PLANNING MALAYSIA:
Journal of the Malaysian Institute of Planners
VOLUME 21 ISSUE 6 (2023), Page 508 – 525

DEVELOPMENT OF CUMULATIVE RAINFALL THRESHOLD FOR LANDSLIDE OCCURRENCE IN PENINSULAR MALAYSIA

Supiah Ali[1], Norhidayu Kasim[2], Afiq Aiman Saiful Anuar[3], Muhammad Imran Ruslan [4] , Wan Nur Aifa Wan Azahar[5], Ahmad Bukhari Ramli[6]

[1,2,3,4,5,6]*Kulliyyah of Civil Engineering,*
UNIVERSITI ISLAM ANTARABANGSA MALAYSIA

Abstract

Significant issues related to landslides are exposed tremendously in Peninsular Malaysia which have an impact on human beings, animals as well as properties. Reported over twenty-eight significant landslides taking place between 1993 and 2011 which resulted in more than 100 deaths in total. Most of the landslides are the consequences of accumulation of water in underground soil which is connected to rainfall threshold. To establish an empirical Cumulative-Duration threshold through linear regression, analysis of 69 landslide incidents undertaken as well as rainfall data sourced from Public Works Department (PWD) and Department of Irrigation and Drainage (DID) were collected. A comprehensive assessment of all gathered parameters conducted to achieve the confidential purpose of this research which is to determine the threshold for cumulative rainfall event duration which can be utilized in early warning systems and planning for future safety measures. Thus, correlation between rainfall patterns and landslide events are observed. Cumulative rainfall threshold produced an equation $E = 9D^{0.3335}$ with identical range of event duration $1 < D < 2448$ h which acts as a critical line of landslide occurrences. Validation of threshold was revised using recent landslide cases to acquire new threshold values to represent current rainfall induced landslides. The threshold serves as an early warning mechanism and planning to protect lives and property.

***Keywords**:* Landslide, Rainfall Threshold, Rainfall Cumulative-Duration Threshold, Early Warning System, Peninsular Malaysia

[1] Master Candidate Email: supiahali099@gmail.com

INTRODUCTION

A landslide is a type of gravitational erosion involves downward movement of rocks, debris or soil due to gravity's force (Cruden and Varnes, 1996; Hungr et al., 2013; Gariano, S. L. and Guzzetti F., 2016). Landslides, whether natural or human-induced, are a global concern causing casualties, property damage, habitat destruction, and other destructive consequences (Akter, A. et al., 2019). Various factors including steep terrain, soil moisture, climate conditions, and human activities can trigger landslides with additional triggers like seismic activity, volcanic eruptions, and flooding. They are often linked to factors like precipitation which can exacerbate their impact and risk (Mohd Yassin, N. A. et al., 2023).

Nevertheless, majority of slope failures are primarily preceded by heavy rainfall and high moisture levels in the soil that existed (Ray, R.L. et al., 2018; Lazzari, M. et al., 2018; Ray, R.L. & Jacobs, J.M., 2007; L. Ray, R., & Lazzari, M., 2020). Presence of water in soil profiles is a crucial factor in triggering landslides and impacting stability of rock slopes. The way slope reacts to rainfall in terms of hydrological features influenced by multitude factors and levels of water in catchment basin (Karam, K., 2005; Sousa, R. L. et al., 2020). In addition, presence of cliff erosion during rainfall season obstructed water flow resulting in an elevated reservoir level and flash floods (Md Saad, M. H. et al, 2023). In Malaysia, landslides are primarily linked to periods of rainfall which conjunction with monsoonal rainfall patterns (Mukhlisin, M. et al., 2015). During monsoon season, tropical climate and substantial monthly rainfall may reach up to 700 mm around Peninsular Malaysia (Batumalai, P. et al., 2023). Consequently, collection of rainfall records for extended period enhance reliability of empirical rainfall thresholds (Sen Zhang et al., 2023). Threshold parameter represents a rainfall index determined by amalgamation of rainfall intensity and cumulative rainfall (Ligong, S. et al., 2022). Rainfall threshold produced beneficial value in predicting landslide occurrences as an early warning system to ensure safety of lives and property (Adele Young et al., 2021; Yuniawan, R. A. et al., 2022; Won Young Lee et al., 2021). Therefore, landslide early warning systems recommended to be established in Malaysia according to empirical relationship between precipitation and landslide occurrences through threshold development (Jamaludin, S. et al., 2011; Maturidi, A.M.A.M. et al., 2020; Ligong, S. et al., 2022).

Study Area

Peninsular Malaysia occupies southern portion of Malay Peninsula in Southeast Asia as shown in Figure 1. It is part of Sundaland, which encompasses Borneo, Java, Sumatra, and connecting shallow seas with several smaller islands (Sani Ado Kasim et al., 2020; van Bemmelen, R.W., 1949). Geographically, it is situated between latitudes of 6° to 1° N and longitudes of 100° to 105° E. It shares a border with Thailand in North, while to the south and southwest which across Strait of Malacca, adjacent to Singapore and Indonesian island of Sumatra. Peninsular Malaysia experiences a tropical climate characterized by two distinct monsoon seasons and an average annual precipitation of approximately 100 inches. Humidity levels remain high throughout the year with average temperatures ranging from 72°F to 90°F while cooler temperatures in mountainous regions ranging from 55°F to 80°F. Terrain of Peninsular Malaysia is characterized by a series of eight mountain ranges that run longitudinally from west to east (Sani Ado Kasim et al., 2020; J.B. Scrivenor, 1931).

Figure 1: Location Map of Peninsular Malaysia
(Sani Ado Kasim et al., 2020; van Bemmelen, R.W., 1949)

Over past five years (2013-2017), this area received an average annual precipitation of 3,000 mm as reported by Malaysian Department of Drainage and Irrigation (DID, 2018). Specifically, Table 1 shown eastern coastal areas of Peninsular Malaysia such as Terengganu and Kelantan have higher annual rainfall figures ranging from 2,900 mm to 3,600 mm in 2017. In contrast, other regions on western coast of Peninsular Malaysia have recorded lower average yearly rainfall value between 1,700 mm to 2,100 mm. Higher amounts in eastern coast contributes to occurrence of shallow landslides throughout entire region (Maturidi, A.M.A.M. et al., 2021).

