Trend analysis of pre-monsoon flash floods for the northeast Haor region of Bangladesh to assess the impact on Boro crop productivity[1]

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Abstract

Introduction: Pre-monsoon (March-May) flash floods observed in the northeast of Bangladesh, known as the "Haor" (saucer or bowl-shaped large tectonic depression) region, have drawn much attention in recent years due to early onset, high frequency, large magnitude, and destructive nature. The Boro crop, which is the primary agricultural production of this region, is adversely damaged by the flash floods. In this study, the trend of the flash floods of the northeast Haor region has been studied to understand past changes and future occurrences and to assess the overall impact on Boro crop productivity.

Material and methods: The trend analysis was carried out on the observed 3 - hourly water level data of 13 hydrological gage stations and daily rainfall data of 2 meteorological gage stations of the Haor region collected from the Bangladesh Water Development Board (BWDB) and Bangladesh Meteorological Department (BMD), respectively. All these stations were located near the Bangladesh-India border, where the flash flood water comes first from the surrounding hilly areas of India; otherwise, the flashy nature may not be discernible in the time series data. The data were processed from 1st March to 15th May, considering the start of the flash flood season and the end of the Boro crop harvesting period, respectively.

The statistical Mann-Kendall (MK) test has been used to analyze the trend at a 5% significance level, and Sen's slope has been used to compute the magnitude of the trend at the same significance level. Lag-1 autocorrelation has been determined before statistical trend analysis. The MK test was directly applied to the data with no autocorrelation, whereas the data showing significant autocorrelation were analyzed through the Trend-Free Pre-Whitening Mann-Kendall (TFPWMK) test. TFPWMK was selected because it can effectively detect trends in significantly serially correlated hydrological data. The trend of early onset of flash floods has also been assessed. Based on the trend analysis results, the impact of flash floods on the key varieties of Boro crops produced in the Haor region was evaluated.

Results: The trend analysis results showed that the trends of maximum water level and relative water level varied from station to station. The study revealed that 6 and 9 stations out of the 13 hydrological stations, respectively, showed an increasing trend in maximum water level and relative water level, among which only 2 and 3, respectively, showed a statistically significant increasing trend at a 5% significance level. More increasing trends were found for the relative water level, which meant that though the peak of flash floods was not increasing, the relative water level in the pre-monsoon season was increasing in recent years compared to past ones. The rainfall trend was also increasing, though it was not statistically significant. Overall, the vulnerability of the Boro crop was increasing.

The trend analysis on peak periods of flash floods showed a decreasing trend, which revealed an early onset of flash floods in recent years. The peak of the flash floods was found to be arriving early in late March-early April (instead of late April-early May), coinciding with the harvesting period of the Boro crop. This early onset of the flash flood warrants catastrophic damage to the Boro crop in future flash floods.

The study further showed that the current Boro varieties- BRRI dhan28, BRRI36, BRRI dhan69, BRRI dhan88 were safer in 'normal flash floods' (late April-early May) but not anymore safer in 'early flash floods' (late March-early April) experienced in recent years.

Conclusion: The study found an increasing trend in the water level, and rainfall in the Haor region. Though the trend hasn't crossed the limit of a 5% significance level in most stations, this could increase exponentially in the future due to climate change impact. Also, changing timelines and the early onset of the flash flood can destroy Boro cultivation in the Haor area and imbalance the food security of the local people. Hence, the changing trend of flash floods in magnitude, pattern, duration, and early onset must be considered for flood risk management and sustainable agricultural production in the Haor region. For example,

more varieties of Boro should be introduced, which can be harvested by the last week of March before the flash flood hits the Haor region. Also, varieties with a shorter growth duration and cold tolerance at the reproductive phase should be prioritized.

1. Introduction

Climate change and its impact is a major concern of the twenty-first century. Global warming-induced changes in temperature, rainfall, and sea level are already evident in many parts of the world, as well as in Bangladesh (Ahmed, 2006; Stocker *et al*., 2013). Climate change is enhancing hazards such as floods, droughts, cyclones, and other hydro-climatic disasters too. Hence, the hydrologic trend analysis has attained much importance in recent years to understand past hydrological changes, predict future trends, and identify climate change impacts on hydrological variables.

The northeast region of Bangladesh consists of many Haors. There are approximately 400 Haors covering an area of about 19,700 km^2 with 23 transboundary rivers that enter Bangladesh from India. Haors are almost round/elliptical shaped tectonically depressed marshy lands. They are used as agricultural lands during the dry period (December to mid-May) and as fisheries during the wet period (June to November). The northeast Haor region of Bangladesh is highly vulnerable to flash floods due to its topological features and geographical location. Most of the rivers of the Haor region have originated from the northern hilly areas of Assam and Meghalaya in India (NERP FAP-6, 1995). Whenever heavy rainfall occurs in these hilly regions, floodwater rapidly runs down the Haor area through the transboundary rivers and channels within a short time (in most cases, 3 to 6 hours only) and inundates the Haor region without any warning (Nowreen *et al*., 2015; NWS, 2016).

Boro is the main crop of the northeastern Haor area. Flash flood adversely affects the Boro crop production of this region and jeopardizes the local people's lives and livelihoods (Khan *et al*., 2012). The flash flood of 2010 destroyed crops of 1,52,000 hectares (1520 km^2), while the flash flood of 2016 damaged about 50,000 hectares (500 km^2) of paddy in more than 100 villages of Sunamganj and Sylhet districts (Roy *et al*., 2019). Around 400,000 hectares (4000 km^2) of land were submerged during the 2017's flood damaging some 2 million tons of rice (DRTMC, 2017). Thus, flash floods before harvesting Boro crops cause an adverse impact on the food security of the northeast region and damage the national economy to a large extent (Khan *et al*., 2012).

In the last three decades, major flash floods occur during 1996, 1998, 2000, 2002, 2004, 2010, 2013, 2016, 2017, and 2019 in the northeast Haor region (Rashid & Yasmeen, 2017). Statistics show that flash floods used to occur in

the northeast Haor region every two or three years. However, the flash floods of 2016 and 2017 happened in two successive years and resulted in huge losses and damages. Moreover, the usual onset of a flash flood in the Haor region is generally from the end of April to mid of May as 'Boishakhi Dhall' when the Boro crop is already harvested or on the way to harvesting in the Haor region (Khalequzzaman, 2019; Rashid & Yasmeen, 2017). When a flash flood occurs earlier (i.e., end of March to early of April) as 'Chaitali Dhall', it overlaps with the Boro harvesting period and causes irreparable damage (Rashid & Yasmeen, 2017). The flash flood of 2017 occurred on 28th March (NIRAPAD, 2017). The flash flood of 2019 also occurred during the first week of April. These flood events in late March or early April, which overlaps with the Boro harvesting period, are not regular in the Haor region. In both years, premature Boro rice went underwater in many Haor areas and caused a huge loss. Also, unplanned local infrastructures and drainage congestion made the flood recession period longer in the Haors. According to the Bangladesh Meteorological Department (BMD), the return period of the early flash flood event is increasing as well (Biswas, 2017). Moreover, the flood level of 2017 flood has been the highest pre-monsoon flood level in the last 100 years. Hence, it is anticipated that flash floods are appearing earlier with higher frequency, larger magnitude, and longer duration due to recent global warming and climate change. As a result, the Haors are becoming more hostile to offer a safe Boro harvest. But such anticipation needs a detailed investigation of the hydro-meteorological variables of the northeast Haor region. In this context, this study presents an investigation of the characteristics of the hydro-meteorological variables of the northeast region to ascertain the presence of trends and explore the above anticipations.

Trend analysis helps in understanding present and past hydrological changes, estimating qualitative future projection, and taking necessary cautions in this regard. Trend analysis is widely used in hydrological time-series studies. Several researchers have carried out hydrological trend analyses so far. For example, Gan (1998); Gan & Kwong (1991); Lettenmaier *et al*. (1994); Burn (1994); Douglas *et al*. (2000); Zhang *et al*. (2000.2001); Kumar *et al*. (2009) and Cong *et al*. (2009) studied the trend of hydrological times series. In Bangladesh, Shahid (2009) explored the spatiotemporal variability of rainfall at 24 gage stations over Bangladesh from 1963-2003. Mirza *et al*. (1998) studied the trends and persistence in precipitation in the Ganges, Brahmaputra, and Meghna River basins. Shahid (2011) inspected the trends in

extreme rainfall events in Bangladesh. Shahid (2010) studied the rainfall variability and the trends of wet and dry periods in Bangladesh. Basher *et al*. (2018) assessed the trends of pre-monsoon and monsoon rainfall over the northeast area. Very recently, Khan *et al*. (2019) quantified the trend of precipitation and temperature of Bangladesh for the period 1981−2010. Besides, Nowreen *et al*. (2015); Sultana (2015) and Roy *et al*. (2019) also studied the extreme hydrological variables of the northeast Haor region of Bangladesh. But none of these studies focus on the trend of the flash flood of the northeast Haor region based on water level and peak period, which are very crucial variables to explore the overall trend of the flash flood. Hence, this study aims to investigate the trend of the hydro-meteorological variables of flash floods of the northeast Haor region of Bangladesh.

