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A Rainfall Intensity-Duration Threshold for Mass Movement in Badulla, Sri Lanka

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Abstract

Mass movement in Sri Lanka is mainly triggered by heavy rainfall. International literature is rich of works defining rainfall intensity-duration models to identify the rainfall threshold for various types of Mass movement. However, studies have not focused to establish a relationship between intensity and duration of rainfall in Sri Lanka. Therefore, this study focused to establish rainfall intensity-duration models to identify the rainfall threshold for mass movements in Badulla district in Sri Lanka, where forty four (44) rainfall events that resulted in same number of landslides during the last three decades were considered. Results indicate the rainfall threshold relationship fits to the log linear model of the exponential function, $I = \alpha \cdot D^{-\beta}$. The constructed I-D curve revealed that short duration (<2 h) and high-intensity (>54 mm/h) in rainfall events can potentially trigger the landslide. However, long-duration (>8 h) and low-intensity (<25 mm/h) in rainfall events may also trigger mass movements in Badulla. As per the results, most mass movements occur during northeast monsoons and inter-monsoons. In general, higher mean rainfall intensities trigger the debris flows, while long-duration rainfall events can trigger both landslides and debris flow. When compared to Sri Lankan mass movements triggering threshold intensities are fairly higher than the global threshold values. It confirms that within Badulla, mass movements are triggered by very high intense and/or long duration rainfalls events only. Further, time series analysis of the rainfall events shows an upward trend of extreme rainfall events, which increased landslide occurring frequency in last six (6) years.

Keywords

Rainfall Intensity-Duration, Rainfall Threshold, Landslide, Debris Flow, Cutting Failure, Slope Failure, Trigger Mass Movements

1. Introduction

Landslide (mass movements) acts on natural and engineered slopes in steep topography [1] [2]. Rainfall and Earthquakes are main triggering factor for mass movements [3] [4] [5] [6], however the rock type, type of bedrock, type of cover material, geotechnical and hydrogeological properties, land use, slope gradient, slope shape, and so on can be considered as contributory other contributory factors [3] [7] [8] [9] [10]. Sri Lanka is located in earthquake free zone [11] Therefore in Sri Lankan contest, rainfall can be considered as a main landslide triggering factor.

Various methods have been proposed in the literature to predict rainfall conditions that are expected to trigger mass movements [5] [12] [13]. These studies have been focused on rainfall parameters such as rainfall intensity, duration, cumulative rainfall, and antecedent rainfall [12]. Relationships between rainfall intensity and duration are the most common estimate of rainfall thresholds for landslides [14] [15] [16]. In case of rainfall-induced landslides, the minimum intensity or duration of rainfall necessary to cause or reactivate a landslide is known as the “rainfall threshold for sliding” [17]. Empirical rainfall thresholds for the initiation of landslides have been proposed at the global (world-wide), regional, and local scale. Review of the literature reveals that no unique set of measurements exists to characterize the rainfall conditions that are likely. Different types of empirical rainfall thresholds for possible initiation of landslides are proposed in the literature. However, most of the similar studies in the Indian subcontinent have established intensity-duration (ID) thresholds, thresholds based on the total event rainfall, and rainfall event-duration thresholds [18].

Badulla district in Sri Lanka is one of the major districts where large-scale landslides are observed during heavy rainfall (**Figure 1**) [19]. Several studies have focused on understanding the underlying landslide triggers in the country [20]. Generally, a continuous rainfall about 200 mm within a period of 3 days makes hilly districts susceptible to landslides [21]. However, around two-day continues 75 - 100 mm rainfall can trigger landslides in sloped cultivated lands in Badulla [22]. In Sri Lanka, an increasing trend in high intense rainfall event during last decade is recorded, especially in the Wet Zone and western slopes in the central hills [23]. Also, the frequency of landslide events per year has increased over the last few decades. A sudden increase is observed in the occurrence of landslides during the period from 2002 to 2008 in Badulla [24]. However, studies have not been focused to establish a relationship between rainfall intensity and duration.

The rainfall intensity and duration analyses are important to study the sliding trends during the past, and such analyses can help to forecast future events under

