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Climate Variability & Establishment of Rainfall Threshold Line for Landslide Hazards in Rangamati, Bangladesh

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Abstract

This study aims to evaluate the impact of extreme rainfall events on landslides under current and past climate scenarios. Rainfall-triggered landslides are analyzed by rainfall estimates, derived using statistics of events. It is established that recent climate changes, mainly temperature and rainfall patterns have significantly increased the rainfall-induced landslide hazards in the Rangamati district, Bangladesh. It is also observed that the temperature and rainfall of Rangamati had increased gradually during the last 40 years (1981-2021). On 13 June 2017, a series of landslides triggered by heavy monsoon rains (300 mm/24 h) occurred and killed more than 112 people in the Rangamati hill district, Bangladesh. The highest annual decade rainfall is 3816 mm, recorded in 2010-21. A relationship between causalities and the number of events has also been established. The analysis shows that both antecedent and single-day major rainfall patterns can influence sliding events. It is established that monsoonal rainfall (June-September) can significantly influence catastrophic landslide hazard events. Finally, two rainfall threshold lines for the researched area are constructed based on antecedent and single-day major rainfall occurrences, as well as the number of fatalities caused by landslides. Total rainfall of 100 mm (16.66 mm/day) during six days appears to define the minimum rainfall that has led to shallow landslides/slope failures, while 210 mm (35 mm/day) within six days appears to define the lowest rainfall that could be a cause of catastrophic landslide in Rangamati district.

Keywords

Climate Change, Antecedent Rainfall, Rainfall Threshold, Catastrophic and Landslide

1. Introduction

Bangladesh's unique geographic situation and extreme reliance on nature make it one of the most susceptible to the effects of global climate change in the coming decades. With mountains and hills encircling almost three-fourths of the nation, along with the channel-shaped Bay of Bengal in the south, the nation has become a meeting place for thunderstorm rain that brings life, but it also places it at risk for the devastating devastation caused by natural disasters. Its physiography and swash morphology also aid in catastrophe reenactment. On June 13, 2017, Bangladesh, particularly Rangamati, felt the effects of climate change. This is a very important issue for environmental and development issues.

Although many studies [1] [2] [3] [4] [5] have discussed various climatic hazards of Bangladesh, its geographical position, geological situation, near flat topography or low relief of the floodplains, low river gradients, low-lying deltaic land, heavy monsoon rainfall, enormous sediments discharge from the Himalayas, and rising temperatures both at land & sea exposes and sporadically evaluate the problem [6] [7] [8]. The geographic situation and its climatic elements are shown in **Figure 1**.

Climate change, including variations in temperature, precipitation, and humidity, affects the countryside. Excessive rainfall and temperature rise during the summer monsoon may make landslides more likely. In the context of accelerating globalization processes, climatic variability and change create new vulnerabilities. Bangladesh has already noticed the effects of climate change, such as monsoonal variation (hotter, irregular, premature rainfall, heavy rainfall over a short period causing landslides). The frequency and severity of extreme weather events or climatic risks may change as a result of a changing climate [9] [10]. This effect might make it harder for Bangladesh and other developing nations to achieve sustainable development.

The main factor causing climate dangers in Bangladesh is rainfall fluctuation. In Bangladesh, drought is brought on by high rainfall variability and heavy rainfall, which results in floods, flash floods, and landslides [11]. Due to inconsistent and incomplete landslide records and the availability of precipitation information, the relationship between precipitation and landslides is frequently complex [12]. Academics have been interested in the connection between climate and landslides because rainfall is the most frequent cause of landslides in many parts of the world [12]. Landslides caused by rainfall are triggered by an increase in groundwater pressure. Although rainfall is one factor contributing to landslides in Bangladesh, research is ongoing to determine the empirical relationship between rainfall and landslide incidence, including the minimum amount of rainfall needed to trigger landslides. The heavy monsoon season in Bangladesh's Rangamati hill district resulted in several landslides. On June 13, 2017, a series of landslides brought on by intense monsoon rains (300 mm/24 h) in Bangladesh's Rangamati hill district killed over 160 people. This calamity resulted in significant losses. This calamity utterly destroyed Rangamati's transportation and

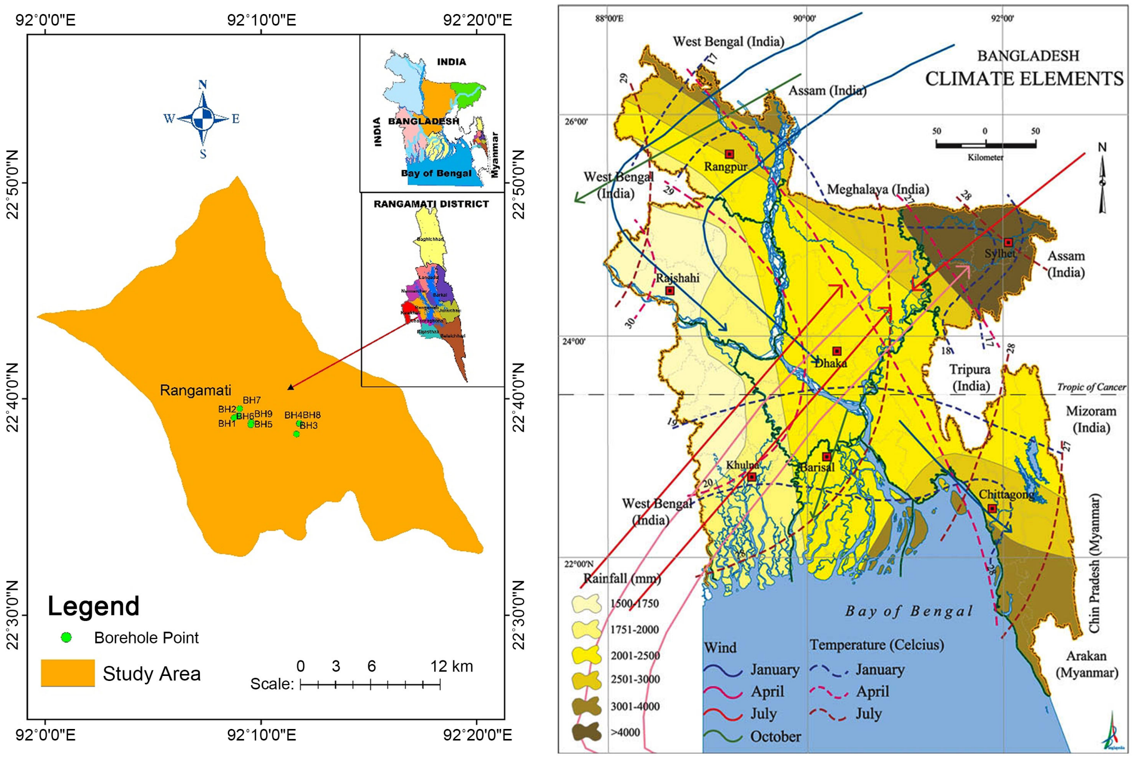


Figure 1. Location Map of Rangamati Sadar area and surroundings with climatic elements (Source: Banglapedia).

communication systems. The analysis of the observed correlation between precipitation features and previous landslide events is the basis for the prediction of landslides triggered by precipitation as of right now [13].

