

Research

Analysis of the onset, withdrawal, and variability of monsoon rainfall in the face of climate change

Md. Shariot-Ullah¹  · Salma Akhter¹ · Tapos Kumar Acharjee¹ · Md. Moudud Hasan²

Received: 7 October 2023 / Accepted: 4 April 2024

Published online: 09 April 2024

© The Author(s) 2024 [OPEN](#)

Abstract

Climate change is affecting the precipitation system in Bangladesh, particularly in the northwestern hydrological zone. This study analyzed the monsoon rainfall variability from 1991 to 2015, revealing a shifting pattern and past trends. This study used the Mann–Kendall test and Sen’s slope (MAKESENS) statistical model to evaluate the annual total rainfall and monsoon rainfall. Approximately 71–78% of the total rainfall occurred during the monsoon season at all stations, with Rangpur being the rainiest and Rajshahi being the driest. The annual rainfall trend decreased, with highly variable arrival and withdrawal days. The monsoon arrived early by 2 to 39 days and late by 1 to 72 days from the reference day. The withdrawal of monsoon rainfall occurred 1 to 38 days early and 1 to 39 days late. These findings can be used to plan and manage agricultural practices at the local level in northwestern Bangladesh.

Keywords Climate change · Rainfall variability · Monsoon · Arrival dates · Withdrawal dates

1 Introduction

The study of spatiotemporal variations in precipitation has received considerable attention in recent years due to its significance in natural systems and human society [1–7]. Based on daily precipitation data, numerous studies have revealed a considerable increase in extreme rainfall events and annual maximums globally [7–9]. Bangladesh belongs to the Asian monsoon regime, defined by a seasonal reversal of surface winds and a distinct seasonality of precipitation (dry and wet) [10, 11]. Geographical location supplies the nation with abundant monsoons and yearly rainfall [12]. This country has a tropical monsoon climate with seasonal variations in precipitation and temperature [13]. The rainy season includes (1) the premonsoon summer from March to May, (2) the monsoon season from June to September, and (3) the postmonsoon autumn season from October to November [14, 15]. Rainfall in Bangladesh is mostly caused by tropical monsoon depressions in the Bay of Bengal [16]. During monsoons, the southwesterly surface wind carries a large amount of moisture from the Bay of Bengal and the Arabian Sea that causes approximately 65–70% of its yearly precipitation [17–20].

Despite its small size, Bangladesh has significant interregional climate variance. The central and northwestern parts of the country are relatively dry. In contrast, the eastern and northeastern regions are characterized by high temperatures, low humidity, and minor seasonal fluctuations in rainfall [21, 22]. Past evidence in the northwestern region revealed that unpredictable rainfall-induced droughts and floods threaten agriculture, ecosystems, and the broader economy [18, 23–26].

✉ Md. Shariot-Ullah, msu_iwm@bau.edu.bd | ¹Department of Irrigation and Water Management, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh. ²Department of Agricultural and Industrial Engineering, Hajee Mohammad Danesh Science and Technology University, Dinajpur 5200, Bangladesh.



Bangladesh, the world's largest delta, is highly vulnerable to climate, weather-related, and geophysical hazards due to its topography and geographical location. The Barind tract in the northwest contributes to the persistence of natural hazards, including drought, hydrometeorological hazards, and geophysical hazards, with frequent droughts on the northern and northeastern sides [27]. Over the last three decades, the northwestern area of Bangladesh has seen severe droughts, irregular rainfall patterns, and temperature rises during monsoon season [28]. According to a study, the Northwest region of Bangladesh is expected to have severe to intense droughts in 2023–2026, 2028, and 2031, with certain areas experiencing very bad droughts [28, 29]. Northwestern Bangladesh experiences a low rainfall pattern, with an average annual rainfall of 1898 mm in the northwestern region compared to 2428 mm in the entire country. This drought-prone area experiences significant crop productivity reduction due to low and variable rainfall patterns. Droughts have previously affected land and population, with the consequences of these droughts not yet fully understood. For instance, in 1978–1979, droughts damaged 42% of farmed land and reduced rice production by nearly two million tons. In northwest Bangladesh, droughts have an influence on food security and water supplies. As a result, in-depth research is needed to comprehend decreased seasonal rainfall and create mitigation strategies to manage droughts [30]. An analysis investigates climatological data on rainfall frequency in Rajshahi, Rangpur, and Dinajpur from 1981 to 2016. The results indicate a decline in annual rainfall, a rise in the number of dry days, and worsening drought conditions in northwest Bangladesh. Since 2000, there has been a rise in the number of dry days throughout certain seasons. Additionally, there has been a notable increase in heat stress trends in Rajshahi and Rangpur, whereas Dinajpur has seen a decrease in these trends [31].

The production of crops is highly dependent on the availability of water in the proper amount and timing. Precipitation and temperature have a significant impact on crop water needs and yield. In contrast, the increased likelihood of flooding owing to increasing rainfall extremes in the latter months of the monsoon might raise the danger of crop damage from flooding [23]. However, as agriculture expanded and the population increased, the proportion of groundwater used for agriculture and household water supply increased from 41 to 75%, while due to the lack of availability of surface water, usage decreased from 59 to 25% from 1982–1983 to 2001–2002 [32–34]. Inadequate water during the main crop-growing season reduces the food production of impoverished subsistence farmers who cannot afford irrigation. If farmers fail to adapt to the erratic nature of precipitation, the danger of production loss rises. Consequently, fluctuations in precipitation have direct implications for food production and profits [35, 36]. The monsoon's starting and cessation dates impact the timing of land preparation, planting, and harvesting for two separate rice seasons (Aus and Aman). A reduction in early monsoon rainfall might render crops reliant on irrigation. To correctly plan and manage agricultural activities, it is necessary to examine the fluctuation in the arrival and cessation of monsoons.

Several previous studies on the characteristics, inter-seasonal and inter-annual variations, length, propagation speed and direction, flood risk, and spatiotemporal variability of monsoon rainfall systems have been conducted, but they are not sufficient enough to comprehend the problem in the study area [37–40]. Furthermore, there is a lack of research on the onset and withdrawal of monsoon rainfall, and the shifting of rainfall over the period has not been done in the case study area. The study of monsoon rainfall variability in Bangladesh's northwest region is crucial for agricultural water management. It helps classify and reveal specific features of the precipitation system during monsoon and pre-monsoon seasons, aiding in the planning and management of local agricultural activities. The specific objectives of the study are:

- 1) to analyze the past trend of monsoon rainfall,
- 2) to observe the arrival and withdrawal pattern of monsoon rainfall, and
- 3) to assess the shifting of monsoon rainfall.