Table 1: Mean Annual Precipitation for 5 Years in Peninsular Malaysia (2013 – 2017)
(DID, 2018; Maturidi, A.M.A.M. et al., 2021)

State	Mean Annual Precipitation for 5 Years (2013 – 2017), (mm)
Perlis	< 1850
Kedah	< 2500
Pulau Pinang	< 2500
Kelantan	< 2900
Perak	< 2300
Terengganu	< 3600
Pahang	< 2100
Selangor	< 2200
Kuala Lumpur	< 2800
Negeri Sembilan	< 1750
Melaka	< 1600
Johor	< 2000

Other than that, geological characteristics of Peninsular region in Figure 2 are categorized into Western, Central, and Eastern belts which based on differences in stratigraphy, structure, and variations in geological as well as geophysical features (Sani Ado Kasim et al., 2020; Metcalfe, 2012). The NNW (north and northwest) structural trends within Peninsular are defined by an alignment of lithological formations, bedding orientations, and planes of folds. Despite being generally stable in tectonic terms and having remained above sea level during the Cenozoic era, there are still limited tectonic activity including fault movements, uplift, tilting, and some localized gentle subsidence in the area (Sani Ado Kasim et al., 2020; P.H., Stauffer et al., 1973; D.J. Gobbett et al., 1973].

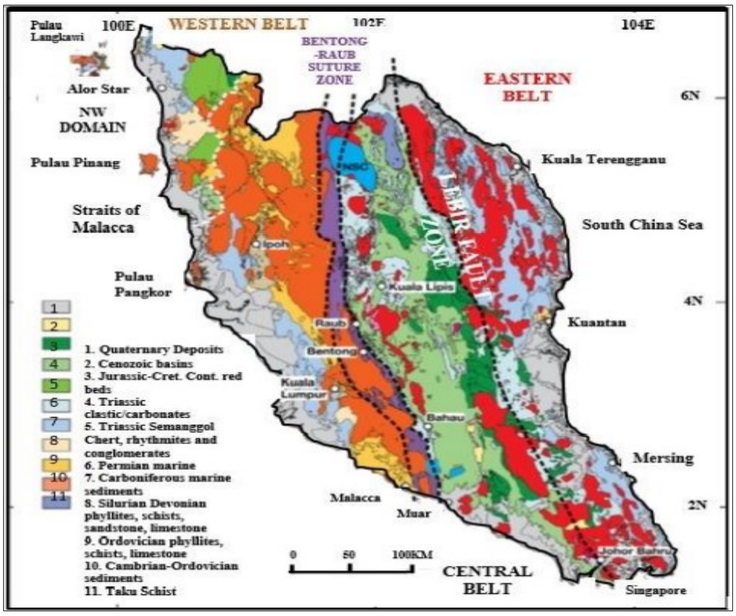

Figure 2: Geologic Map of Peninsular Malaysia
(Metcalfe, 2012)

Moreover, estimated approximately 90% of the granitic materials in the region were formed across all geological belts with various types of granites having distinct ages and processes of intrusive igneous activity. In contrast, other geological structures within the region were shaped through sedimentary and metamorphic processes which resulted in a diverse range of rock units including shale, sandstone, limestone, schist, and phyllite. However, coastal areas of Peninsular Malaysia in eastern and western regions are primarily characterized by quaternary or marine deposits. These deposits consist of continental soil types such as clay, sand, silt, peat and minor gravel components (Pour, Amin Beiranvand and Hashim, Mazlan; 2015).

RESEARCH METHODOLOGY

Methodology

Data collection will involve acquiring required information from relevant government agencies related to landslides which are Public Works Department (PWD) and Department of Irrigation and Drainage (DID). In order to calculate rainfall thresholds, it is imperative to utilise precipitation data sources. One such source is the Department of Irrigation and Drainage (DID), which serves primary precipitation data provider consisting of date, duration, and cumulative rainfall. Furthermore, rainfall data obtained from nearby rain gauge stations suggested to be located within five to twenty kilometres from location of landslides which established a strong correlation between rainfall and landslides. Rainfall data prior to a landslide event considered as additional antecedent analysis obtained from Public Works Department (PWD). Detailed information about selected landslide cases including date, failure location, rain gauge ID, rainfall duration and cumulative rainfall are presented further in analysis of empirical cumulative-duration (E-D) threshold section. Specific analyses of rainfall events triggering landslides are conducted further using spreadsheet software or Microsoft Office Excel to extract relevant parameters for establishing E-D threshold.

ANALYSIS AND DISCUSSION

Essential rainfall parameters are cumulative rainfall and rainfall duration which obtained through analysis of rainfall events that interrelate with landslides. The primary objective of this study is to establish cumulative rainfall-duration (E-D) threshold which includes consistent rainfall duration data to generate scattered data points. Additionally, cumulative rainfall was extracted during time series analysis of rainfall data. This comprehensive analysis involved 69 cases of landslides happening around Peninsular Malaysia to develop (E-D) thresholds.

Analysis conducted with collection of hourly rainfall data from preceding days leading up to the landslide events, adhering to specified rainfall input requirements as illustrated in Figure 3. Rainfall event duration was measured from onset of rainfall until occurrence of shallow landslides. It was calculated after surpassing a non-rainfall gap (NRG) or inter-event period at least 24 consecutive hours without rainfall (Nikolopoulos et al., 2014; Rosi et al.,2016). However, this analysis considers factors such as soil pore water pressure influenced by infiltration and evaporation processes as potential triggers of shallow landslides. Additionally, NRG found to be highly sensitive to threshold, it determined event duration and subsequently impacts generated plots (Guzzetti et al., 2007). Cumulative rainfall event (E) and event duration (D) are obtained from analysis of rainfall patterns conducted act as overview of relationship between rainfall infiltration and landslide occurrences in Peninsular Malaysia.

