The Dhaka University Journal of Earth and Environmental Sciences, Vol. 11 (1): 2022

Empirical Approach Based Rainfall Threshold Estimation for Landslide Occurrence in Cox's Bazar District, Bangladesh

Ritu Roy[1], Dewan Mohammad Enamul Haque[1 2] *, Shamima Ferdousi Sifa[1], Sumya Tasnim[1], Tonoy Mahmud[1] and Tanzim Hayat[1]

[1]Department of Disaster Science and Climate Resilience, University of Dhaka, Dhaka 1000, Bangladesh
[2]Department of Geology & Geophysics, Louisiana State University, USA

Manuscript received: 14 June 2022; accepted for publication: 01 November 2022

ABSTRACT: Rainfall threshold estimation empirically to forecast rainfall-induced landslide events provides crucial information to reduce landslide impact. The landslide events triggered by rainfall are common in Cox's Bazar district, especially during the monsoon season. Geological settings and climatic conditions make this area more landslide-prone leading to huge losses of lives and property. Establishing an effective early warning system based on a rainfall threshold value has become a top priority to save people's lives, the economy, and the environment. We have employed three empirical approaches to estimate rainfall thresholds. Intensity-Duration, Event-Duration, and Antecedent Rainfall thresholds are the most conventional rainfall methods to identify the lowest amount of rainfall that triggers landslide. The Intensity-Duration (ID) and Event-Duration (ED) rainfall threshold equations are calculated using a simple power-law curve. For 5% exceedance probability level ID defined as: T_5: I = 3.63 $D^{-0.1313}$ & ED as T_5: E = 3.63 $D^{0.8687}$. Similarly, for 1% exceedance probability level ID defined as: T_1: I= 2.78 $D^{-0.1313}$ & T_1: E = 2.78 $D^{0.8687}$ for ED. Both 1% and 5% rainfall threshold equations are the minimum rainfall threshold equations. Since the 5% exceedance probability threshold line delineates the lower end of all the observed data points for landslide events, it is considered the minimum threshold line for Cox's Bazar. According to the 5% exceedance probability level threshold equation, mean intensity of 2.39 mmh^{-1} or 57.4 mm cumulated rainfall in 24 hours is required to initiate a landslide event. Whereas, for longer duration events such as 120h, rainfall intensity of 1.93 mmh^{-1} or continuous rainfall of 232 mm appears to be sufficient in landslide initiation. There is a less than 5% chance of a landslide below this threshold limit. In the context of 3-day and 5-day antecedent rainfall thresholds, we found that a minimum of 130 mm in 72 h (3-day) and 210 mm in 120 h (5-day) could initiate a landslide event. We have compared our thresholds with a few global and local rainfall threshold estimates.

Keywords: Rainfall-Induced Landslides; Rainfall Thresholds; Early Warning; Empirical Approach; Cox's Bazar

INTRODUCTION

Rainfall-triggered landslide events are a common recurring problem in hilly regions of Bangladesh (Haque et al., 2017). Since 2000, around 725 people have lost their valuable lives along with massive damage to properties due to landslide impact in Bangladesh (Sultana, 2020). Recently, Cox's Bazar district has become more vulnerable among the hilly districts because around one million Rohingya refugees live at unpredictable risk of landslides and flooding (Tehrani & Hüsken, 2019). Moreover, the frequency of landslide hazards is aggravating because of the increasing rate of extreme rainfall and storm events caused by climate change (Stefano Luigi et al., 2016). Anthropogenic interventions like rapid unplanned urbanization, indiscriminate logging, increasing exposure to proximal hilly areas, and lack of risk awareness among locals also act as the root cause of landslide damage and loss (Hosenuzzaman et al., 2022). Though responsible authorities took a few mitigation strategies based on recent studies, the amount of loss and damage due to landslide disasters is still significant (Sultana & Tan, 2021).

Landslide early warning always acts as an effective way out in reducing landslide impact. During the monsoon period, the soil becomes saturated from infiltrating excessive rainwater, increasing pore water pressure and causing landslides (Nazionale et al., 2007). Therefore, a rainfall threshold estimation is necessary to establish a monitoring system for rainfall-induced landslide occurrences to save life & property. A rainfall threshold is estimated based on the minimum or maximum amount of precipitation that can cause a landslide. A minimum threshold line indicates the least quantity of rain required to initiate a landslide hazard. On the other hand, maximum rainfall

Corresponding author: Dewan Mohammad Enamul Haque
Email: dewan.dsm@du.ac.bd

DOI: https://doi.org/10.3329/dujees.v11i1.63713

threshold lines provide the highest amount of rainfall required to initiate landslides (Glade et al., 2000).

There exist two widely used rainfall threshold models: one is physical-based (process-based, conceptual), and another is an empirical-based (historical, statistical) threshold model (Aleotti, 2004). Physical-based threshold models necessitate accurate spatial data on the hydrological, lithological, morphological, and soil variables to identify the beginning of slope collapses. However, often spatial information remains not available for large areas. In addition, the precision of the data is another factor of complexity. Additionally, this method is ineffective for forecasting deep-seated landslide occurrences and works best for predicting shallow landslides (Idrogeologica et al., 2010). Because of this approach's limitations, a new approach has been adopted for local to global scales: the empirical data-based approach (Monsieurs et al., 2018). This method uses statistical analysis to calculate potential rainfall thresholds based on previous rainfall (which caused landslides) (Luciani et al., 2010). The upper and lower boundary lines are often displayed in Cartesian, semi-logarithmic, or logarithmic coordinates to determine the minimum and maximum threshold values of rainfall amount that triggered landslides (Nazionale et al., 2007). More precisely, a statistical study of historical rainfall events in previous landslide disasters is used to create empirical rainfall threshold models (S. L. Gariano et al., 2017). Rainfall Intensity-Duration (ID), rainfall Event-Duration (ED), and Antecedent Rainfall (AR) conditions are the most often employed in different combinations to establish empirical thresholds (Monsieurs et al., 2018).

Here we have utilized these three empirical approaches to determine rainfall thresholds that can potentially trigger landslides in Cox's Bazar. These empirical approaches depend on statistical analysis of the local precipitation conditions. It also depends on the geographical extent of the area. A threshold can be determined globally, nationally, regionally, and locally. Regional rainfall thresholds are chosen for an area extending for several thousand square kilometers, and local thresholds include an area of some hundreds of kilometers (Guzzetti et al., 2007). The district of Cox's Bazar has a total size of 2,491.86 km^2. Therefore, a regional threshold for this region will function effectively due to similar topography and climatic traits (Segoni et al., 2018).

To determine rainfall threshold values for Cox's Bazar, we have selected 30 landslide events from 1997 to 2021 based on an extensive literature review, and corresponding rainfall data is collected from Bangladesh Meteorological Department. We have assumed that prolonged rainfall events primarily cause these events. For Intensity-Duration (ID) rainfall threshold, rainfall intensity and duration parameters have been used. For rainfall Event–Duration (ED), we have utilized cumulative rainfall and duration parameter. On the other hand, the 3-day and 5-day antecedent rainfall threshold have two parameters, one is event day rainfall, and the second is consecutive cumulative rainfall. Scientists have used different statistical methods to determine the threshold curve (Glade et al., 2000). Among them, the Frequentist statistical approach is the most used approach to assess rainfall Intensity-duration (ID) and rainfall Event–Duration (ED) minimum rainfall threshold curve (Vennari et al., 2014).

