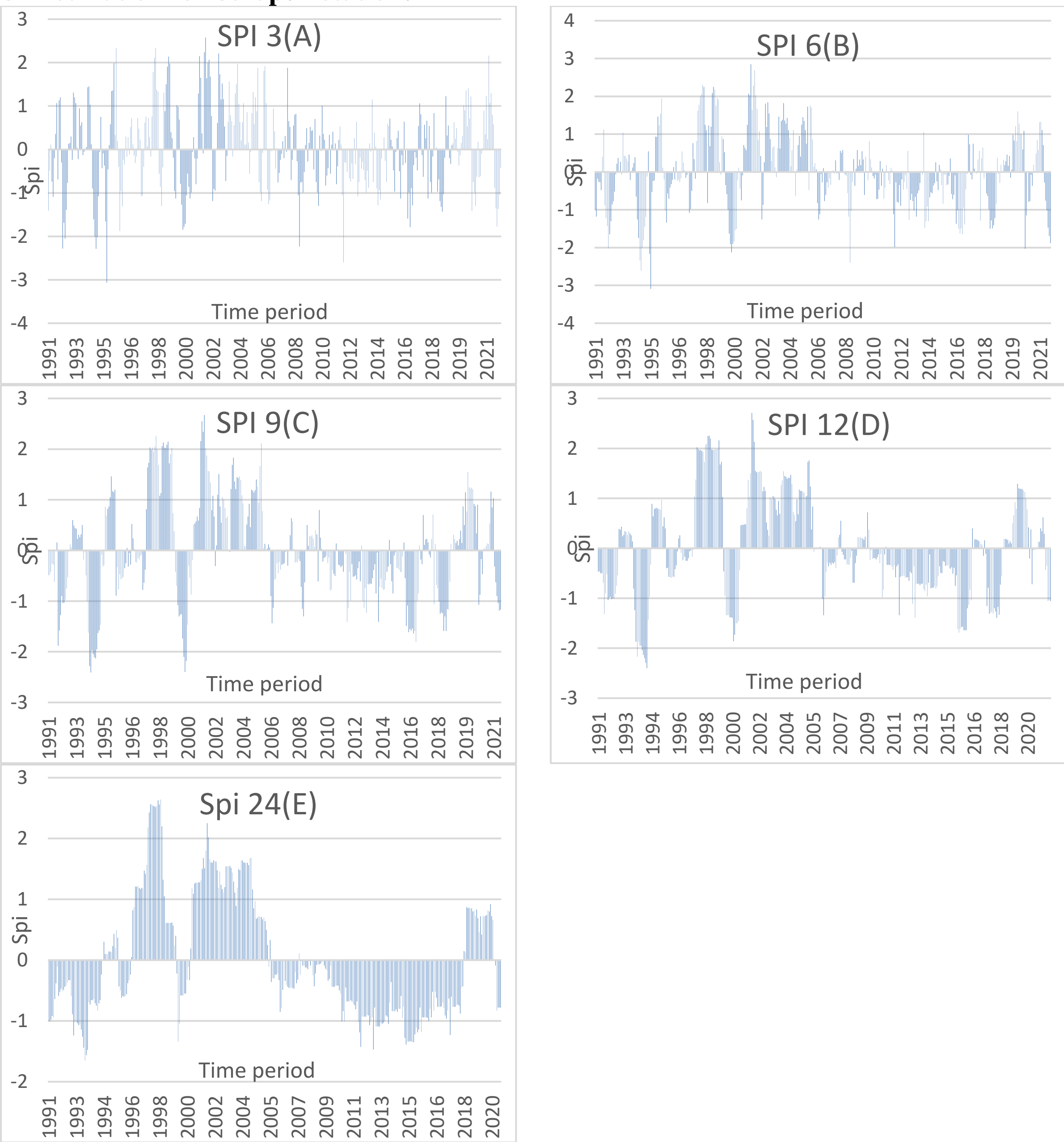


Fig 8: Variation of SPI (A,B,C,D,E)(calculated based on 3,6,9,12 and 24 months' time scale) for the whole period (1991-2023) at Saidpur Station

SPI variation for Bogra station:

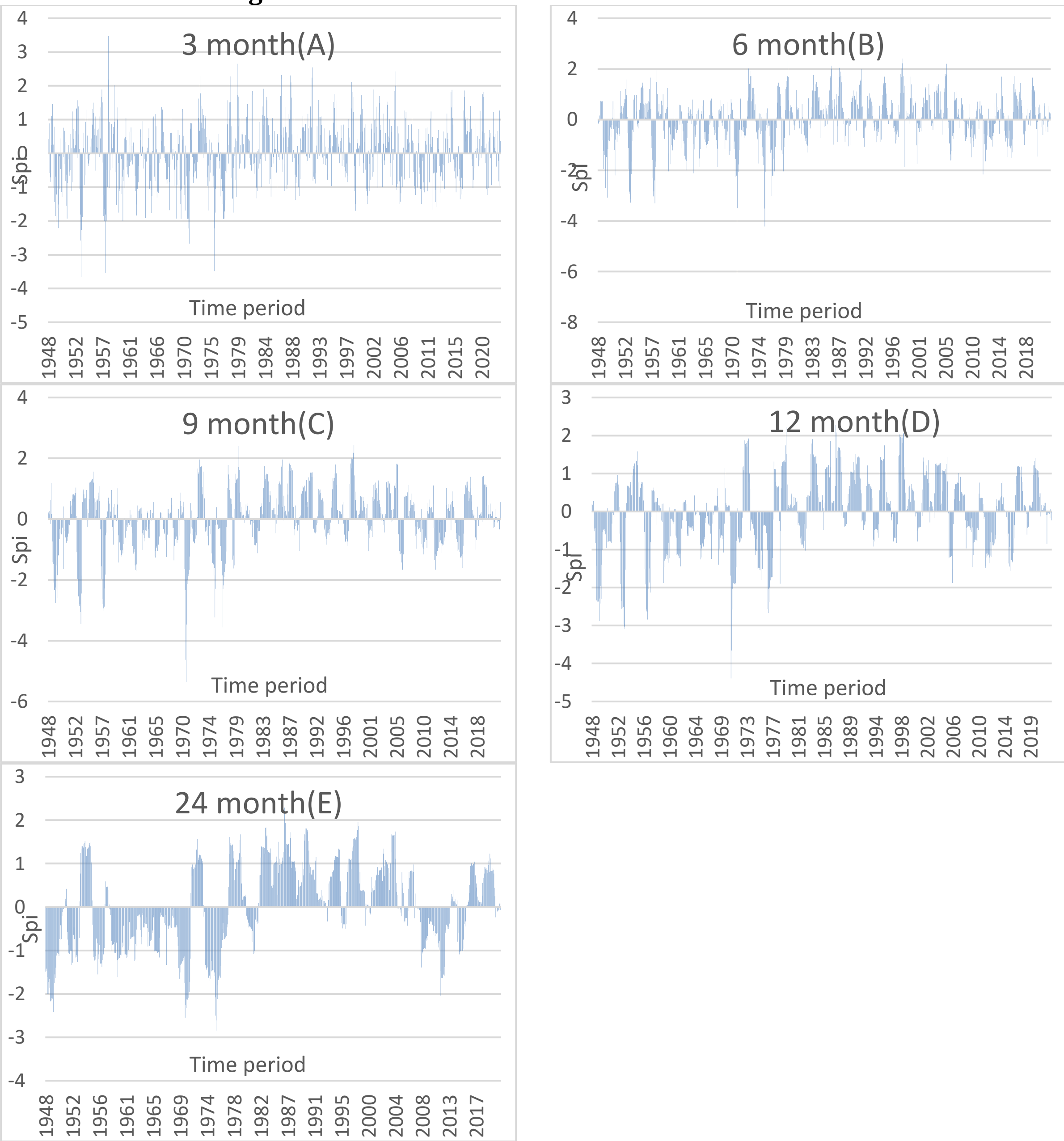


Fig 9: Variation of SPI(A,B,C,D,E) (calculated based on 3,6,9,12 and 24 months' time scale) for the whole period (1948-2023) at Bogra Station

SPI variation for Dimla station:

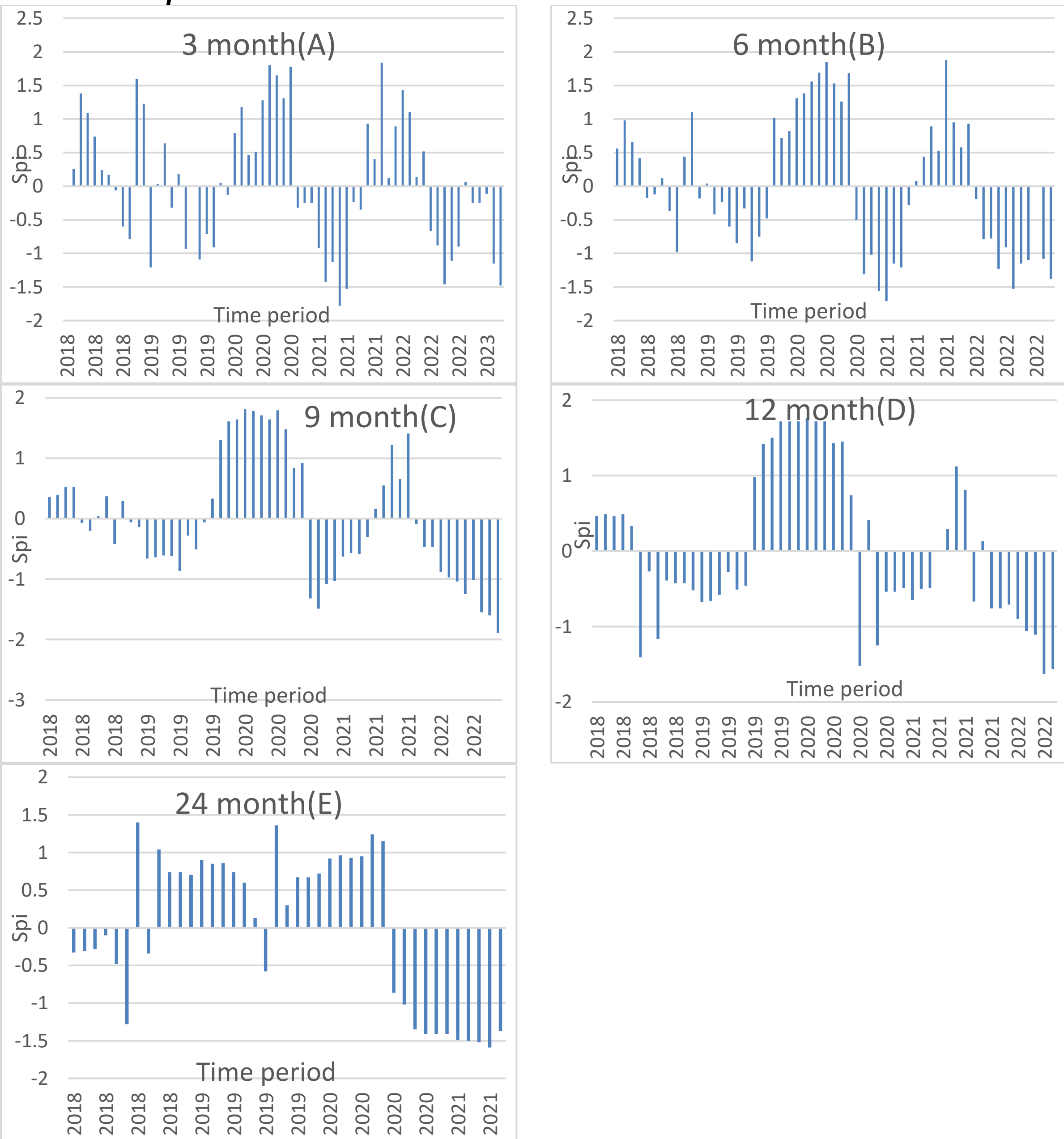


Fig 10: Variation of SPI (A,B,C,D,E) (calculated based on 3,6,9,12 and 24 months' time scale) for the whole period (2018-2023) at Dimla Station.

SPI variation for Tarash station:

Fig 11: Variation of SPI (A,B,C,D,E) (calculated based on 3,6,9,12 and 24 months' time scale) for the whole period (2018-2023) at Tarash Station

SPI variation for Rajarhat station:

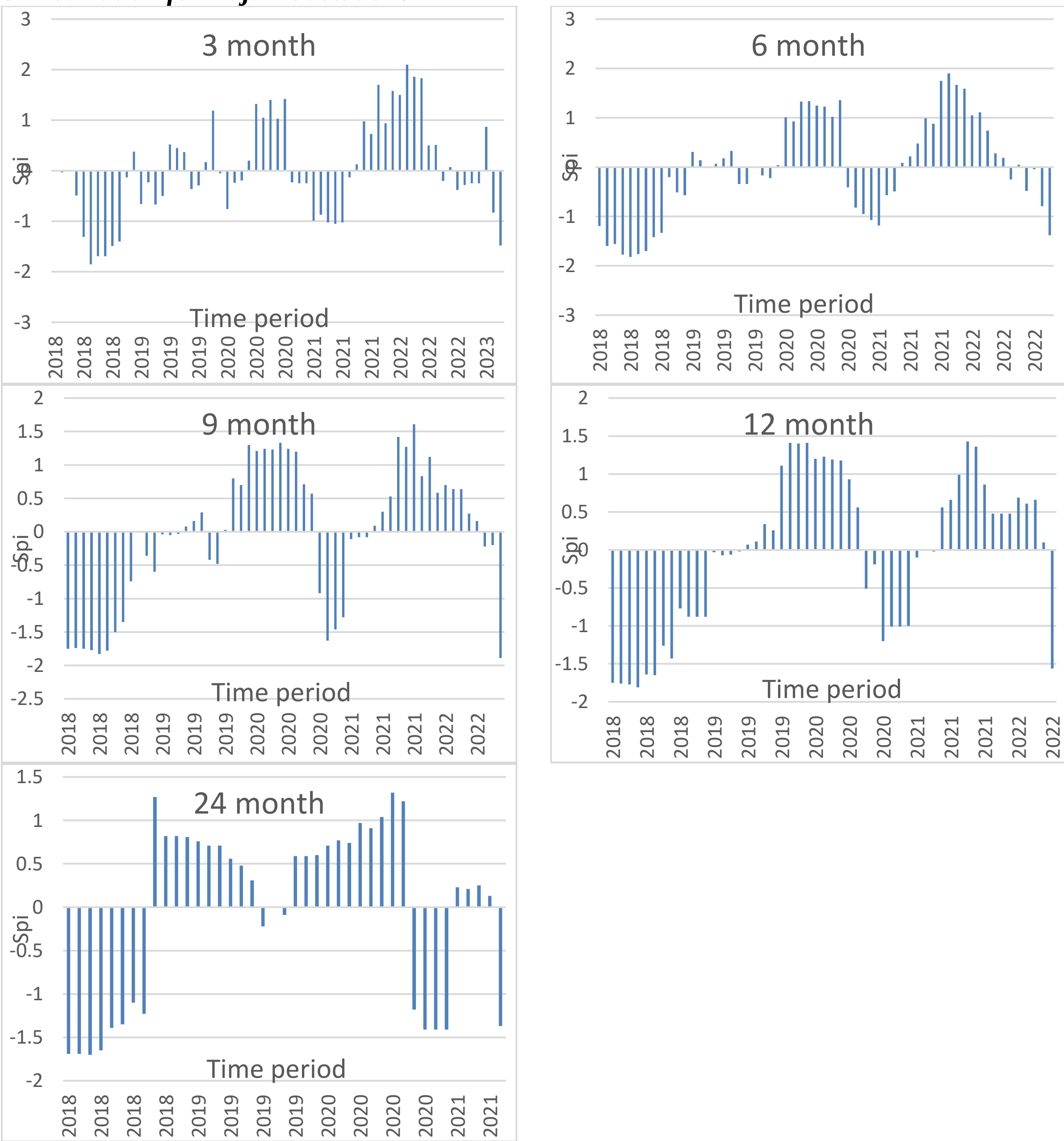


Fig 12: Variation of SPI (A, B, C, D, E) (calculated based on 3,6,9,12 and 24 months' time scale) for the whole period (2018-2023) at Rajarhat Station.

SPI variation for Dinajpur station:

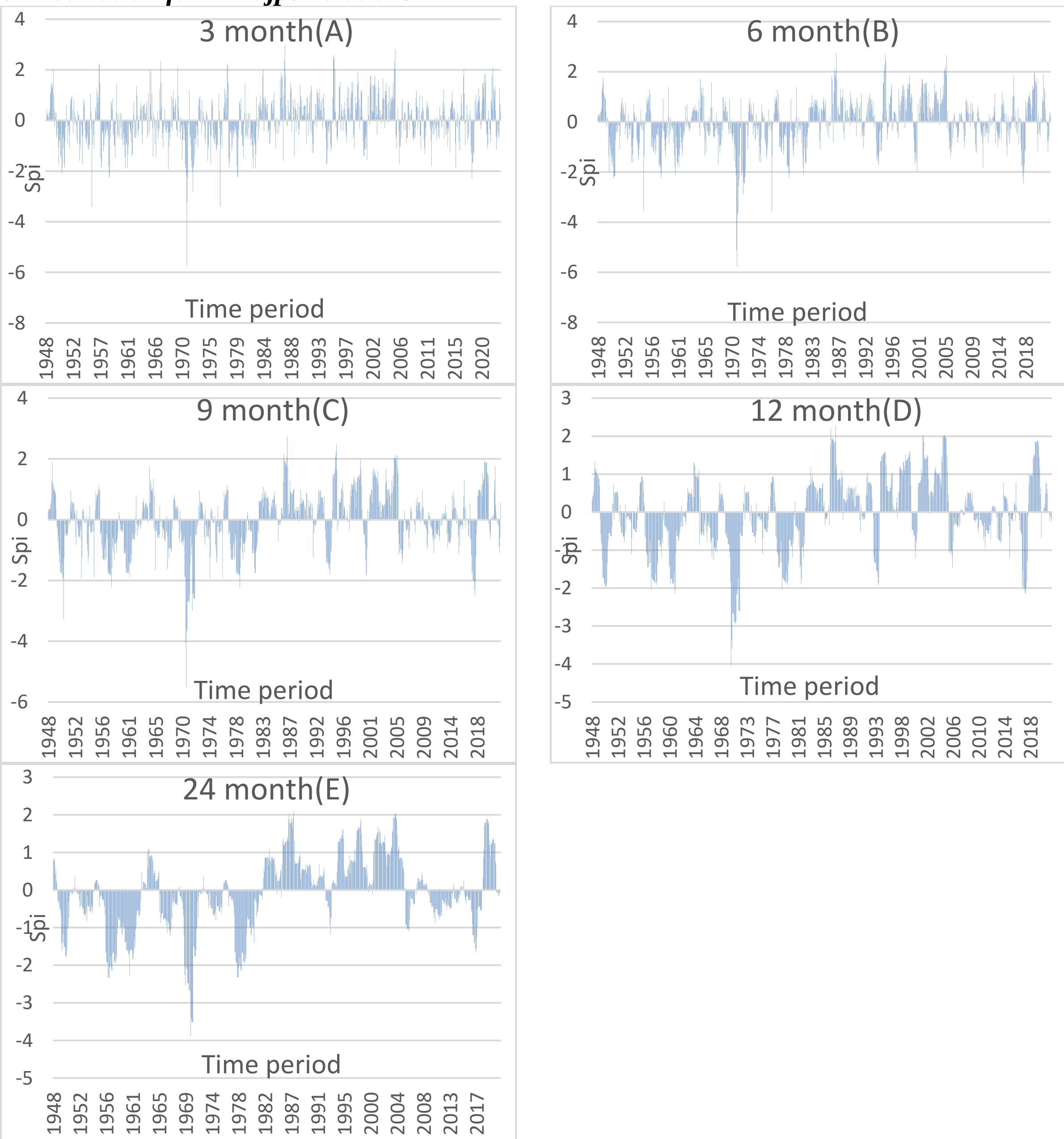


Fig 13: Variation of SPI (A,B,C,D,E) (calculated based on 3,6,9,12 and 24 months' time scale) for the whole period (1948-2023) at Dinajpur Station

SPI variation for Ishwardi station:

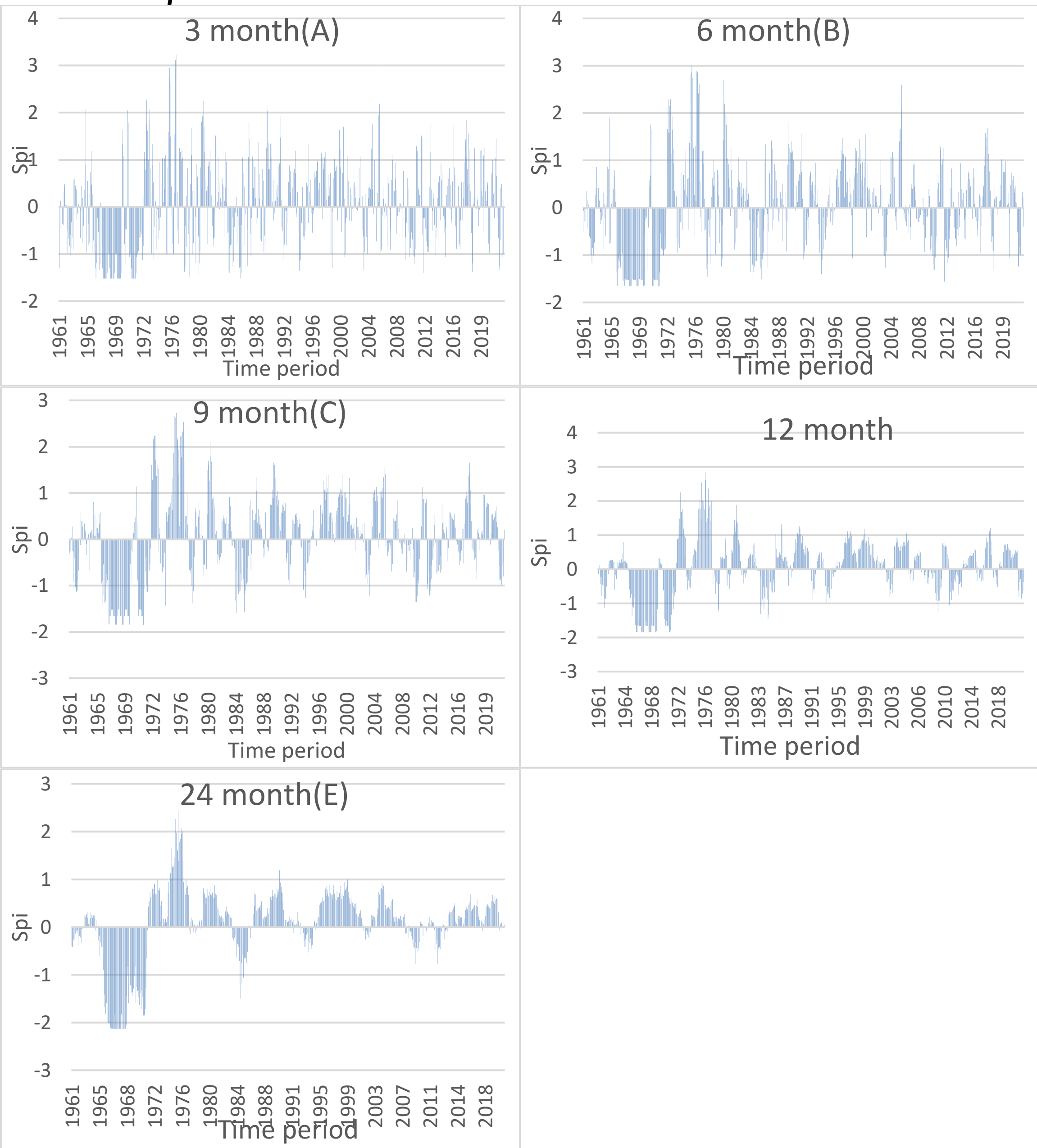


Fig 14: Variation of SPI (A, B, C, D, E) (calculated based on 3,6,9,12 and 24 months' time scale) for the whole period (1961-2023) at Ishwardi Station

SPI variation for Rajshahi station:

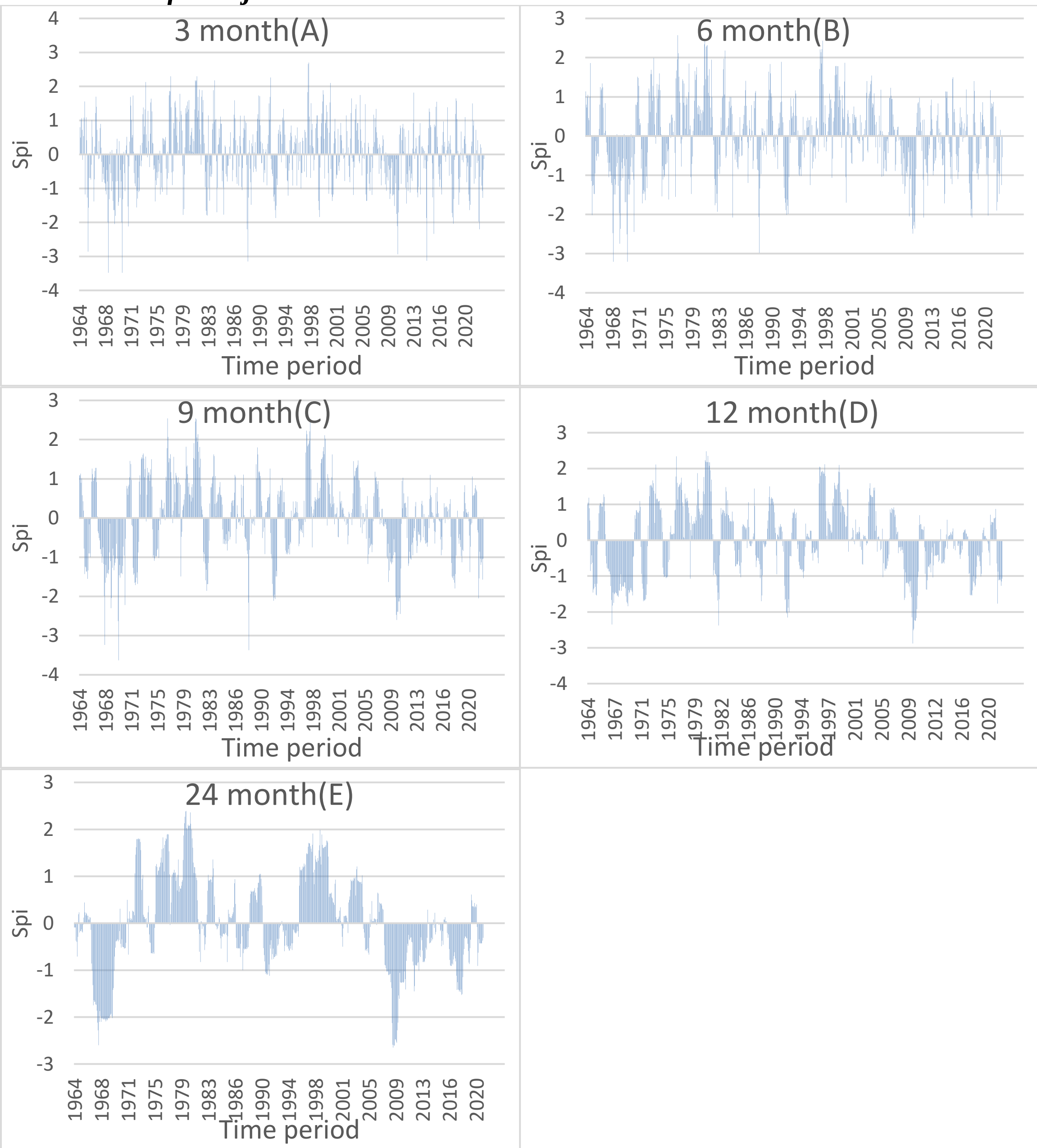
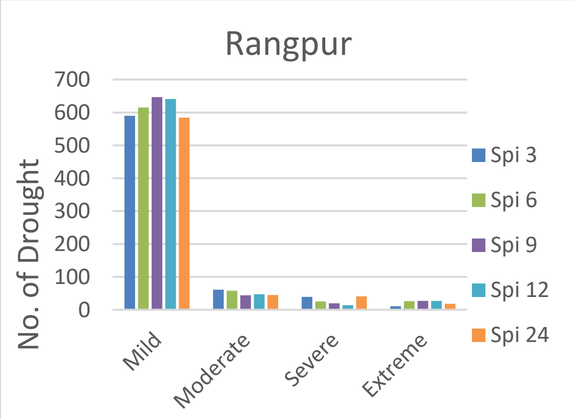
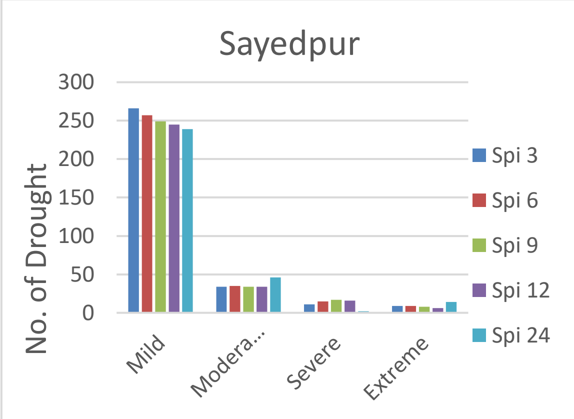
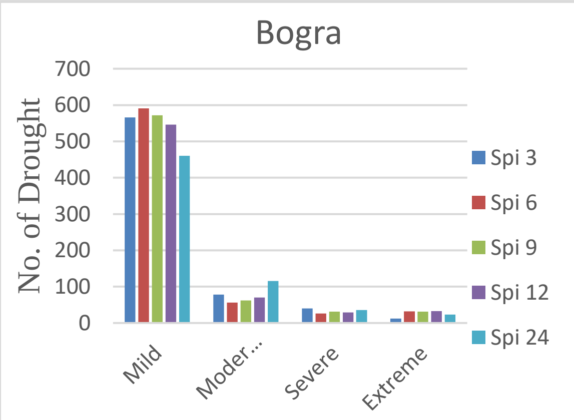


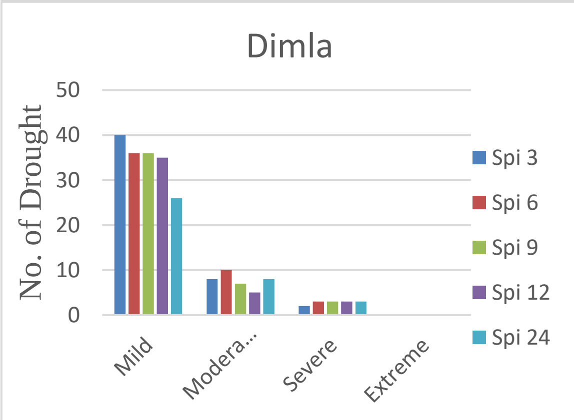
Fig 15: Variation of SPI(A,B,C,D,E) (calculated based on 3,6,9,12 and 24 months' time scale) for the whole period (1964-2023) at Rajshahi Station

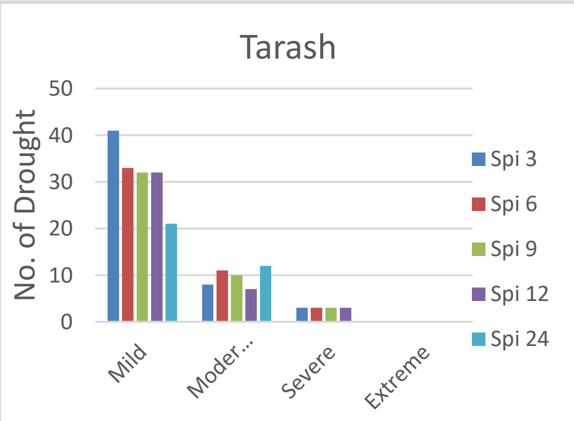
Variation of Drought number of each type at each stations:

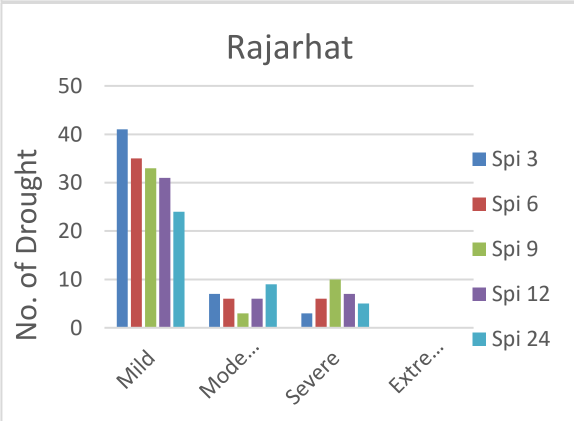


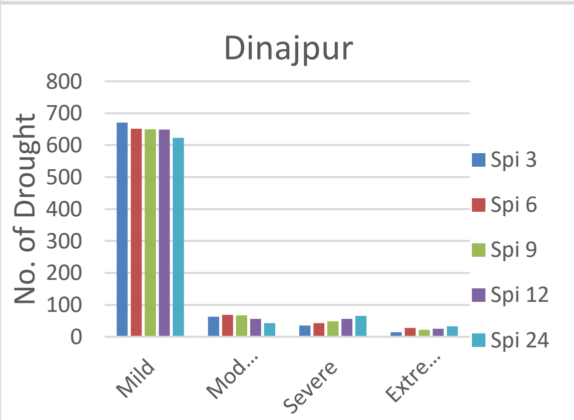


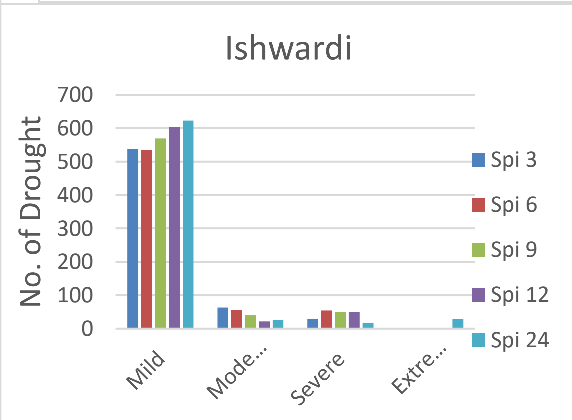












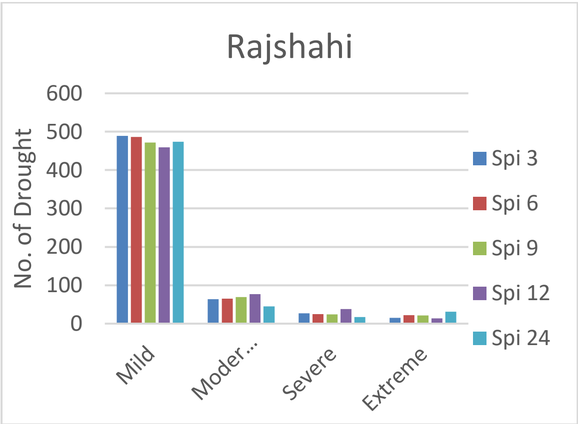


Fig 16: Variation of Drought number of each type at 9 stations (Rajshahi, Bogra, Ishwardi, Tarash, Rangpur, Dinajpur, Dimla, Rajarhat, Saidpur)

Fig 20 shows that mild and moderate droughts are most frequent, while extreme droughts are rare. Shorter time scales (3–6 months) have more drought events, whereas longer scales show fewer occurrences.

Drought Severity Assessment Using Standardized Precipitation Index (SPI):

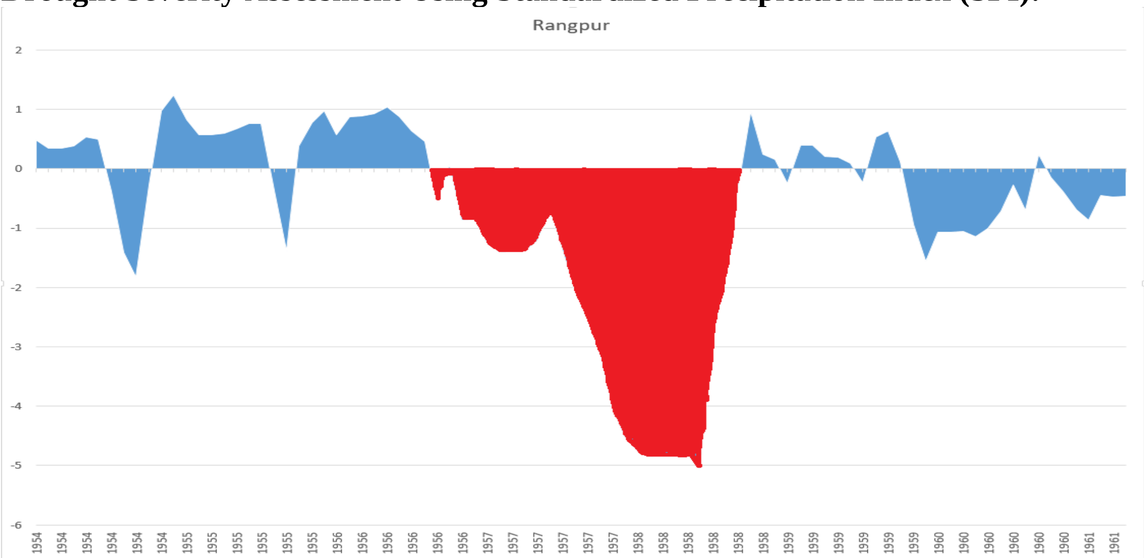


Fig 17: The most severe drought among all station.

Fig 21 indicates that the highest SPI (-5.07) at the 9-month time scale occurred in Rangpur, experiencing a very severe drought lasting 37 months from June 1956 to July 1959. This suggests that drought severity depends not only on the drought index values but also on duration.

SOCIOECONOMIC IMPACT ASSESSMENT

Agricultural Sector:

Droughts have a direct impact on crop yield through reduced water availability, leading to diminished agricultural productivity and varying effects on different crop types. Economic repercussions include lower farm income, affecting local economies and resulting in job losses across the farming sector and related industries. Food security issues arise due to crop failures, causing local food shortages and potentially impacting global food markets, which may lead to malnutrition in vulnerable areas. Socially, drought can drive migration from rural to urban areas as individuals seek alternative income sources. In response, governments can implement policies to support affected farmers and promote adaptive strategies to enhance resilience against future droughts. Long term, droughts pose environmental risks, jeopardizing ecosystem health and necessitating an understanding of their recurring patterns for effective risk management. Droughts significantly affect both the livestock and fisheries sectors through reduced water availability, leading to lower production and compromised animal health. The decline in output can result in economic losses for farmers and fishers, causing potential increases in market prices that may worsen food insecurity for consumers. Drought impacts rural livelihoods, prompting migration and heightened poverty as communities struggle with diminished protein sources. To adapt, strategies such as improved water management, diversification of income sources, and enhanced early warning systems can help mitigate these effects.

Water Resources:

Surface water availability is vital in assessing meteorological drought as it impacts water supply for industrial, agricultural, and human needs. Key factors include precipitation deficit, which reduces river and reservoir levels; monitoring of streamflow and river levels to understand water availability; reservoir storage management during dry periods; the interaction between surface water and groundwater affecting overall water availability; water quality concerns due to higher concentrations of contaminants; and the ecological impacts of reduced water levels on biodiversity and ecosystems. Overall, analyzing these aspects aids in managing water resources and formulating adaptation strategies during drought conditions. Groundwater depletion impacts multiple sectors significantly. In agriculture, irrigation-dependent farmers may face reduced yields, threatening food security and increasing poverty levels. Rural communities rely on groundwater for drinking, and its depletion can lead to shortages, affecting health and potentially prompting migration due to limited resources. Economically, jobs in agriculture may decline, and industries relying on groundwater may incur higher costs. Environmentally, ecosystems may suffer from biodiversity loss and land subsidence due to excessive pumping. Policy responses may include regulations to manage water use, with government interventions needed to support affected communities. Climate change necessitates adaptation strategies in agriculture and water management, alongside efforts to reduce water demand. Strengthening community understanding of sustainable practices can enhance resilience to drought. Overall, a comprehensive approach involving community engagement, sustainable management, and policy initiatives is crucial for addressing the socioeconomic effects of groundwater depletion.