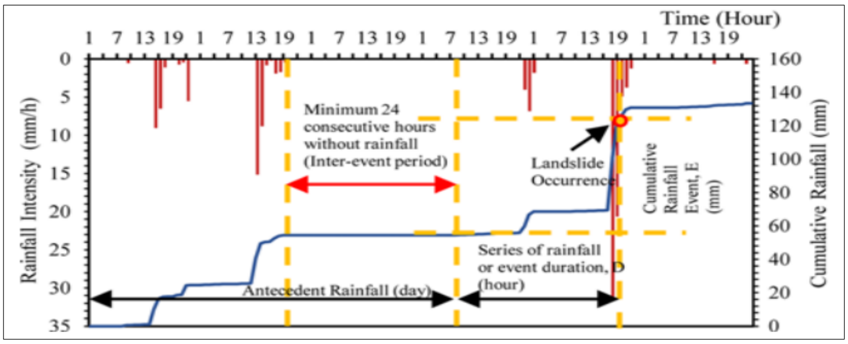

Figure 3: The Inputs to Derive Rainfall Parameters
(Maturidi, A.M.A.M. et al., 2021)

Derived Rainfall Parameters

Peninsular Malaysia is characterized by variety of geological features where main composition consists of interbedded layers, minor intercalations and other elements which more comprehensible to be observed. Based on 69 selected landslide cases as illustrated in Figure 4, showed that 57% or 39 cases were associated with igneous rock types which particularly granite. Next, sedimentary rocks accounted 29% of total landslides with rock units like limestone, sandstone, and shale. Only 14% of landslides were metamorphic rock types such as phyllite, schist and slate. Consequently, frequent monitoring in areas with granitic rock formations is crucial due to heightened susceptibility towards landslides.

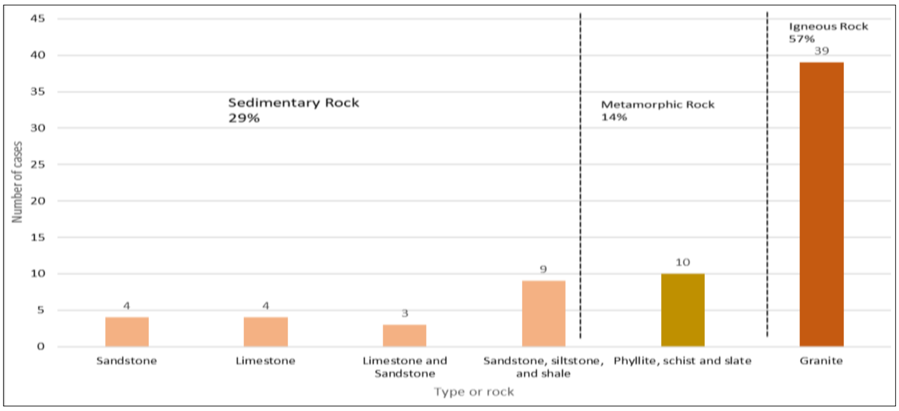

Figure 4: Classification for Geologic Rock Type for Selected Landslide Events in Peninsular Malaysia

Empirical Cumulative - Duration (E-D) Threshold

Scatter plots of data from parameters of 69 landslide cases have been applied to graphs and relationship between cumulative rainfall (E) and event duration (D) are obtained in Figure 6. Vertical axis represented Cumulative Rainfall (E) in millimeters, while horizontal axis represented Event Duration (D) in hours. Best-fit line is established and an equation represents correlation between Cumulative Rainfall (E) and Event Duration (D) using empirical methods is established. Coefficient from this general equation defined Cumulative Rainfall-Event Duration threshold. Furthermore, boundary line for threshold is drawn parallel to lowest plot indicating minimum E-D threshold as separation of stability zone and failure zone. Slope of curve, represents β value maintained as best-fitting line. Simultaneously, new values for α and D are obtained by projecting the drawn curve with respect to y-axis. Based on developed graphs, equations of (E-D) threshold can be expressed as follow:

$$E = 9D^{0.3335} \ (1 < D < 2448)$$

Using the equation, $\alpha = 9$ and $\beta = 0.3335$ which serve as predictive factors of future landslides in the Peninsular Malaysia region based on historical landslide events. Range of rainfall duration capable of triggering landslides falls between 1 hour and 2448 hours as shown in Figure 5. Furthermore, Table 2 recorded cumulative rainfall amount leading to landslide triggering ranged from 45.5 mm to 1280.5 mm. In accordance with established thresholds parallel to the minimum point of cumulative rainfall, if the rainfall event lasts less than 10 hours, it would take 19.34 mm of cumulative rainfall to initiate a landslide. Conversely, if rainfall continues uninterrupted for over 100 hours, 42.35 mm of cumulative rainfall is sufficient to trigger landslides. These results are reasonable considering time required for water to penetrate soil layer sufficiently to induce slope failure varies depending on specific slope conditions. Empirical E-D threshold developed in Peninsular Malaysia can be effectively useful for specific authority in producing an early warning system. Thus, some efforts can be made to reduce impact of landslide occurrences at affected areas by initiating an emergency response plan.