In this research, we have estimated the landslide-related rainfall threshold for Cox's Bazar district using Intensity-Duration, Event-Duration, and Antecedent rainfall approaches. We cross-validated and compared these empirical approaches with the established global and local threshold. Eventually, the most accurate regional minimum rainfall threshold value for Cox's Bazar district is determined, which will be helpful for policymakers and humanitarian organizations to design early warning systems.

STUDY AREA

Almost every year, Cox's Bazar district of Chittagong hill tracts are affected by landslide disasters during monsoon for excessive rainfall. The district covers 2,491.85 square kilometers (962.10 square miles), of which 940.58 km^2 are covered in forests. About half of the district's total area and the coastal islands occupy the hilly region. The map (Fig. 1) defines the study area between latitudes 20º43' and 21º56' north and between longitudes 91º50' & 92º23' east (Banglapedia, 2021).

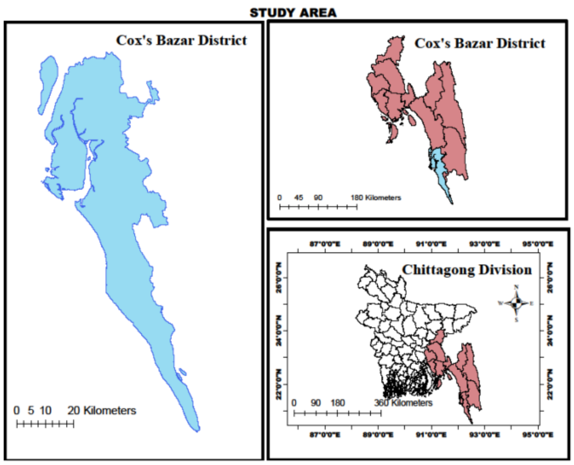


Figure 1: Location of the Study Area

The geological conditions make this area landslide-prone. The main soil types in the study area are fine to medium-grained weakly cemented sandstone with various hues, including yellow, brown, grey, and clayey sandstone. In addition, the surface lithology of the site is comparatively loose and less compact. This area has a tropical monsoon climate characterized by high temperature, excessive rainfall, and humidity. 4285 mm of rain falls annually on average. The region is chilly and dry from November to March, hot and sunny from April to May (the pre-monsoon season), and hot and humid with heavy rains from June to October (the monsoon season). From May to October, high rainfall occurs in the monsoon period. The monthly average rainfall graph for the year 1997-2021 represents temporal variation of rainfall amount (Fig. 2). The maximum rainfall is generally encountered in June, July, and August. Moreover, the highest average monthly rainfall is in July, about 1018.66 mm. That is why major landslide events occurred during these three months of the monsoon (Ahmed, 2015).

At the same time, this district is overwhelmed by the vast population of Rohingya refugees, which is now around 1 million, and the population density is about 46,000/km^2. New development or expansion of the camp led to more forest destruction, and thus more people and structures were vulnerable to landslide events (UNHCR, 2019). These geological, climatic, and human-induced activities have led to destructive landslide events in this area in the recent past. In 2021, about eight people died in this region in rainfall-induced landslide events (The Daily Star, 2021).

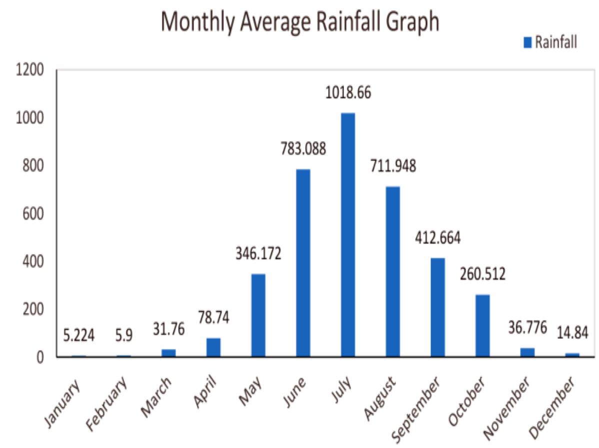


Figure 2: Cox's Bazar District's Monthly Average Rainfall (1997-2021)

MATERIALS AND METHODS

Data and Software

The rainfall amount was collected for certain landslide events to estimate the empirical rainfall threshold. The rainfall measurements include cumulative rainfall (total amount of rainfall for an event), rainfall duration, rainfall mean intensity and antecedent rainfall (3-day and 5-day). All the landslide event-date used in this research was collected from secondary sources like articles, reports, newspapers, and websites; the associated rainfall measurement is collected from Bangladesh Meteorological Department. For rainfall threshold analysis, previous landslide events information is necessary. However, we found that a detailed landslide information log is lacking. Especially information like landslide location (latitude/longitude), landslide event time of failure, and landslide type is often missing. Only the date of occurrence of significant events and the name of the administrative region was found in different articles, reports, newspapers, and websites. From 1997 to 2021, 30 landslide cases were found from these sources (table 1). Most landslide events are recorded in June, July, and August—months of maximum rainfall (Fig. 2) in the study area.

Additionally, information on 3-hourly rainfall is gathered from the Bangladesh Meteorological Department (BMD) for relevant landslide incidents. From this raw data, the cumulated rainfall (continuous rainfall from the day started rainfall to before the day landslide occurred) and duration (the period between the beginning and finish of a rainfall event) of the corresponding landslide event was calculated. We had to count the amount of continuous rain that started before the landslide event day, as the exact time of the incident is unknown. The gap between two consecutive rainfall events is identified by the 24-hour rainfall gap (Maturidi et al., 2021). Mean intensity was derived by dividing the total amount of rain cumulated rainfall (E) by the duration of the rainfall event (D). The rainfall analysis found the duration range between 30<h<237 (around 1 day to 10 days), and the mean intensity ranged from 2mm/h to 8.44 mm/h There were no records for shorter-duration incidents, like the incidence of three hours, due to a number of reasons, including the fact that the monsoon season delivers continuous rain across this climatic zone and the time of the collapse wasn't accurately known. We have used **R**-open source software to analyze this research's statistical analysis (Core R Team, 2019).