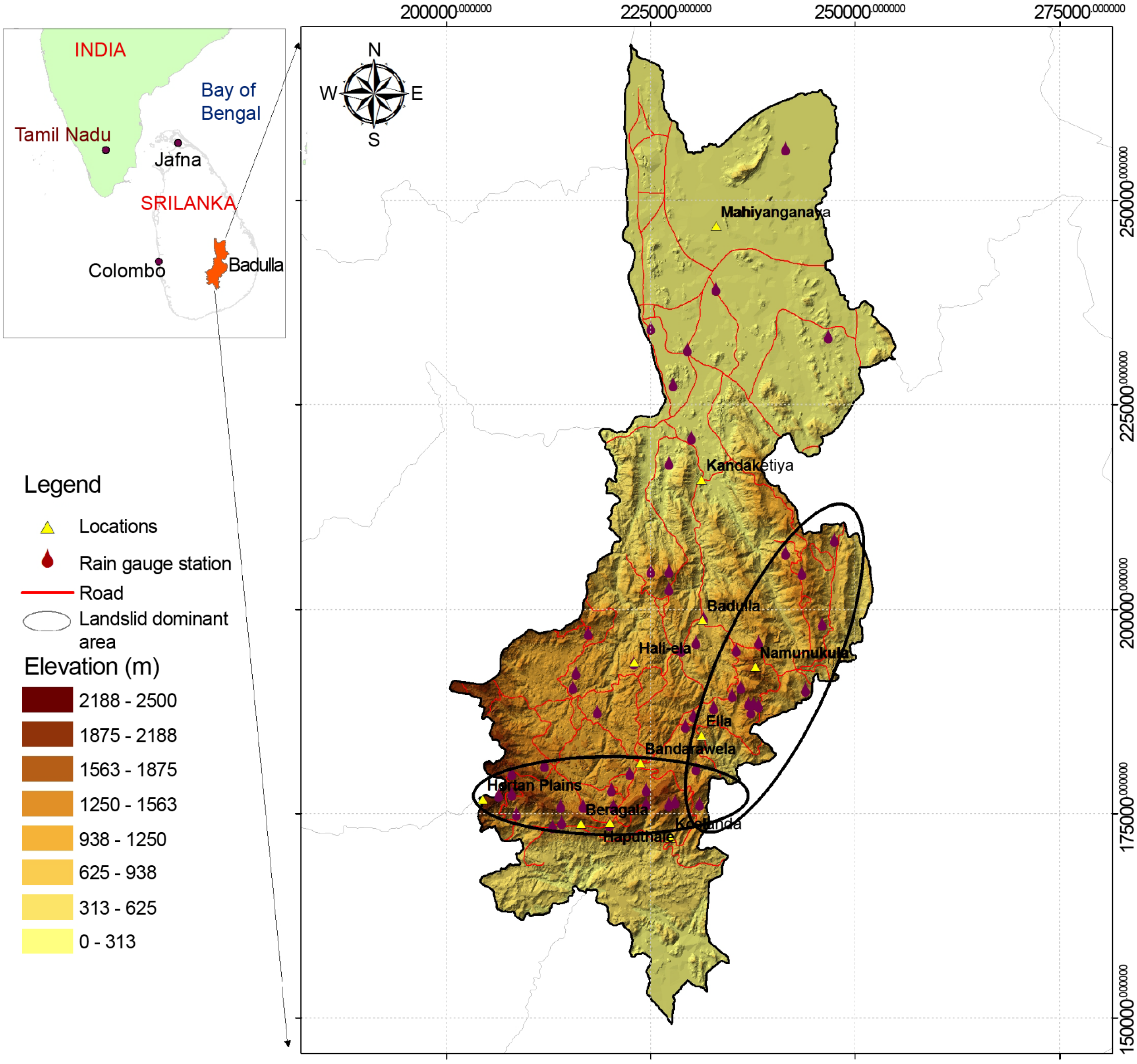

Figure 1. Map showing elevation distribution of Badulla district and location of rain gauge stations. Triangles denote important locations for past landslides. Elevations based on 1:50 000 maps (1998) Department of Survey, Sri Lanka.

heavy rainfall. Therefore, the major aim of this study is to investigate the rainfall variation in the last few decades and to study the temporal pattern of landslides. Further, the study expects to analyze rainfall events that have caused landslides in Badulla, to define the threshold for possible occurrence of landslides.

2. Study Area and Physical Setting

Badulla is about 230 km away from Colombo towards the eastern slopes of the central hills of Sri Lanka (**Figure 1**).

2.1. Demography and Geographical Description of the Area

The population of Badulla district is approximately 886,000, with 1:1 male to female ratio. Although 47% of residents are employed, the high rate of dependency reaches 54% of the population [25]. Fifty percent of the population is included in the labor force due to the large number of employees in plantation agriculture. Badulla has been recognized as one of the districts with highest poverty levels with lower per capita income [26].

Badulla district is located in the southeastern mountainous terrain in Sri Lanka and represents an area of 2870 km^2 (**Figure 1**). Physiographically, it is a complex region with mountain peaks, dissected plateaus, escarpments, and narrow valleys. Most mountains are extended from middle to southern area, whereas the northern area of the district is demarcated by a flat terrain (**Figure 1**). The eastern mountain region of the district has an elevation range from 1200 to 1800 m. The north-south aligned a mountain range link to well-known Namunukula and Lunugala ranges that rise to over 1200 m. The extreme south of the district demarcated by a steep escarpment is a section of the Koslanda plateau with an elevation of 300 - 1000 m above mean sea level (**Figure 1**).

2.2. Climatic Conditions of the Area

Rainfall over Sri Lanka is characterized by its tropical location and by the monsoonal regime, and thus has a significant seasonal variation in the rainfall pattern. There are four climatologic seasons in Sri Lanka, namely, the northeast monsoon from December to February, the southwest monsoon from May to September, the first inter-monsoon from March to April, and the second inter-monsoon from October to November. The north-east monsoon provides a high rainfall to the eastern slopes, but the south-west monsoon and inter-monsoon is relatively dry (500 - 750 mm). The average annual rainfall of Badulla is around 2000 mm and has a clear variation along the terrain. Northern and southern-most extremities have 900 mm annual average and Uva Basing has 1700 mm. However, over 2500 mm is in the eastern Namunukula and Lunugala ridges [27].

The rainfall regimes differ with the region's geography. The northern-most tips of the Lunugala ridges received 40% - 50% of the annual rainfall by north-east monsoons, 30% - 40% during the inter-monsoons, and 12% - 20% in south-west monsoons [27]. Especially the rain shadow areas of Uva Basin receive maximum rainfall during the inter-monsoons. In general, Badulla and Diyatalawa cities have 43% - 47% of the total annual rainfall during the inter-monsoons (March-April and October-November), 35% and north-east monsoons, and 22% during the south-west monsoon (December-February). However, along the southern and eastern edges of the basin, south-west monsoon exceeds the north-east.

2.3. Geology and Land Use around the Landslides

Precambrian high-grade metamorphic rocks in Sri Lanka belong to three major geological units known as the Highland, Wanni, and Vijayan Complexes. Badulla district is located in the eastern section of the Highland Complex, which is composed of meta-igneous rocks and meta-sedimentary rocks [28]. The meta-igneous rocks comprise granitic, charnockitic, and quartzofeldspathic gneisses, along with metabasites and syenitic gneiss [29]. The meta-sedimentary rocks are mostly meta-pelites, meta-arkoses, and meta-greywackes [30]. However, north-east flat region of the district consist of Wanni Complex rocks.

With respect to spatial distribution, most landslides appear to occur in the Uva, Central, and Southern, provinces. Especially, Badulla, Nuwara Eliya, Kegalle, Rathnapura, Galle, Matara, and Kalutara are the most landslide prone districts. In general, higher incidences are reported within the Badulla district. In addition, approximately 66.9% of the land area in Badulla district is prone to landslides [22] therefore, Badulla is considered as one of the landslide prone districts of Sri Lanka.