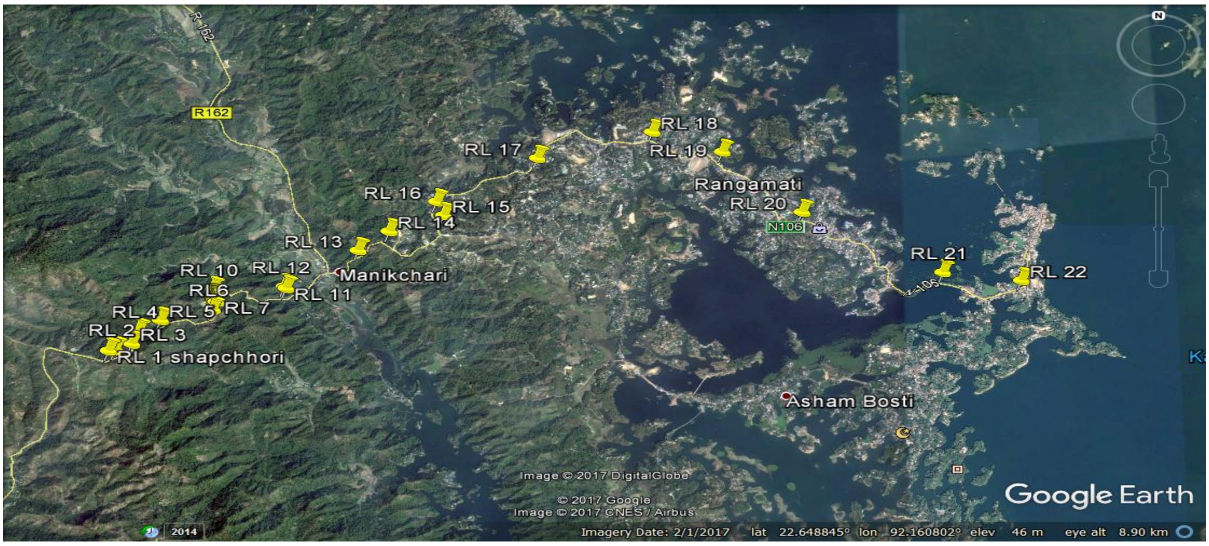
Landslides

Landslides are a major problem throughout the world due to their disastrous impact [14]. Landslides are occurring increasingly regularly in Bangladesh. Both a physical method (such as high-resolution image-based and supporting data) and an empirical method (such as rainfall datasets) can be used to calculate the threshold.

A threshold may specify the amount of rainfall, soil moisture, or hydrological conditions that when achieved or surpassed, are likely to cause landslides in rainfall-induced landslides [15] [16] [17]. Hossain *et al.* [18] Defined the empirical method to establish rainfall thresholds lined by three groups firstly, the threshold line obtained from rainfall data for specific landslide events. Secondly, it's based on cumulative or antecedent rainfall conditions and incorporates hydrological thresholds. The authors used the first and second methods to establish the rainfall thresholds line for landslide hazards in Rangamati, Bangladesh.

The geological structure of Bangladesh's hilly districts presents several risks, such as landslides or mudslides are shown in **Figure 2**.

Landslides are caused by rainfall by loosening the soil packing, altering pore water pressure inside the soil, and making the hills' soils heavier [18]. In recent years, Rangamati has had heavy rainfall, which has worsened the landslide situation by increasing the frequency of landslide hazard incidents. Small or significant monsoonal rainfall often causes the majority of these landslides.



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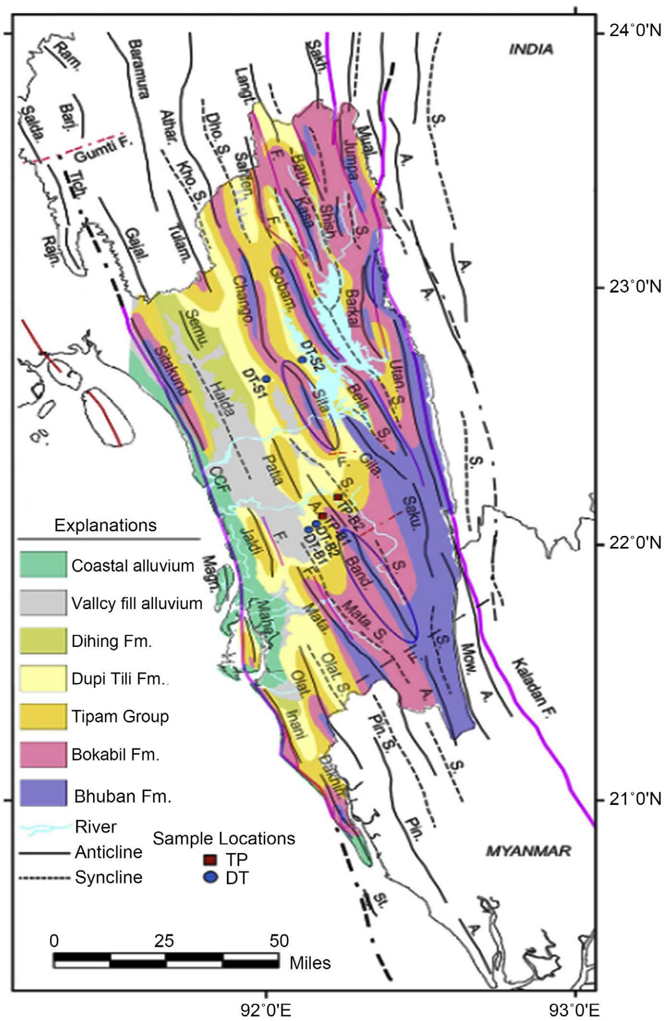


(b)

Figure 2. Simplified geological and tectonic map of the Chittagong-Tripura Fold Belt (CTFB) area of the Bengal Basin (modified after Hossain *et al.* 2019) and occurred landslide point on 13 June 2017.

Heavy rains in Rangamati in recent years have made the landslide scenario worse by increasing the frequency of landslide danger situations. The bulk of these landslides are frequently caused by small or considerable monsoonal rainfall. [19] [20] noted the research region as a highly high susceptibility zone for Rangamati landslide hazards due to both natural disasters like precipitation and human activity like hill cutting and development. Understanding the rainfall patterns that cause landslides is so essential. [21] examined rainfall data from the Cox's Bazar rain gauge station and demonstrated that the trend in precipitation from 1980 to 2015 is rising with time. This type of monthly pattern of rainfall also impacts groundwater levels. Antecedent precipitation also influences rainfall thresholds [22]. High-intensity, brief rainstorms without any prior precipitation caused debris flows and shallow slides to form in colluvium and weathered rocks.

This issue has been thoroughly explored over the past few decades to determine the threshold for describing when a landslide is anticipated to occur [18] [23]-[28]. According to [29] the Rangamati district in Bangladesh utilized a similar method to assess the impact of recent rains and set a threshold for landslide events. In the past several years, there has been considerable growth in the analyses and techniques used to determine a threshold, including the use of advanced statistical techniques and landslide susceptibility levels [30] [31] [32]. The research aims to establish a rainfall threshold line for shallow landslide hazards in the study area.

2. Materials and Methods

The Climatic Division of the Bangladesh Meteorological Department (BMD) provided rainfall information for Rangamati for the past 40 years. The data were chosen based on their availability, maximum data length accuracy, and consistent spatial distribution. The suspected data were eliminated and designated as blank after these observed data were visually examined. There is no national database for landslide hazards in Bangladesh. Various government and non-government organizations, such as Banglapedia, the Comprehensive Disaster Management Program (CDMP II), the Bangladesh Bureau of Statistics (BBS), the Bangladesh Network Office for Urban Safety (BNUS), the Asian Disaster Preparedness Center (ADPC), the Bangladesh Disaster Report, as well as several daily newspapers and online news sources, were used to compile the data on recent landslides.