Table 1: Historical Landslide Event Date with Location Name

Landslide event number	Date of Occurrence	Location name	source
1	7/11/1997	*Cox's Bazar*	(Jafor Mia et al., 2017)
2	6/16/2003	*Lighthouse para , Cox's Bazar town*	(Comprehensive Disaster Management Programme II, 2012)
3	7/29/2003	*Kalatali, Purba Kalatali Adharsha gram*	(Comprehensive Disaster Management Programme II, 2012)
4	7/3/2008	*Teknaf upazila*	(Comprehensive Disaster Management Programme II, 2012)
5	7/6/2008	*Mahajanpara a in Cox's Bazar Town*	(Comprehensive Disaster Management Programme II, 2012)
6	8/18/2008	*Bhaditala village, Sadar*	(Sarwar, 2008)
7	6/13/2010	*Adorsha Para, South lar para*	(Comprehensive Disaster Management Programme II, 2012)
8	6/15/2010	*Himchari*	(Comprehensive Disaster Management Programme II, 2012)
9	6/24/2012	*Near Cox's Bazar town*	data.nasa.gov
10	10/30/2012	*Near Cox's Bazar town*	www.thefinancialexpress-bd.com
11	6/26/2015	*Ramu, Cox's Bazar sadar*	data.nasa.gov
12	7/27/2015	*Cox's Bazar town, near radar station*	www.thedailystar.net
13	9/1/2015	*Cox's Bazar sadar*	old.epaper.jugantor.com
14	7/24/2017	*Near Lighthouse, Cox's Bazar sadar*	www.thedailystar.net
15	7/25/2017	*Ramu Upazilla*	www.nirapad.org.bd
16	6/14/2017	*Shatghoriapara village, Teknaf upazila*	archive.dhakatribune.com/bangladesh
17	7/5/2017	*ukhiya upazila, palongkhali union*	bdnews24.com/bangladesh
18	5/4/2018	*Kutupalong refugee camp*	www.irrawaddy.com
19	6/11/2018	*Ukhiya, Teknaf*	www.thedailystar.net
20	7/25/2018	*Sadar And Ramu*	www.thedailystar.net
21	7/28/2018	*Cox's Bazar sadar*	www.nirapad.org.bd
22	5/11/2019	*Balukhali,ukhiya*	www.nirapad.org.bd
23	7/6/2019	*Balukhali refugee camp,uhiya*	www.dailysabah.com
24	7/14/2019	*Chakaria*	www.daily-bangladesh.com
25	9/9/2019	*Fokirmura and Urumerchhara area under Teknaf upazila*	www.thedailystar.net
26	7/27/2021	*ukhiya and Maheskhali upazilla*	archive.dhakatribune.com
27	7/28/2021	*Nhilla Union, Teknaf Upazilla*	www.prothomalo.com
28	6/5/2021	*Mainarghona a camp in Ukhiya's Balukhali union and at Chakmarkul camp in Teknaf's Hoaikong union*	archive.dhakatribune.com
29	6/19/2021	*Maheskhali upazila, harairchara village*	www.prothomalo.com
30	5/27/2021	*Teknaf upzila*	www.nirapad.org.bd

Data Source*: *Rainfall data- (Bangladesh Meteorological Department, 2022).

METHODS

Rainfall Intensity Duration (ID) Thresholds

Intensity duration rainfall threshold is the most widely accepted form of rainfall threshold, which is being calculated using rainfall mean intensity and rainfall duration parameters that contributed to previous landslide events (Guzzetti et al., 2007).

According to Nazionale et al. (2007), the most general form of intensity-duration threshold is defined as a simple power-law curve equation:

$$I = c + \alpha\, D^{-\beta}$$

In the above equation, rainfall mean intensity is assigned as I in $mmhr^{-1}$ and duration of a rainfall event is assigned as D in hr, and the scaling constant (intercept) and shape parameter (slope) is denoted as α and β, respectively (Peruccacci et al., 2012). The accepted ID thresholds are approved for different rainfall durations and intensities ranges. Choosing an empirical threshold curve is critical because it is independent of physical (like hydrological, meteorological, and geological) factors (Reichenbach et al., 1998). For the maximum of the ID thresholds, equation c = 0 (Nazionale et al., 2007). When the c = 0 equation is a simple power-law equation:

$$I = \alpha\, D^{-\beta} \text{ .... } (1)$$

The frequentist method is the most used analytical method to identify the power-law equation's intercept and slope (Luciani et al., 2010). The frequency analysis of the rainfall parameters served as the foundation for this specific statistical analysis technique.

A highly sparsed dataset needs to be log-transformed for data normalization. At first, the equation is log-transformed into a linear equation to easily be analyzed as a linear regression model. The model's slope and intercept were then determined using linear regression analysis.

$$\log (I)=\log(\alpha)-\beta\log(D) \text{ .... } (2)$$

The two variables, mean rainfall Intensity (I) and Duration (D), are log-transformed and plotted in the log10-log10 graph to illustrate the potential correlation of I-D values for every landslide occurrence. Linear modeling is carried out using R open-source software to identify the possible association between Mean intensity and Duration (Idrogeologica et al., 2010).

To get the z-score value for various probability level of a normal distribution, the "qnorm" function in the programme R was used. To calculate the intercept α of the 1%, 5%, 50%, 75% and 95% exceedance probability threshold curve, the corresponding Z-score value is used to find the distance from the mean intercept α_{50} of the ID linear model. The slope of the different exceedance threshold curves is the slope of best fit line T_{50} (slope=β) which is constant, but the intercept varies according to the z-value of the distribution.

Rainfall Event Duration (ED) Thresholds

In specific ways, event-duration thresholds are the same as rainfall intensity-duration thresholds, which prevents needless conversions between cumulative rainfall and rainfall mean intensity. This cutoff point will provide the precise amount of rain required to trigger an event (Peruccacci et al., 2012). Adopting a reproducible method to define rainfall thresholds is necessary (Guzzetti et al., 2007). According to Luciani et al. (2010), the ED rainfall threshold lines are represented using the same frequentist statistical technique as the ID rainfall threshold. The equation is changed, though (Peruccacci et al., 2012).

The modified equation is:

$$E = \alpha D^{\gamma} \text{ .... } (3)$$

In the above equation, cumulated rainfall is assigned as E in mm, duration of rainfall event is designated as D in hr, α is the intercept, and ɣ denotes the slope of the power-law equation. Here, $\gamma = -\beta+1$ where β is the slope of the corresponding ID power-law threshold $I=\alpha D^{-\beta}$, with the mean rainfall intensity I (in mmh^{-1}).

The equation is log-transformed into a linear equation to easily be analyzed as a linear regression model.

$$\log (E)=\log(\alpha) +\gamma \log(D) \text{ .... } (4)$$

The two variables, Cumulated rainfall (E) and Duration (D), are log-transformed and plotted in the log10-log10 graph to illustrate the potential correlation of E-D values for every landslide occurrence. Linear modeling is carried out using an open-source software named R to identify the possible association between Cumulated Rainfall and Duration (Idrogeologica et al., 2010).

The ED threshold curve's intercept and slope are calculated using the same procedure as the ID threshold curve.