In this study, the trend of two important hydro-meteorological variables, flood level (maximum and relative water level) and rainfall (average, maximum, and total rainfall), is studied with non-parametric Mann-Kendall and Sen's Slope tests. A common characteristic of the hydrologic data is autocorrelation which affects the presence of trends in the time series data is not studied in most of the trend analysis studies in Bangladesh. Therefore, in the presence of autocorrelation, the Mann-Kendall test was performed with the trend-free pre-whitening (TFPW) test. Simultaneously, the peak-time of flash floods over the years has also been assessed graphically, which is not studied in any literature yet. So, this study is designed to address all these research gaps and carry out trend analysis with the meteorological data from two gage stations and hydrological data from thirteen gage stations of the northeast Haor area. All the stations are located near the Bangladesh – India border as otherwise; the flashy nature may not be discernible in the time series data. Finally, based on the observed trend results, the impact of flash flood on the key varieties of Boro crop produced in the Haor region is evaluated.

2. Materials and Methods

2-1. Study Area

The north-eastern region of Bangladesh covers approximately 24,500 km^2, bounded by the international border with India to the north and east, the Old Brahmaputra River to the west, and the Nasirnagar (to Madhabpur) and Meghna River to the south (Figure 1). The larger portion of this region is the Haor basin and is characterized by numerous large, deeply flooded depressions. The core northeast Haor basin is extended over four districts-

Sunamganj, Habiganj, Sylhet, and Moulavibazar as well as Netrokona, Kishoreganj, and Brahmanbaria districts outside the core area, covering a total area of about 1.99 million hectares (19,900 km^2) and accommodating about 19.37 million people. The Haor region is well known for its unique hydro-ecological characteristics, which remain dry for about six months and under-water for the rest of the year. During winter, cultivatable land of the area is used to produce Boro crop. During monsoon, the same area is turned into a breeding place for open water fishery, hosting a wide range of biodiversity. Annual rainfall varies from 2200 mm along the western boundary to 5800 mm in its northeastern corner (CEGIS, 2012). Over 80% of the rainfall occurs during the monsoon season from June to October. Temperatures usually vary from 26 to 31°C in the pre-monsoon period, 28 to 31°C in the rainy season, and 26 to 27°C in winter (NERP FAP-6, 1995).

Geographically, this area is surrounded by Meghalaya in the north, Tripura, and Mizoram in the south, and Assam and Manipur in the east. Twenty-three transboundary rivers enter Bangladesh in the northeast region. The Haor region is mainly drained by the Surma-Kushiyara river system, which receives water from the three transboundary river systems of Meghalaya, Barak, and Tripura situated in the north, east, and southeast, respectively, across the border of India (CEGIS, 2012). Early flash flood causes extensive damage to the standing Boro crop and thus destroys the single cropped agriculture of this area. The locations of the nominated hydro-meteorological gage stations are shown in Figure 1. These stations are on different rivers of the northeast Haor region of Bangladesh, as shown in Figure 1 and tabulated in Supp. Table 1. Hydrologically, this region is comprised of the floodplains of the Meghna River and its tributaries and finally discharging to Bhairab Bazar of Kishoreganj District. As shown in Figure 1, these stations are located very close to the international border of Bangladesh with India. The gage stations near the surrounding hills were selected to capture the peak of flash floods before it is attenuated. The details of the selected gage stations are given in Supp. Table 1 and Supp. Table 2.
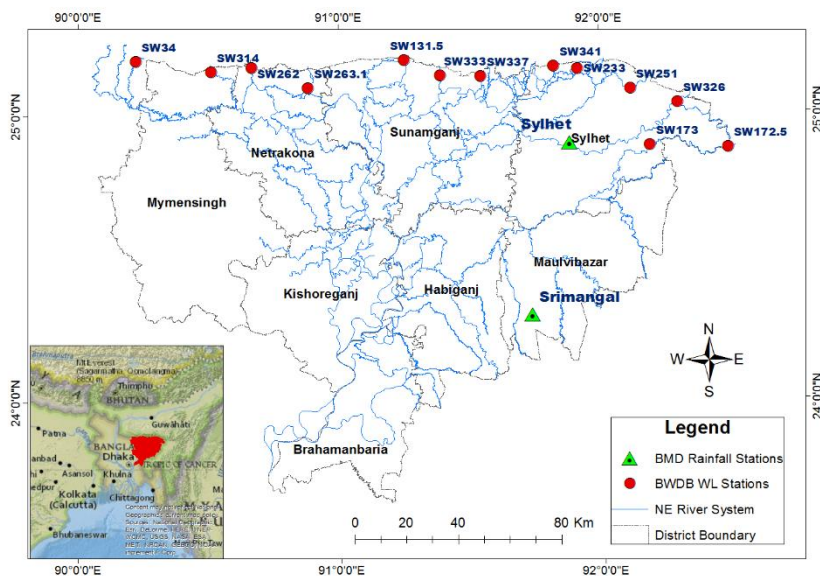
Fig. 1. Locations of the hydro-meteorological gage stations considered in the study

2-2. Hydro-metrological Data Collection

In this study, the trend of water level and rainfall data were analyzed. The 3-hourly water level data from 13 gage stations were collected from the Bangladesh Water Development Board (BWDB) (Supp. Table 1) from 1996 to 2017. The daily rainfall data of Sylhet and Srimangal stations was collected from the Bangladesh Meteorological Division (BMD) from 1948 to 2017 (Supp. Table 2). All the collected data was processed for the pre-monsoon season from 1st March to 15th May. The water level data collected are in Public Works Datum (mPWD) unit, which is approximately 0.46 m below the mean sea level (FFWC, 2020).

2-3. Data Processing

The annual maximum water level time series considering the period between 1st March and 15th May for each year is calculated. Another parameter named; relative water level (m) is used, which here represents the difference in water level (mPWD) of each day relative to the water level (mPWD) of the first day of the pre-monsoon season (i.e., 1st March) of the corresponding year. This parameter estimates the change (either increase or decrease) in water level on each day of the pre-monsoon season with respect to the first day of the pre-monsoon season. Later, the average relative water level (m/day) is

calculated for each year, which is further used to form an annual time series of the relative water level to perform trend analysis. On the other hand, the collected rainfall data is processed to determine the maximum, average, and total rainfall of each year. In each case, the time period from 1st March to 15th May of each year is used in the analysis. 1st March is considered the start of the flash flood season and 15th May is considered the end of the harvesting period of the Boro crop (BWDB, 2006).

2-4. Homogeneity Test

The Homogeneity test is conducted to detect any non-climatic variations in the rainfall data caused by changes in observation practices/instruments, observation time, site relocation, etc. Because "Inhomogeneity" can interfere with the proper assessment of any climate trends and extremes. Usually, the Pettitt test, Standard Normal Homogeneity Test (SNHT), Buishand Range test (BRT), Von Neumann ratio (VNR) test, etc., are conducted (Chang *et al*., 2017; Kocsis *et al*., 2020). In this study, the non-parametric Pettitt test (Pettitt, 1979) is performed at a significance level of 5% to detect inhomogeneity in the precipitation data. It is a change-point analysis. This test detects the change point (CP) in a time series and determines if a significant shift exists in the time-series. The time series is divided into two parts at the location of the CP and provides mean values before and after the CP. The test is conducted using the 'pyHomogeneity' package of Python.