Land use of Badulla district is mostly covered by scrubs (≈790 km^2), home gardens (≈582 km^2), and forests (≈335 km^2). Main plantations around hilly regions are tea cultivations (≈890 km^2) while flat terrain in the northern region is predominant by paddy lands (≈270 km^2 [25] [27]).

3. Methodology

The methodology used in this study mainly consisted of two components: 1) collection of landslide and rainfall records in Badulla district from 1986 to 2014 and evaluate the trend and patterns of the landslide occurrences and rainfall variability; and 2) analysis of the relationship between rainfall and landslide occurrence using empirical models. Data was collected from NBRO and Metrological Department of Sri Lanka. The parameters and analysis model were obtained from the referred from previous international studies.

3.1. Mass Movement Database

A total of 44 mass movements caused by rainfall events were analyzed during the 28 years from 1986 to 2014. Mass movement data were compiled from NBRO Sri Lanka. NBRO has been classified Mass movement events based on material type and type of movement in such a way that, Debris flow, Rock fall, Cutting failure, Earth slip, and Landslide. Temporal variability of different types of landslide events and corresponding annual average rainfall illustrated in **Figure 2**.

Further secondary data was collected including the type of the landslide, location, and approximate time which mass movement taken place (to the closest hour) of each event and summarized in a table.

3.2. Site Selection, and Incorporate Mass Movement Data into Rainfall

Rainfall records were obtained from 54 rain-gauge stations located within the district established by Metrological Department and National Building Research Organization (NBRO) of Sri Lanka. This data series provided records of rainfall

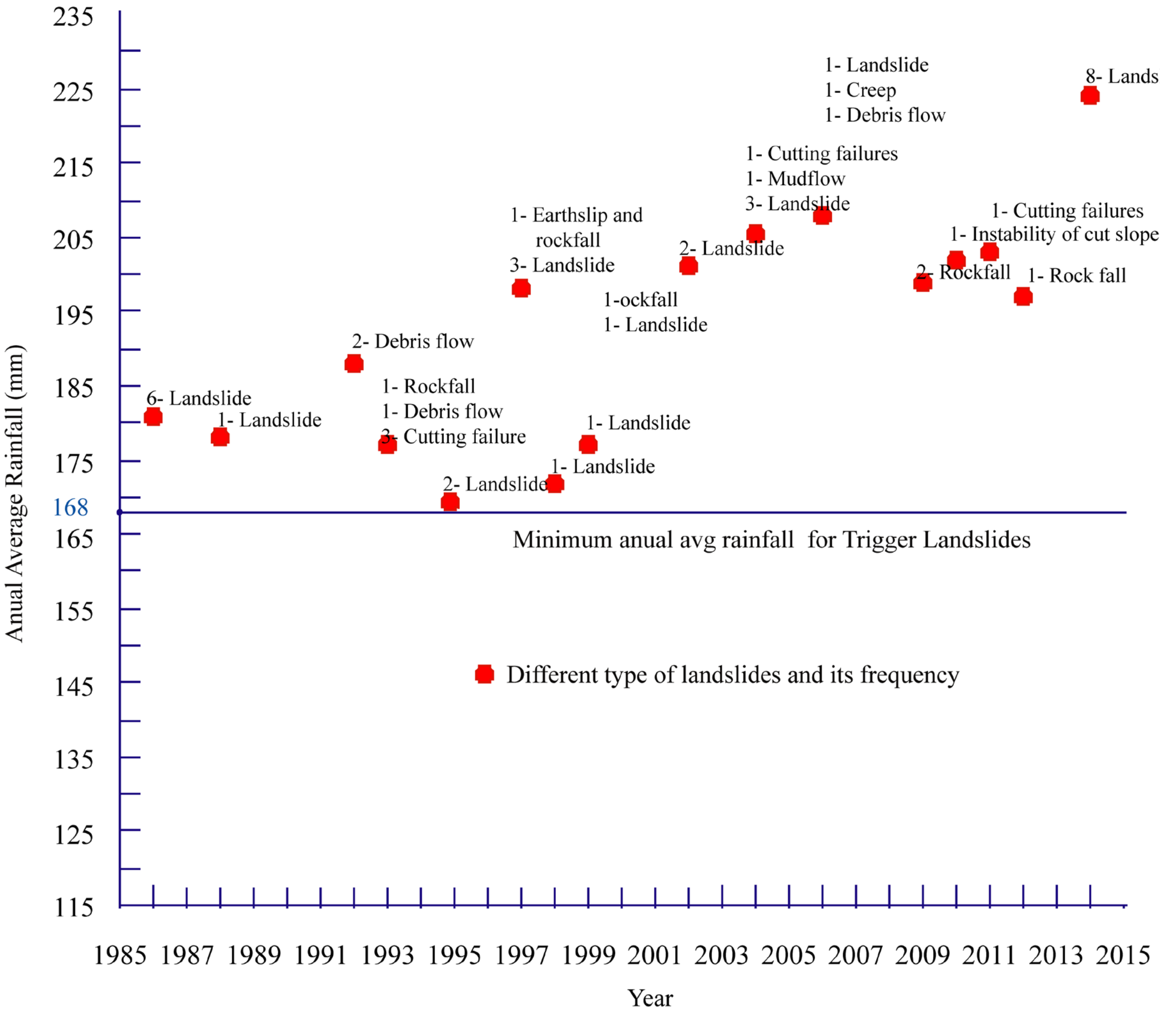

Figure 2. Figure shows the seasonal distributions of large scale landslides: from 1986 to 2014 based on source Meteorological Department and NBRO, Sri Lanka.

data of 28 years including occurrences of mass movements. Mass movements, for selected rainfall was verified by using archival newspapers and remote sensing data. According to NBRO, 44 mass movements had been occurred during the considered period from 1986 to 2014. Because of that, hourly cumulative rainfall 72 hrs prior to the taken place each and every mass movements, and the duration (hrs) of that rainfall were obtained from the located rain-gauge stations belongs to Metrological Department and NBRO of Sri Lanka.