Antecedent Rainfall Thresholds (AD)

The antecedent rainfall threshold equation is determined using the antecedent rainfall conditions of past landslide events. The number of antecedents varies from 3 to 30 days in the case of shallow landslides and deep-seated landslides, respectively (Aleotti, 2004; Chleborad et al., 2006). The quantity of rain occurring for five days before a landslide is known as the 5-day antecedent rainfall, and the threshold model shows how the rainfall on the event day triggers landslides. To establish the 5-day and 3-day antecedent rainfall threshold, the values of daily rain and the antecedent rainfall are plotted in the Y and X axes, respectively. A manual drawing of the envelope curve identifies the bottom end of the depicted points. The line represents the following linear mathematical equation:

$$y = mx + c$$

Where m and c indicate the slope and intercept, respectively. Finally, the slope m is determined from the graphed data using the following equation:

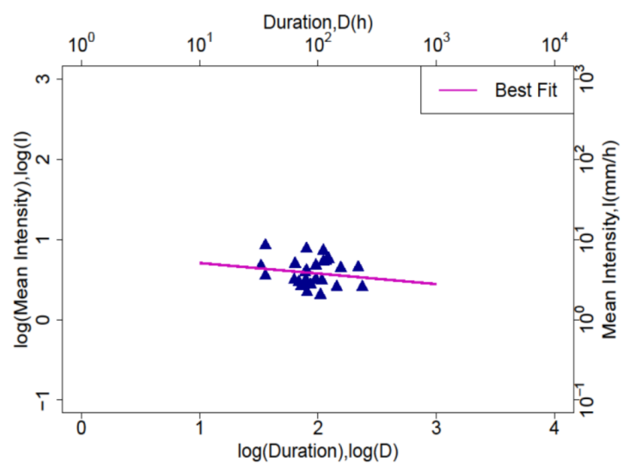
$$m = -\frac{y}{x}$$

Thus the rainfall threshold for 3 days and 5 days have been determined using the same process (Chleborad, 2000; Crozier, 1999). For this research, only 3-days and 5-dyas antecedent rainfall threshold is selected to determine the minimum threshold value for initiating a shallow landslide event.

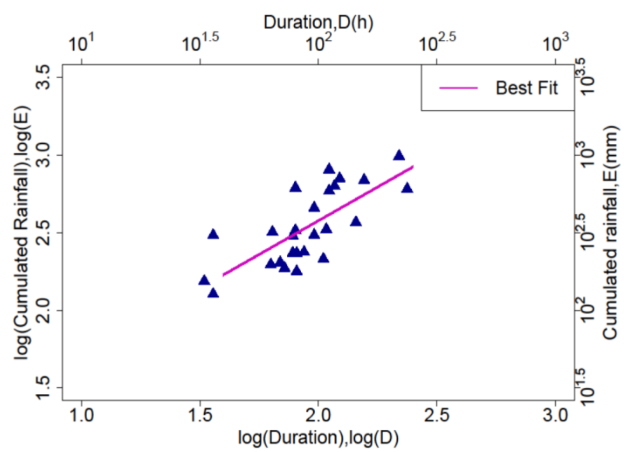
RESULTS AND DISCUSSIONS

Intensity Duration (ID) Rainfall Thresholds and Event-Duration (ED) Rainfall Thresholds

We used the rainfall data related to 26 past landslides in the Cox's Bazar region between 1997 and 2021. Four out of 30 landslide events are removed since they have zero rainfall (the required rainfall data is missing) value. We have used the Frequentist approach to calculate multiple probability level thresholds for rainfall-induced landslide events. The purple line in figure 3 is the best-fit line from this statistical analysis for both the ID and ED threshold. The variables (Mean intensity, duration) and (Cumulated rainfall, duration) in figure 3 are the distribution of rainfall circumstances depicted as blue triangles that have led to historical landslide incidents. The best fit line was found through the use of linear regression modeling. The slope and intercept values of the threshold line for both ID and ED were extracted from this model. The slopes β and Ɣ were obtained through this model and are constant for different linear quantile regressions. β= -0.1313 and Ɣ= 0.8687, respectively, are the slope values for the ID and ED rainfall models. But the model intercept will be changed at the corresponding exceedance probability threshold curve. The slope value of the ED model is higher than the ID model. These two threshold models have a significant disparity because of how the rainfall data is distributed. Compared to the ID model's lower value, which reflected the data's lowest variance, the cumulative rainfall (E) value is dispersed in the ED model (I). Our Mean Intensity (I) ranged from 2 mm/h to 8.44 mm/h, while the Cumulated Rainfall (E) ranged from 100 to 1000 mm. Figure 3 simplifies how the data is distributed and how its parameters relate to one another. Even if the slope of the ID model is lower, it is still larger than 0.1, which is still a considerable value.



(a)



(b)

Figure 3: Best Fit Line for Empirical Datasets (a) ID and (b) ED

In Figure 4, the x-axis shows the residuals for both the ID and ED models; the probability density function of the model's residuals is fitted with a Gaussian function. The z-score value for various probabilities (1%, 5%, 50%, 75%, and 95%) was calculated using the quantile normal distribution. Figure 5 displays the threshold line for 1% and 5% probability in vertical lines. The intercept of the different threshold line is calculated using the distance between the mean value and corresponding probability level z-score value.

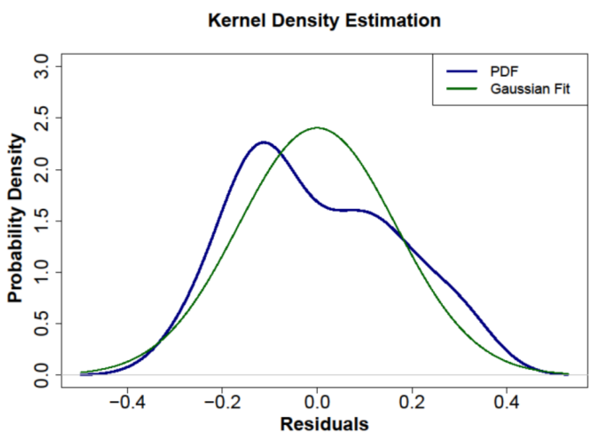


Figure 4: The Distribution of Residuals Fitted with a Gaussian Function

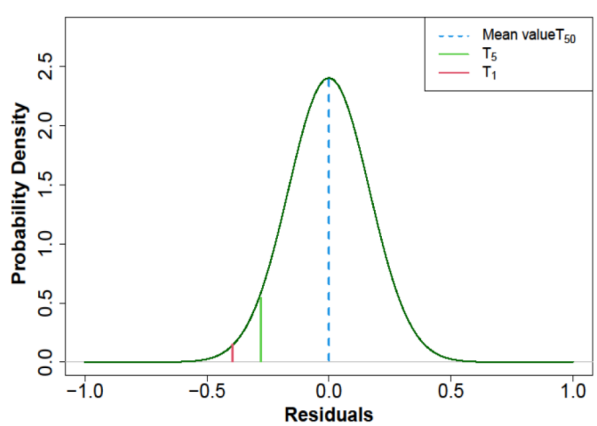
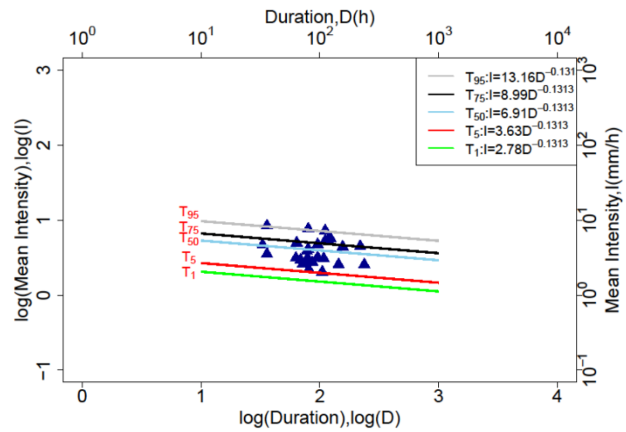
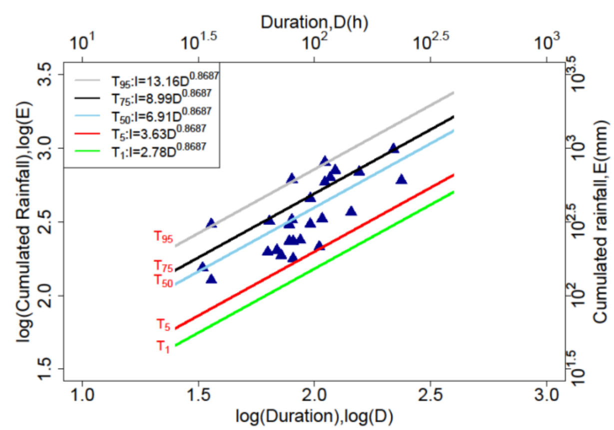