Table 2: Derived Rainfall Parameters

	Date	Location of Slope Failure	Rg Station	Rainfall Duration, D (hr)	Cumulative Rainfall, E (mm)
1	23/11/1993	KM 25.5, Kuala Lumpur - Karak Highway	3217005 Gombak Damsite	80	64
2	17/10/1996	Kampung Baru, Gelang Patah, Johor	1534002 Pusat Kemajuan Per. At Pekan Nanas	28	184.3
3	15/5/1999	Jalan Wangsa 1, Bukit Antarabangsa, Selangor	3116003 I/Pejabat Jps Malaysia At W.Persekutuan.	131	151.5
4	24/2/2000	Kampung Sri Damai dekat Taman Kencana, Ampang	3117102 Taman Miharja At W. Persekutuan	50	112
5	20/11/2002	Taman Hillview, Hulu Klang, Selangor	3117070 Jps Ampang, Kuala Lumpur	92	203.8
6	5/11/2004	Jalan Tengah 6, Taman Sri Harmonis, Gombak, Selangor	3217002 Empangan Genting Klang	126	205
7	6/11/2006	Kuari Gunung Jerai, Gurun, Kedah	5704055 Kedah Peak	50	73.5
8	22/3/2007	Precinct 9, Putrajaya	2916001 Puncak Niaga	52	210
9	23/4/2008	Wangsa Height Condominium, Bukit Antarabangsa	3114113 Jln. Sg. Udang At Segambut	83	92
10	30/11/2008	Ulu Yam Perdana, Kuala Selangor, Selangor	3416029 Tmn. Desa Kelisa	34	130.7
11	6/12/2008	Taman Bukit Mewah, Bukit Antarabangsa	3114113 Jln. Sg. Udang At Segambut	38	87
12	19/9/2009	Wangsa Height Condominium, Bukit Antarabangsa	3114005 Km 10 Ulu Kelang At Uk Height	1	66
13	21/5/2011	Rumah Anak Yatim At Taqwa, Batu 14, Hulu Langat, Selangor	3118105 Balai Polis Batu 14	126	123.2
14	7/8/2011	Perkampungan Orang Asli Sungai Ruil, Brinchang	0180041rf Gunong Brinchang At Cameron Highlands Pahang	120	50
15	13/9/2013	Bukit Bendera	5302003 Kolam Takongan A.Itam	235	411.5
16	10/11/2013	Jalan Sultan Abu Bakar Brinchang, Cameron Hghland	4414040 Mardi C.Highland	107	126.9
17	10/11/2013	Jalan Sultan Abu Bakar Brinchang	0180041rf Gunong Brinchang At Cameron Highlands Pahang	144	114.5
18	7/1/2014	Lebuhraya Mahameru ke Jln Tun Razak	3117070 Pusat Penyelidekan At Jps Ampang	117	167.3
19	18/5/2014	Kampung Baru Road, Sungai Buloh	3010001 Taman Ehsan At Kg. Melayu Subang	3	66
20	5/6/2014	Taman Cheng Perdana, Cheng, Melaka	2221008 Pusat P'tani Sg. Udang	3	79.8
21	5/11/2014	Pekan Ringlet, Lembah Bertam	4414037 Boh Bhg. Boh	7	74.9
22	6/11/2014	Sungai Kabok di Lembah Bertam	0550451rf Ldg. Boh (Bhg. Boh) At Pahang	1200	700

	Date	Location of Slope Failure	Rg Station	Rainfall Duration, D (hr)	Cumulative Rainfall, E (mm)
23	18/11/2014	Genting Highlands	3317004 Genting Sempah	121	95.5
24	27/11/2014	Rumah Rakyat Kampung Panchor, Senawang (Lorong Mahsuri 1)	2719001 Setor Jps. Sikamat	155	256.2
25	30/11/2014	Jalan Dahllia 6, Taman Bunga Raya	0290321rf Sungai Putat At Batu Berendam Melaka	240	176
26	2/12/2014	Jalan Batu 4, Kuala Slim, Slim River	0190161rf Ldg. Trolak At Perak	288	262.5
27	19/12/2014	Jalan Kenyir - Aring (30 km from Jeneris Intersection)	5129040 Rumah Pam Paya Rapat	113	834.2
28	1/1/2015	Jalan Kampung Laut, Tumpat	0730561rf Kg. Kebakat	480	867
29	1/1/2015	Bandar Damai Perdana, Cheras	0231521rf Jam. Petaling At Jln. Klang Lama W.Persekutuan	288	223.5
30	6/1/2015	Jalan Raya Timur Barat Grik-Jeli FT004(Perak Kelantan)	0730441rf Kg. Jeli	576	1280.5
31	13/6/2015	Desa Jasmine, Nilai	0240061rf Ldg. Labu At Negeri Sembilan	312	1111.5
32	24/8/2015	Taman Cherry Park, Indera Mahkota, Kuantan	0570111rf Ranc. Pam Paya Pinang At Pahang	216	177
33	4/11/2015	Batu 15, Jalan Gombak - Bentong	0551701rf Genting Sempah At W.Persekutuan	264	259.5
34	7/11/2015	Kilometer 4.75, Jalan Kuala Kubu-Raub	3517022 Kampung Pertak	166	206.9
35	9/11/2015	Jalan Tapah-Ringlet	0180521rf S.K. S. Kijang Cndriang At Perak	408	346
36	11/11/2015	Kuala Lumpur - Karak Expressway, Pahang	3317004 Genting Sempah	35	66.6
37	13/11/2015	Route 68, SK Bukit Tinggi, Karak	0550341rf Kuala Marong At Bentong Pahang	312	201.5
38	16/11/2015	Jalan Raja Chulan	0230641rf I/Pejabat Jps Malaysia At W.Persekutuan	528	412
39	23/5/2016	Taman Mawar, Kuala Terla	0550991rf Ldg. Teh Sg. Palas At Cameron Highlands	1896	299
40	25/11/2016	Rumah Peranginan TNB Sharples, Tanah rata	0550361rf Ldg. Boh (Kwsn. Kilang) At Pahang	2568	150.5
41	10/12/2016	Hutan Matau Gelannggi 5 & 6, Jerantut, Pahang	3726073 Sg. Jerik	93	151.2
42	25/12/2016	Rumah Penginapan Tenaga Nasional Bhd (TNB) di Bungalow Sharpless, Tanah Rata	0550361rf Ldg. Boh (Kwsn. Kilang) At Pahang	288	102
43	25/12/2016	Kilometer 55, Jalan Ringlet -	0550461rf Ldg. Boh	240	99.5