3.3. Estimation of the Causative Amount of Rainfall

Throughout the preliminary field survey and satellite image observation, it is observed that rain gauges stations are not always exactly located close to mass movement sites however, to threshold analysis, the cumulative rainfall and duration of rainfall for triggering each mass movement is essential [31]. Therefore, to estimate the causative amount of rainfall for each and every 44 landside events in Badulla from 1986 to 2014, interpolation technique was adopted within the GIS environment. The interpolation ordinary Kriging and a spherical semi-variogram model were used to estimate hourly rainfall data at each landslide location over the duration of a rainfall event. Ordinary Kriging and a spherical semi-variogram model can be considered as most accurate methods to estimate rainfall in mountainous areas in Sri Lanka [32]. A continuous rainfall event is considered to begin when hourly rainfall surpasses 4 mm and ends when hourly rainfall decreases below 4 mm over the next six consecutive hours [33].

3.4. Threshold Analyses

A threshold is defined as the level or the value that must be exceeded to produce a given effect or result [34]. Rainfall thresholds for mass movement are defined as the best separators of rainfall conditions that resulted and did not result in slope instability. Rainfall thresholds for mass movement can be modeled by establishing relationship between rainfall and intensity, further it can be used to predicted possibility to mass movements under the rainy conditions [35].

In this study the causative amount of mean rainfall (mm) and consequent duration (hr) were obtained from the beginning of each of 44 rainfall events to the time of mass movement occurrence. The mean rainfall intensity per hour (I, mm/hr) was calculated for each mass movement (**Table 1**). The rainfall amount varies largely depending on the main reliefs of the Badulla region under such circumstances it is better use mean rainfall rather than peal rainfall [36].

International literature revealed that various methods have been used to establish the relationship between rainfall intensity and duration [12] [37], however the general form of the relationship between rainfall intensity and duration given as an exponential function as in follows

$$I = \alpha \cdot D^{-\beta} \tag{1}$$

i.e., a simple exponential function, where α is a scaling constant (intercept), and β is the shape parameter (slope). The Equation (1) is commonly used for model the Intensity and Duration in many studies.

Exponential equations can be written as logarithmic equations and vice versa. In this study exponential rainfall intensity and duration relationship ($I = \alpha \cdot D^{-\beta}$) were converted into linear form, because linear model can overcome the problems associated with the fitting of data into exponential form. For that exponential function transformed into logarithmic form as given below

$$\ln(I) = \ln(\alpha) - \beta \ln(D) \tag{2}$$

Equation (2) is the liner form of the Equation (1). Rainfall intensity (*I*) and duration (*D*) was log transformed and then a plotted ln(*I*) against ln(*D*) for 44 rainfall events from 1986 to 2014 in same graph. This liner function (I-D) has been empirically proved for a wide range of time durations [14]. Variability difference mass movement types (debris flow, landslides, mud flow, slope failures, etc.) related to each rainfall events were illustrated by different colors in the ln(*I*) vs. ln(*D*) as shown in **Figure 3**.

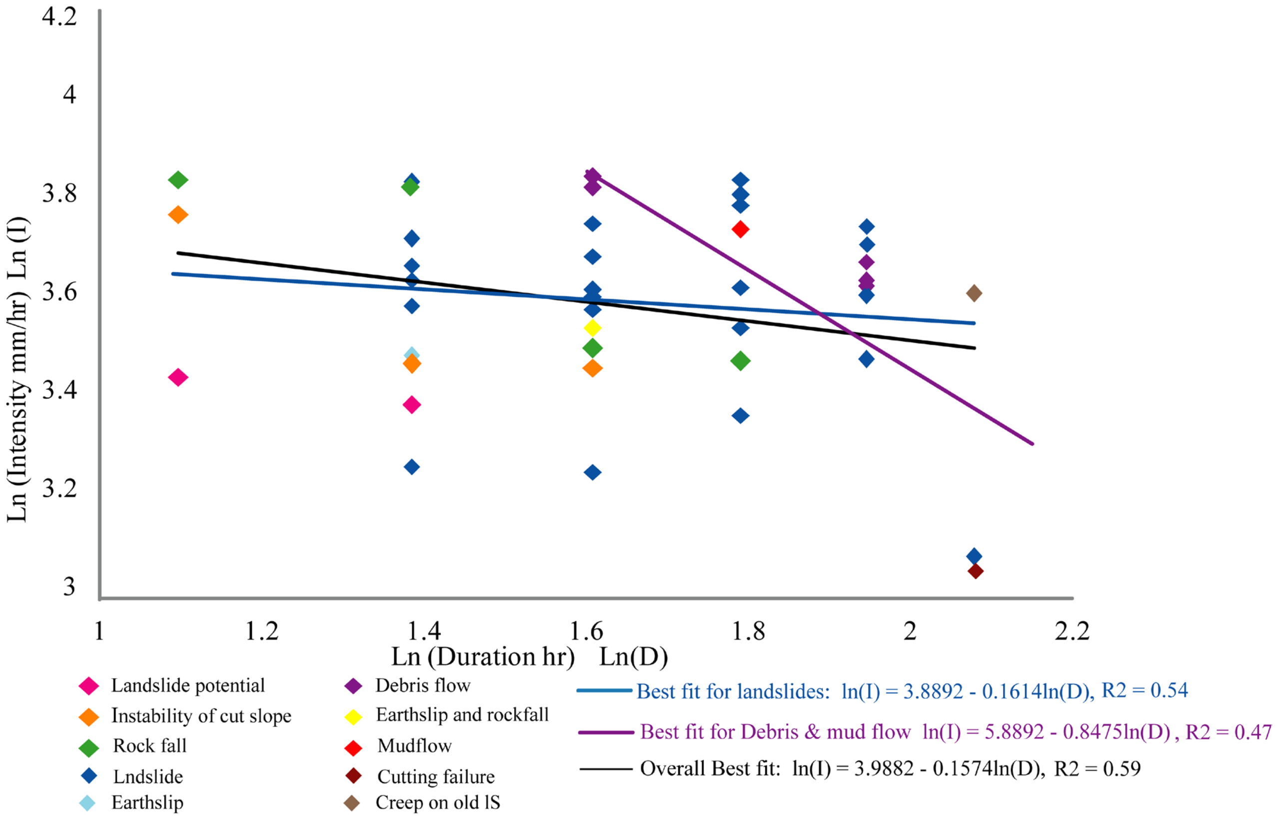

Figure 3. Discrimination plot of critical rainfall intensity-duration for Badulla district.