Figure 5: Graphical Representation of the 1% and 5% Exceedance Probability Threshold Line

Then we substitute the intercept and slope value in equation (2) and convert it to the rainfall threshold equation (1) for ID threshold line. Similarly, we added the intercept and slope value in equation (4) and converted it to the rainfall threshold equation (3) for ED threshold line. These equations represent the minimum rainfall threshold curve for the possibility of rainfall-induced landslide incidents in Cox's Bazar district. The graphical representation is shown below (Fig. 6):



(a)



(b)

Figure 6: Different Exceedance Probability Level Threshold Curve and Corresponding Equation for Cox's Bazar District a) Intensity-Duration (ID) b) Event-Duration (ED)

Threshold equations that are obtained from ID and ED models for different exceedance probability levels are displayed in table 2:

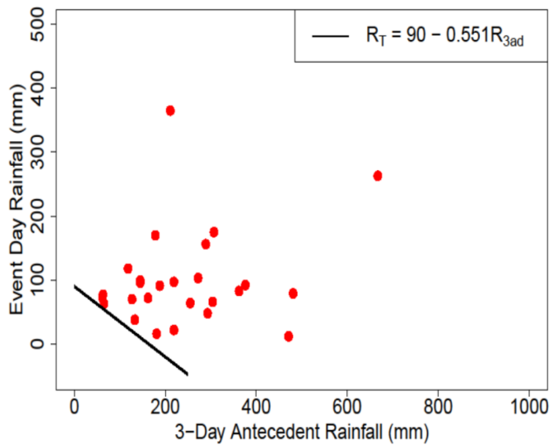
Table 2: Summary of Varying Threshold Equations

Exceedance Probability (%)	*ID Equation*	*ED Equation*	*3hour* Mean Intensity(mm/h)/Cumulative rainfall (mm)	*24 hour* Mean Intensity(mm/h)/Cumulative rainfall (mm)	*72 hour* Mean Intensity(mm/h)/Cumulative rainfall (mm)	*120 hour* Mean Intensity(mm/h)/Cumulative rainfall (mm)
1%	T_1: $I = 2.78\ D^{-0.1313}$	T_1: $E = 2.78\ D^{0.8687}$	2.4/7.2	1.83/44	1.6/114	1.48/177
5%	T_5: $I = 3.63\ D^{-0.1313}$	T_5: $E = 3.63\ D^{0.8687}$	3.14/9.4	2.39/57.4	2.07/149	1.93/232
50%	T_{50}: $I = 6.91\ D^{-0.1313}$	T_{50}: $E = 6.91\ D^{0.8687}$	6/18	4.55/109	3.94/283	3.68/442
75%	T_{75}: $I = 8.99\ D^{-0.1313}$	T_{75}: $E = 8.99\ D^{0.8687}$	7.78/21	5.92/142	5.13/369	4.79/575
95%	T_{95}: $I = 13.16\ D^{-0.1313}$	T_{95}: $E = 13.16\ D^{0.8687}$	11.39/34.18	8.67/208	7.5/540	7.02/842

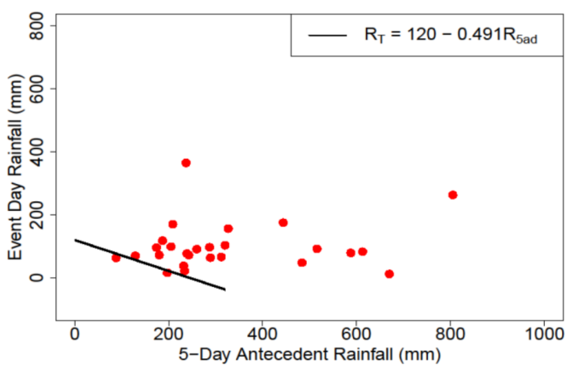
Typically, the threshold line at a 5% exceedance probability level is considered the lowest threshold curve for a landslide incidence, below which the likelihood of landslide occurrence is expected to be less than 5%. In our study, almost all landslide events remained above the threshold value. The higher the probability level, the higher value of the threshold curve. The constant of Duration α is varied at different exceedance levels. The lower value of α at the 5% threshold line indicates that the lower amount of rainfall could initiate rainfall in Cox's bazar region as this region is characterized by comparatively less compact soil. It is observed from the different threshold values that high intensity with shorter duration (1-3 days) and low intensity with longer duration (5-10 days) event is prominent in this region. We defined the short duration as 1 to 3 days and the longer duration event as 5 to 10 days since the rainfall duration range of previous landslide occurrences ranged between 1 and 10 days in this study. Additionally, Table 2 demonstrated that the 3-hour rainfall event had a higher intensity than the long-duration occurrences. However, the value is below the expected level due to data limitations.

3-Day and 5-Day Antecedent Rainfall Thresholds (3-AD/5-AD*)*

In the antecedent rainfall threshold model (Fig. 7), X-axis represents 3-day and 5-day antecedent rainfall, and Y-axis indicates event day rainfall. The manual drawing of the envelope curve identifies the bottom end of the depicted points. The line represents the following linear mathematical equation. The equation is the minimum rainfall threshold value for the antecedent model. The envelope curve equation for 3-day antecedent $R_T = 90 - 0.551R_{3ad}$, and for 5-day antecedent, $R_T = 120 - 0.491R_{5ad}$, is used to calculate the threshold value for each day.



(a)



(b)

Figure 7: Antecedent Minimum Rainfall Threshold Envelop for Cox's Bazar District a) 3-Day Antecedent Rainfall b) 5-Day Antecedent Rainfall Threshold

The rainfall below the threshold line (black line) will not cause landslides (Fig. 7). According to the 3-day and 5-day antecedent threshold equations, the event day rainfall is 90mm and 120mm if the antecedent rainfall is 0mm. We estimated the threshold exceedance of our dataset using this threshold equation. The slope value (Fig. 7) signifies the contribution of antecedent rainfall compared to event day rainfall. For instance, the slope value of 0.55 suggests a 55% contribution for the 3-day antecedent rainfall. Whereas 49% of the 5-day antecedent rainfall triggered the landslide. Additionally, 3 out of the 26 landslide incidents, or 11% of the dataset, are found not to reach the threshold level for the 3-day and 5-day antecedent thresholds. Therefore, the antecedent rainfall situation significantly impacts the likelihood of landslides than event day rainfall in this region.