2-5. Trend Analysis

Trend analysis refers to detecting any changes in environmental, hydrologic, or climatic parameters or any population variables over time or in space. In this study, temporal trend analysis was carried out both graphically and statistically.

i) Statistical Analysis: Statistical analysis is a reliable technique for trend analysis. Both parametric (applicable to independent and normally distributed data) and non-parametric (applicable to independent data) methods are available for detecting the presence of significant trends in hydrologic or climatological time series. In this study, two non-parametric methods (Mann-Kendall and Sen's slope estimator) were used to detect the water level and rainfall trend.

ii) Mann- Kendall Test (MK): The Mann- Kendall test (Mann, 1945; Kendall, 1975) (MK) is a highly preferred and widely accepted test for examining the presence of the monotonically increasing or decreasing trend of

the variable of interest over the period without specifying the linearity or non-linearity of the trend (Hamed, 2008; Tabari *et al*., 2011; Mondal *et al*., 2012; Basher *et al*., 2018; Meshram *et al*., 2020; Mirabbasi *et al*., 2020; Sattari *et al*., 2020). If xi (where, i=1, 2…, n), that means x_1, x_2...x_n is the time series of length n, then the Mann-Kendall test statistic S is given by Eqs. 1 and 2:

$$S = \sum_{i-1}^{n-1} \sum_{j-i+1}^{n} sgn\left(x_j - x_i\right) \qquad (1)$$

where,

$$sgn\left(x\right) = \begin{cases} 1 \ for \ x > 0 \\ 0 \ for \ x = 0 \\ -1 \ for \ x < 0 \end{cases} \qquad (2)$$

The null hypothesis H_0 for the test is ''there is no significant trend in the time series''. If H_0 is true, then S is normally distributed with,

$$E(S) = 0 \qquad (3)$$

$$V(S) = \frac{n\,(n-1)(2n+S)}{18} \qquad (4)$$

where, $E(S)$ is the mean and $V(S)$ is the variance of S. Then the Mann–Kendall Z is given by Eq. 5:

$$Z = \begin{cases} \frac{S-1}{\sqrt{V\,(S)}} \ for \ S > 0 \\ 0 \qquad for \ S = 0 \\ \frac{S+1}{\sqrt{V\,(S)}} \ for \ S < 0 \end{cases} \qquad (5)$$

A positive value of S indicates an increasing trend, whereas a negative value indicates a decreasing trend. The test statistic Z gives the significance level of rejecting the null hypothesis.

iii) Sen's Slope Estimator (TSA): Sen (1968) developed a non-parametric procedure for estimating the slope of a trend. Trend analysis with Mann-Kendall and Sen's slope is a combined trend analysis tool used widely in hydrology. These tests efficiently detect the trend of hydrometeorological variables. The magnitude of trends is generally determined using the Theil–Sen approach (TSA) (Thiel, 1950; Sen, 1968). The TSA slope β is given by Eq. 6:

$$\beta = median \left[\frac{x_j - x_i}{j-i}\right] \qquad (6)$$

iv) Autocorrelation: Autocorrelation refers to the correlation of a time series with its past values. Hydrological time series, such as annual mean and annual minimum streamflow or precipitation, may often display statistically

significant serial correlation. In such cases, the existence of serial correlation increases or decreases the probability that the Mann-Kendall test detects a significant trend (von Storch, 1995) or not. For example, the existence of a positive serial correlation in a time series increases the probability that the MK test will detect a significant trend. On the contrary, the influence of the negative autocorrelation on the MK test may tend to underestimate the probability of detecting trends (Yue *et al*., 2002). Hence, the presence of autocorrelation may influence the trend analysis outcome. Therefore, the determination of autocorrelation before carrying out trend analysis is suggested. The correlation coefficient (r_k) of a time series is determined using the following equation:

$$r_k = \frac{\frac{1}{n-k}\sum_{i-1}^{n-k}(x_i-\bar{x})(x_{i+k}-\bar{x})}{\frac{1}{n}\sum_{i-1}^{n}(x_i-\bar{x})^2} \qquad (7)$$

If $\frac{-1-1.96\sqrt{n-k}}{n-k} \leq r_k \leq \frac{-1+1.96\sqrt{n-k}}{n-k}$, then the data are defined as serially independent at a 5% significance level. So, the influence of the correlation needs to be eliminated from the dataset before applying the Mann Kendall test.

v) Mann – Kendall Test with Pre-Whitening (PWMK): Pre-Whitening Mann – Kendall test has been recommended by von Storch (1995) and has been further used by Douglas *et al*. (2000) and Zhang *et al*. (2000.2001) to reduce the influence of lag 1 autocorrelation (k=1) component on the application of the MK test:

$$Y_i = X_t - r_1 X_{i-1} \qquad (8)$$

vi) Mann – Kendall Test with Trend Free Pre-Whitening (TFPWMK): The PWMK deals with the influence of serial correlation on the MK test but does not address the potential interaction between trend and autocorrelation when both exist in a time series. Hence, PWMK may give erroneous results if a time series without any auto-correlation has a trend. Therefore, Yue *et al*. (2002) introduced a new technique named Trend Free Pre-Whitening (TFPWMK) for detecting trends in significantly serially correlated hydrological series with the following steps:

1) The slope β of a trend in sample data is estimated by the TSA. If the slope is almost equal to zero, it is unnecessary to continue conducting the trend analysis. If it differs from zero, then it is assumed to be linear, and the sample data are de-trended by:

$$x_i' = x_i - (\beta * i) \qquad (9)$$

where x_i is a hydrologic variable, x'_i is the de-trended variable, β is the TSA slope, and i represents the ith hydrologic variable.

2) The lag– 1 serial correlation coefficient r_1 of the de-trended series x'_i is computed using equation (9), where $k = 1$. The lag– 1 serial correlation coefficient is removed from the de-trended series to get a residual series (y'_i) as below:

$$y'_i = x'_i - (r_1 * x'_{i-1}) \qquad (10)$$

3) This pre-whitening procedure after de-trending the series is referred to as the trend-free pre-whitening (TFPW) procedure. The residual series after applying the TFPW procedure should be independent. The trend ($\beta * i$) is added back to the residual series to get a blended series (y_i):

$$y_i = y'_i + (\beta * i) \qquad (11)$$

4) The MK test is then applied to the blended series (y_i) to assess the significance of the trend.

In many of the recent studies, this method has been used to determine trends in streamflow (Yusoff *et al.*, 2021), rainfall (Mallick *et al.*, 2021), temperature (Gadedjisso-Tossou *et al.*, 2021), etc.

3. Results and Discussion

3-1. Homogeneity Test Result on Rainfall

The Petite test is conducted on the maximum, average, and total rainfall time series of Srimangal and Sylhet. If the p-value is higher than alpha = 0.05, the series is homogeneous. Table 1 presents the summary result of the test and shows that all the datasets are homogenous (p value > alpha = 0.05), which means there is no change of observing site or instruments, or observing practices, or observing time during this time period except non-climatic variations if exists.

3-2. Trend Analysis on Water Level and Rainfall

In this study, the trend analysis was carried out on water level (maximum and relative water level) and rainfall (average, maximum, and total rainfall) time series both graphically and statistically. At first, the best fit line was drawn in each case to observe an upward or downward trend of the hydrological dataset. Visual trend analysis was inspected by graphical plotting in each of the cases, as shown in Figures 2, 3, and 4.

Table 1. Petite Homogeneity test results on rainfall
at 5% significance level

Data Type	Station ID	Station Name	P-value	Before CP	After CP	Comment
AVG	41891	Sylhet	p=0.09695	mu1=8.26	mu2=10.53	Homogenous
	41915	Srimangal	p=0.6114	mu1=5.93	mu2=7.34	Homogenous
MAX	41891	Sylhet	p=0.86755	mu1=182.5	mu2=108.77	Homogenous
	41915	Srimangal	p=0.2023	mu1=82.32	mu2=101.16	Homogenous
TOTAL	41891	Sylhet	p=0.0599	mu1=604.52	mu2=793.34	Homogenous
	41915	Srimangal	p=0.5164	mu1=439.65	mu2=545.89	Homogenous

Later, statistical trend analysis is conducted using the Mann-Kendall test and Sen's slope. However, Lag-1 autocorrelation was determined before statistical trend analysis. The stations having no autocorrelation were directly investigated by the MK test, whereas the stations showing significant autocorrelation were analyzed through TFPWMK. Here, TFPWMK was preferred to PWMK because PWMK deals with the influence of serial correlation on the MK test but does not address the interaction between trend and autocorrelation process. There can be a case where a trend exists in a time series even though the time series does not comprise an autocorrelation process, and in such a situation, the use of PWMK can be erroneous. Hence, TFPWMK, introduced by Yue *et al*. (2002), is preferred for detecting trends in significantly serially correlated hydrological series. Table 2 shows the number of stations showing significant lag-1 autocorrelation (at 5% significance level). It is found from Table 2 that 2 stations (SW 131.5 and SW 314) out of the 13 water level stations show significant lag-1 autocorrelation in case of maximum water level time series. Only one station (SW 131.5) shows significant lag-1 autocorrelation in the case of relative water level time series. Hence, these auto-correlated stations are directly investigated by Mann-Kendall with TFPW, while the rest of the stations are assessed with the conventional Mann-Kendall test. All the statistical tests are conducted at a 5% significance level. The trend analysis results, both statistical and visual, on the maximum water level, average water level, and rainfall (average, maximum, and total) are tabulated in Tables 3, 4, and 5, respectively.