Rainfall conditions, ln(I) vs. ln(D), that have resulted in landslides is fitted (least square method) with a linear equation of the type $\log(I) = \log(\alpha) - \beta\log(D)$ which is entirely equivalent to the exponential function in linear coordinates. Then log-linier regression model was established for most common mass movement types in Badull district.

The Independent Samples t Test was conducted compares the means of rainfall intensity of landslides and means of rainfall intensity of Mud/debris flow in order to determine whether there is statistical evidence that the associated population means are significantly different.

3.5. Analyses of Temporal Variability of Rainfall and Landslides

Annual average daily rainfall and landslide data were analyzed for the period from 1986 to 2014 in Badulla district. Trend analysis examined the variation in rainfall and landslide patterns using Minitab 20 (Minitab Inc). Nonparametric Chi-Square goodness of fit test was employed to study the association between month (season) and occurrence of landslides using SPSS 19 ($p < 0.05$).

Temporal variation of landslide events is therefore vital to determine the significance of the landslide trend, and nonparametric Mann-Kendall test was conducted using SPSS 19 ($p < 0.05$). The calculations are described below:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} singn\left(x_i - x_j\right) \quad (3)$$

where, S is the sum of signs of differences between any two observations for a series x_n. Also, where sign (z) is 0 when z is zero, and 1 when $z >$ and −1 when $z < 1$.

4. Results and Discussion

In the considered period, *i.e.* from 1986 to 2014, the rainfall pattern in Badulla depicted a noticeable change; analogous to the rainfall change, landslide occurrences also showed an increasing trend having two events per year. A threshold was fitted to the liner form of I-D curve, expressed as $\ln(I) = 3.9882 - 0.1570 \ln(D)$.

4.1. Rainfall Intensity-Duration (I-D) Threshold

The I-D threshold for mass movements is identified on an I-D plot as the minimum rainfall for which a landslide could occur (Chen, 2015).

Thresholds for the possible initiation of rainfall-induced landslides in the Badulla district were identified from the log-linier model of the I-D exponential function. Mean rainfall intensity for all mass movements ranged from 25 mm/h to 54 mm/h with an average of 42 mm/h, and rainfall duration ranged between 3 - 8 h with an average of 5 h (**Table 1**). Minimum cumulative rainfall was 119 mm and the maximum was 339 mm with an average of 107 mm. A considerable range of rainfall durations and cumulative rainfall suggests that different meteorological and hydrological conditions are likely to initiate landslides within the Badulla district.

Average rainfall intensity, duration, and cumulative rainfall for debris flow/mud flow were 49 mm/h, 7 h, and 260 mm respectively, and those for landslides were 41 mm/h, 5 h, and 210 mm respectively (**Table 1**).

This study established an empirical linear regression line I-D plot, considering all 44 mass-movement events summarized in **Table 1**, landslide and debris/mud flow separately, and thresholds were established for overall mass movements, landslides and debris/mud flow for Badulla district (**Figure 3**). The resultant linear regression equations for these three conditions are as follows:

$$\mathrm{Ln}(I) = 3.9882 - 0.1570 \ln(D) \ (3 < D < 8 \text{ h; all mass movements, } R^2 = 59\%) \quad (4)$$

$$\mathrm{Ln}(I) = 3.8892 - 0.1614 \ln(D) \ (5 < D < 8 \text{ h; landslides only, } R^2 = 54\%) \quad (5)$$

$$\mathrm{Ln}(I) = 5.8892 - 0.8475 \ln(D) \ (5 < D < 8 \text{ h; debris \& mud flow only } R^2 = 47\%) (6)$$

This threshold are fitted to the mean values of the data point reflects the approximate average rainfall conditions necessary to trigger any mass movement in Badulla district. The equation for all mass movements (Equation (4)) indicates that short duration (<2 h) and high-intensity (>53.75 mm/h) rainfall events can potentially trigger any mass movement in Badulla district. However, long-duration (>8 h) and low-intensity (<24.6 mm/h) rainfall events may also trigger mass movements in Badulla district.

Independent sample t-test and resultant p-values (<0.05) indicate that mean

Table 1. Date of occurrences and rainfall characteristics of 42 rainfalls that trigger the landslides in Badulla.