Furthermore, the minimum antecedent threshold rainfall value—210 mm for 5 days and 130 mm for 3 days- exceeds our antecedent threshold equation study. According to this particular strategy, landslide occurrences in our research location must be initiated by at least 130mm of 3-day antecedent and 210mm of 5-day antecedent rainfall before the event, which is the lowest amount of rainfall that could initiate a landslide.

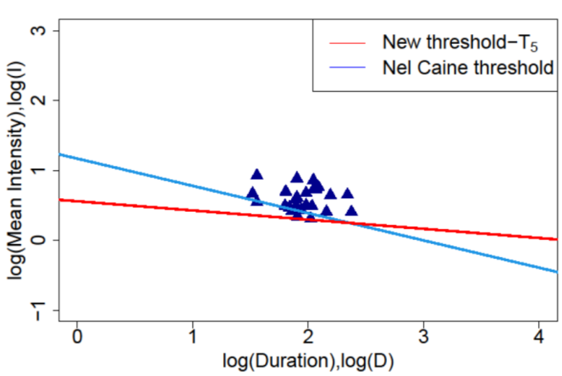
RESULT INTERPRETATION

The first two models, ID and ED thresholds, provide 1%, 5%, 50%, 75%, and 95% exceedance probability level threshold curve equation shown in table 2 with corresponding rainfall threshold values at various durations. Note that both T_1 and T_5 thresholds are minimum regional rainfall threshold. The first model, the ID threshold model, gives the minimum rainfall conditions by 1% and 5% rainfall thresholds. Considering this aspect, the 5% exceedance probability threshold value is the most reliable minimum threshold equation, as the chance of a landslide event is below 5%. According to the 5% exceedance probability threshold curve for short-duration rainfall events, such as 24h, 2.39 mmh^{-1} intensity of rainfall is necessary to initiate landslide events. For extended events such as 72h, 2.07 mmh^{-1} rainfall could be sufficient if the rain continues for 72h. If rainfall continues for 5 days, then for 120h, mean intensity of 1.93 mmh^{-1} will be adequate to trigger landslide events. From our analysis, shorter-duration rainfall events with higher mean intensity and extended-duration rainfall events with lower mean intensity are susceptible to landslide hazards in our area of interest. The second ED threshold model is less complex than the Intensity duration threshold model. ED minimum rainfall thresholds are equivalent to the ID rainfall thresholds. Relatively shorter duration, such as 24h, 57.4 mm, cumulated rainfall necessary to initiate a landslide event. As the cumulated rainfall is used to retrieve the rainfall mean intensity of the rainfall events by dividing the cumulated rainfall measurement by the duration of the rainfall event, I = E/D so it's more simplified than the ID threshold. If the rain continues for 5 days (120h), 232mm cumulated precipitation is required to initiate a landslide event in contrast to the 5-day antecedent rainfall threshold model, which indicates that a minimum of 210mm of rainfall are necessary to cause landslides. However, for the 3 days, the total rainfall of 149 mm is essential for ED threshold. The 3-day antecedent graph shows 130 mm rainfall needed, which aligned with our 72 hr ID-ED threshold curve at a 5% exceedance probability level. From the observation, it is proved that these models are perfect for both shorter and longer-duration rainfall events. When the rainfall conditions exceed the minimum threshold line, or on the threshold line, an early warning should be given as soon as possible to reduce the consequences of a landslide event.

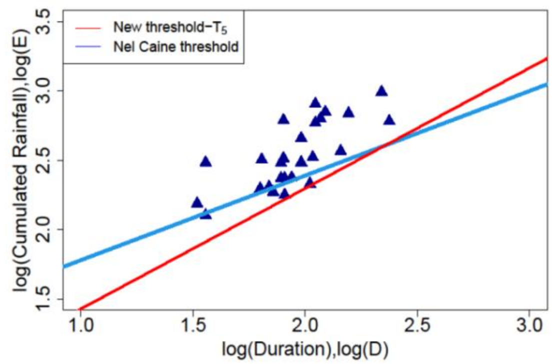
We have used three empirical rainfall threshold estimation methods so that undesirable circumstances, such as false positives and false negatives could be avoided. Also these may be avoided by employing multiple threshold lines (He et al., 2020; Valenzuela et al., 2019). The risk-free thresholds shown as the green line in figure 6 are the ED and ID 1% exceedance probability level thresholds. There is no observed data point of landslide event below this line. Accordingly, the likelihood of missing a warning is less than 1% below this threshold. The likelihood of a landslide occurrence is higher than 5% of the estimated mean intensity/cumulated rainfall above the 5% threshold line. Therefore, these lines should be considered the minimum or lowest threshold value. The red line (5% exceedance threshold line) in figure 6 is considered a warning to take measures and monitor the situation. The 50%, 75%, and 95% threshold lines above this red line are regarded as the highest or upper threshold levels. Studies suggest a greater-than-50 percent chance of a landslide occurrence if mean intensity I or cumulated rainfall E exceed the 50% exceedance probability threshold level.

Threshold Estimation Validation and Research Limitations

We have compared our estimated ID and ED rainfall thresholds for Cox's Bazar district with the established global threshold proposed by Caine (1980). A general global rainfall threshold equation for ID rainfall threshold: $I = 14.82\ D^{-0.39}$ and for ED threshold: $E = 14.82\ D^{0.61}$. This threshold reasonable for periods of 10 minutes to 10 days (Guzzetti et al., 2008).



(a)



(b)

Figure 8: Comparison between Caine's (1980) Proposed Global Rainfall Threshold and Our Estimated Regional Threshold (a) ID, (b) ED

Figure-8 compares the Caine's (1980) proposed global threshold and a new regional threshold for Cox's Bazar. The global threshold value is higher than the regional threshold value of Cox's Bazar. For the Caine global threshold, a minimum of 274mm of cumulated rainfall is necessary to trigger a landslide. The new regional threshold for Cox's Bazar indicates that a minimum of 232 mm cumulated rainfall in 120h will be enough for the landslide initiation. This discrepancy is worth noting and has emerged from limited rainfall-induced landslide inventory information. The result depends on the total number of empirical data points (abundance) and how well they are distributed. Generally, the frequentist method provides better accuracy for large data sets. Another reason behind the result is the soil of Cox's Bazar region. It is characterized by poorly consolidated sandstone which ranges from fine to medium-grained, as well as clayey sandstone, whose colors are from yellow to brown to grey (Ahmed, 2015). So, a small amount of rainfall can cause severe slope failures. Additionally, this global threshold considers many climatic locations, whereas this study investigated the rainfall threshold for an area of a comparatively limited extent.