The annual and seasonal data were prepared, processed, and plotted using the monthly in-situ data. According to [33] the data for December from one year was combined with the data for January and February of the following year to represent the winter value of the following year and a similar method was used for all other seasons when calculating seasonal values. Using the 2016 version of Microsoft Excel, all data were examined. To interpret the impact of rainfall on the landslides, correlation, and regression of rainfall data were studied, compared, and evaluated using MS Excel. The rainfall threshold lines for landslide hazards of [29] [34] [35] [36] approaches are established.

3. Results and Discussions

3.1. Analysis of Climatic Parameters

The surface air temperature and rainfall data of the last forty (40) years (1981-2021) the of Rangamati area have been analyzed to assess the trends of mentioned climatic parameters. The temperature and rainfall data of the study area maintained by BMD have been shown in **Figure 1** to visualize the climatic conditions of the Rangamati area very accurately and distinctly.

3.2. Temperature Data Analysis

The trends of temperature have been analyzed for the research area using data from 40 years (1981-2021). The seasonal and annual variation of temperature of the Rangamati area is illustrated here.

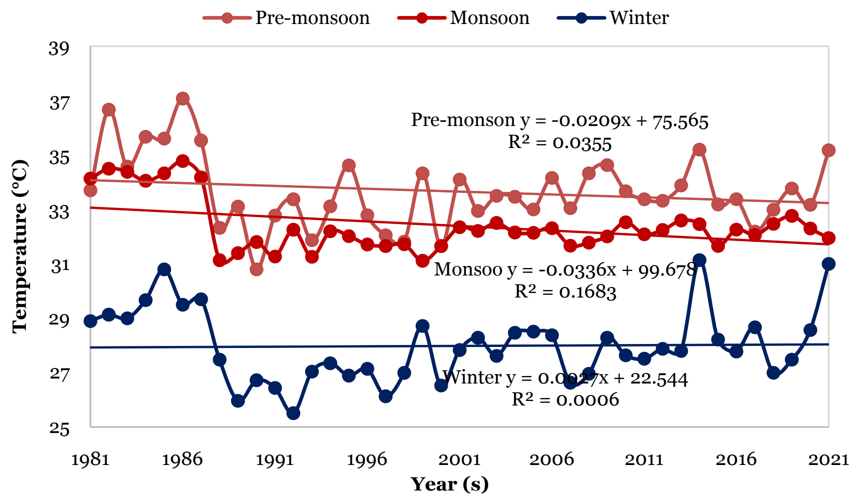
3.2.1. Seasonal Variation in Temperature

The seasonal trend analysis of temperature during the last 40 years based on observed data from Rangamati stations is discussed below. **Figure 4** shows that at Rangamati in winter, the maximum temperature was highest at 31.6˚C in 2010 and lowest at 27.17˚C in 2018. In the case of monsoon, the highest 36.73˚C and the lowest 31.68˚C maximum temperature were recorded in 2003 and 2017 respectively, while the minimum highest 25.98˚C and lowest 24.1˚C were in 2019 and 2017 respectively. In pre-monsoon, the highest was 38.27˚C and the lowest was 32.17˚C in 2010 and 2017 respectively, whereas the highest was 23.43˚C in 2016 and the lowest was 20˚C in 1984 minimum temperature recorded.

Considering the three seasons, it is clear that the monsoon's maximum and minimum temperatures were the highest (**Figure 3**). The increasing trend of maximum temperature was highest in monsoon (R = 0.1683) compared to other seasons namely; winter (R = 0.0006) and pre-monsoon (R = 0.0355) respectively (**Figure 3**). Moreover, minimum temperature showed an increasing trend for all seasons, where monsoon (R = 0.1016) depicted the highest increasing trends followed by winter (R = 0.2344) and pre-monsoon (R = 0.0068) respectively (**Figure 4**).

3.2.2. Annual Variation of Temperature

The annual temperature analysis shows that Rangamati station gives a positive trend in maximum temperature but an increasing rate at minimum temperature with a negative trend. The highest maximum surface temperature was 34.91˚C in the 2010 year and the lowest was 31.7˚C in 2017. After 2010 the surface temperature decreased trend and in 2017 it reached the lowest temperature and then increased the temperature trend till recent years. The maximum surface temperature is increasing by 0.0012˚C per year while the increasing rate of minimum surface temperature is 0.0176˚C/year from 1981 to 2021 (**Figure 4**).



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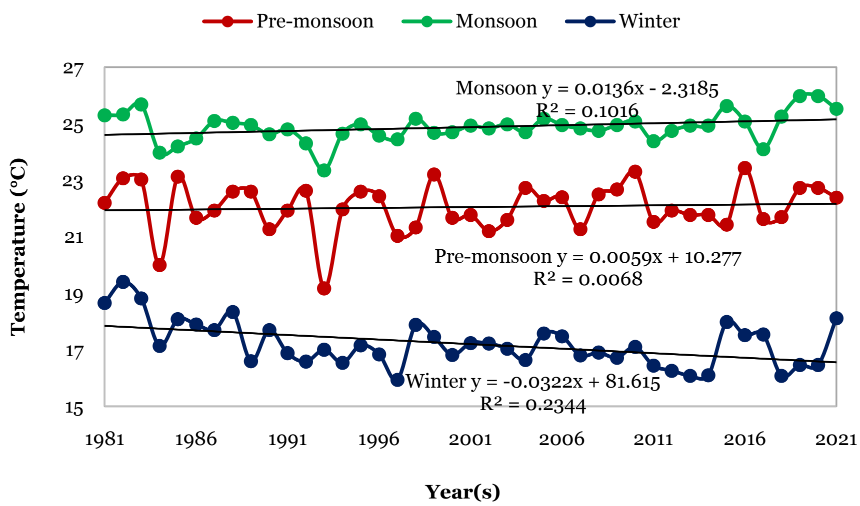

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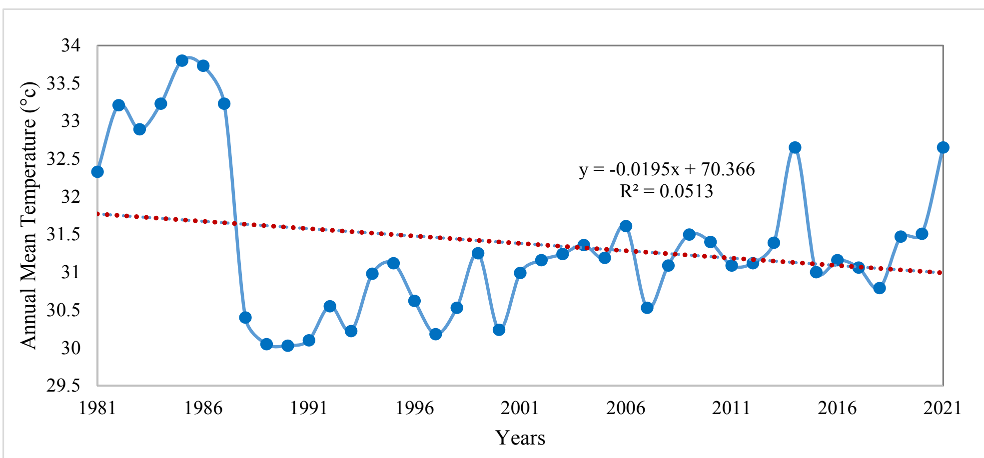
Figure 3. Seasonal maximum (a) and minimum (b) temperature variation of Rangamati Area's station from 1981-2021.