The paper is structured as follows: Sect. 2 contains detailed descriptions of the case study area, rainfall and wind-speed data collected by the Bangladesh Meteorological Department (BMD) for the selected stations, analysis of the past trend of monsoon rainfall, criteria for determining the arrival and withdrawal dates, and the shifting of monsoon rainfall. The results and discussion are presented in Sect. 3. Furthermore, Sects. 4 and 5 present conclusions and recommendations, respectively. An acknowledgement section has been included at the end of the conclusions and recommendations sections.

2 Materials and methods

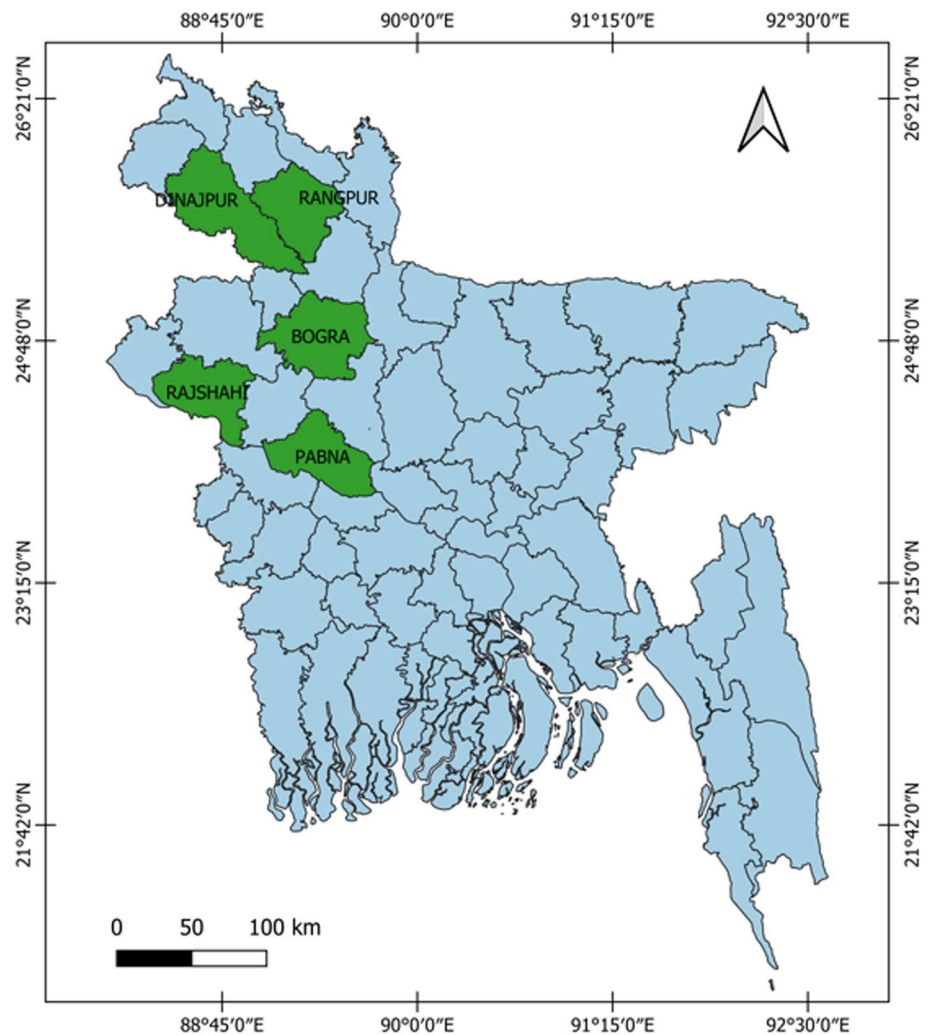
2.1 Study area

The northwestern region of Bangladesh (between 23°47'45"N and 25°46'34"N latitude and 88°00'37"E and 89°49'11"E longitude) is one of its largest hydrological zones (34,515 km², 3.5% of total area) and is characterized by two landforms—the Barind Tract and dissected and undulating flood plains. The Barind Tract features a unique physiographic unit with extensive terraced highlands encompassing 8720 km² between the lowland floodplains of two major rivers, locally known as the Padma and Jamuna Rivers (the main channel of the lower Brahmaputra) [41]. The Rajshahi and Rangpur administrative divisions govern 16 districts. The study area, comprising Bogura, Rangpur, Dinajpur, Pabna, and Rajshahi districts (Fig. 1), features dry humid and highly variable low yearly rainfall (1927 mm). The monthly average temperature is very high compared to the rest of Bangladesh. The summer temperatures range from approximately 25 to 35 degrees Celsius, while winter temperatures range from approximately 9 to 15 degrees Celsius [42]. The average reference crop evapotranspiration (ET_o) is also relatively high (1309 mm) [43].

2.2 Data collection and analysis

Daily rainfall and wind speed data of the past 25 years (1991–2015) for the Bogura, Rangpur, Dinajpur, Rajshahi, and Pabna meteorological stations were collected from the Bangladesh Meteorological Department (BMD).

Fig. 1 The Northwestern Hydrological Zone of Bangladesh



2.2.1 Criteria for the determination of arrival and withdrawal dates of monsoon rainfall

Monsoons are traditionally defined as seasonally reversing winds accompanied by corresponding changes in precipitation, but they are now used to describe seasonal changes in atmospheric circulation and precipitation associated with the asymmetric heating of land and sea [44]. Usually, the term monsoon is used to refer to the rainy phase of a season-changing pattern, although technically there is also a dry phase [14, 45, 46]. Any rainfall of 5 mm or more for successive three-day periods along with south-easterly or southerly wind direction is considered monsoon rainfall [47]. The BMD fixed 1 June as the monsoon arrival date and 30 September as the withdrawal date for the region [18]. However, it is not feasible to set the exact date of monsoon arrival and withdrawal date [48]. Some criteria were provided by Ahmed and Karmakar [47] to identify the arrival and withdrawal dates of monsoons in Bangladesh. Two variables, rainfall amount and wind vector, are considered to observe the arrival and withdrawal date of the monsoon. Due to data unavailability, only the first criteria and literature regarding monsoon rainfall were taken into consideration to adopt the reference day (first day of May) for the observation of arrival and withdrawal days. The mean daily temperature and relative humidity can also be used as additional criteria during the early stages of the analysis, but as they did not provide any additional information, they were not used in the determination of the arrival and withdrawal date of the summer monsoon.