Socioeconomic Effects of Bangladesh:

In Bangladesh, meteorological droughts pose significant socioeconomic challenges. The agriculture sector suffers from crop failures due to insufficient rainfall, leading to food shortages and increased prices. Livestock also face health issues from water scarcity. Reduced agricultural output affects food security, necessitating more imports and pushing up costs, which disproportionately impacts vulnerable populations. Water resources dwindle, affecting industrial, drinking, and farming needs, while economic impacts include a direct negative influence on GDP and livelihood losses for farming communities. Additionally, drought can exacerbate malnutrition among at-risk groups and prompt migration to urban areas, straining city infrastructure. The government needs to implement relief measures, such as financial and food assistance for those affected by droughts in Bangladesh. Long-term adaptation strategies are also crucial, including improved water management, promoting drought-resistant crops, and investing in alternative water sources. These efforts are vital to mitigate the impact of climate-induced droughts on agriculture, food security, energy, and the economy, while supporting vulnerable populations and managing resources effectively.

ADAPTION AND MITIGATION STRATEGIES FOR DROUGHT

Drought Monitoring and Early Warning System:

Early warning and monitoring systems for droughts aim to assess and mitigate the impacts on sectors like agriculture and water resources. These systems employ data collection from various sources, including sensors and satellite imaging, to monitor key parameters like temperature and soil moisture. Advanced analytics and models interpret this data to forecast drought trends and develop drought indices for standardized severity reporting. An effective early warning system includes an alert mechanism to signal drought conditions, facilitating timely action from stakeholders such as farmers and government agencies. The systems also incorporate technological advancements like big data and machine learning to enhance monitoring accuracy. Ultimately, these systems enable informed decision-making to alleviate the adverse effects of drought on communities.

Promotion of Drought Tolerant Crops and Agriculture Practice:

Drought-resistant plants employ strategies such as stomatal closure, limited growth, and enhanced root systems to cope with drought. To mitigate drought effects, conserving water is essential for maintaining availability for humans and wildlife. Certain crops known for their drought resistance include beans, broccoli, chard, corn, cowpeas, cucumber, eggplant, and various grains.

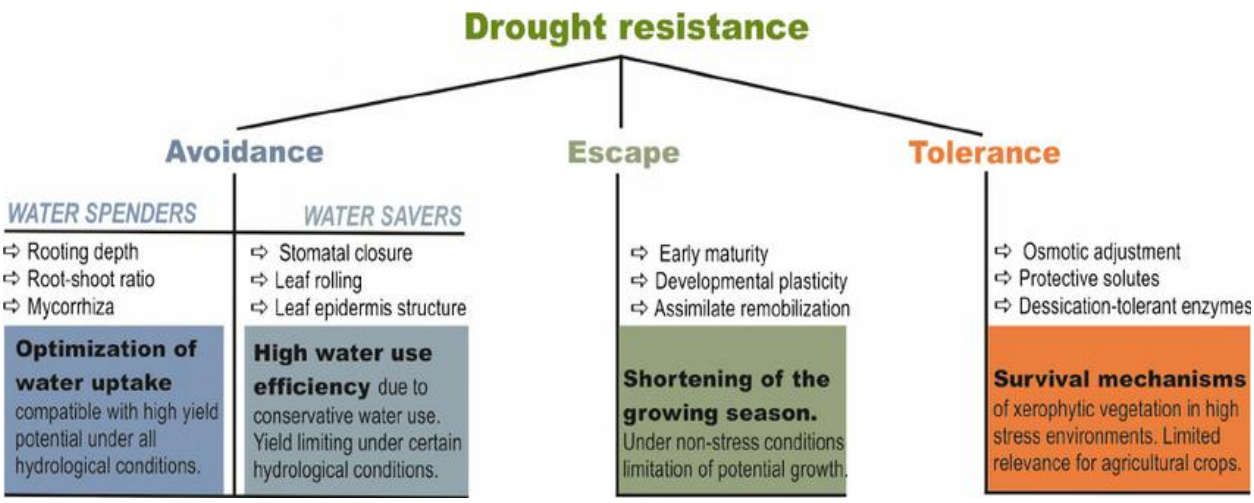


Figure 18: Drought Resistance According to Levitt (1980)

Land Management and Mitigation:

Drought significantly hampers agriculture and access to food and water, contributing to global food and water insecurity. Severe drought can displace communities, complicating efforts to eliminate hunger and malnutrition by 2030. To counteract drought impacts, effective land management practices are essential, promoting proactive drought risk management and enhancing ecosystem resilience. A deeper understanding of how land management connects to drought mitigation is crucial for better policy and action targeting. Human land-use decisions play a vital role in water scarcity and drought severity, illustrating the intricate relationship between human activity, drought, and climate change.

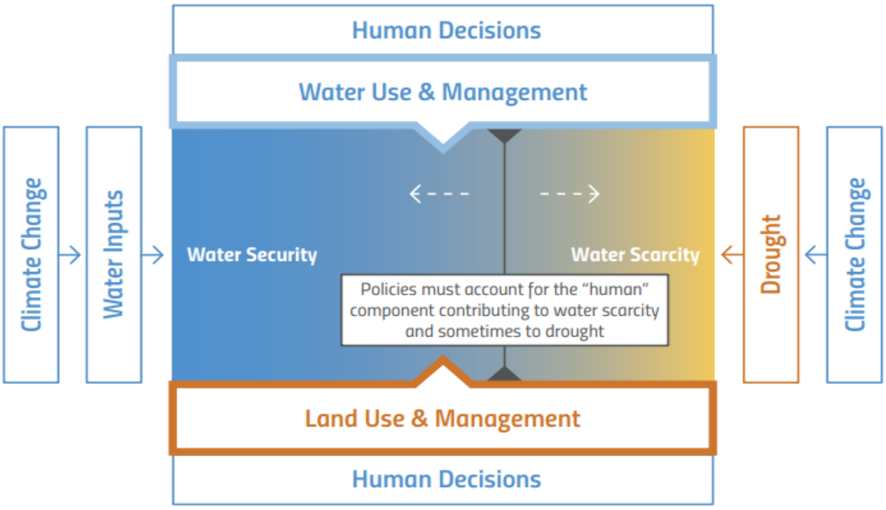


Figure 19: Human decisions impacting land, water and drought

Strengthening Social Safety Nets and Livelihood Support:
To enhance drought resilience, it's vital to emphasize community-based activities that strengthen social safety nets and support livelihoods. This includes improving water access, promoting sustainable farming, and educating locals about drought-resistant crops. Strong safety nets and diverse income sources can make communities more resilient to drought's impacts, protecting families from natural disasters and economic shocks. In developing countries, particularly in Bangladesh, social safety net programs play a crucial role in providing income support and reducing poverty, thereby helping to diminish child labor and enhance social protection by utilizing significant national budget resources.

CONCLUSION AND RECOMMENDATIONS

Summary of Findings and Key Insights and Goals:
The SPI (Standardized Precipitation Index) quantifies drought across various time scales, indicating wetter conditions with positive values and drier ones with negative values. It is essential in assessing meteorological droughts, with negative SPI numbers marking the presence and severity of drought. By analyzing different time frames, SPI helps identify both temporary and permanent dryness patterns, informing impacts on ecosystems, water supplies, and agriculture. Drought severity is classified into four levels: mild, moderate, severe, and extreme, guiding response efforts. The goals for drought management include reducing exposure and vulnerability, enhancing resilience, transforming systems, and implementing effective preparation and recovery strategies while sharing drought risks across communities.