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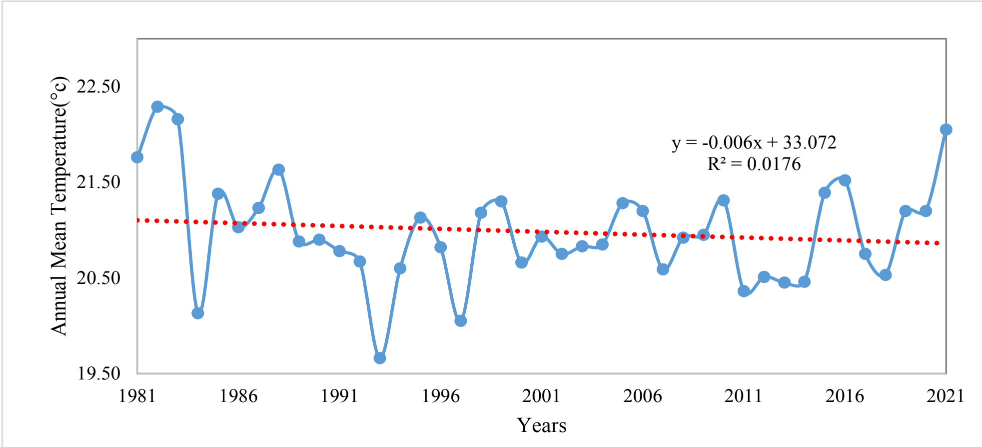


(b)

Figure 4. Annual average temperature variation of Rangamati Area's (a) Maximum temperature (b) Minimum temperature from 1981-2021.

3.3. Rainfall Data Analysis

The variation of average precipitation concerning months, seasons, and year's data is presented and also their pattern of change is discussed in the research area. Statistical analysis has been undertaken to analyze temporal rainfall variation and trends in the Rangamati area.

3.3.1. Seasonal Variation of Rainfall

From a meteorological point of view, there are four distinct seasons in Bangladesh-winter (December-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-November) [37]. The highest percentage of annual rainfall during monsoon seasons falls on Bangladesh's Chittagong and Chittagong Hill Tracts, where it exceeds 82% [33]. The lowest percentage of annual rainfall during monsoon seasons falls on Srimangal, where the Rangamati area is approximately 60% - 62%. Over 300 mm of rain fell in the Chittagong Hill Tracts in the 24 hours leading up to June 13th, 2017. Huge landslides were caused by this torrential rain in the three districts of Rangamati, Bandarban, and Chittagong.

The attached **Figure 5** displays rainfall totals of 717 mm from NASA satellite-based data from the Integrated Multi-satellite Retrievals (IMERG) for the Global Precipitation Mission (GPM) on June 12-14, 2017.

According to **Figure 6**, there has been an increasing trend for monsoon, pre-monsoon, and post-monsoon seasons over Rangamati throughout the past 40 years (1981-2021), while there has been a declining trend for winter seasons. In contrast to the pre-monsoon season, which exhibits a slightly falling tendency, the winter season exhibits a slightly increasing trend with a regression value (R^2) of 0.000003 mm/year. The overall trend during the monsoonal and post-monsoonal seasons is upward, with regression values (R^2) of 0.007 mm and 0.0022 mm per year, respectively.

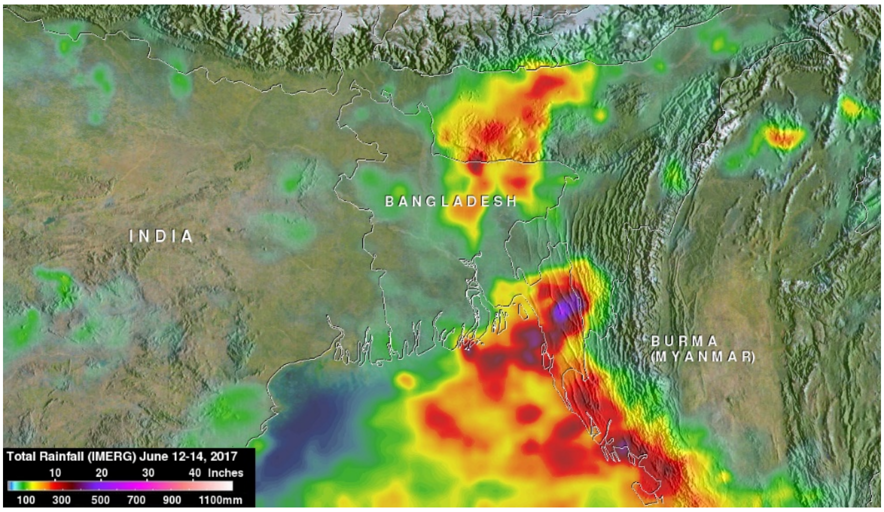


Figure 5. Bangladesh's Heavy Rainfall Examined with NASA's IMERG (NASA).

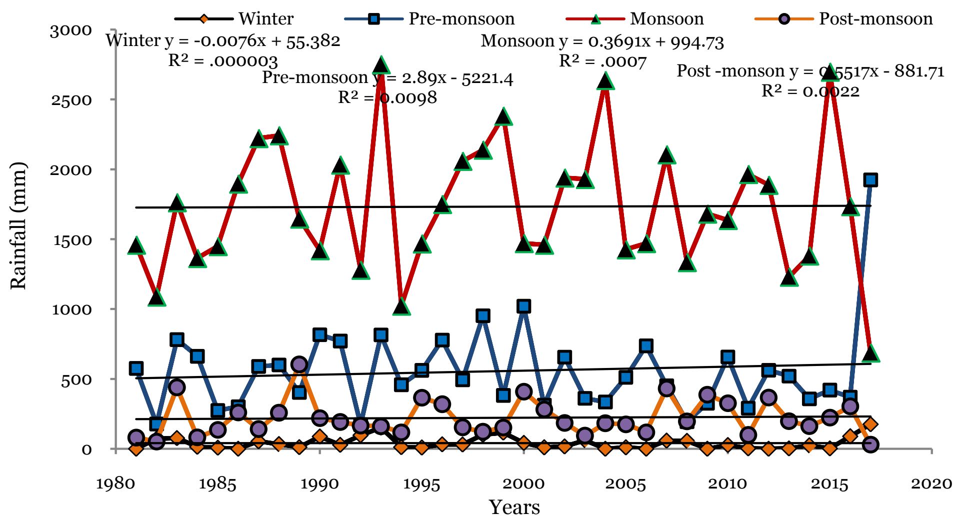


Figure 6. Seasonal rainfall variations & trends in Rangamati (1981-21).

From this study, it has been noted that monsoons produce the heaviest rainfall (1500 mm to 2700 mm) of any other season. This examination of seasonal rainfall also reveals that the monsoon season has the highest rainfall totals while the winter has the lowest. It has been distinguished that the monsoon season also has the greatest fluctuation in rainfall. The inter-annual variability in the study area is shown by the time series plots of seasonal rainfall. While [36] noted that yearly rainfall in the rainy season accounts for 72% of rainfall in the summer season, the summer monsoon is the primary rainy season in our country, accounting for roughly 68 percent of annual rainfall during the summer monsoon season.