The criteria for the determination of the arrival date of monsoon rainfall as reported by Ahmed and Karmakar [47] are as follows:

- i. The first day of three or more consecutive days having at least 5 mm of rainfall, and
- ii. The southerly or southeasterly winds for the rest of the season.

These investigators mentioned that the withdrawal of the monsoon starts in the reverse direction to the arrival. Moreover, the detection of the withdrawal date is more complex than the arrival date in Bangladesh. However, the following criteria were provided to identify the withdrawal date of monsoon rainfall:

- i. The last day of three or more consecutive days having at least 5 mm rainfall, and
- ii. The northwesterly or northerly wind for the rest of the time.

2.2.2 Calculation of the shifting of monsoon rainfall

The shifts in the arrival and withdrawal days of the monsoon rainfall were calculated for the five stations by taking 1 May as the reference day, and then the 25-year (1991–2015) average was computed for each of the five stations.

2.2.3 Trend analysis

The MAKESENS program was used to analyze the trend and magnitude of annual total and monsoon rainfall based on the nonparametric Mann–Kendall test and the nonparametric Sen's method. In this work, the MAKESENS model of the Mann–Kendall test and Sen's slope estimate for the trend of the time series of yearly data were employed. The nonparametric Mann–Kendall test is used to determine if a monotonic increasing or decreasing trend exists. Sen's approach is a nonparametric method for determining the slope of a linear trend. Z-statistics, a deterministic indicator of the trend, is a statistic that is determined using the Mann–Kendall test. The slope of the trend lines indicates whether the trend is rising or declining. The slope also influences the amplitude of the trend [49–52].

3 Results and discussion

3.1 Past trend of the annual total rainfall and monsoon rainfall

Table 1 shows trend statistics for annual total rainfall and monsoon rainfall derived from the Mann–Kendall trend test and Sen's method. The negative trends indicate a decreasing trend. During the 1991–2015 period, annual total and monsoon rainfall at the Bogura, Rangpur, Dinajpur, and Rajshahi stations decreased. Bari et al. [53] conducted a study analyzing

Table 1 Trend statistics of annual total and monsoon rainfall at the Bogura, Rangpur, Dinajpur, Rajshahi, and Pabna stations during 1991–2015

Stations		Mann–Kendall test	Significance level	Sen's slope
Bogura	Total rainfall	– 3.50	***	– 0.063
	Monsoon rainfall	– 2.47	*	– 0.018
Rangpur	Total rainfall	– 2.47	*	– 0.013
	Monsoon rainfall	– 3.78	***	– 0.034
Dinajpur	Total rainfall	– 2.27	*	– 0.010
	Monsoon rainfall	– 3.11	**	– 0.135
Rajshahi	Total rainfall	– 4.05	***	– 0.070
	Monsoon rainfall	– 2.82	**	– 0.011
Pabna	Total rainfall	– 0.28	NS	– 0.005
	Monsoon rainfall	NS	NS	NS

*, ** and *** indicate significance at the 0.05, 0.005 and 0.001 levels of significance, respectively

seasonal and annual rainfall trends in the northern region of Bangladesh. The annual total rainfall at the Pabna station decreased, but there was no significant trend in monsoon rain. The study reveals that northern Bangladesh experiences non-significant decreases in monsoon rainfall, with increasing pre- and post-monsoon trends. Seasonal fluctuations are observed at most stations, with a decreasing trend observed after the early 1990s.

Figure 2a–e depicts the total annual and monsoon rainfall, as well as their trend lines, at the five stations from 1991 to 2015. Rangpur had the highest annual rainfall (2193 mm) of the five stations (Fig. 2a), while Rajshahi had the lowest (1394 mm) (Fig. 2d). During the monsoon season, all stations received between 71 and 78% of their total rainfall. For the Bogura station, 2005 was the wettest year (Fig. 2a), with 2975 mm of total rainfall, 1800 mm (60.5%) of which was monsoon rainfall. The lowest rainfall at this station occurred in 1994, when the total rainfall was 1142 mm, with monsoon rainfall accounting for 812 mm (71.1%).

In 1994, the Rangpur station experienced the least amount of rainfall during the study period presented in Fig. 2e. The total rainfall was 1301 mm, with monsoon rainfall accounting for 861 mm, approximately 66.18% of the total. The station was identified as the rainiest in 2002. The total rainfall was 3127 mm, with monsoon rainfall accounting for 2303 mm, which represents 73.65% of the total. The year with the highest amount of rainfall at Dinajpur station was 2005, as shown in Fig. 2c. The total rainfall in 2005 was 2975 mm. The monsoon rainfall accounted for 1800 mm, representing around 60.5% of the total rainfall. The lowest amount of rainfall occurred in 1994. The total rainfall was 1142 mm, with monsoon rainfall accounting for approximately 71.1% of the total at 812 mm. In 1997, Rajshahi station experienced a total rainfall of 2062 mm, with 1821 mm of it occurring during the monsoon season, which accounted for about 88.31% of the total rainfall. This made 1997 the rainiest year at Rajshahi station. The least amount of rainfall was recorded in 2010 at Rajshahi station. The total rainfall was 792 mm, with monsoon rainfall accounting for 507 mm, which represents 64.02% of the total. Pabna station experienced the lowest amount of rainfall in 2010. The monsoon rainfall accounted for approximately 64.09% of the total rainfall, which was 573 mm out of 894 mm (Fig. 2e). The year 1997 experienced the highest amount of rainfall at Pabna station. The total rainfall was 1878 mm, with monsoon rainfall accounting for 1459 mm, which is 77.69% of the total.