	Date	**Location of Slope Failure**	**Rg Station**	**Rainfall Duration, D (hr)**	**Cumulative Rainfall, E (mm)**
		Tanah Rata	(Bhg. Selatan) At Pahang		
44	31/12/2016	Terowong KTM di Bukit Abu, Dabong	5320039 Ldg. Kuala Gris	28	201.6
45	22/1/2017	Jalan Aring 8 ke Kenyir	4726001 Gunung Gagau	122	268.1
46	27/1/2017	Batu 14, Lebuh Raya Timur Barat, Jeli menghala ke Grik	5518035 Lubok Bungor	257	606.1
47	4/6/2017	Kampung Syukor, dungun terengganu	4730002 Kg. Surau At Kuala Jengai	99	122.9
48	21/9/2017	Jalan Tun Sardon - Bukit Baru Road, Paya Terubong, Pulau Pinang	5302002 Pintu A.Bagan	23	99.1
49	4/11/2017	Bendera Hill	5302001 T/Air Besar Sg. Pinang	15	151
50	4/11/2017	KM 392 (train route) antara Dabong dan Bukit Abu	5320039 Ldg. Kuala Gris	35	47.8
51	5/1/2018	Ladang Lada, Tanjung Bungah, Pulau Pinang	5402002 Kolam Bersih P.Pinang	55	216.7
52	3/2/2018	Jalan Sungai Koyan-Cameron Highlands	0551171rf Kuala Medang At Pahang	456	239
53	14/10/2018	Kilometer 78.8, Kampung 3, Terla	0550991rf Ldg. Teh Sg. Palas At Cameron Highlands	72	45.5
54	19/10/2018	Jalan Paya Terubong, Balik Pulau, Georgetown, Pulau Pinang	5402002 Kolam Bersih Pulau Pinang	87	78.9
55	23/10/2018	Jalan Bukit Lama from Bayan Lepas to Balik Pulau Georgetown	5302002 Pintu A.Bagan	18	95.7
56	24/10/2018	Batu 51, Jalan Kuala Kuala Terla, Kampung Raja, Cameron Highlands	4514032 Ldg Teh Sg. Palas	57	63.8
57	24/10/2018	Batu 51, Jalan Kuala Kuala Terla, Kampung Raja	0180041rf Gunong Brinchang At Cameron Highlands Pahang	1320	505.5
58	4/11/2018	Kampung Pelangai Hilir, Kuala Pilah	2722003 Sg.Kepis At Pej. Felcra Site 1	263	213
59	25/5/2019	Jalan Ulu Merah and Jalan Ringlet-Blue Valley, Cameron Highland ('19)	0550991rf Ldg. Teh Sg. Palas At Cameron Highlands	168	132.5
60	18/8/2021	Jalan Gunung Jerai (section 0.00 - 11.0)	0030071rf Sekolah Menengah Gurun At Kedah	144	107.5
61	30/10/2021	Jalan Baling-Pengkalan Hulu (Jalan Lama) (section 1.5)	0180411rf Dispensari Kroh At Perak	168	197.5
62	3/11/2021	Jalan Kg. Lahar/Kg. Teluk Sg. Durian (section 1.60 - 1.63)	0050141rf Pulai At Kedah	432	415.5
63	21/11/2021	Jalan Bentong - Gua Musang (section 16.00 - 16.1)	0550531rf Merapoh At Pahang	864	448
64	18/12/2021	Stesen Pemancar Gelombang Mikro Gunung Telapak Buruk, Seremban	0270261rf Kg. Bahru Pantai At Negeri Sembilan	432	262

	Date	Location of Slope Failure	Rg Station	Rainfall Duration, D (hr)	Cumulative Rainfall, E (mm)
65	18/12/2021	Jalan Genting Peras (section 41.8)	0550681rf Kg. Relai At Kg. Baharu Negeri Sembilan	72	141
66	26/12/2021	Kilometer 35.4 Jalan Tranum ke Bukit Fraser, Raub	0550221rf Jkr Jeruas At Pahang	336	345.5
67	26/2/2022	Jalan Dari Simpang Kuala Nal (Pasir Era ke Temangan - Sempadan Jajahan Kuala Krai / Machang) (section 4.2)	0730041rf Ldg. Kuala Nal	96	382.5
68	7/3/2022	Jalan Guchil/Batu Balai/Simpang Tiga Pahi (section 8.1)	0730121rf Sek. Men. Teknik Kuala Kerai	2448	507
69	12/3/2022	Jalan Pangsun, Kampung Lubok Kelubi, Hulu Langat	0240011rf Ldg. Dominion At Selangor	864	300

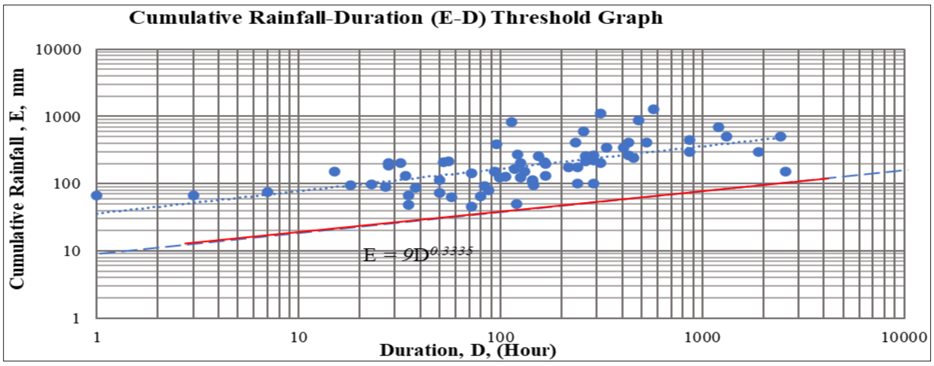

Figure 5: Empirical Cumulative Rainfall - Duration (E-D) Graph

Comparison with Selected I-D Threshold Worldwide

Various factors affect landslide occurrences triggered by rainfall. Climatic factors exert an influence on rainfall threshold across different locations based on numerous countries (Guzzetti et al., 2007). Gathered seven empirical E-D thresholds from various regions around the world which consist of global, regional or local as its geographical scope and connected into a single graph. Positioning of each threshold is typically by its threshold value and slope of curve. Figure 6 displays seven selected thresholds from diverse regions and localities with range of event duration between 1 to 100.