Complete secondary data sets of meteorological parameters from weathering monitoring stations in the Rangamati district were used for the past 40 years (1981-2021) to better understand the changing pattern of climatic conditions (especially temperature and rainfall). The average temperature was a maximum

(32.65˚C) and a minimum (20.98˚C) in 2010-2021. Whereas, the average temperature from 2000-2009 was (31˚C) and the minimum was (20.90˚C). Moreover, the highest rainfall (3816 mm) was recorded in 2010-2021 and the lowest (1388 mm) in 1981-1989 while the average rainfall of 2000-2009 (2507 mm).

It is observed that from this study of rainfall variation and trend over the Rangamati area is an increasing trend of annual rainfall but there is a decreasing trend of seasonal rainfall of pre-monsoon and winter periods in the investigated area.

3.3.2. Annual Variation of Rainfall

As mentioned earlier, all the rainfall data is provided by Bangladesh Meteorological Department (BMD), there is a rain gauge station at Rangamati Sadar maintained by BMD. This data is later correlated with the landslide event data to establish the threshold line.

It is observed from **Figure 6**, the annual rainfall trend is showing an increasing trend with a regression $R^2 = 0.0131$ mm/year. From the two decades of data, a decadal maximum increase in rainfall data is also observed in 1993 & 2017. The increasing annual rainfall trend showed in **Figure 7**.

3.3.3. Monthly Variation of Rainfall

The monthly rainfall distribution for the last four (4) decades has shown a significant difference (**Figure 8**) between the wet (April-September) and the dry (October-March) seasons (**Figure 5**). Most (~90% of total landslides) of the landslides events in the area occurred between June to August during the highest rainfall months in the wet period of the year. About 95% of the total landslides occurred in June (with average monthly rainfall of >1733 mm) during the period from 1981 to 2021. From all the monthly variations in the rainfall graph, it is established that the highest amount of precipitation occurred in the monsoonal period (June -September). But in recent times, maximum precipitation has increased from May to October.

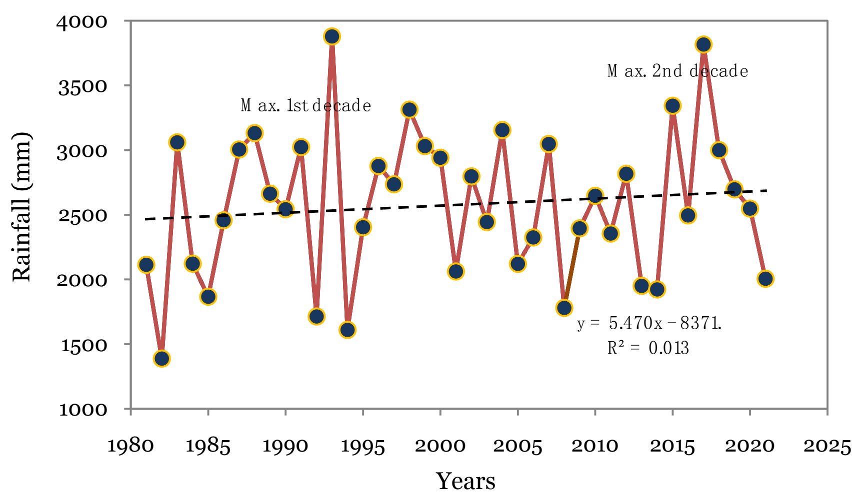


Figure 7. Increasing annual rainfall in Rangamati from 1981-to 2021.

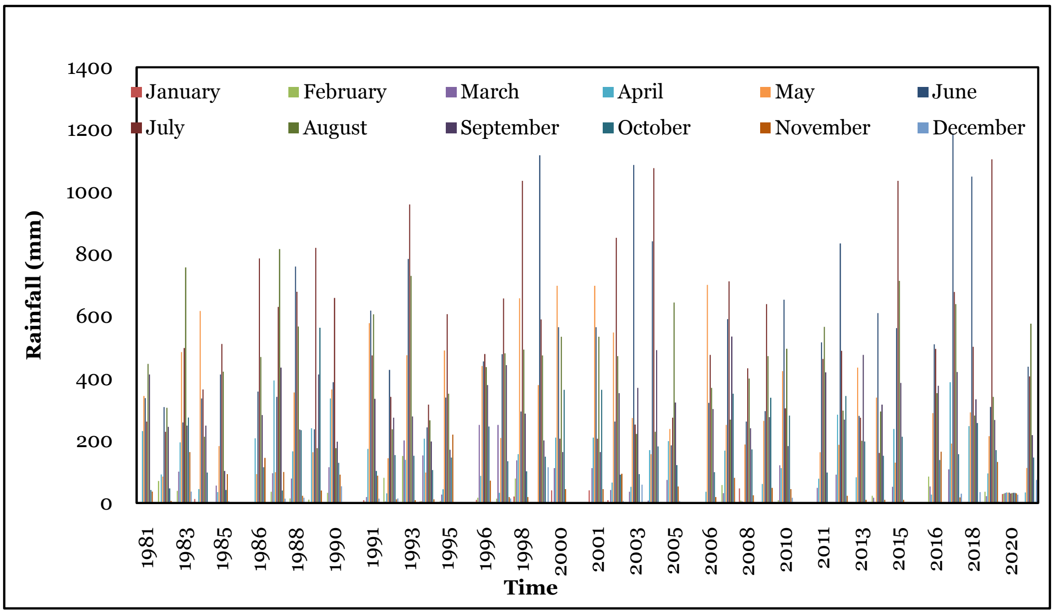


Figure 8. Monthly rainfall variation of Rangamati district in for last 4 decades.

3.3.4. Cumulative Rainfall Data Analysis

The cumulative 30-day and 3-day rainfall were used in the rainfall intensity to cause the rainfall threshold model for landslide occurrence in the Rangamati area. The cumulative rainfall data is based on 7 historical landslides that occurred from 1990 to 2017. [38] Pointed out that a threshold line from rainfall measurements requires very little input data to establish the threshold line. Moreover, the study area has occurred very few historical landslide events. Authors have been followed by [23] [35] [39] [40] focused either on the relationship between daily rainfall and cumulative rainfall or used ID threshold established by continuous rainfall events. Also, the rainfall event and the cumulative rainfall are indirectly merged. **Figure 9** shows the rainfall intensity for a cumulative 30-days and a cumulative 3-days with 7 landslides event in the research area.

Of the major landslides that happened 86% is cumulative 30 days and minor landslides engaged 98% in cumulative 3 days are shown in **Figure 10**.

3.4. Correlation between Rainfall Volume and Landslide Event

The average rainfall of the Chittagong Hill Tract area was recorded at >2735 mm (Bangladesh Meteorological Department 2021). The highest rainfall happens in May, June, July, and August. Landslide frequency in the Rangamati district is highest in the months of the monsoon period. It shows strong relationships between landslides and rainfall volume. More rainfall increases the probability of landslides.

The hills of Rangamati mainly comprise sandstone, shale, and siltstones which have been unsaturated to partially saturate to varying degrees. Seepage patterns with increasing infiltration and development of pore water pressure (P.W.P) can build up within the soil layers that might trigger landslide moves downward causing a landslide in the investigated area. The suction of the unsaturated soil zone can play a vital role in the case of landslide events in Chittagong and CHT areas [23]. According to [40] Precipitation patterns can significantly impact landslide threats to life events in Bangladesh. A summary of some landslide events and the amount of rainfall causing respective landslides from (2007 to 2017) in the Rangamati district is listed in Table 1 which is used to formulate rainfall threshold values of the investigated area. Table 2 has shown the normalized cumulative rainfall data for Rangamati to delineate the rainfall threshold estimation.