A declining pattern of rainfall during the monsoons has been noted in the northwestern region. Several studies demonstrate a consistent pattern across various stations, particularly in the northwestern hydrological zone of Bangladesh [18, 53, 54]. The tropical monsoon depression significantly contributes to the substantial rainfall during the summer monsoon in Bangladesh. A low-pressure monsoon system enters the country from the Bay of Bengal, moving from south to north, and is deflected by the Meghalaya Plateau towards the northwestern direction. The depression moves inland and consistently decreases the moisture content through circulation, resulting in reduced rainfall in the northwestern part of Bangladesh [55–57].

3.2 Arrival and withdrawal pattern of monsoon rainfall

Figure 3a–e depicts the arrival and withdrawal dates of the monsoon at the Bogura, Rangpur, Dinajpur, Rajshahi, and Pabna stations from 1991 to 2015. The arrival and withdrawal days varied for all five stations. Arrival dates ranged from 4 May to 26 July in Bogura, 1 May to 6 June in Rangpur, 4 May to 25 June in Dinajpur, 10 May to 10 July in Rajshahi, and 4 May to 23 August in Pabna station. The withdrawal day ranges from 19 August to 27 October in Bogura, 1 September

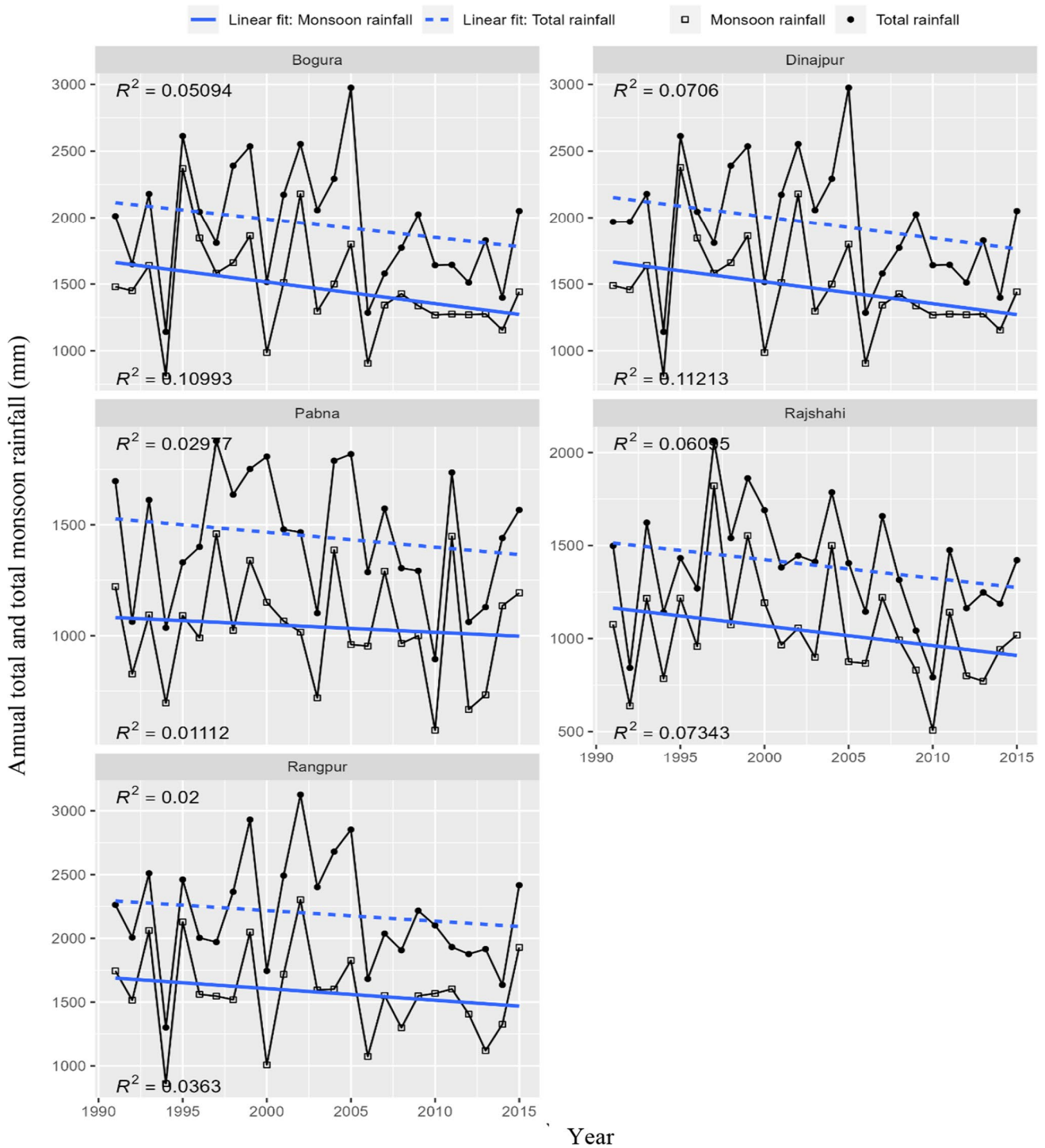


Fig. 2 Annual total and total monsoon rainfall at the a Bogura, b Rangpur, c Dinajpur, d Rajshahi, and e Pabna stations