Based on Table 3, illustrated E-D threshold curve line of Present Study (2023) appears as shallowest slope in Figure 6. The slope indicates cumulative rainfall over time in 2023 having a huge amount led to landslide occurrences. In comparison to other global thresholds, Present Study (2023) threshold is notably higher. This discrepancy attributed based on Malaysia's monsoon season, which brings heavy rainfall annually leading to an increased quantity of water accumulated in soil. Consequently, reduced strength of soil properties and initiate a soil movement. Additionally, power of D represented by the β value which varies across different locations. This value signifies slope of threshold line where a steeper curve, a higher β value. The Present Study (2023) categorised as region maintains a value of 0.3335 for (E-D) threshold while value proposed by Brunetti (2013) is 0.43 and 0.7 from He (2019) which exceeds 0.5 value of threshold. Based on local extent, Peruccacci (2012) having a threshold value of 0.38 and Vennari (2013) suggested value of 0.41. Innes (1983) with a value of 0.504 and Kanji (2003) proposed 0.4 are global levels. These illustrates different regions may exhibit distinct climatic conditions linked to causes of landslides.

Table 3: Selected Rainfall Thresholds

Authors	Area under study	Extent	The Proposed Threshold	Range (h)
(Innes, 1983)	World	Global	E = 4.93D0.504	0.1<D<100
(Kanji, 2003)	World	Global	E = 22.4D0.41	n.a
(Peruccacci, 2012)	Abruzzo, Marche, Umbria, Italy	Local	E = 7.4D0.38	1<D<1212
(Brunetti, 2013)	Italy	Regional	E = 7.85D0.43	1<D<1080
(Vennari, 2013)	Calabria, Italy	Local	E = 5.8D0.41	1<D<415
(He, 2019)	China	Regional	E = 0.53D0.7	1<D<44
(Present Study, 2023)	Peninsular Malaysia	Regional	E = 9D0.3335	1<D<2448

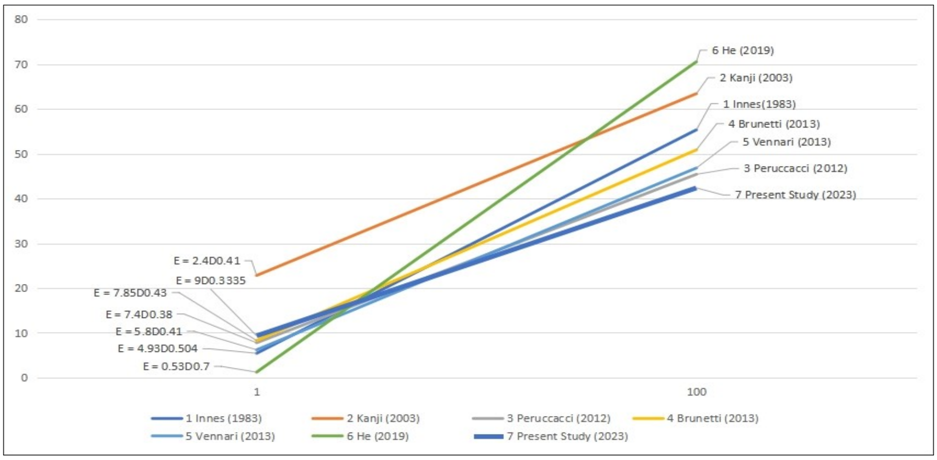

Figure 6: Threshold Comparison of Worldwide

Validating the Developed Cumulative Rainfall - Duration (E-D) Thresholds

Validation of threshold done through comparison with recent landslide-triggering rainfall events. Purpose of this threshold was to predict landslides in Peninsular Malaysia by determining the minimum cumulative rainfall required to trigger small-scale landslides. Table 4 shows ten recent landslide cases were selected between 2021 and 2023 where back analysis of rainfall was conducted to derive parameters including cumulative rainfall and event duration. These rainfall parameters were compared to existing rainfall threshold and observations made on the position whether above or below threshold line. A plot considered a True Positive event when it exceeded the threshold indicating an accurate prediction. However, it categorized as False Negative event if landslide occurred below the threshold. Then, new threshold value is produced by lowering the curve align with lowest plot. This approach aimed to develop an accurate threshold for future prediction of shallow landslides.

Based on observations illustrated in Figure 7, all selected cases resulted in True Positive occurrences when using the (E-D) threshold. True positive phenomena strongly indicate accuracy of (E-D) threshold produced based on previous landslide cases in predicting incoming landslides. However, in real-time precipitation monitoring, two additional scenarios to be considered for E-D thresholds which are false positives and true negatives. False positive is false alarm where a landslide happened below the line of threshold while true negatives indicate no landslide occurrence but lies above the line (Valenzuela et al., 2019). Both false positives and false negatives are undesirable outcomes for E-D thresholds as consequently affect losses and casualties. If the threshold triggers a false alarm, authorities may face safety-related losses however if the threshold misses a landslide event or known as false positive, it could result in fatalities, injuries, and property damage. Nevertheless, crucial to emphasize any mitigation in experiencing effects of landslides which beyond human control. In enhancing effectiveness of landslide early warning system-based rainfall threshold, automatic rain gauges, total stations, inclinometers, and alarm devices must be installed especially in landslide-prone areas near highways, public facilities, and residential areas. Thus, well functioning systems making (E-D) threshold more reliable to be landslide prediction indicators as an early warning system.