Year	Month	Date	**Landslide information**			
			Avg. Accumulation mm	Duration hr	Avg. Intensity mm/hr	Type
1986	January	6	316	7	45	Landslide
1986	January	7	259	7	37	Landslide
1986	January	9	119	4	30	Landslide
1986	January	9	244	5	49	Landslide
1986	January	10	237	6	40	Landslide
1986	January	10	197	5	39	Landslide
1986	January	10	205	5	41	Landslide
1988	December	21	165	4	41	Landslide
1992	November	16	319	7	46	Debris flow
1992	November	16	305	7	44	Debris flow
1993	December	16	310	6	52	Debris flow
1993	December	17	179	4	45	Rockfall
1993	December	26	198	8	25	Cutting failure
1995	April	17	212	4	53	Landslide
1995	July	24	228	5	46	Landslide
1997	November	17	257	6	43	Earth slip
1997	November	19	268	5	53	Landslide
1997	November	19	289	6	48	Landslide
1997	November	19	215	4	54	Landslide
1998	November	16	149	3	50	Landslide
1998	November	17	180	4	45	Landslide
1999	October	5	147	5	29	Landslide
2002	April	23	198	6	33	Landslide
2002	April	24	206	5	41	Landslide
2004	December	21	198	6	33	Cutting failures
2004	December	22	182	5	36	Cutting failures
2004	December	23	211	5	42	Landslide
2004	December	23	320	6	53	Mudflow
2006	November	22	307	7	44	Landslide
2006	December	20	338	8	42	Creep on old lS
2006	December	20	316	7	45	Debris flow
2009	January	20	199	5	40	Rock fall
2009	January	20	189	4	47	Rock fall landslide
2010	January	26	160	3	53	Instability of cut slope
2011	November	23	221	6	37	Cutting failures
2012	December	21	160	3	53	Rock fall
2014	October	29	306	6	51	Landslide-Mud flow
2014	October	30	197	8	25	Landslide
2014	October	30	174	4	44	Landslide
2014	October	30	149	4	37	Earth slip
2014	October	30	189	5	38	Landslide
2014	October	30	107	3	36	Landslide potential
2014	October	30	149	4	37	Instability of cut slope
2014	October	30	135	4	34	Landslide potential
Max			338	8	54	
min			107	3	25	
Avg.			218	5.3	42.2	
Std			62	1	8	

rainfall intensity of landslides and mean rainfall intensity of debris/mud flows are significantly different at 95% confidence level.

4.2. Comparing I-D Thresholds for Badulla with Those of Other Part of the World

Established empirical I-D thresholds for mass movements in Badulla from all type of mass movements, landslide and debris/ mud flow were compared with those for other areas of the world is essential.

Worldwide threshold for debris flows developed by Caine (1980), log liner form that worldwide threshold given by $\ln(I) = 2.6959 - 0.92\ln(D)$. This worldwide threshold falls below the Badulla it indicates much rainfall required to trigger any mass movement in Badulla with compared to the global scenario.

[12] (2015) established thresholds for all mass movements, landslides and debris flows in Taiwan, The equation for all mass movements show that short-duration (e.g., 16.1 mm/h) rainfall events can trigger mass movements at any time. But, low-intensity (e.g., <8.8 mm/h) rainfall events required long-duration (e.g., >71 h) for trigger mass movements. When compared to Sri Lankan mass movements triggering threshold intensities are fairly higher than the Taiwanese threshold values. It confirms that within Badulla, mass movements are triggered by very high intense and/or long duration rainfalls events only with compared to Taiwan.

4.3. Temporal Distribution of Rainfall and Landslides

Figure 4 presents the annual average rainfall variation, which illustrates a one direction upward trend in weather pattern changes over the last 28 years. The rainfall distribution pattern revealed a 172 mm annual average mean with 32 mm of standard deviation, while showing 43% of fairly high coefficient of variance. However, after year 2000, coefficient of variance was recorded as 63%, indicating highest rainfall variability than the previous years.

Such unusual rainfall patterns resulted in heavy rainfall events and dry spells throughout the last 28 years, and this uncertainty trend of rainfall was rapidly amplified after year 2000 (**Figure 4**). Overall positive direction of mean deviation of rainfall indicates that higher probability in extreme rainfall events in the future, which was a common phenomenon in landslide prone areas [6]. According to previous studies, Badulla district is vulnerable to climatic changes and it already drives an increase in extreme weather events in the future [38].

However, the data displays a sudden positive mean deviation of average rainfall during the period of 2000 to 2014 (**Figure 4**). This pattern has a closer relationship to the temporal distribution of mass movements during the considered period (**Figure 5**). This may conclude that frequently high mean deviation of rainfall results higher probability to occur mass movements.

During the period of 1986-2014, 44 large scale mass movement events were clearly identified and recorded in table (**Table 1**). According to **Figure 5** and

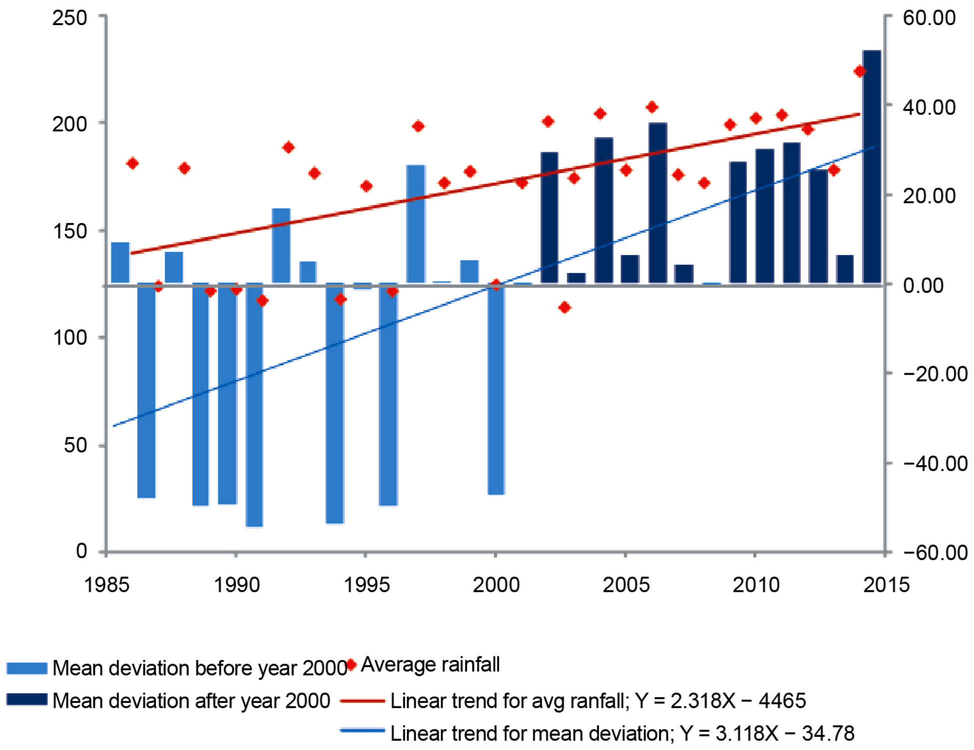

Figure 4. Bar chart shows the annual average rainfall and mean deviation from 1986 to 2014 for Badulla district.