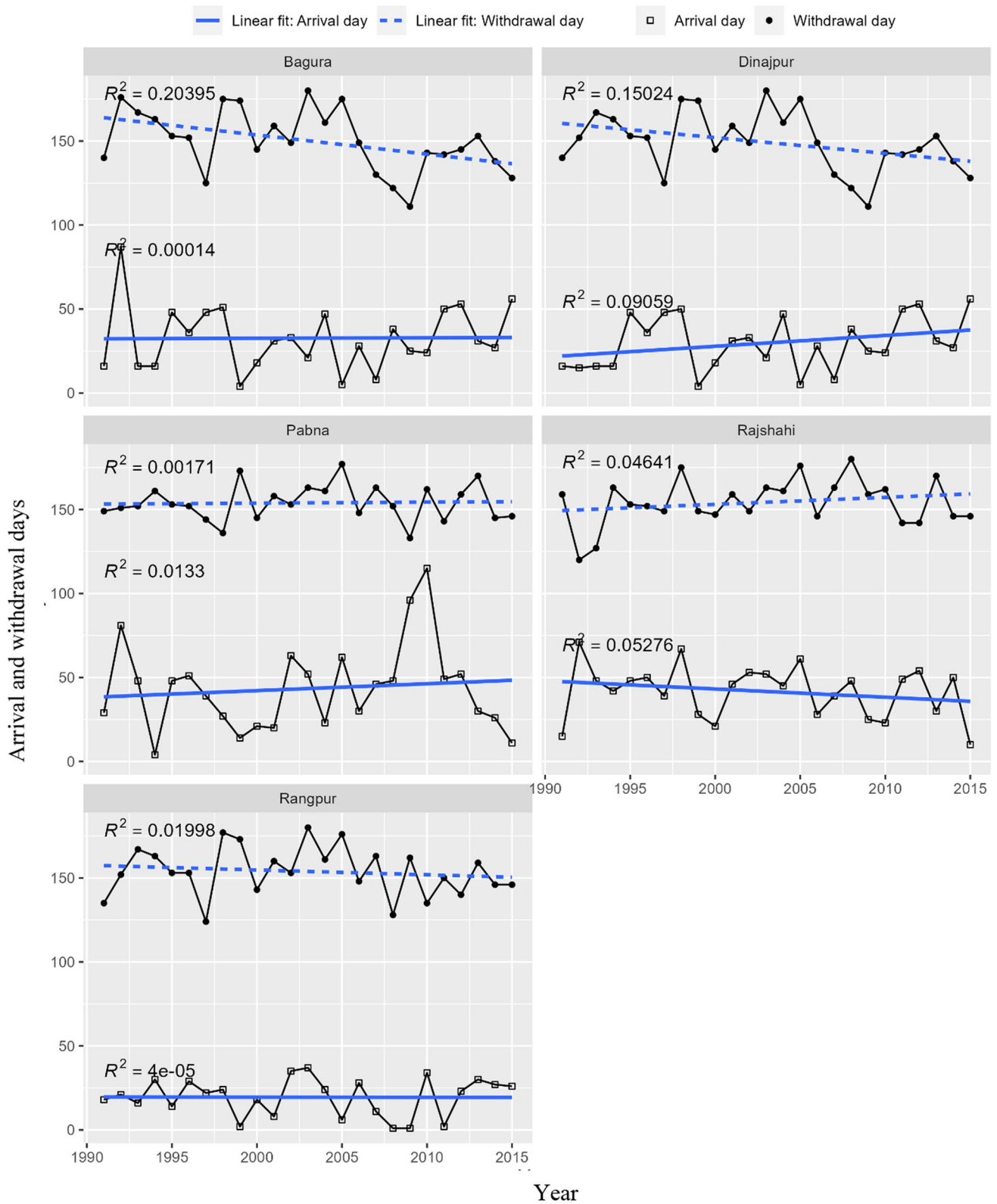


Fig. 3 Arrival and withdrawal pattern of the monsoon at the **a** Bogura, **b** Rangpur, **c** Dinajpur **d** Rajshahi, and **e** Pabna stations

to 27 October in Rangpur, 19 August to 27 October in Dinajpur, 28 August to 27 October in Rajshahi, and 10 September to 20 October in Pabna station.

3.3 Shifting of arrival and withdrawal dates of monsoon rainfall

The shifting of the monsoon's arrival and cessation was calculated from the information illustrated in Fig. 3a–e. Table 2 presented the shifting of Early and late arrival and withdrawal of monsoon rainfall at Bogura, Rangpur, Dinajpur, Rajshahi, and Pabna stations during 1991–2015 from the reference day 1 May.

For the Bogura station, on average, the 33rd day (2 June) after the reference day (1 May) was taken as the baseline to analyze the shifting of the monsoon arrival day, and the 150th day (27 September) after the reference day was taken as the baseline to observe the shifting of the monsoon withdrawal day. In most of the years, the monsoon started 2 to 28 days earlier, but in some years (1992, 1995, 1996, 1997, 1998, 2004, 2008, 2011, 2012, and 2015) it started 3 to 54 days later compared to the baseline. The withdrawal date of the monsoon fluctuated. The range of early withdrawal was between 3 and 30 days, while the late withdrawal was between 1 and 39 days. The 20th day after the reference day (1 May), i.e., 20 May, was taken as the baseline to analyze the shifting of the monsoon arrival day, and the 154th day after the reference day (1 May), i.e., 1 October, was taken as the baseline to observe the shifting of the monsoon withdrawal day at Rangpur station. At this station, the arrival day and withdrawal day fluctuated greatly according to the reference day. The early arrival of the monsoon ranged from 2 to 19 days, and the late arrival ranged from 1 to 17 days. On the other hand, the early withdrawal of the monsoon ranged from 1 to 30 days, whereas the late withdrawal ranged from 5 to 26 days. At Dinajpur station, 30 May (30th day after the reference day, 1 May) was taken as the baseline to analyze the shifting of the arrival day of the monsoon, and 26 September (149th day after the reference day, 1 May) was taken as the baseline to observe the shifting of the withdrawal day of the monsoon. The arrival and withdrawal days fluctuated according to the reference day at this station. The monsoon started 2 to 26 days early or 1 to 26 days late, whereas the monsoon ended 4 to 38 days early or 3 to 31 days late. The arrival day and withdrawal day fluctuated greatly at Rajshahi station. The monsoon started 3 to 32 days early or 3 to 29 days late, whereas the monsoon ended 1 to 34 days early or 5 to 26 days late. The 42nd day after the reference day (1 May), i.e., 11 June, was taken as the baseline to analyze the shifting of the arrival day of the monsoon, and the 154th day after the reference day (1 May), i.e., 1 October, was taken as the baseline to observe the shifting of the withdrawal day of the monsoon. The monsoon started 4 to 39 days early or 3 to 72 days late, whereas the monsoon ended 1 to 21 days early or 4 to 23 days late at Pabna station. Twelve June (43rd day after the reference day, 1 May) was taken as the baseline to analyze the shifting of the monsoon arrival day, and 1 October (154th day after the reference day, 1 May) was taken as the baseline to observe the shifting of the monsoon withdrawal day. At this station, the arrival day and withdrawal day fluctuated greatly according to the reference day (Table 2).