From Tables 3, 4, and 5, it is observed that though positive trends are found in the majority of the stations, all of these are not statistically significant. The trend of maximum water level was significant at 4 stations, among which 2 were with an increasing trend while the others were with a decreasing trend

(Table 3). Six of the 13 stations visually showed an increasingly upward trend, while only 2 showed a statistically significant increasing trend at a 5% significance level. In the case of relative water level, 9 out of 13 stations showed an increasing trend, among which 3 stations showed a significant upward trend (Table 4). No station showed a decreasing trend in the case of the relative water level. So, it can be inferred that though the maximum water level showed both significant upward and downward trend (2 with a decreasing trend and 2 with an increasing trend), the relative water level showed only significant upward trend at 3 stations. This signifies that though the flood peak is not increasing, the total floodwater in the pre-monsoon season is increasing in recent years compared to past years. That means the duration of floods is increasing over time. This may happen due to:

i) increase in rainfall intensity, frequency and pattern due to global warming and climate change,

ii) several flood peaks in one flash flood season,

iii) increase in surface runoff following a rain event and decrease in water-carrying capacity of natural drainage network within the watershed to accommodate the surface runoff,

iv) reduce in land elevations in the floodplain in comparison to the riverbed and sea level,

v) sedimentation of the rivers and siltation of the riverbed,

vi) drainage congestion and waterlogging caused due to unplanned roads and embankments etc., which interferes with the natural flow of surface water in the Haor region and results in a net loss of water-carrying capacity during floods.

As a result, the residence time of the flash flood is increasing in the floodplain. This increase in water depth, flood duration, and high residence period significantly increases the vulnerability of the Boro crop to flash floods.

Table 2. The number of stations showing significant lag-1 autocorrelation at 5% significance level

| Type of Variable		No of total stations	No. of Lag 1 AC stations
WL	Water level	13	2 (SW 131.5, SW314)
	Relative Intensity		1 (SW 131.5)
Rainfall	Average Rainfall	2	-
	Maximum Rainfall		-
	Total Rainfall		-
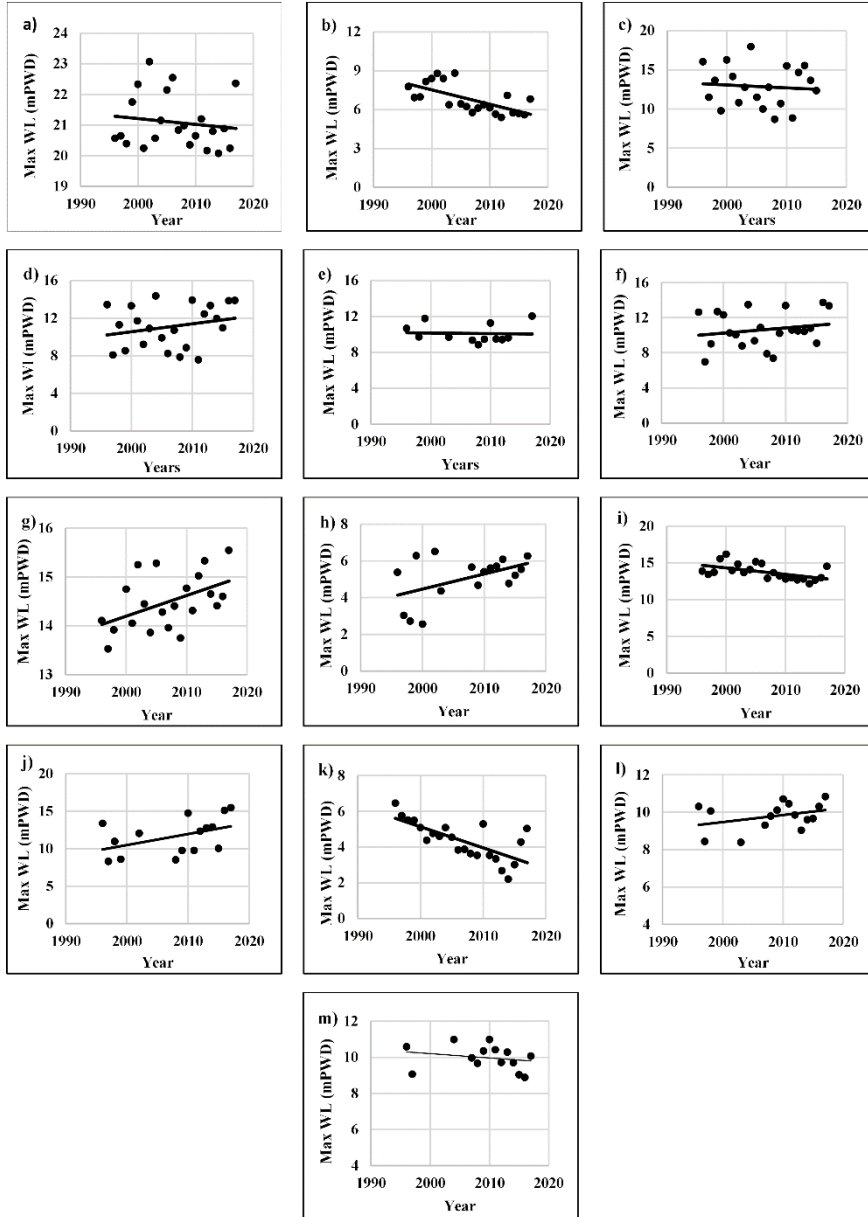
Fig. 2. Trend of maximum water level (mPWD) of flash flood over the years a) SW 34 (Nakuagaon) b) SW 131.5 (Laurergarh Saktiarkhola) c) SW 172.5 (Amalshid) d) SW 173 (Sheola) e) SW 233 (Protappur Piyan Gang) f) SW 251 (Sarighat) g) SW 262 (Bijoypur) h) SW 263.1 (Kalmakanda) i) SW 314 (Ghosegaon) j) SW 326 (Lubachara) k) SW 333 (Muslimpur) l) SW 337 (Urargaon) m) SW 341 (Chella Sonapur)
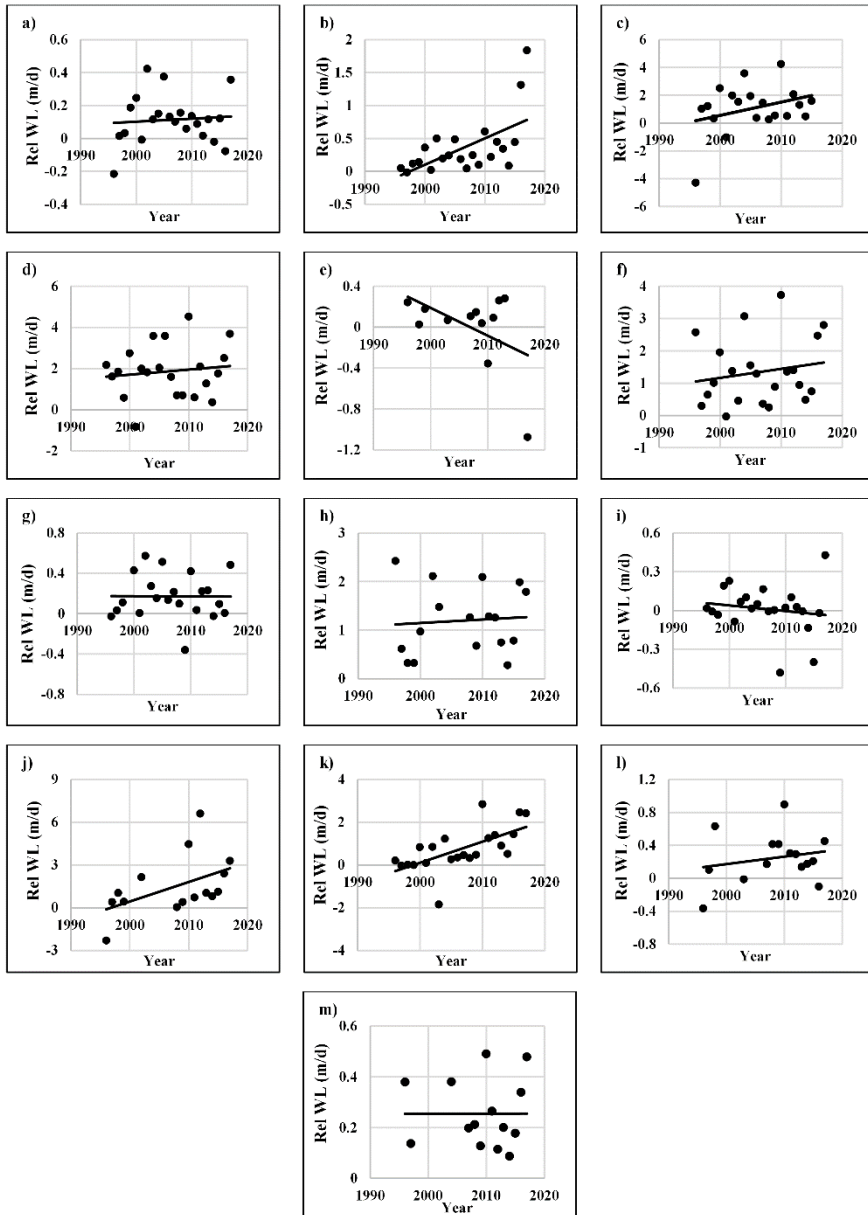
Fig. 3. Trend of relative water level (m/d) of flash flood over the years a) SW 34 (Nakuagaon) b) SW 131.5 (Laurergarh Saktiarkhola) c) SW 172.5 (Amalshid) d) SW 173 (Sheola) e) SW 233 (Protappur Piyan Gang) f) SW 251 (Sarighat) g) SW 262 (Bijoypur) h) SW 263.1 (Kalmakanda) i) SW 314 (Ghosegaon) j) SW 326 (Lubachara) k) SW 333 (Muslimpur) l) SW 337 (Urargaon) m) SW 341 (Chella Sonapur)
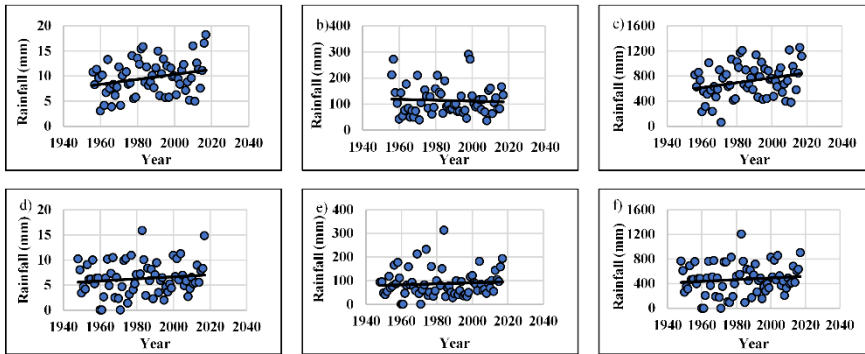
Fig. 4. Trend of a) average, b) maximum and c) total rainfall of flash flood
for 41891 (Sylhet) and trend of d) average, e) maximum, and f) total rainfall
of flash flood for 41915 (Srimangal)