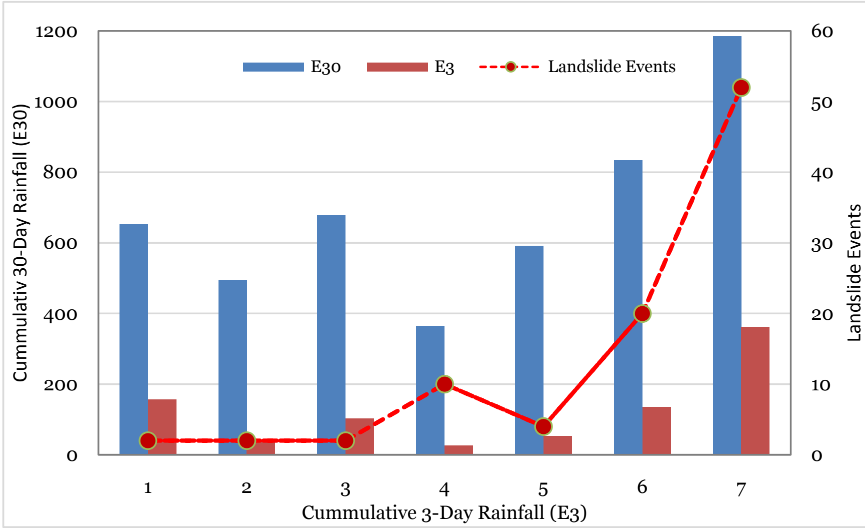
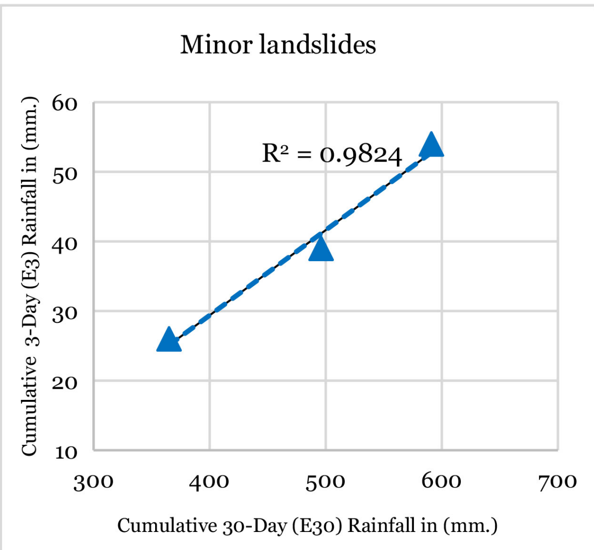


Figure 9. Total rainfall on cumulative 30-day rainfall and cumulative 3-day rainfall for rain gauge and 7 landslide events in Rangamati Sadar Area.



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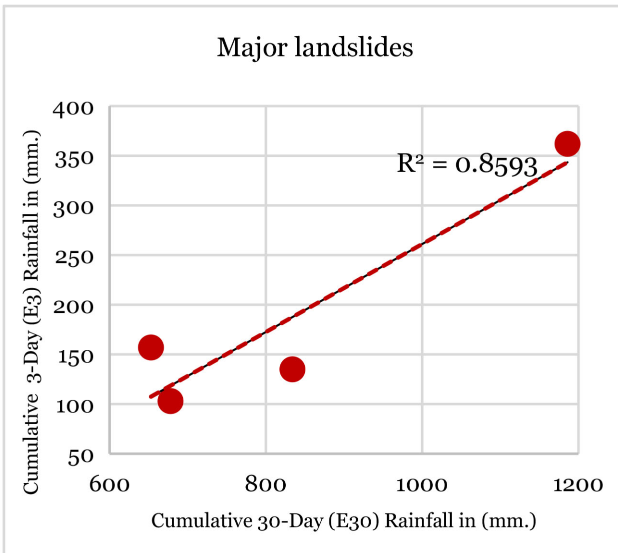

(b)

Figure 10. Scatter plot on cumulative 30-day rainfall and cumulative 3-day rainfall for rain gauge and landslide (a) major and (b) minor events in Rangamati Sadar Area.

Table 1. Rainfall data for several landslides that occurred in Rangamati in recent history (after CDMP, BMD, and Newspaper) here "0" refers to the day of the landslides.

Landslide ID	Date	Rainfall amounts in mm before landslide event									No of slides	No of fatalities
		7	6	5	4	3	2	1	0	+1		
6	18-07-2017	0	1	37	50	4	7	92	122	2	2	0
5	13-06-2017	0	53	145	2	0	19	343	374	228	52	152
4	25-06-2012	0	1	1	1	6	17	112	216	11	20	150 injured
3	11-08-2010	89	21	9	5	1	0	38	139	10	02	0
2	15-06-2010	0	0	0	14	0	99	58	116	4	02	0
1	11-06-2007	52	4	16	0	21	7	26	146	14	04	3
0	30-05-1990	0	0	0	14	3	9	14	0	11	10	30

Table 2. Normalized cumulative rainfall data for Rangamati.

Landslide ID	168 hour	144 hour	120 hour	96 hour	72 hour	48 hour	24 hour	0 hour	24 hour
6	0	0.013	0.178	0.581	0.114	0.044	0.135	0.109	0.007
5	0	0.675	0.875	0.605	0.114	0.165	0.637	0.446	0.821
4	0	0.688	0.879	0.616	0.286	0.272	0.801	0.639	0.861
3	0.631	0.95	0.923	0.674	0.314	0.272	0.857	0.765	0.896
2	0.631	0.95	0.923	0.837	0.314	0.899	0.941	0.868	0.911
1	1	1	1	0.837	0.914	0.943	0.979	1	0.961
0	1	1	1	1	1	1	1	1	1

3.5. Landslide Occurrence with Climate Change

The seasonal distribution of landslides events for Rangamati is shown in **Figure 6** which plots the seasonal distribution for landslides that occurred in Rangamati with the average monthly rainfall. A total of 92 landslide events data from 1990 to 2017 were plotted represented by 05 landslide IDs. A very clear correlation between rainfall and landslide can now be observed.

Distribution of Major and Antecedent Rainfall of Landslides Occurring Months in the Recent Past

Two natures of rainfall events control the area's soil properties, *i.e.*, Antecedent, and major rainfall as shown in **Figure 11**. High magnitudes of rainfall events with the least duration are recognized as major rainfall events. On the other hand, several rainfalls occurring on consecutive days with an amount of rainfall ranging from 2 mm to any amount above 2 mm. are acknowledged as antecedent rainfall [36].