The arrival and withdrawal days did not follow any particular pattern in the study area, which analyzed shifting in a more complex manner. In many cases, aerographic lifting by the hills and mountains or vegetation and land cover types are the reasons for regional or local variations in the rainfall pattern. Anthropogenic activities such as agriculture practices and deforestation may also have influences on changing rainfall trends or shifting monsoons at the local level [58].

4 Conclusions

Between 1991 and 2015, annual total and monsoon rainfall in northwest Bangladesh decreased. During the monsoon season, the region's five meteorological stations receive approximately 71–78% of their total rainfall. Rangpur station received the most rain (2193.36 mm per year), while Rajshahi received the least (1393.60 mm). The monsoon season lasted from May 1 to August 23, and ended between August 19 and October 27. So, the monsoon season in northwest Bangladesh lasts from 1 May to 27 October. The monsoon arrived 2 to 39 days early and lasted 1 to 72 days, and it ended 1–38 days earlier and 1–39 days later than the reference day. There is no clear trend or pattern in the shift in arrival and cessation days, indicating uncertainty in adjusting crop planning to changing climatic parameters over time.

Table 2 Early and late arrival and withdrawal of monsoon rainfall at Bogura, Rangpur, Dinajpur, Rajshahi, and Pabna stations during 1991–2015

Year	Bogura		Rangpur		Dinajpur		Rajshahi		Pabna	
	AD	WD	AD	WD	AD	WD	AD	WD	AD	WD
1991	-17	-10	-2	-19	-14	-9	-27	+5	-14	-5
1992	+54	+26	+1	-2	-15	+3	+29	-34	+38	-3
1993	-17	+17	-4	+13	-14	+18	+6	-27	+5	-2
1994	-17	+13	+10	+9	-14	+14	0	+9	-39	+7
1995	+15	+3	-6	-1	+18	+4	+6	-1	+5	-1
1996	+3	+2	+9	-1	+6	+3	+8	-2	+8	-2
1997	+15	-25	+2	-30	+18	-24	-3	-5	-4	-10
1998	+19	+25	+4	+23	+20	+26	+25	+21	-16	-18
1999	-29	+24	-18	+19	-26	+25	-14	-5	-29	+19
2000	-15	-5	-2	-11	-12	-4	-21	-7	-22	-9
2001	-2	+9	-12	+6	+1	+10	+4	+5	-23	+4
2002	0	-1	+15	-1	+3	0	+11	-5	+20	-1
2003	-12	+30	+17	+26	-9	+31	+10	+9	+9	+9
2004	+14	+11	+4	+7	+17	+12	+3	+7	-20	+7
2005	-28	+25	-14	+22	-25	+26	+19	+22	+19	+23
2006	-5	-1	+8	-6	-2	0	-14	-8	+13	-6
2007	-25	-20	-9	+9	-22	-19	-3	+9	+3	+9
2008	+5	-28	-19	-26	+8	-27	+6	+26	+5	-2
2009	-8	-39	-19	+8	-5	-38	-17	+5	+53	-21
2010	-9	-7	+14	-19	-6	-6	-19	+8	+72	+8
2011	+17	-8	-18	-4	+20	-7	+7	-12	+6	-11
2012	+20	-5	+3	-14	+23	-4	+12	-12	+9	+5
2013	-2	+3	+10	+5	+1	+4	-12	+16	-13	+16
2014	-6	-12	+7	-8	-3	-11	+8	-8	-17	-9
2015	+23	-22	+6	-8	+26	-21	-32	-8	-32	-8

AD indicates Arrival Day and WD indicates Withdrawal Day. (+) the sign indicates late arrival and withdrawal according to the baseline and (-) sign indicates the early arrival and withdrawal according to the baseline

4.1 Recommendation

The study investigates monsoon rainfall variability in Bangladesh's northwest region, focusing on its seasonal variations. It aids in understanding precipitation system features, planning regional agricultural activities, and optimizing water management [59]. The findings can be used for community-level planning and policymaking, enhancing water resource management policies.

Acknowledgements We are thankful to Professor Dr. Md. Abdul Mojid and Professor Dr. M. G. Mostofa Amin, Department of Irrigation and Water Management, Bangladesh Agricultural University, for their generous support throughout the process. The authors also extend their sincere gratitude to the editors and reviewers for their invaluable insights and professional comments.