The rainfall of the selected stations showed a positive non-significant trend, but none of these stations exhibited a statistically significant trend at a 5% significant level (Table 5). Here, as Sen's slope is zero and the Z value (0.012) is very low, the maximum water level of Sylhet is designated as no trend. In every case, all of the stations show the same positive or negative trend both statistically and graphically except few stations. The maximum water level trend in SW 233, relative water level trend in SW 34 and SW 341, and maximum rainfall trend in Sylhet (marked with * in Tables 3, 4 and 5) show different significant upward/ downward trends - statistically and graphically. The graphical approach adopted in this study is mainly the least-squares regression method. The least-squares regression method is a parametric statistical method that is not appropriate in the presence of outliers. On the other hand, Sen's slope is a non-parametric and distribution-free method that is robust against outliers (Fernandes and Leblanc, 2005). Hence, few differences are found in cases with very low Z and Sen's slope values.

The statistical trend analysis results on the maximum water level and relative water level of the flash flood are summarized in Figure 5 and Figure 6. The trend results are demonstrated in the figures as - "Positive-Significant", "Positive-Not Significant", "No trend", "Negative-Not Significant", and "Negative-Significant". A summary of the trend analysis on average rainfall, maximum rainfall, and total rainfall is presented in Figure 7.

3-3. Trend Analysis on Flash Flood Peak Period

The occurrence of the annual maximum water level (peak flood) of each year for the 13 gage stations is presented in Table 6, which shows that the total

number of flood peaks found in March is only 23. On the other hand, the number of peaks in May is relatively high, 121 in total. It shows the fact that the flash flood is usually observed in May rather than March. However, in recent years, several flood peaks have been observed in late March to early April, coinciding with the harvesting period of the Boro crop. To investigate this incident, the trend of the flash flood peak is assessed.

The trend of the flash flood peak period cannot be assessed by the statistical Mann Kendall test. Hence, a simple but innovative technique is used to observe the flash flood peak time trend in this study. The peak time of the flash flood (maximum pre-monsoon water level) is plotted against the years in Figure 8. In this figure, specific day-month of the flash flood peaks are plotted against the corresponding years, and the upward and downward trend is observed from the graph. Here, the upward/ positive trend line denotes that the flash flood peak is approaching from March to May. On the contrary, the downward/ negative trend line indicates that the peak of the flash floods is progressing towards March, which further means that the flash flood is occurring earlier compared to the past.

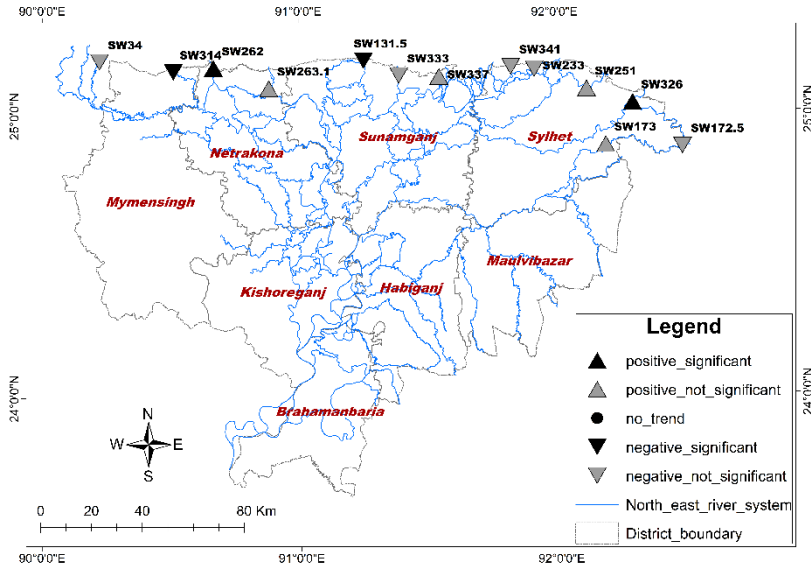**Table 3.** Trend analysis of maximum water level

Station ID	Station	River	n	AC Coefficient (r1)	Lower Band	Upper Band	Lag-1 AC	Visual Trend	Mann Kendall			TFPWMK		
									Test Z	5% Sig.	Sen's Slope	Test Z	5% Sig	Sen's Slope
SW34	Nakuagaon	Bhogai-Kangsa	22	-0.096	-0.488	0.388	No	-	-0.536	(-) I	-0.016			
SW131.5	Laurergarh Saktiarkhola	Jadukata	22	0.523	-0.488	0.388	Yes	-				-2.748	(-) S	-0.085
SW172.5	Amalshid	Kushiyara	20	-0.219	-0.518	0.406	No	-	-0.357	(-) I	-0.046			
SW173	Sheola	Kushiyara	22	-0.131	-0.488	0.388	No	+	0.902	(+) I	0.084			
*SW233	Protappur Piyan gang	Piyan	12	-0.106	-0.720	0.520	No	linear	-0.206	(-) I	-0.004			
SW251	Sarighat	Sari-Gowain	22	0.025	-0.488	0.388	No	+	0.902	(+) I	0.053			
SW262	Bijoypur	Someswari	21	0.031	-0.502	0.397	No	+	2.144	(+) S	0.046			
SW263.1	Kalmakanda	Someswari	17	-0.252	-0.573	0.439	No	+	1.442	(+) I	0.090			
SW314	Ghosegaon	Nitai	22	0.573	-0.488	0.388	Yes	-				-2.567	(-) S	-0.080
SW326	Lubachara	Lubachara	15	-0.040	-0.621	0.467	No	+	2.276	(+) S	0.218			
SW333	Muslimpur	Jhalukhali	22	0.105	-0.488	0.388	No	-	-0.592	(-) I	-0.023			
SW337	Urargaon	Noyagang	15	0.106	-0.621	0.467	No	+	1.140	(+) I	0.041			
SW341	Chella Sonapur	Omayan Chella	14	0.024	-0.649	0.482	No	-	-1.480	(-) I	-0.054			