Table 4: Rainfall Parameters for the Latest Event

	Location of slope failure	**State**	**Rainfall Duration, D (hr)**	**Cumulative rainfall, E (mm)**
1	Jalan Gunung Jerai (section 0.00 - 11.0)	Kedah	144	107.5
2	Jalan Baling-Pengkalan Hulu (Jalan Lama) (section 1.5)	Perak	168	197.5
3	Jalan Kg. Lahar/Kg. Teluk Sg. Durian (section 1.60 - 1.63)	Kedah	432	415.5
4	Jalan Bentong - Gua Musang (section 16.00 - 16.1)	Pahang	864	448
5	Stesen Pemancar Gelombang Mikro Gunung Telapak Buruk, Seremban	Negeri Sembilan	432	262
6	Jalan Genting Peras (section 41.8)	Negeri Sembilan	72	141
7	Kilometer 35.4 Jalan Tranum ke Bukit Fraser, Raub	Pahang	336	345.5
8	Jalan Dari Simpang Kuala Nal (Pasir Era ke Temangan - Sempadan Jajahan Kuala Krai / Machang) (section 4.2)	Kelantan	96	382.5

	Location of slope failure	State	Rainfall Duration, D (hr)	Cumulative rainfall, E (mm)
9	Jalan Guchil/Batu Balai/Simpang Tiga Pahi (section 8.1)	Kelantan	2448	507

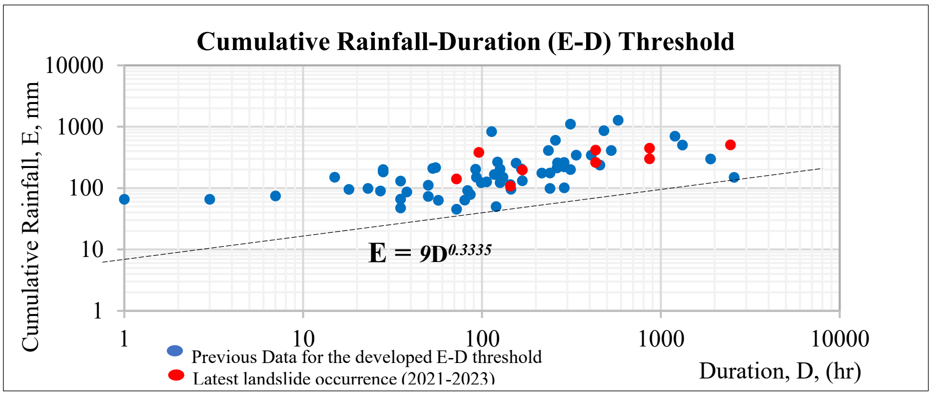

Figure 7: Validation of Recent Events on E-D Threshold

CONCLUSION

This study aimed to address landslide-related issues in Peninsular Malaysia by establishing empirical rainfall thresholds to enhance landslide forecasting. Analyses conducted using data obtained from PWD and DID where empirical thresholds established using precipitation data from 69 historical landslide events. In this study, rainfall durations fell within a range of $1 < D < 2448$ hours and proposed Cumulative Rainfall-Event Duration (E-D) threshold was $E = 9D^{0.3335}$ where the curve determined minimum cumulative rainfall required triggered shallow landslides. This threshold was found to be lower and more extensive than thresholds in other regions, primarily due to high precipitation levels in the humid tropical climate of Peninsular Malaysia. The study also validated the threshold using recent landslide events, aiming to improve accuracy and early prediction of landslides. The integration of these rainfall-induced landslide thresholds with advanced tools and devices help reduce the impact of landslides and facilitate emergency response planning in affected areas.

ACKNOWLEDGMENTS

The authors express gratitude to the staff of Slope Engineering Branch, Public Works Department of Malaysia for providing essential landslide data. The authors are also thankful to Drainage and Irrigation Department of Malaysia and Malaysia Meteorology Department for supplying meteorological data.

REFERENCES

Berglund, E., Westerling, R., & Lytsy, P. (2017). Housing Type and Neighbourhood Safety Behaviour Predicts Self-rated Health, Psychological Well-being and Freq Zhang S, Pecoraro G, Jiang Q, Calvello M (2023). Definition of Rainfall Thresholds for Landslides Using Unbalanced Datasets: Two Case Studies in Shaanxi Province, China. *Water. 15*(6):1058. https://doi.org/10.3390/w15061058

Adele Young;Biswa Bhattacharya;Chris Zevenbergen; (2021). A rainfall threshold-based approach to early warnings in urban data-scarce regions: A case study of pluvial flooding in Alexandria, Egypt . *Journal of Flood Risk Management*, (), –. doi:10.1111/jfr3.12702

Yuniawan, R. A., Rifa'i, A., Faris, F., Subiyantoro, A., Satyaningsih, R., Hidayah, A. N., Hidayat, R., Mushthofa, A., Ridwan, B. W., Priangga, E., Muntohar, A. S., Jetten, V. G., Westen, C. J. van, Bout, B. V. den, & Sutanto, S. J. (2022). Revised Rainfall Threshold in the Indonesian Landslide Early Warning System. *Geosciences, 12*(3), 129. https://doi.org/10.3390/geosciences12030129

Won Young Lee;Seon Ki Park;Hyo Hyun Sung; (2021). The optimal rainfall thresholds and probabilistic rainfall conditions for a landslide early warning system for Chuncheon, Republic of Korea . *Landslides*, (), –. doi:10.1007/s10346-020-01603-3

Sani Ado Kasim, Mohd Suhaili Ismail, Ahmad Mohamed Salim (2020). Cenozoic Stratigraphy, Sedimentation and Tectonic Setting, Onshore Peninsular Malaysia: A Review. Retrieved from : https://www.atlantis-press.com/article/125950023.pdf

C.S. Hutchison (1989). Geological Evolution of South-East Asia. Vol. 13, Clarendon Press, Oxford, pp. 368.

C.S. Hutchison(1996). South-East Asian oil, gas, coal and mineral deposits. Oxford Univ. Press.