Author contributions Md Shariot-Ullah^{1*}: Conceptualize and prepared the manuscript, Salma Akhter¹: Data analysis and preparation of the draft, Tapos Kumar Acharjee¹: Reviewed the draft and improved, Md Moudud Hasan²: Reviewed, processed the figures and improved the draft.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Competing interests The authors have declared that no competing interests exist.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Chen X, Quan Q, Zhang K, Wei J. Spatiotemporal characteristics and attribution of dry/wet conditions in the Weihe River Basin within a typical monsoon transition zone of East Asia over the recent 547 years. *Environ Model Softw*. 2021. <https://doi.org/10.1016/j.envsoft.2021.105116>.
2. Ezaz GT, Zhang K, Li X, Shalehy MH, Hossain MA, Liu L. Spatiotemporal changes of precipitation extremes in Bangladesh during 1987–2017 and their connections with climate changes, climate oscillations, and monsoon dynamics. *Glob Planet Change*. 2022;208: 103712. <https://doi.org/10.1016/J.GLOPLACHA.2021.103712>.
3. Forzieri G, Miralles DG, Ciais P, et al. Increased control of vegetation on global terrestrial energy fluxes. *Nat Clim Change*. 2020;10(4):356–62. <https://doi.org/10.1038/s41558-020-0717-0>.
4. Loo YY, Billa L, Singh A. Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geosci Front*. 2015;6(6):817–23. <https://doi.org/10.1016/J.GSF.2014.02.009>.
5. Rahman MN, Azim SA, Jannat FA, Hasan Rony MR, Ahmad B, Sarkar MAR. Quantification of rainfall, temperature, and reference evapotranspiration trend and their interrelationship in sub-climatic zones of Bangladesh. *Heliyon*. 2023. <https://doi.org/10.1016/J.HELION.2023.E19559>.
6. Rahman MN, Azim SA. Spatiotemporal evaluation of rainfall trend during 1979–2019 in seven climatic zones of Bangladesh. *Geol Ecol Landsc*. 2023;7(4):340–55. <https://doi.org/10.1080/24749508.2021.2022425>.
7. Fattah MA, Hasan MM, Dola IA, et al. Implications of rainfall variability on groundwater recharge and sustainable management in South Asian capitals: an in-depth analysis using Mann Kendall tests, continuous wavelet coherence, and innovative trend analysis. *Groundw Sustain Dev*. 2024;24: 101060. <https://doi.org/10.1016/J.GSD.2023.101060>.
8. Alexander LV, Zhang X, Peterson TC, et al. Global observed changes in daily climate extremes of temperature and precipitation. *J Geophys Res Atmos*. 2006;111(D5):5109. <https://doi.org/10.1029/2005JD006290>.
9. Nicholson SE, Funk C, Fink AH. Rainfall over the African continent from the 19th through the 21st century. *Glob Planet Change*. 2018;165:114–27. <https://doi.org/10.1016/J.GLOPLACHA.2017.12.014>.
10. Das P. *The Monsoons*. National Book Trust, New Delhi, India. Published online 1995.
11. Webster PJ. *The elementary monsoon*. Monsoons, 3. Published online 1986. <https://ci.nii.ac.jp/naid/10003544915/>.
12. Devkota LP, Quadir DA, Ferdousi N, Khan AQ. Rainfall over SAARC Region with Special Focus on Teleconnections and Long Range Forecasting of Bangladesh Monsoon Rainfall. 2006.
13. Jubly JF, Rahman SH. Estimation of Arrival and Withdrawal Date of Rainy Season in Bangladesh. *Bangladesh Journal of Environmental Research*. Published online 2021. Accessed March 1, 2024. https://www.researchgate.net/publication/352838718_Estimation_of_Arrival_and_Withdrawal_Date_of_Rainy_Season_in_Bangladesh.
14. Shahid S. Rainfall variability and the trends of wet and dry periods in Bangladesh. *Int J Climatol*. 2010;30(15):2299–313. <https://doi.org/10.1002/JOC.2053>.
15. Wahiduzzaman M, Luo JJ. A statistical analysis on the contribution of El Niño–Southern Oscillation to the rainfall and temperature over Bangladesh. *Meteorol Atmos Phys*. 2021;133(1):55–68. <https://doi.org/10.1007/S00703-020-00733-6/FIGURES/11>.
16. Barry RG, Chorley RJ. *Atmosphere, weather, and climate*. Routledge; 2009.
17. Rahman M, Md. Validation of regional climate model simulation with observational data over Bangladesh. Published online 2006. Accessed February 29, 2024. <http://lib.buet.ac.bd:8080/xmlui/handle/123456789/2360>.
18. Ahasan M, Chowdhury MA, Quadir D. Variability and trends of summer monsoon rainfall over Bangladesh. *J Hydrol Meteorol*. 2010;7(1):1–17. <https://doi.org/10.3126/jhm.v7i1.5612>.
19. Mannan M, Chowdhury M, Karmakar S. Prediction of rainfall over Southeastern part of Bangladesh during Monsoon Season. *Int J Integrated Sci Technol*. 2016;2(12).
20. Singh RB, Mal S. Trends and variability of monsoon and other rainfall seasons in Western Himalaya, India. *Atmos Sci Lett*. 2014;15(3):218–26. <https://doi.org/10.1002/ASL2.494>.
21. Acharjee T, Ullah M. Irrigation requirement and possibility of high-temperature stress of wheat for different planting dates under climate change in Bogura, Bangladesh. *J Bangladesh Agric Univ*. 2021. <https://doi.org/10.5455/JBAU.41181>.
22. Salem GSA, Kazama S, Shahid S, Dey NC. Impact of temperature changes on groundwater levels and irrigation costs in a groundwater-dependent agricultural region in Northwest Bangladesh. *Hydrol Res Lett*. 2017;11(1):85–91. <https://doi.org/10.3178/HRL.11.85>.
23. Mohsenipour M, Shahid S, Ziarh GF, Yaseen ZM. Changes in monsoon rainfall distribution of Bangladesh using quantile regression model. *Theor Appl Climatol*. 2020;142(3–4):1329–42. <https://doi.org/10.1007/s00704-020-03387-x>.