Table 3: Different Proposed Rainfall Thresholds for the Different Study Area

Reference	Study Area	Extent	Threshold Equation
Caine (1980)	World	Global	$I = 14.84D^{-0.39}$
F.Guzzetti et al. (2007)	Italy	Regional	$I = 18.6D^{-0.81}$
Fausto Guzzetti et al. (2008)	World	Global	$I = 2.2D^{-0.44}$

Saito et al. (2010)	Japan	Regional	$I = 2.18D^{-0.26}$
Kanungo & Sharma (2014)	Garhwal Himalaya, India	Local	$I = 1.82D^{-0.23}$
Nolasco-Javier et al. (2015)	Northern Philippines	Regional	$I = 6.46D^{-0.28}$
Chen et al. (2015)	Taiwan	Regional	$I = 18.1D^{-0.17}$
Maturidi et al. (2021)	Peninsular Malaysia	Regional	$I = 37.8D^{-0.114}$
Dikshit & Satyam (2018)	Kalimpong, India	Local	$I = 3.52\ D^{-0.41}$

The threshold equations in Table 3 have different intercept and slope values based on the different geological and climatic contexts. According to a few authors, tropical and subtropical areas should have greater slope values than the mountain environment (Dahal & Hasegawa, 2008; F. Guzzetti et al., 2007). Some authors, like Maturidi et al. (2021) and Chen et al. (2015), identified a lower slope value for a regional threshold. We discovered that among these thresholds, the Garhwal Himalayan range required only 21 mm of rainfall over 24 hours to start a landslide, indicating that the area's high elevation makes it susceptible even in the context of a small amount of rainfall. In contrast, our threshold shows that 57.4 mm of rain (in 24 hours) is required to start a landslide in Cox's Bazar district. This clarification showed how various thresholds differed based on meteorological, topographical, and regional contexts. The only threshold equivalent to our created model is Caine's (1980) global threshold (Fig. 8).

We also tried comparing our threshold estimation with similar studies in the Chittagong hill tracts. Ali et al. (2018) found that the threshold values for landslides in Chittagong City are 100 mm of rainfall in 3 hours, 200 mm in 24 hours, and 350 mm in 72 hours. This research also indicates that 100mm of rainfall is required to start an event, whereas our study (table 2) reveals that the susceptible rainfall according to maximum threshold value is 34.1mm in 3 hours, 208mm in 24 hours, and 540mm in 72 hours. However, we should not consider the maximum threshold value for a landslide occurrence because all the landslide events fall under this threshold line, so the minimum rainfall threshold value needs to be considered. Our retrieved minimum rainfall threshold value is 9.4mm in 3 hours, 57.4mm in 24 hours, and 149mm in 72 hours. It is important to note that this estimated threshold is presented as probability levels ranging from 1% to 95% to address the uncertainty issue. The threshold-related inconsistencies may be due to the different considered event-date and associated rainfall amount information. Moreover, a national study on shallow landslides found greater than 40 mm/day of rainfall for 2–7 days could initiate a landslide event in Chittagong city (Khan et al., 2012). Interestingly, the result of this study is aligned with our estimation.

CONCLUSIONS

Rainfall threshold information is necessary for landslide early warning system development. Rainfall is the most sensitive triggering factor in landslide susceptibility assessment. Therefore, ID and ED-based rainfall thresholds are being determined for our study area. Studies exist where the global rainfall threshold and rainfall threshold for selected climatic zones are well established (e.g., Idrogeologica et al., 2010; Guzzetti et al., 2010; Nazionale et al., 2007). Only a few studies previously tried to estimate the rainfall threshold for Chittagong city (Khan et al., 2012; Ali et al., 2018). However, a rainfall threshold determination attempt is taken for the Cox's Bazar district employing multiple empirical approaches to cross-validate and thus fine-tune the threshold estimation effort. We have compared our results with established global models and found a few discrepancies. This discrepancy is worth noting and has emerged from rainfall-induced landslide inventory information unavailability. To conclude, we have provided rainfall intensity (mm/hr) and cumulative rainfall (mm) thresholds for 3, 24, 72, and 120 hours (table 2). This detailed threshold scenario will help design an early warning system to save people's lives and property in Cox's Bazar district.

ACKNOWLEDGEMENT

The authors would acknowledge the gracious support of the BB-FEES (Bangladesh Bank-Faculty of Earth and Environmental Sciences) research grant for sponsoring and promoting this research.

REFERENCES

Ahmed, B., 2015. Landslide susceptibility modelling applying user-defined weighting and data-driven statistical techniques in Cox’s Bazar Municipality, Bangladesh. Natural Hazards, 79(3), 1707–1737. https://doi.org/10.1007/s11069-015-1922-4

Aleotti, P., 2004. A warning system for rainfall-induced shallow failures. Engineering Geology

73(3–4), 247–265. https://doi.org/10.1016/j.enggeo.2004.01.007

Ali, R. M. E., Tunbridge, L. W., Bhasin, R. K., Akter, S., Uddin, M. Z., Khan, M. M. H., 2018. Landslide susceptibility of Chittagong City, Bangladesh, and development of landslides early warning system. Engineering and Mathematical Topics in Rainfall. https://doi.org/10.5772/intechopen.74743

Banglapedia, 2021. Cox's Bazar District

BMD, 2022. Bangladesh Meteorological Department

Caine, N. (1980). The Rainfall intensity: duration control of shallow landslides and debris flows. Geografiska Annaler. Series A, Physical Geography 62(1/2), 23. https://doi.org/10.2307/520449

Chen, C.-W., Saito, H., Oguchi, T., 2015. Rainfall intensity–duration conditions for mass movements in Taiwan. Progress in Earth and Planetary Science 2(1), 14. https://doi.org/10.1186/s40645-015-0049-2

Chleborad, A. F., 2000. Preliminary method for anticipating the occurrence of rainfall-induced landslides in Seattle, Washington, 30. https://doi.org/Open-File Report vol. 00-469

Chleborad, A. F., Baum, R. L., Godt, J. W., 2006. Rainfall thresholds for forecasting landslides in the Seattle, Washington, area-exceedance and probability, U. S. Geological Survey Open-File Report, 1064.

Comprehensive Disaster Management Programme II, 2012. Landslide inventory & Land-use mapping, DEM preparation, precipitation threshold value & establishment of early warning devices. Retrieved from http://www.landslidebd.com/wp-content/uploads/2017/02/27_Report_Landslide_Inventory_DEM_Preparation.pdf

Core R Team., 2019. A language and environment for statistical computing. Retrieved from http://www.r-project.org

Crozier, M. J., 1999. Prediction of rainfall-triggered landslides: A test of the antecedent water status model. Earth Surface Processes and Landforms 24(9), 825–833. https://doi.org/10.1002/(SICI)1096-9837(199908)24:9<825::AID-ESP14>3.0.CO;2-M

Dahal, R. K., Hasegawa, S., 2008. Representative rainfall thresholds for landslides in the Nepal Himalaya. Geomorphology 100(3), 429–443. https://doi.org/https://doi.org/10.1016/j.geomorph.2008.01.014

Dikshit, A., Satyam, D. N., 2018. Estimation of rainfall thresholds for landslide occurrences in Kalimpong, India. Innovative Infrastructure Solutions 3(1), 1–10. https://doi.org/10.1007/s41062-018-0132-9

Gariano, S. L., Rianna, G., Petrucci, O., Guzzetti, F., 2017. Assessing future changes in the occurrence of rainfall-induced landslides at a regional scale. Science of the Total Environment, 596–597, 417–426. https://doi.org/10.1016/j.scitotenv.2017.03.103

Gariano, Stefano Luigi, Guzzetti, F., 2016. Landslides in a changing climate. Earth-Science Reviews 162, 227–252. https://doi.org/10.1016/j.earscirev.2016.08.011

Glade, T., Crozier, M., Smith, P., 2000. Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical "Antecedent Daily Rainfall Model." Pure and Applied Geophysics 157(6–8), 1059–1079. https://doi.org/10.1007/s000240050017

Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C. P., 2007. Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorology and Atmospheric Physics 98(3–4), 239–267. https://doi.org/10.1007/s00703-007-0262-7

Guzzetti, Fausto, Peruccacci, S., Rossi, M., Stark, C. P., 2008. The rainfall intensity-duration control of shallow landslides and debris flows: An update. Landslides 5(1), 3–17. https://doi.org/10.1007/s10346-007-0112-1

He, S., Wang, J., Liu, S., 2020. Rainfall event-duration thresholds for landslide occurrences in China. Water (Switzerland) 12(2). https://doi.org/10.3390/w12020494

Hosenuzzaman, M., Kibria, M. G., Sarkar, R., Abedin, M. A., 2022. Landslide, agricultural vulnerability, and community initiatives: A case study in South-East part of Bangladesh. In: R. Sarkar, R. Shaw, & B. Pradhan (Eds.), Impact of climate change, land use and land cover, and socio-economic dynamics on landslides (pp.