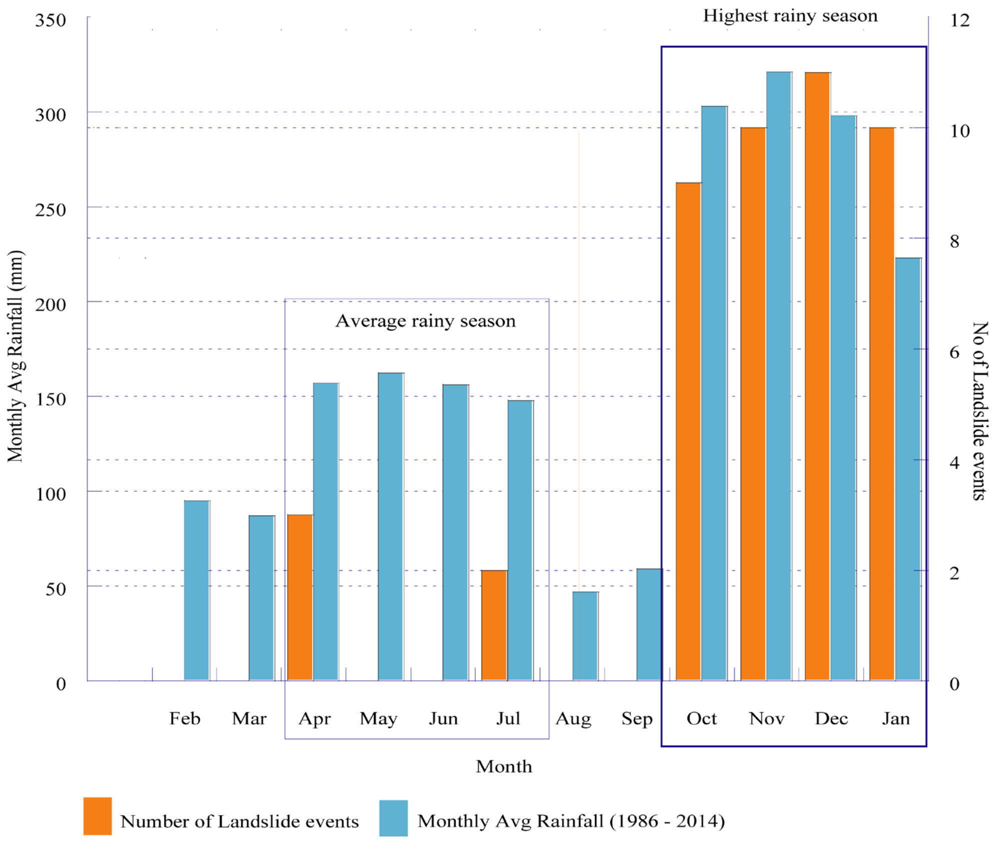

Figure 5. Bar chart shows temporal variability of large scale landslides in Badulla from 1986 to 2014.

Table 1, from 1986 to 2000, only 20 incidents were recorded while lowering annual average of mass movements to 2 incidents per year. Although totally 24 incidents were recorded from 2000 to 2014, it exceeded the annual average of mass movements occurrences to over two incidents per year. Temporal variability of mass movements demonstrated an upward trend of mass movement events from 1986, while showing 0.12 events per month.

According to the Mann-Kendall test, landslide trend is significant at 95% confidence level. If this rainfall trend and mass movement pattern will continue to the future, it can be conclude that landslides hazards in Badulla may be higher than the past decades. Sri Lankan government also prophesied that rise of landslides in Badulla due to the extreme rainfall events from year 2000 to future.

4.4. Impact of Seasonal Rainfall Variation on Landslides

Generally, mass movements are more common during rainy sessions in Sri Lanka, and thus seasonal distribution of mass movements demonstrate a clear link with the seasonal variation of rainfall (Figure 5). Highest rainfall is received in northeast monsoon (November to January) and first inter-monsoon (April to July), which is reflected in the seasonal variation of landslides (Figure 5).

The records of landslides are high in the months of April, May, and July, and once again from November to January, indicating a clear relationship with first inter-monsoon and northeast monsoon seasons respectively (Figure 5). According to Metrological Department, Sri Lanka, approximately 60% - 80% of rainfall is received during the northeast monsoon; therefore, the northeast monsoon period (November to January) has the highest recorded landslides occurrences than the first inter-monsoon period in Badulla. According to this study, approximately 80% of mass movements occurred in northeast monsoon period. Graphically it can be proved that there is a clear link between climatic seasons and occurrences of mass movements. According to Chi-Square goodness test there is a significant relationship exist between monsoon period, and the occurrence of landslide at 95% confidence level ($p < 0.05$).

4.5. Possible Average Conditions for the Occurrence of Landslides

In Sri Lanka, landslide process begins with rainfall but is affected by many other factors; therefore it is impossible to determine the possible rainfall level to initiate landslides. This study revealed that landslides are a result of heavy precipitation and when average monthly rainfall exceeds 168 mm/month, the occurrence of landslides becomes more dominant in the district. Worldwide studies have shown that this value may vary from 150 mm/month to 200 mm/month in the global context [39]. Nonetheless, according to few cases of the present study, even if rainfall exceeded 168 mm/month, no landslides were observed (Figure 6).

This may be due to the role played by predisposing factors such as proper land management practices and stable geological settings. However, no recorded landslide below 168 mm/month level is available during the last 28 years.