It is necessary to differentiate between the antecedent rainfall duration and major rainfall intensity because soil fabric conditions are dependent on rainfall patterns in the hilly regions of Bangladesh. Shallow and deep landslides are of

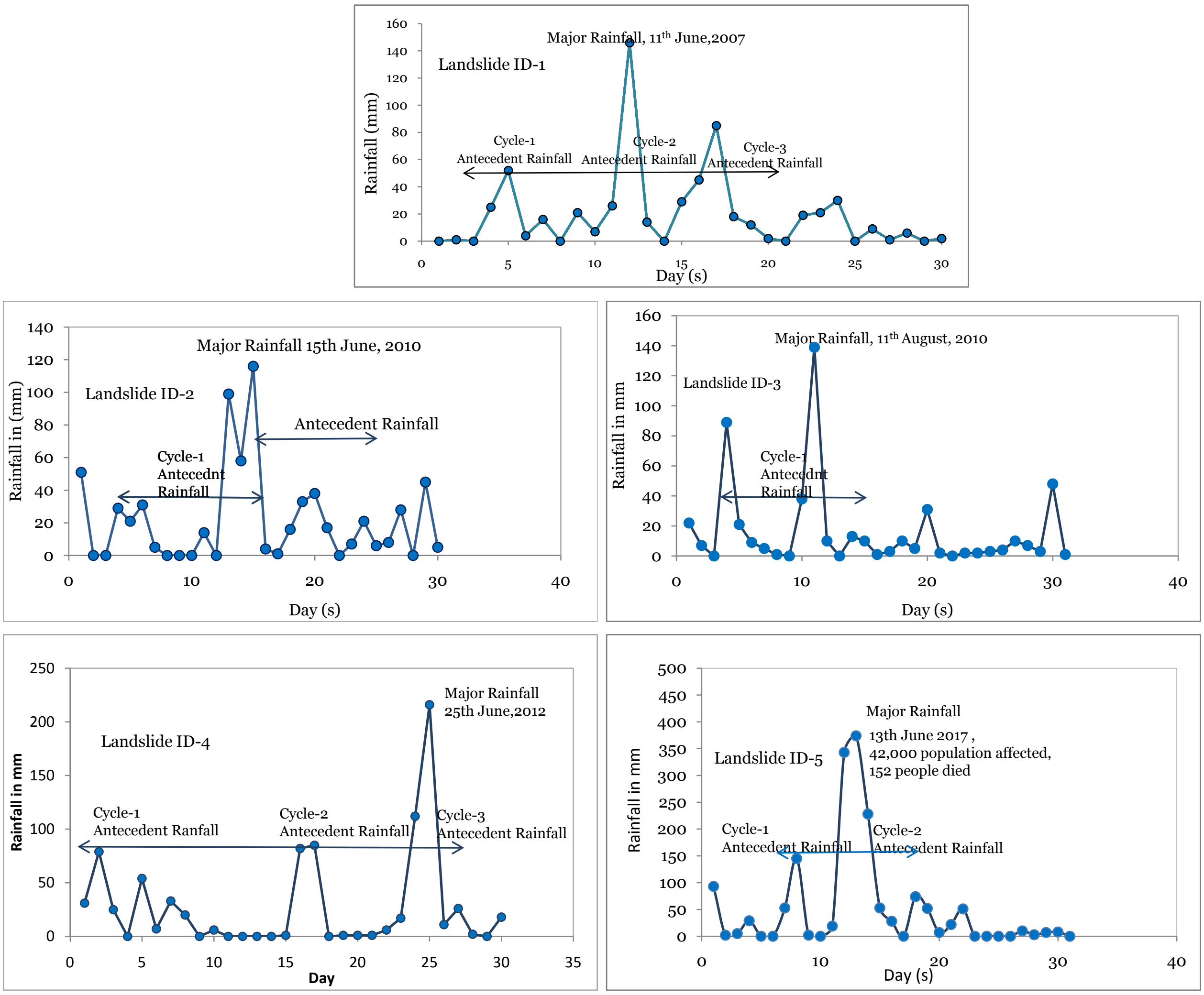

Figure 11. Distribution of major and antecedent rainfall on some landslide events.

different origins in terms of rainfall-induced landslides, so it is useful to discriminate the dependency of Shallow and deep-seated failure on the distribution between antecedent and major rainfall.

Short-duration high-intensity rainfalls are a recognized cause of shallow landslides. Shallow landslides are often generated in steep slopes of soil or weathered rock during the most intense part of a storm. Loose and weak soils are especially susceptible to shallow landslides, as the soil may get eroded by surface water or fail to increase pore pressure. Storms of very high intensity and short duration (e.g., 1 hr.) may create such high surface runoffs and result in erosion and possible generation of debris flows [41].

The antecedent rainfall's contribution to triggering debris flows is widely recognized. Seasonal variations are affecting temperature and rainfall, *i.e.*, affecting evapotranspiration. In colder periods, the ground will stay saturated for a longer period after rainfall, compared to warmer periods; this may significantly affect the amount of antecedent rainfall needed to cause a landslide. The significance of antecedent rainfall in an area may thus depend on both season and climate

[42]. The landslide hazards in the Rangamati area with the distribution of antecedent and major rainfall in the occurring months in the recent past are described by the following discussion and graphical representation.

3.6. Rainfall Threshold Line for Rangamati

The role of antecedent rainfall (*i.e.*, the rainfall in the consecutive days leading up to the landslide event) as opposed to the daily rainfall at the time the event occurred in every landslide event in the Rangamati area. It has been observed that in most landslide-occurring months the duration of antecedent rainfall is short (*i.e.*, there are several cycles of antecedent rainfall in one month) and after heavy rainfall, slope failure occurs (**Figure 11**). Therefore, an attempt has been made to establish a minimum rainfall threshold line using five days of antecedent rainfall and the daily rainfall at the time of the event as discussed by [21] [26].

Figure 12 depicts the minimum threshold line in terms of causalities. The lower threshold line tells that a total rainfall of 100 mm for six consecutive days before landslides (equivalent to a sustained 16.66 mm/day for six days) is sufficient for shallow landslides to take place and a total rainfall of about 210 mm for six consecutive days before landslides (equivalent to a sustained 35 mm/day for six days) is sufficient for deep-seated landslides (e.g. 13th June 2017, Rangamati Sadar area, 160 people died, about 52 landslides) which causes a huge loss of human lives and property.

Figure 12 shows that some landslides have occurred after heavy one-day rainfalls with little antecedent rainfall (11 June 2007 Rangamati area). However, it can also be seen that other landslide events occurred with low daily rainfall but where the five-day antecedent rainfall is significant (e.g., landslides ID 1, 2, 3, 4 & 5 in 2007, 2010, 2010, 2012 & 2017 years respectively. This suggests that the conditions for failure are indicated by total rainfall since either daily or antecedent rainfall can induce failure.

The Second method has been applied to establish a rainfall threshold line according to [35] in the journal IJECE. This method is based on cumulative 3-day and 30-day rainfall of historical landslides, which is the rainfall threshold line parameter. **Figure 13** shows the rainfall threshold (E3-E30) diagram for historical rainfall that has resulted in landslides rainfall threshold line based on major and minor landslide threshold equation analysis.

[34] Developed a method to establish a link between normalized cumulative rainfall and the number of days before the disaster days. According to the data, a landslide could happen in Rangamati if there is 210mm of rain in 72 hours. This data also supports the (E3-E30) cumulative rainfall of previous landslides.

It is observed from the above analysis of antecedent rainfall (**Figure 12**) exceeded 210 mm during the 72 hrs (**Figure 14**). Or E3 days then, the rainfall threshold for the event of a major landslide. In contrast, minor landslides might occur if the rainfall exceeds 100 mm in 72 hours (**Figure 14**). Or, E3 days rainfall threshold. However, landslide data suggests the importance of rainfall intensity events and antecedent rainfall having a great influence on triggering slope failures.