Note: "+" = upward trend, "- "= downward trend, "S" = significant at 5% significance level, and "I" = not significant at 5% significance level, n = Record Length (years)

Table 4. Trend analysis of relative water level

Station ID	Station	River	n	AC Coefficient (r1)	Lower Band	Upper Band	Lag-1 AC	Visual Trend	Mann Kendall			TFPWMK		
									Test Z	5% Sig.	Sen's Slope	Test Z	5% Sig.	Sen's Slope
*SW34	Nakuagaon	Bhogai-Kangsa	22	-0.105	-0.488	0.388	No	+	-0.226	(-) I	-0.002			
SW131.5	Laurergarh Saktiarkhola	Jadukata	22	0.431	-0.488	0.388	Yes	+				2.446	(+) S	0.025
SW172.5	Amalshid	Kushiyara	20	-0.130	-0.518	0.406	No	+	0.811	(+) I	0.027			
SW173	Sheola	Kushiyara	22	-0.219	-0.488	0.388	No	+	0.226	(+) I	0.009			
SW233	Protappur Piyan gang	Piyan	12	-0.139	-0.720	0.520	No	-	-0.206	(-) I	-0.004			
SW251	Sarighat	Sari-Gowain	22	-0.012	-0.488	0.388	No	+	0.733	(+) I	0.025			
SW262	Bijoypur	Someswari	21	-0.257	-0.502	0.397	No	linear	0.000	No trend	0.000			
SW263.1	Kalmakanda	Someswari	17	0.184	-0.573	0.439	No	+	0.165	(+) I	0.007			
SW314	Ghosegaon	Nitai	22	0.111	-0.488	0.388	No	-	-0.847	(-) I	-0.004			
SW326	Lubachara	Lubachara	15	-0.086	-0.621	0.467	No	+	2.474	(+) S	0.157			
SW333	Muslimpur	Jhalukhali	22	0.241	-0.488	0.388	No	+	3.835	(+) S	0.080			
SW337	Urargaon	Noyagang	15	0.054	-0.621	0.467	No	+	0.446	(+) I	0.005			
*SW341	Chella Sonapur	Omayan Chella	14	-0.068	-0.649	0.482	No	linear	-0.109	(-) I	-0.002			

Note: "+" = upward trend, "- "= downward trend, "S" = significant at 5% significance level, and "I" = not significant at 5% significance level, n = Record Length (years)

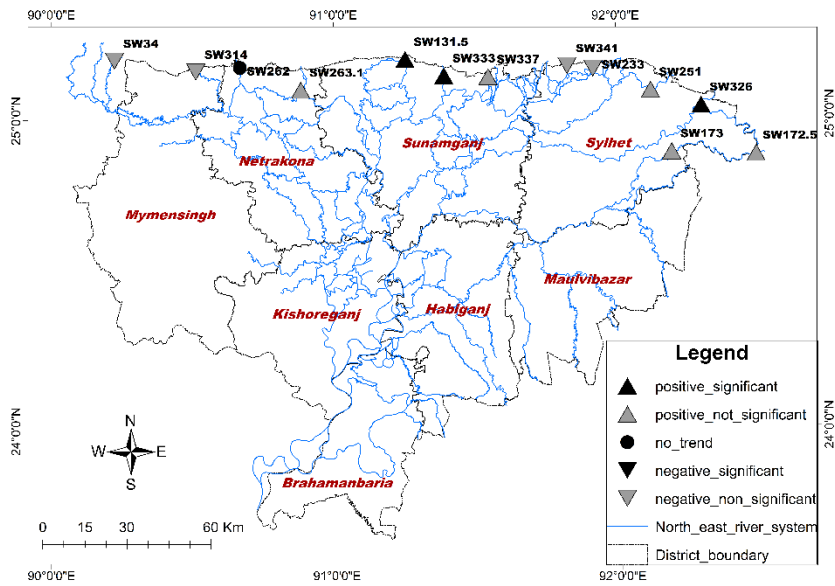**Fig. 5.** Summary of the trend analysis on the maximum water level

Fig. 6. Summary of the trend analysis on the relative water level
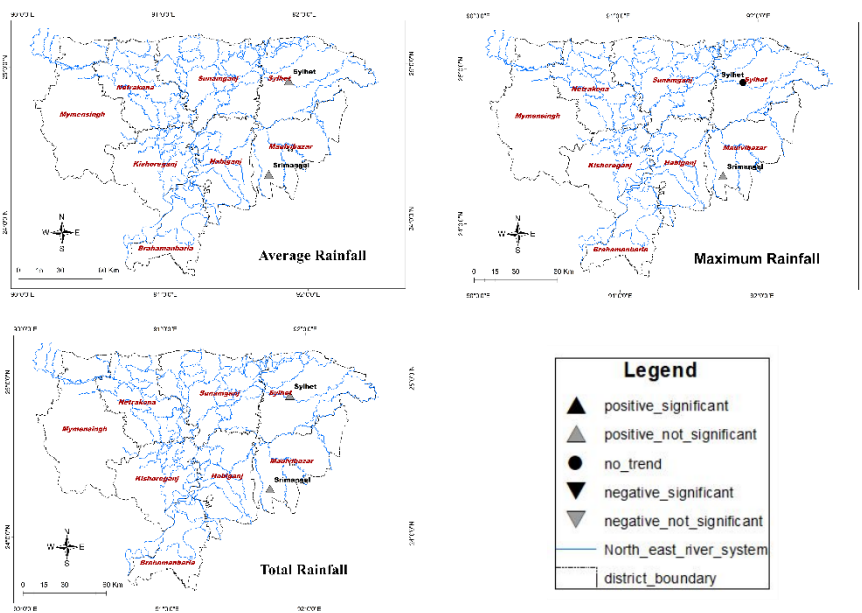

Fig. 7. Summary of the trend analysis on rainfall – average rainfall, maximum rainfall, and total rainfall

Table 5. Trend analysis of rainfall

Type	Index	Station Name	n	Auto Correlation Coefficient (R1)	Lower Band	Upper Band	Lag -1 Auto Corre lation	Visual Trend	Mann Kendall Test		
									Test Z	5% Sig.	Sen's Slope
Avg.	41891	Sylhet	61	0.003327	-0.2721	0.23822	No	+	1.711	(+) I	0.047
	41915	Srimangal	69	0.143409	-0.2543	0.22452	No	+	0.938	(+) I	0.019
Max	*41891	Sylhet	61	0.209205	-0.2721	0.23822	No	-	0.012	No trend	0.000
	41915	Srimangal	69	0.0792	-0.2543	0.22452	No	+	0.870	(+) I	0.230
Total	41891	Sylhet	61	0.006392	-0.2721	0.23822	No	+	1.811	(+) I	3.795
	41915	Srimangal	69	0.111488	-0.2543	0.22452	No	+	1.005	(+) I	1.490

Note: "+" = upward trend, "- "= downward trend,
"S" = significant at 5% significance level,
and "I" = not significant at 5% significance level,
n = Record Length (years)

It can be found from Figure 9 that 10 out of 13 stations showed a downward trend which means that flash flood is advancing towards March-April, much earlier than before. Hence, it can be concluded that the recent climate change phenomena are affecting the flash flood pattern of the Haor region. Flash flood peaks are now approaching towards March-April, which presumes huge loss and damage of the Boro crop of the northeast Haor area. Usually, the harvesting period of Boro starts from the first or second week of April, and all the crops are harvested by the first or second week of May. Though a variety of high-yielding and modern Boro varieties are cultivated nowadays. However, the traditional harvesting period of Boro is yet in between the first week of April and that of May.