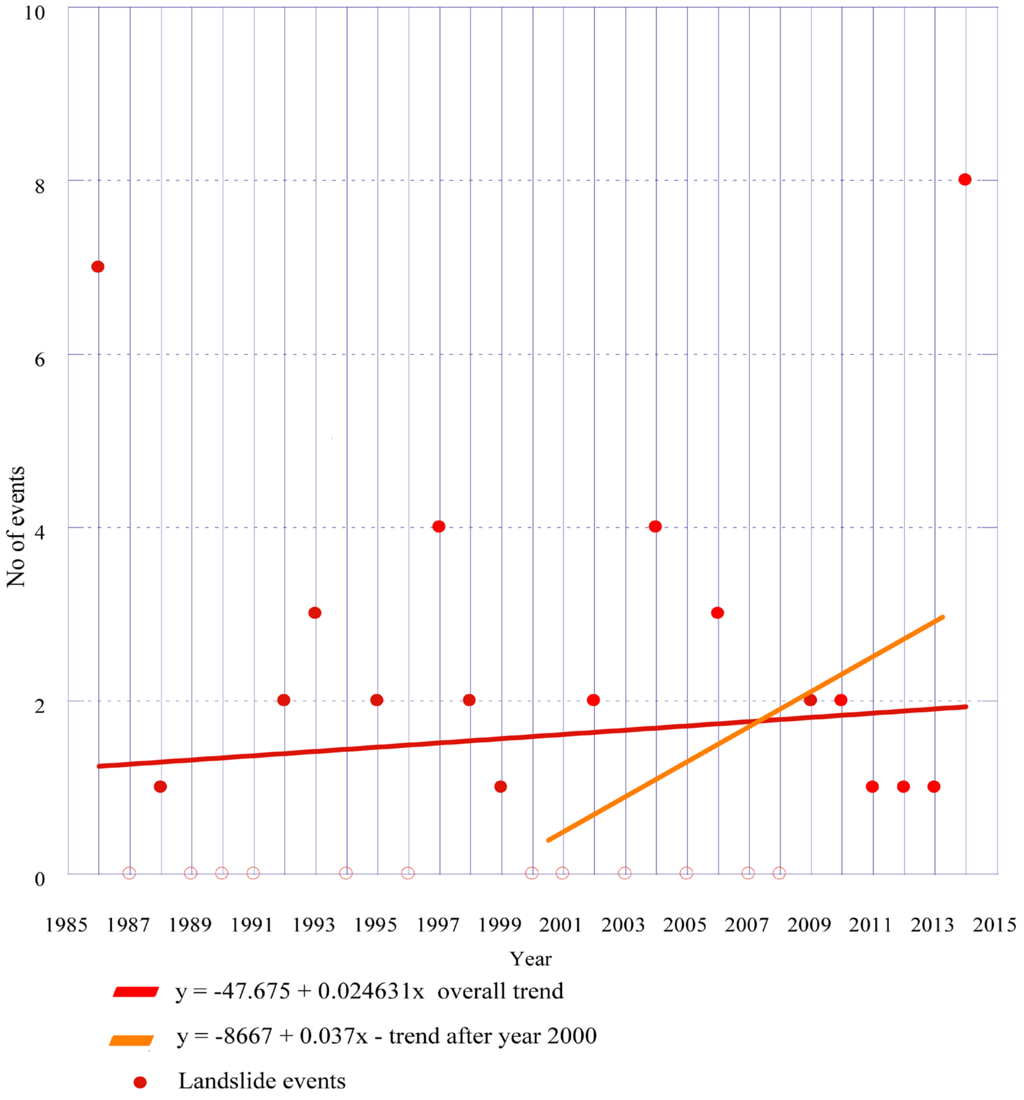

Figure 6. Scatter plot represents monthly average rainfall from 1986 to 2015. Red dots denote large scale landslides.

4.6. Limitations of the Study

Developed log-linear model can determine the amount of precipitation needed to trigger landslide in Badulla district. However, limitations exist. In study, log-liner model developed by studying individual rainfall events and corresponding landslides however, other landslide initiation control factors such as morphological, lithological differences, soil characteristics, human activities have not been considered. But these data are difficult to collect and model precisely over large areas. Developed log-linear model can be calibrated using rainfall events for which precipitation measurements and the location and the time of slope failures are known.

Regional and local ID thresholds are the fact that thresholds defined for a specific administrative region in this study it was Badulla district. If ID thresholds based on specific administrative region then it would not be possible to export it for surrounding regions. Therefore it is recommended to consider climatological boundaries rather than the administrative boundaries in further studies.

5. Conclusions

This study confirmed that most landslides occur in Badulla district during northeast monsoons and inter-monsoon seasons and indicated that a strong correlation exists between frequency of landslides and rainfall seasons of the district. The rainfall shows increasing trends in Badulla district within last three decades. This could indicate the amount of rainfall per day may have increased. In particular, the number of landslides occurred per year increased over the period of 28 years. However, the sudden upsurge on landslide occurrences from 2002 to 2014 can be due to the increase of rainfall intensity during that period. This study could conclude a direct proportional relationship between the amount of rainfall per day and the frequency of landslide events in Badulla district. This will lead to the potential landslide hazards having an increasing trend.

The established I-D threshold reveled that short-duration rainfall events and higher mean rainfall intensities were required to trigger debris/mud flow, while long-duration rainfall events can trigger both landslide and debris flow with almost the low rainfall intensity. This study also demonstrated the importance of peak rainfall intensity to trigger any type of mass movement in Badulla. Generally, most mass movements (83%) occurred within 5 - 6 h of peak rainfall.

Comparing our I-D thresholds with those from other areas of the world shows that the I-D threshold for Badulla is relatively high, particularly for long-duration rainfall events. As Taiwan is characterized by high-relief topography and complex geology (**Figure 1**), both of which facilitate mass movements, this observation seems contradictory. Thick forest cover in the Badulla district had minimized the impact of heavy rainfall to trigger the mass movements. Therefore, lands in the region are well adjusted to the extreme climatic conditions of the region with compared to other part of the world.

Badulla district is more vulnerable to deforestation and forest degradation as results of human activities. Reduction of forest cover may cause to change the rainfall threshold value for mass movement in the region that will increase landslide hazard within the district.

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