Limitations of the Study:
The Standardized Precipitation Index (SPI) has several limitations in assessing drought conditions. It relies solely on precipitation data, neglecting factors like temperature, humidity, and soil moisture, which can provide an incomplete picture of drought. SPI may not fully capture geographic variations in drought severity and is affected by the timeline chosen for analysis; different timeframes can lead to varying results. Additionally, it

presumes constant statistical characteristics of precipitation, which may not hold true due to climate change. While SPI focuses on current precipitation, understanding drought onset and persistence requires knowledge of prior soil moisture and hydrological conditions. The subjective selection of threshold values for classifying drought levels can lead to inconsistent assessments. The quality of precipitation data also impacts SPI's reliability, and it may be less effective in areas with diverse climates. Furthermore, SPI does not consider socioeconomic factors, which are essential for a comprehensive understanding of drought impacts. Although useful for historical analysis, SPI's predictive capabilities are limited. Recognizing these limitations can enhance drought studies and management approaches by encouraging the use of additional methodologies and data sources.

Future Directions for Research and Action:
To enhance the Standardized Precipitation Index (SPI) methodology, researchers should consider regional drought variations, non-stationarity in precipitation, and climate change impacts. Integrating SPI with other weather indices can provide a broader drought analysis, while expanding seasonal studies may improve understanding of drought patterns relevant to agriculture. Developing short-term prediction models based on SPI can aid in early response strategies. Additionally, linking SPI findings with assessments from various sectors will give a more holistic view of drought impacts. Investigating climate change's role in drought frequency and severity, along with incorporating remote sensing data for improved monitoring, is essential. Collaborative efforts among researchers and policymakers are crucial for addressing drought-related challenges effectively.

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Conflict of Interest

The author(s) declared no conflict of interest.

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Table 3: Monthly rainfall data for Rangpur station [23]

Station: Rangpur												
Monthly Rainfall in mm.												
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Spt.**	**Oct.**	**Nov.**	**Dec.**
1954	20	0	0	0	275	944	602	211	101	90	0	0
1955	20	3	8	55	124	566	892	562	160	19	5	0
1956	12	1	5	12	278	769	488	501	149	424	11	0
1957	0	0	0	0	111	439	352	249	38	10	0	0
1958	2	0	0	55	171	0	0	0	0	0	0	0
1959	29	0	257	102	366	583	0	275	90	586	0	103
1960	0	0	56	6	252	0	471	0	488	91	3	0
1961	0	28	10	57	279	440	265	141	150	341	1	5
1962	9	4	7	4	409	464	210	572	137	66	0	0
1963	0	0	66	75	187	399	566	0	304	72	5	0
1964	4	7	6	68	269	554	477	140	177	200	0	0
1965	0	4	38	63	362	249	277	553	133	12	17	0
1966	11	0	1	12	272	126	302	324	109	48	25	1
1967	1	0	140	152	73	248	474	153	333	149	0	0
1968	2	10	140	200	155	555	653	214	352	150	1	1
1969	19	1	55	88	295	407	636	420	309	45	38	0
1970	29	6	5	39	162	527	503	440	242	39	5	0
1971	12	2	0	0	0	121	298	438	403	250	49	0
1972	0	42	53	31	100	239	325	0	201	118	1	0
1973	8	7	8	23	392	744	192	94	531	222	12	4
1974	12	9	8	35	458	855	274	111	685	254	44	10
1975	2	6	3	146	445	116	468	0	290	123	0	0
1976	0	0	1	116	203	427	500	436	157	54	1	0
1977	0	0	0	140	320	550	384	334	101	155	0	12
1978	0	0	8	150	289	394	530	196	511	60	7	0
1979	1	15	4	36	0	291	677	510	202	132	0	0
1980	3	14	22	38	354	426	276	579	340	68	0	0
1981	20	10	13	137	432	0	0	0	0	0	0	47
1982	0	7	5	100	99	649	473	347	455	64	1	1
1983	6	0	46	0	272	329	636	339	258	281	0	28
1984	28	4	17	116	545	989	812	376	684	172	0	5
1985	0	33	44	237	352	569	770	331	398	127	0	21
1986	0	0	2	106	265	383	452	283	518	196	27	32
1987	0	20	84	57	155	485	1314	557	353	216	6	0
1988	0	33	37	165	285	369	451	633	496	19	35	1
1989	7	18	2	0	335	219	719	110	414	48	4	2
1990	1	57	82	134	354	393	306	396	439	325	0	0
1991	38	1	1	41	302	593	162	264	726	106	2	27
1992	13	10	0	89	245	348	248	367	552	129	4	2
1993	49	0	30	62	190	633	499	572	358	91	26	0
1994	16	29	28	49	212	427	202	97	135	106	0	0
1995	3	3	4	1	158	369	568	388	804	51	109	3
1996	13	0	0	39	232	396	479	353	333	159	0	0
1997	19	14	3	113	230	276	523	338	410	16	2	27
1998	0	12	50	173	202	333	473	458	255	409	0	0
1999	0	0	7	228	336	447	436	829	337	303	8	0
2000	1	15	3	283	416	438	166	232	172	19	0	0

Station: Rangpur												
Monthly Rainfall in mm.												
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Spt.**	**Oct.**	**Nov.**	**Dec.**
2001	0	1	23	38	235	481	341	346	550	470	7	0
2002	8	6	38	376	290	913	582	287	521	99	7	0
2003	8	23	109	143	160	573	633	183	206	340	0	24
2004	9	0	39	196	347	352	653	133	464	484	0	3
2005	11	9	61	93	271	428	671	400	328	581	0	0
2006	0	1	2	85	367	472	271	96	235	120	8	25
2007	0	47	16	39	233	568	558	149	277	138	12	0
2008	36	1	49	74	273	444	232	396	227	175	0	0
2009	0	0	9	158	270	336	304	832	77	231	0	0
2010	0	0	0	169	237	650	346	240	332	122	4	2
2011	0	20	13	28	261	306	389	542	366	6	1	0
2012	7	2	2	191	212	369	445	187	405	57	0	0
2013	0	14	4	115	383	327	296	268	229	280	0	0
2014	0	26	1	15	214	255	110	362	599	53	0	0
2015	25	24	15	123	298	524	234	687	484	3	0	0
2016	12	0	123	49	313	390	749	118	285	120	0	6
2017	3	0	120	172	358	97	344	547	105	146	0	0
2018	0	0	13	151	365	347	169	213	144	33	0	7
2019	0	28	2	141	347	288	594	223	517	149	0	0
2020	7	2	32	194	347	390	803	181	1035	119	0	0
2021	0	0	4	27	292	201	194	424	193	384	0	5
2022	8	82	0	178	276	585	246	309	164	73	0	0
2023	0	0	51	45	388							