Hence, the flash floods of May used to be less harmful for Boro cultivation. But if the timing of the flash flood shifts towards March-April, the Boro crop of the northeast Haor will be damaged severely, which will significantly imbalance the food security of the local people as well as destroy the overall economy of the country. Hence, this changing timeline and early onset of the flash flood can bring catastrophic effects on the Boro cultivation of the northeast Haor area.
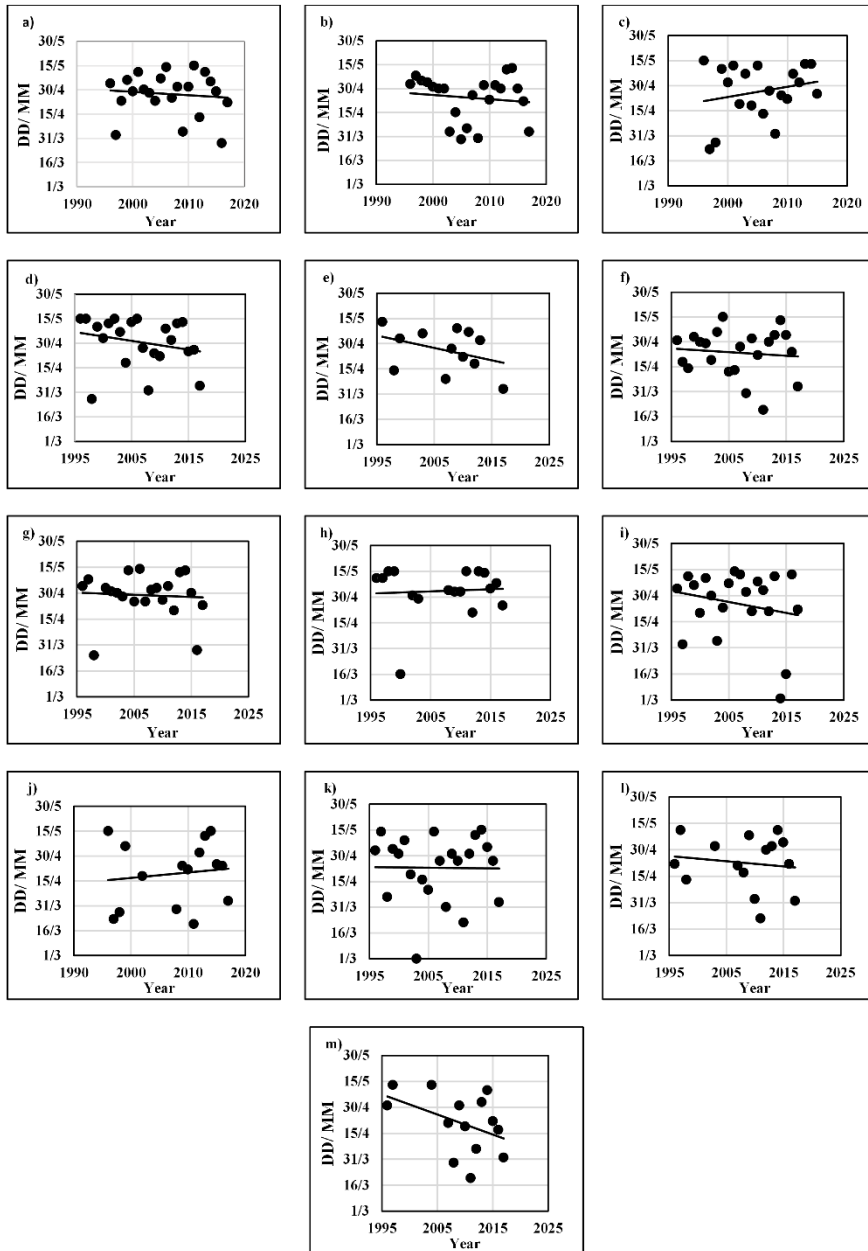
Fig. 8. Plotting of flash flood peak-time (DD/MM means Day/Month) over the years a) SW 34 (Nakuagaon) b) SW 131.5 (Laurergarh Saktiarkhola) c) SW 172.5 (Amalshid) d) SW 173 (Sheola) e) SW 233 (Protappur Piyan Gang) f) SW 251 (Sarighat) g) SW 262 (Bijoypur) h) SW 263.1 (Kalmakanda) i) SW 314 (Ghosegaon) j) SW 326 (Lubachara) k) SW 333 (Muslimpur) l) SW 337 (Urargaon) m) SW 341 (Chella Sonapur)
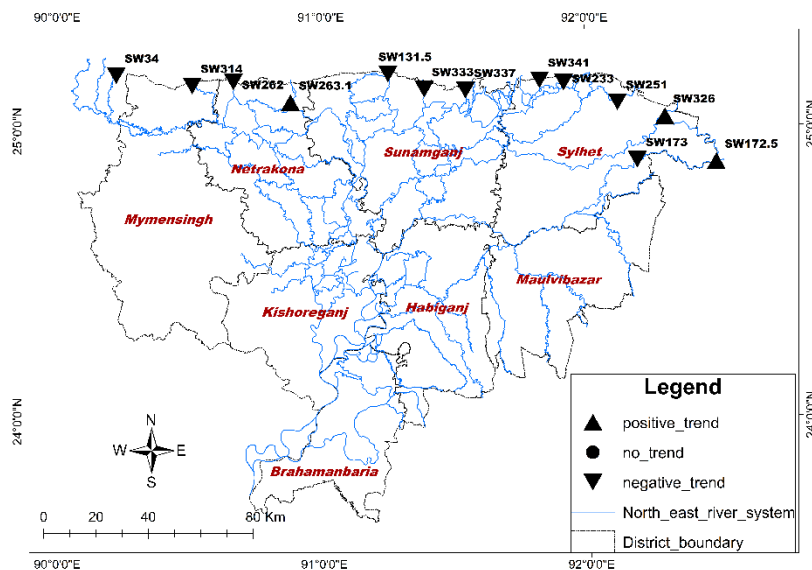
Fig. 9. Summary of the trend analysis on flash flood peak period

3-4. Impact of Flash Flood Peak Time on Boro Productivity

Boro crop in the Haor areas generally faces three major challenges: i) failure of timely crop establishment, ii) cold injury in the reproductive stage, and iii) flash flood damage at the premature to mature stage (Biswas, 2017). The seedbed preparation depends on the time of receding of monsoon floodwater (Jun-Oct) in the Haor area. The early seedbed preparation in October encounters cold shock at the reproductive phase in late February to early March, which may cause severe sterility. On the other hand, the late seedbed preparation in December encounters a flash flood at the late growth stage of the crop. So, the short time window between seeding and harvesting already makes Boro cultivation critical for the farmers. The earlier famous Boro varieties are BR14 in the mid-1980s and BR18, BR19, etc., until the release of the varieties BRRI dhan28 and BRRI dhan29. The other recent popular varieties are BRRI dhan36, BRRI dhan69, etc. BRRI dhan58 is a new introduction that is getting popular as its growth duration is in between BRRI dhan28 and BRRI dhan29, and quality is similar to BRRI dhan29. BRRI dhan88 is another recent rice variety released in 2018 and is cultivated in some of the areas of the northeast Haor region as confirmed by a Local Agriculture Officer of Netrokona. The harvesting time of BRRI dhan88 is nearly 7 days earlier than BRRI dhan28. Hence it is highly recommended for Haor regions.

Table 7 presents the seeding and harvesting time of primary varieties of Boro rice and their associated flash flood risk. The timelines of different Boro varieties are mostly taken from Rashid & Yasmeen (2017) and BRRI (2021) and later, cross-checked with local farmers and Local Agriculture Officer. The seeding dates may vary by one or two weeks as it depends on draining out of the water from Haors. The harvesting dates may also vary by one or two weeks due to the unavailability of the laborers/late or early maturity of the crops. In the current study, the flash floods occur in late April (3rd week) to early May (1st week) and onwards are classified as "Normal Flash Flood", and the ones that occur in and before late March (3rd week) to early April (2nd week) are classified as "Early Flash Flood". It is observed that the previous variety BR18 has early harvesting compared to BR14. Hence, BR18 is free from the "Normal Flash Flood" risk but not free from the "Early Flash Flood" risk. Among the two mega varieties BRRI dhan28 and BRRI dhan29, the BRRI dhan28 was highly popular among the farmers due to its early growth. However, the recent flash floods around late March (e.g., flash flood of 2017) to early April (e.g., flash flood of 2019) cause a lot of damage to BRRI dhan28. Besides, BRRI dhan36, BRRI dhan69, BRRI dhan88 are special rice variants that were introduced with a shorter growth period to save Boro from the normal flash flood. However, since the onset or peak of the flash flood intending towards March last week to April 1st week, none of these varieties are safer anymore. To save the Boro rice crop from early flash floods, we need to develop Boro rice varieties with a shorter growth duration and cold-tolerant during the reproductive stage. Only then Boro crops might be safe against early flash floods through early harvesting.