I. Metcalfe (2013). Tectonic evolution of the Malay Peninsula. *Journal of Asian Earth Sciences*, 76, pp. 195-213.

P.H., Stauffer (1973). Cenozoic: In Geology of the Malay Peninsula (West Malaysia and Singapore). (Edited by D.J. Gobbett & C.S. Hutchison), Wiley-Interscience, New York, pp. 143–176.

D.J. Gobbett, H.D. Tjia, Tectonic History. In: Gobbett D. J. & Hutchison, C.S. (eds). (1973). Geology of the Malay Peninsula, Wiley-Interscience, New York, pp. 305-330.

I. Metcalfe (2011). Tectonic Framework and Phanerozoic Evolution of Sundaland. Gondwana Research, 19, pp. 3–21.

C. Makoundi, K. Zaw, R.R, Large, S. Meffre, C.K. Lai, T.G. Hoe (2013). Geology, geochemistry and metallogenesis of the Selinsing gold deposit, central Malaysia, *Gondwana Research, 26*(1), pp. 241-261.

R.W. van Bemmelen (1949). The Geology of Indonesia. 1A: General Geology of Indonesia and adjacent archipelago, 2: economic geology, 1B: portfolio and index, First Edition, Government Printing Press, The Hague, pp. 732. Advances in Engineering Research, volume 200 277

J.B. Scrivenor, The Geology of Malaya. Macmillan and Co. Ltd., London, 1931.

Pour, Amin Beiranvand; Hashim, Mazlan (2015). Structural mapping using PALSAR data in the Central Gold Belt, Peninsular Malaysia. *Ore Geology Reviews, 64*(), 13–22. doi:10.1016/j.oregeorev.2014.06.011

Stefano Luigi Gariano, Fausto Guzzetti (2016). Landslides in a changing climate, *Earth-Science Reviews*, Volume 162, Pages 227-252, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2016.08.011.

Akter, Ayesha & Megat Mohd Noor, Megat Johari & Goto, Masa & Khanam, Shamsunnahar & Parvez, Ahmed & Rasheduzzaman, Md. (2019). Landslide Disaster in Malaysia: An Overview. *International Journal of Innovative Research and Development*. 8. 10.24940/ijird/2019/v8/i6/JUN19058.

Mohd Yassin, N. A., Adnan, N. A., & Md Sadek, E. S. S. (2023). Analysis Of Flash Flood Potential Index (FFPI) And Scenarios Assessment In Shah Alam Using Gis Approach. *Planning Malaysia, 21*(26). https://doi.org/10.21837/pm.v21i26.1255

Rita Leal Sousa, Eurípedes Vargas Jr., Helder I. Chaminé, Luis Ribeiro e Sousa & Karim Karam (2021). Risk assessment on landslides focused on the role of the water: examples from model regions (Rio de Janeiro State and Hong Kong). 10.1007/s42452-021-04300-5. https://doi.org/10.1007/s42452-021-04300-5

L. Ray, R., & Lazzari, M. (2020). Introductory Chapter: Importance of Investigating Landslide Hazards. IntechOpen. doi: 10.5772/intechopen.94279

Mukhlisin, M., Matlan, S. J., Ahlan, M. J., & Taha, M. R. (2015). Analysis of Rainfall Effect to Slope Stability in Ulu Klang, Malaysia. *Jurnal Teknologi, 72*(3). doi:10.11113/jt.v72.4005

Md Saad, M. H., Kamarudin, M. K. A., Toriman, M. E., Abd Wahab, N., Ata, F. M., Abu Samah, M. A., Mohd Saudi, A. S., & Manoktong, S. N. (2023). Analysis Of The Flash Flood Event And Rainfall Distribution Pattern On Relau River Basin Development, Penang, Malaysia. *Planning Malaysia, 21*(25). https://doi.org/10.21837/pm.v21i25.1224

Batumalai, P.; Mohd Nazer, N.S.; Simon, N.; Sulaiman, N.; Umor, M.R.; Ghazali, M.A. (2023). Soil Detachment Rate of a Rainfall-Induced Landslide Soil. Water 15, no. 12: 2149. https://doi.org/10.3390/w15122149

Muaz Abu Mansor Maturidi, A., Kasim, N., Abu Taib, K., Nur Aifa Wan Azahar, W., & Ahmad Tajuddin, H. (2021). Empirically Based Rainfall Threshold for Landslides Occurrence in Peninsular Malaysia. *KSCE Journal of Civil Engineering*, (), –. doi:10.1007/s12205-021-1586-4

Ligong, S., Sidek, L. M., Hayder, G., & Mohd Dom, N. (2022). Application of Rainfall Threshold for Sediment-Related Disasters in Malaysia: Status, Issues and Challenges. *Water, 14*(20), 3212. https://doi.org/10.3390/w14203212

Jamaludin, S.; Ali, F. (2011). An overview of some empirical correlations between rainfall and shallow landslides and their applications in Malaysia. Electron. *J. Geotech. Eng*., 16, 1429–1440.

Maturidi, A. M. A. M., Kasim, N., Taib, K. A., & Azahar, W. N. A. W. (2021). Rainfall-induced landslide thresholds development by considering different rainfall parameters: A Review. *Journal of Ecological Engineering, 22*(10), 85-97.

Maturidi, A. M. A. M., Kasim, N., Taib, K. A., Azahar, W. N. A. B. W., & Husain, N. M. H. (2020, September). Rainfall-Induced Landslides in Cameron Highland Area, Malaysia. In IOP Conference Series: Materials Science and

Engineering (Vol. 917, No. 1, p. 012019). IOP Publishing.
Maturidi, A. M. A. M., Kasim, N., Taib, K. A., Azahar, W. N. A. W., & Tajuddin, H. A. (2020). Empirically based rainfall threshold for landslides occurrence in Cameron highlands, Malaysia. *Civil Eng Architect, 8*(6), 1481-1490.

Received: 12th July 2023. Accepted: 13th October 2023