123–145). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-16-7314-6_5

Idrogeologica, P., Nazionale, C., Alta, M., 2010. Rainfall thresholds for the possible occurrence of landslides in Italy (October 2009), 447–458.

Jafor Mia, A., Haque Farazi, A., Ilias Mahmud, M., Author, C., 2017. Factors affecting slope stability for triggering rainfall induced landslide at Chittagong City: a case study on 2007 and 2008 landslides. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN 14(4), 43–48. https://doi.org/10.9790/1684-1404044348

Kanungo, D. P., Sharma, S., 2014. Rainfall thresholds for prediction of shallow landslides around Chamoli-Joshimath region, Garhwal Himalayas, India. Landslides 11(4), 629–638. https://doi.org/10.1007/s10346-013-0438-9

Khan, Y. A., Lateh, H., Baten, M. A., Kamil, A. A., 2012. Critical antecedent rainfall conditions for shallow landslides in Chittagong City of Bangladesh. Environmental Earth Sciences 67(1), 97–106. https://doi.org/10.1007/s12665-011-1483-0

Luciani, S., Brunetti, M. T., Valigi, D., Guzzetti, F., Peruccacci, S., Rossi, M., 2010. Rainfall thresholds for the possible occurrence of landslides in Italy. Natural Hazards and Earth System Science 10(3), 447–458. https://doi.org/10.5194/nhess-10-447-2010

Maturidi, A. M. A. M., Kasim, N., Taib, K. A., Azahar, W. N. A. W., Tajuddin, H. B. A., 2021. Empirically based rainfall threshold for landslides occurrence in Peninsular Malaysia. KSCE Journal of Civil Engineering 25(12), 4552–4566. https://doi.org/10.1007/s12205-021-1586-4

Mohammad, D., Haque, E., Mahmud, T., Sifa, S., Tarin, M. A., 2017. Landslide susceptibility assessment based on satellite image processing and Bi-Variate statistical modeling for Rangamati District, Bangladesh. Bangladesh Journal of Physics 23(November), 93–106. https://doi.org/10.13140/RG.2.2.16092.03203

Monsieurs, E., Dewitte, O., Demoulin, A., 2018. A susceptibility-based rainfall threshold approach for landslide occurrence. Natural Hazards and Earth System Sciences Discussions (November), 1–25. https://doi.org/10.5194/nhess-2018-316

Nazionale, C., Alta, M., Stark, C. P., 2007. Rainfall thresholds for the initiation of landslides in Central and Southern Europe RAINFALL THRESHOLDS FOR THE INITIATION OF (December). https://doi.org/10.1007/s00703-007-0262-7

Nolasco-Javier, D., Kumar, L., Tengonciang, A. M. P., 2015. Rapid appraisal of rainfall threshold and selected landslides in Baguio, Philippines. Natural Hazards 78(3), 1587–1607. https://doi.org/10.1007/s11069-015-1790-y

Peruccacci, S., Brunetti, M. T., Luciani, S., Vennari, C., Guzzetti, F., 2012. Lithological and seasonal control on rainfall thresholds for the possible initiation of landslides in central Italy. Geomorphology 139–140, 79–90. https://doi.org/10.1016/j.geomorph.2011.10.005

Peruccacci, S., Teresa, M., Luciani, S., Vennari, C., Guzzetti, F., 2012. Geomorphology lithological and seasonal control on rainfall thresholds for the possible initiation of landslides in central Italy. Geomorphology 139–140, 79–90. https://doi.org/10.1016/j.geomorph.2011.10.005

Reichenbach, P., Cardinali, M., De Vita, P., Guzzetti, F., 1998. Regional hydrological thresholds for landslides and floods in the Tiber River Basin (central Italy). Environmental Geology 35(2), 146–159. https://doi.org/10.1007/s002540050301

Saito, H., Nakayama, D., Matsuyama, H., 2010. Relationship between the initiation of a shallow landslide and rainfall intensity—duration thresholds in Japan. Geomorphology 118(1), 167–175. https://doi.org/https://doi.org/10.1016/j.geomorph.2009.12.016

Sarwar, G. M., 2008. Landslide tragedy of Bangladesh. The First World Landslide Forum, 18-21 November 2008, United Nations University (UNU), Tokyo, Japan, (November), 18–21. Retrieved from https://www.academia.edu/3588839/Landslide_Tragedy_of_Bangladesh

Segoni, S., Piciullo, L., Gariano, S. L., 2018. A review of the recent literature on rainfall thresholds for landslide occurrence. Landslides 15(8), 1483–

1501. https://doi.org/10.1007/s10346-018-0966-4

Sultana, N., 2020. Analysis of landslide-induced fatalities and injuries in Bangladesh: 2000-2018. Cogent Social Sciences 6(1), 1737402. https://doi.org/10.1080/23311886.2020.1737402

Sultana, N., Tan, S., 2021. Landslide mitigation strategies in southeast Bangladesh: Lessons learned from the institutional responses. International Journal of Disaster Risk Reduction 62, 102402. https://doi.org/https://doi.org/10.1016/j.ijdrr.2021.102402

Tehrani, F. S., Hüsken, L., 2019. Landslide susceptibility mapping of refugee camps in Bangladesh. Proceedings of the International Conference on Natural Hazards and Infrastructure.

The Daily Star, 2021. Retrieved from https://news.climate.columbia.edu/2019/11/22/landslide-risk-rohingya-refugee-camps/

UNHCR, 2019. Refuge response in Bangladesh. Retrieved from https://data2.unhcr.org/en/situations/myanmar_refugees

Valenzuela, P., Zêzere, J. L., Domínguez-Cuesta, M. J., Mora García, M. A., 2019. Empirical rainfall thresholds for the triggering of landslides in Asturias (NW Spain). Landslides 16(7), 1285–1300. https://doi.org/10.1007/s10346-019-01170-2

Vennari, C., Gariano, S. L., Antronico, L., Brunetti, M. T., Iovine, G., Peruccacci, S., … Guzzetti, F., 2014. Rainfall thresholds for shallow landslide occurrence in Calabria, southern Italy. Natural Hazards and Earth System Sciences 14(2), 317–330. https://doi.org/10.5194/nhess-14-317-2014