The people of Bangladesh are aware of the usual flash flood around late April to the 1st week of May, but not with a flash flood that happened recently from the last week of March to the 1st week of April. The policymakers are now expecting a very short-duration variety that could be harvested by the last week of March. The best way to eliminate the flash flood damage is to have a variety of growth duration at best 120-130 days with cold tolerance at the reproductive phase. To develop such a variety, we have to find parent(s) having a short growth duration and the ability to tolerate the cold at the reproductive phase. BRRI has already collected some cold-tolerant parents from Nepal. Some of the genotypes like IR77496-31-2-1-3, IR77504-36-3-3-1, BR7528-2R-20-1, IR73789-19-1, IR62266-42-6-2, PSBRC68, BG358-1, BG358-3 have tolerance at the reproductive stage (Biswas, 2017). IRRI and Rural Development Administration in Korea is also working with IRRI breeding lines like IR66160-121-4-4-2 and more through the classical molecular approach (Biswas, 2017).

The short-duration varieties could be harvested from the Australian rice varieties too. BRRI should communicate with relevant scientists and exploit the potentialities of the different breeding varieties available in Bangladesh as well.

Table 6. Number of flood peaks in March, April, and May 1st-May 15th

Station ID	Station	n	Peak at March	Peak at April	Peak at May 1st - May 15th
SW34	Nakuagaon	22	1	10	11
SW131.5	Laurergarh Saktiarkhola	22	2	11	9
SW172.5	Amalshid	20	2	8	10
SW173	Sheola	22	1	8	13
SW233	ProtappurPiyan	12	0	6	6
SW251	Sarighat	22	2	12	8
SW262	Bijoypur	21	2	8	11
SW263.1	Kalmakanda	17	1	3	13
SW314	Ghosegaon	22	2	8	12
SW326	Lubachara	15	4	6	5
SW333	Muslimpur	22	3	8	11
SW337	Urargaon	15	1	8	6
SW341	Chella Sonapur	14	2	6	6
	Total Event		23	102	121

Note: n = Record Length (years)

Table 7. Seeding and Harvesting of major Boro crops and associated flash flood risk

Boro Variety	Date of Seeding	Date of Harvesting	*Normal Flash Flood Risk	*Early Flash Flood Risk
BR14	4 Nov	3rd week Apr	✓	✓
	19 Nov	4th week Apr	✓	✓
BR18	30 Oct	1st week Apr	✗	✓
	14 Nov	2nd week Apr	✗	✓
BRRI dhan28	1 Nov	1st week Apr	✗	✓
	15 Nov	2nd week Apr	✗	✓
BRRI dhan29	1 Nov	3rd week Apr	✓	✓
	15 Nov - 30 Nov	4th week Apr - 2nd week May	✓	✓
BRRI dhan36	1 Nov	1st week Apr	✗	✓
	15 Nov	2nd week Apr	✗	✓
BRRI dhan58	20 Nov	3rd week Apr	✓	✓
	16 Dec	4th week Apr - 1st week May	✓	✓
BRRI dhan69	1 Nov	2nd week Apr	✗	✓
	15 Nov	3rd week Apr	✓	✓
BRRI dhan88	15 Nov	1st week Apr	✗	✓
	30 Nov	2nd week Apr	✗	✓

Note: * Here, "✓" means 'yes' flood risk and "✗" means 'no' flood risk

4. Conclusion

In this study, the trend of flash floods of the northeast Haor region of Bangladesh was analyzed based on the water level, rainfall, and peak period of the flash flood. The study was carried at thirteen water level gage stations and two rainfall gage stations near the Bangladesh-India border, where the flash flood water comes first from Meghalaya. The petite homogeneity test confirms that the rainfall data are homogenous at the selected stations. The trends of water level and rainfall were assessed by statistical Mann-Kendall and TFPWMK tests along with visual observations. The stations having no autocorrelation were directly investigated by the MK test, whereas the stations showing autocorrelation were analyzed through TFPWMK.

From the best-fit plots, both water level and relative water level show a high upward trend indicating a potential of high magnitude flash flood in the near future. However, the number of stations showing significant statistical trends (5% significance level) was not many. For most of the stations, the trend on the water level was found statistically insignificant at a 5% significance level. The number of stations showing a significant trend on maximum and the relative water level was 4 and 3, respectively. It was also found that the maximum water level showed statistically significant upward (2 stations) and downward (2 stations) trends at 4 stations, but the relative water level showed only significant upward trends at 3 stations. This justifies the fact that though the peak of flash floods was not increasing, the overall floodwater in the pre-monsoon season is increasing significantly, which may cause long-term waterlogging and drainage congestion and ultimately, leading to massive loss and damage to Boro crop. It is also found that though rainfall showed an increasing trend, no statistically significant trend (either upward or downward) was observed.

The trend analysis in peak periods of flash flood events showed downward slopes, which denotes an early shift in the peak time of the flash flood. The peak period of the flash flood is approaching towards March-April, indicating early onset of flash flood and catastrophic damage of Boro crop. This is worrisome because more rainfall in late March and early April means increased early flash floods incidents in the Haor region. All the popular Boro variants such as BRRI dhan28, BRRI dhan36, BRRI dhan69, BRRI dhan88 were introduced to save Boro in normal flash floods, and none of these are efficient in combating early flash floods. So, it will cause havoc on the Boro crop in the future. Hence, it can be concluded that the climate change phenomena have an influence on the water level, rainfall, and early onset of

the flash flood. Though this influence hasn't crossed the limit of 5% significance level yet, this could increase exponentially in the future in manifolds. Hence, this increasing trend must be kept in mind while implementing structural and non-structural interventions concerning flood risk management in the region. For example, more varieties of BRRI should be introduced, which can be harvested by the last week of March before the flash flood hits the Haor region. Also, varieties having a growth duration at best 120-130 days with cold tolerance at the reproductive phase should be given priority. Also, the Boro plantation dates depend on draining out of the monsoon floodwater from Haors, which can be delayed to early December due to unplanned infrastructure constructions (roads, embankments, etc.) and drainage systems. Local influential people also sometimes help to delay draining out the water as it helps to get more fisheries. Hence, the drainage congestion and water logging problem after the monsoon flood and during the pre-monsoon period should be improved by increasing the water-carrying capacity of the drainage network in the entire watershed. Crop insurance can be introduced with the subsidized premier by the Government to save the farmers from huge loss and damage from Boro crops. In this way, we might protect the Boro crop and overall agriculture of the northeast Haor region of Bangladesh from flash floods in the upcoming days.

5. Acknowledgements

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Supplementary Materials

Supp. Table 1. List of Selected Water Level Stations (BWDB) of the northeast Haor region

No.	Station ID	Station	River	District	Latitude	Longitude	Type
1	SW34	Nakuagaon	Bhogai-Kangsa	Sherpur	25.192	90.224	NTWL
2	SW131.5	Laurergarh Saktiarkhola	Jadukata	Sunamganj	25.193	91.254	NTWL
3	SW172.5	Amalshid	Kushiyara	Sylhet	24.878	92.492	NTWL
4	SW173	Sheola	Kushiyara	Sylhet	24.887	92.194	NTWL
5	SW233	Protappur_Piyan	Piyan	Sylhet	25.157	91.919	NTWL
6	SW251	Sarighat	Sari-Gowain	Sylhet	25.087	92.121	NTWL
7	SW262	Bijoypur	Someswari	Netrokona	25.169	90.668	NTWL
8	SW263.1	Kalmakanda	Someswari	Netrokona	25.096	90.880	NTWL
9	SW314	Ghosegaon	Nitai	Mymensingh	25.155	90.512	NTWL
10	SW326	Lubachara	Lubachara	Sylhet	25.036	92.300	NTWL
11	SW333	Muslimpur	Jhalukhali	Sunamganj	25.139	91.390	NTWL
12	SW337	Urargaon	Noyagang	Sunamganj	25.134	91.547	NTWL
13	SW341	Chella Sonapur	Omayan Chella	Sunamganj	25.167	91.827	NTWL

Supp. Table 2. List of Selected Rainfall Stations (BMD) of the northeast Haor region

No.	Index	Station Name	District	Latitude	Longitude
1	41891	Sylhet	Sylhet	24.90	91.88
2	41915	Srimangal	Srimangal	24.30	91.73