24. Rahman AM. Rainfall variability and linear trend models on north-west part of Bangladesh for the last 40 years. *Am J Appl Math.* 2016;4(3):158. <https://doi.org/10.11648/j.ajam.20160403.16>.
25. Shahid S, Behrawan H. Drought risk assessment in the western part of Bangladesh. *Nat Hazards.* 2008;46(3):391–413. <https://doi.org/10.1007/S11069-007-9191-5>.
26. Alam J, Rahman S. Monitoring meteorological and agricultural drought dynamics in Barind region Bangladesh using standard precipitation index and Markov chain model. *Int J Geomatics Geosci.* Published online 2013.
27. ADB. Bangladesh Climate and Disaster Risk Atlas: Exposures, Vulnerabilities, and Risks—Volume II | Asian Development Bank. Published 2021. Accessed March 1, 2024. <https://www.adb.org/publications/bangladesh-climate-disaster-risk-atlas-volume-2>.
28. Rahman MN, Rony MRH, Jannat FA. Spatiotemporal evaluation of drought trend during 1979–2019 in seven climatic zones of Bangladesh. *Heliyon.* 2021;7(11): e08249. <https://doi.org/10.1016/j.heliyon.2021.e08249>.
29. Rahman SM, Matin A, Al Mamun A, Rahman SM, Sultana R, Saba S. Frequency of Droughts in Northwestern Bangladesh. Published online 2022.
30. Rahman SM, Faruk MO, Rahman MH, Rahman SM. Drought index for the region experiencing low seasonal rainfall: an application to northwestern Bangladesh. *Arab J Geosci.* 2022;15(3):1–15. <https://doi.org/10.1007/S12517-022-09524-2>.
31. Karmakar S. Patterns of climate change and its impacts in northwestern Bangladesh. *J Eng Sci.* 2019;10(2):33–48. Accessed February 29, 2024. <https://www2.uet.ac.bd/JES/>.
32. BADC. Survey Report on Irrigation Equipment and Irrigated Area in Boro/2001 Season, Bangladesh Agricultural Development Corporation, Dhaka, Bangladesh. Published online 2002.
33. Shahid S. Spatial assessment of groundwater demand in Northwest Bangladesh. *Int J Water.* 2010;5(3):267–83. <https://doi.org/10.1504/IJW.2010.03059>.
34. Khan MSH, Haque ME, Ahmed M, Mallick J, Islam ARMT, Fattah MA. Quantitative analysis and modeling of groundwater flow using visual MODFLOW: a case from subtropical coal mine, northwest Bangladesh. *Environ Dev Sustain.* 2023. <https://doi.org/10.1007/S10668-023-04052-9>.
35. Etzold B, Ahmed AU, Hassan SR, Neelormi S. Clouds gather in the sky, but no rain falls. Vulnerability to rainfall variability and food insecurity in Northern Bangladesh and its effects on migration. *Clim Dev.* 2014;6(1):18–27. <https://doi.org/10.1080/17565529.2013.833078>.
36. Mukarram MMT, Al-Kafy A, Mukarram MMT, et al. Perception of coastal citizens on the prospect of community-based rainwater harvesting system for sustainable water resource management. *Resour Conserv Recycl.* 2023;198:107196. <https://doi.org/10.1016/J.RESCONREC.2023.107196>.
37. Mannan M, Samarendra K. Proceedings of SAARC Seminar on Application of Weather and Climate forecasts in the Socio-economic Development and Disaster mitigation, Climate Feature of the Thunderstorm Days and ... In: ; 2008.
38. Rafiuddin M, Uyeda H, Islam MN. Characteristics of monsoon precipitation systems in and around Bangladesh. *Int J Climatol.* 2010;30(7):1042–55. <https://doi.org/10.1002/JOC.1949>.
39. Shahid S, Khairulmaini OS. Spatio-temporal variability of rainfall over Bangladesh during the time period 1969–2003. *Asia Pac J Atmos Sci.* 2009;43(5):375–89.
40. Montes C, Acharya N, Stiller-Reeve MA, Kelley C, Hassan SMQ. Interannual variability of monsoon onset and withdrawal in Bangladesh. *Atmos Sci Lett.* 2021;22(11): e1069. <https://doi.org/10.1002/ASL.1069>.
41. Riches CR. The High Barind Tract: a challenging drought-prone agricultural environment. International Rice Research Institute (IRRI). Published online 2008:3–6. Accessed August 10, 2021. <https://agris.fao.org/agris-search/search.do?recordID=QR2008000027>.
42. Habiba U, Shaw R, Takeuchi Y. Farmers' adaptive practices for drought risk reduction in the northwest region of Bangladesh. *Nat Hazards.* 2014;72(2):337–59. <https://doi.org/10.1007/S11069-013-1011-5/TABLES/6>.
43. Mainuddin M, Mahbulul Alam M, Maniruzzaman M, et al. Irrigated agriculture in the northwest region of Bangladesh. Published online 2019.
44. Farhana S. Characterizing rainfall trend in Bangladesh by temporal statistics analysis. 4th Annual Paper Meet and 1st Civil Engineering Congress. Published online 2011:978–984.
45. IPCC. The regional impacts of climate change: an assessment of vulnerability. 2007.
46. Mondal MS, Jalal MR, Khan MSA, Kumar U, Rahman R, Huq H. Hydro-meteorological trends in southwest coastal Bangladesh: perspectives of climate change and human interventions. *Am J Clim Change.* 2013;02(01):62–70. <https://doi.org/10.4236/ajcc.2013.21007>.
47. Ahmed R, Karmakar S. Arrival and withdrawal dates of the summer monsoon in Bangladesh. *Int J Climatol.* 1993;13(7):727–40. <https://doi.org/10.1002/JOC.3370130703>.
48. Das PK (Prosad K). The monsoons. Published online 1995:252.
49. Finnish Meteorological Institute. MAKESENS-application for trend calculation. Published 2002. Accessed August 6, 2021. <https://en.ilmaitteenlaitos.fi/makesens>.
50. Kendall MG. Rank correlation methods. 4th ed. London: Charles Griffin; 1975.
51. Mann HB. Nonparametric tests against trend. *Econometrica.* 1945;13(3):245. <https://doi.org/10.2307/1907187>.
52. Fattah MA, Gupta SD, Farouque MZ, et al. Spatiotemporal characterization of relative humidity trends and influence of climatic factors in Bangladesh. *Heliyon.* 2023;9(9):e19991. <https://doi.org/10.1016/j.heliyon.2023.e19991>.
53. Bari SH, Rahman MTU, Hoque MA, Hussain MM. Analysis of seasonal and annual rainfall trends in the northern region of Bangladesh. *Atmos Res.* 2016;176–177:148–58. <https://doi.org/10.1016/J.ATMOSRES.2016.02.008>.
54. Rahman MA, Kamal SMM, Billah MM. Rainfall variability and linear trend models on north-west part of Bangladesh for the last 40 years. *Am J Appl Math.* 2016;4(3):158–62. <https://doi.org/10.11648/J.AJAM.20160403.16>.
55. Ahmed R, Kim IK. Patterns of daily rainfall in Bangladesh during the summer monsoon season: case studies at three stations. *Phys Geogr.* 2003;24(4):295–318. <https://doi.org/10.2747/0272-3646.24.4.295>.
56. Ramage CS. Monsoon meteorology. Academic Press; 1971.
57. Shahid S. Rainfall variability and changes in Bangladesh during the last fifty years. In: *Rainfall: Behavior, Forecasting and Distribution.* 2012:23–44.

58. Rahman MR, Lateh H. Climate change in Bangladesh: a spatio-temporal analysis and simulation of recent temperature and rainfall data using GIS and time series analysis model. *Theor Appl Climatol.* 2017;128(1–2):27–41. <https://doi.org/10.1007/S00704-015-1688-3/FIGURES/11>.
59. Bahiru TK, Aldosary AS, Al-Kafy A, et al. Geospatial approach in modeling linear, areal, and relief morphometric interactions in Dabus river basin ecology for sustainable water resource management. *Groundw Sustain Dev.* 2024;24:101067. <https://doi.org/10.1016/J.GSD.2023.101067>.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.