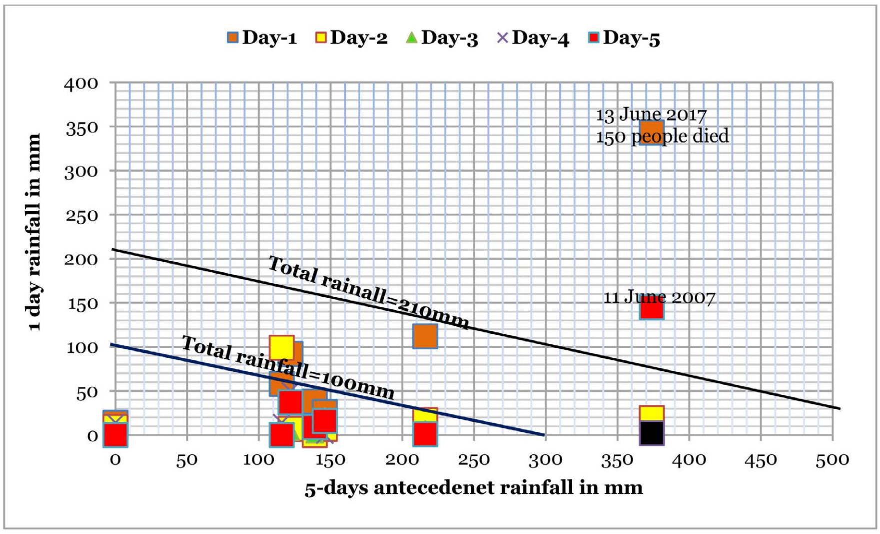

Figure 12. Establishment of Rainfall threshold line for the Rangamati area.

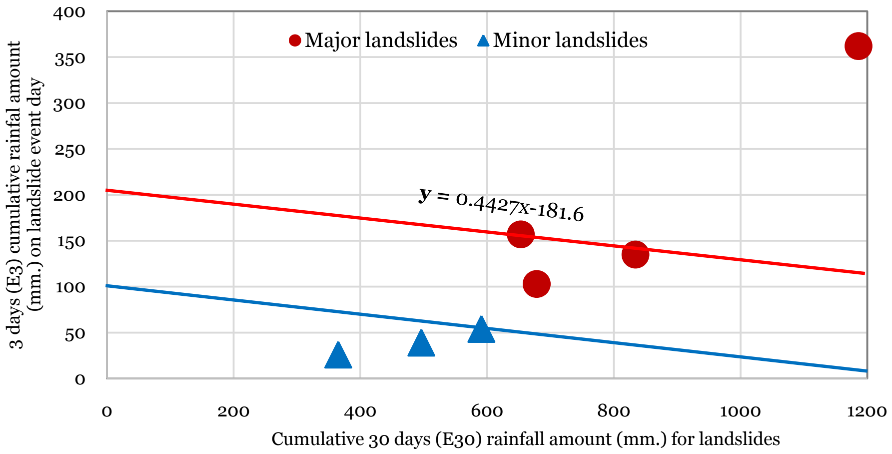

Figure 13. Plotting of E3-E30 diagram for historical rainfall to rainfall threshold.

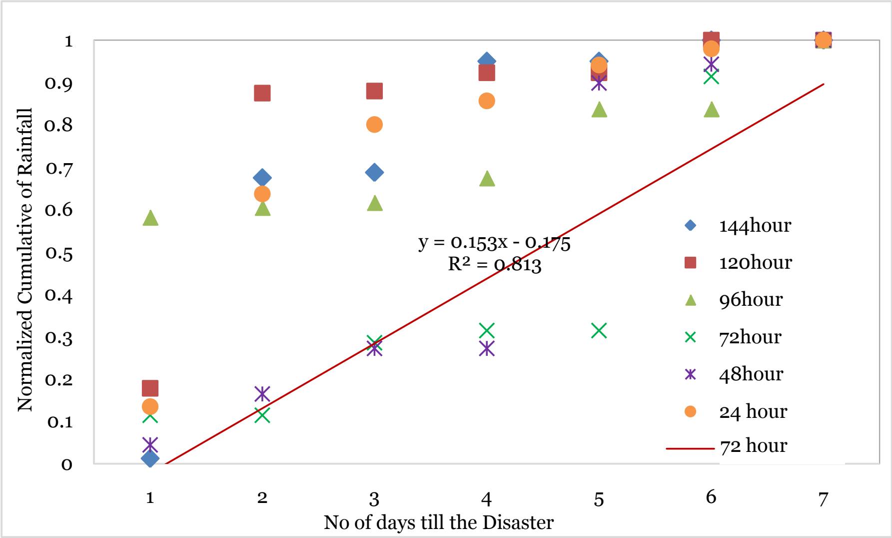

Figure 14. Normalized cumulative rainfall data for Rangamati.

4. Conclusions

This research evaluates the current climate change and its effects on landslide hazards in the Rangamati Sadar region.

This study reveals that the climate is changing in recent days (2010-2021) compared to previous decades, which is established by the gradual increase of temperature and rainfall rate. This increase in temperature enhances the evaporation rate causing a significant change in rainfall intensity and volume. This changing rainfall pattern influences the landslide events in the investigated area during the monsoon period.

The climatic condition of the investigated area shows that the highest amount of rainfall occurs within the monsoon period (June-September) and the lowest during the winter period (December-February) of each year. But in recent days except for the monsoon period, the second highest peak of rainfall also occurs in May month of the pre-monsoon period and October month of the post-monsoon period, which is almost average of 221 mm - 556 mm. As a result, the duration of maximum precipitation is increased (May-October).

Moreover, the seasonal rainfall pattern evaluation and their relationship to landslide hazard events might be recognized that the monsoonal duration is longer and has influenced the hazards in the study area. It has been determined that the researched area's catastrophic landslides are caused by monsoonal rains.

The overall pattern of rainfall data over the previous 40 years shows that rainfall is increasing as a result of recent climate change.

It is determined from the number of landslide events and the amount of rainfall that either antecedent rainfall alone or antecedent rainfall combined with single-day rainfall amount causes landslide hazard events to occur in the researched location. Significant landslide hazard events can also be greatly influenced by both the antecedent and major rainfall events. The lower threshold line indicates that a total rainfall of 100 mm for six days before landslides, which is equivalent to a sustained 16.66 mm per day for six days, is enough to cause shallow landslides, while a total rainfall of about 210 mm for six days before landslides, which is equivalent to a sustained 35 mm per day for six days, is enough to cause deep-seated landslides, such as the one that killed 160 people on June 13, 2017, in Rangamati Sadar area.

Based on past landslides' cumulative 3-day and 30-day rainfall, which serves as the threshold for rainfall, according to the findings, a shallow landslide may be caused by 40 mm of rain during a 72-hour downpour or 100 mm during a 144-hour downpour.

Finally, utilizing the fatalities, incidents, and cumulative rainfall amount, a threshold line for rainfall is developed for landslide hazard occurrences to occur in the Rangamati area.

The prime goal of the current study is to ascertain how climate change would impact the likelihood of landslides in the study area. The findings of this study help characterize, identify, assess, and create a landslide hazards early warning system in the Rangamati region of Bangladesh. These results will lower the risk of landslides in the Rangamati area for all stakeholders. Additionally, communities will benefit from this research on continual awareness of slopes if precipitation threshold limits have been exceeded.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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