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Rainfall Threshold for Landslide Warning in Southern Thailand – An Integrated Landslide Susceptibility Map with Rainfall Event – Duration Threshold

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ABSTRACT

Southern Thailand is one of hotspots for landslides. So far, the rainfall triggered landslides in this region caused many sufferers and fatalities. On the basis of the rainfall data that triggered ninety-two landslide events during 1988–2018 and the landslide susceptibility maps published by the Department of Mineral Resources (DMR), this study introduced rainfall event-duration (*ED*) thresholds, namely ED^m and ED^h thresholds, for the places classified as the modest and the huge susceptibility levels, respectively. The modest susceptibility is a combination of very low, low, and moderate landslide susceptibility levels indicated in DMR maps. The huge susceptibility is a combination of high and very high landslide susceptibility levels indicated in DMR maps. Indicated by an area under the receiver operating characteristic curve (*AUC*), the ED^m and ED^h thresholds yielded the significantly better predictability than the original threshold did. Furthermore, the ED^m threshold yielded the perfect prediction with *AUC* of 1.00.

Keywords: rainfall threshold; landslide susceptibility level; contingency matrix; skill scores.

INTRODUCTION

Since the year 2000, the number of landslides per year has been increasing in Thailand (Schmidt-Thomé et al., 2017). Southern Thailand lies on the narrow part of the Malay Peninsula the landforms comprise two parallel mountain chains running north–south: the Phuket and Nakhon Srithammarat ranges; situated to the west and east, respectively. According to the report from the Department of Mineral Resources in 2019, this region is one of Thailand's hotspots for landslides. The landslides in 1988, which was known among of the worst natural disasters in the Thailand's history, also occurred in the Southern Thailand. Works on landslide risk assessment constitute one of vital contributions in landslide mitigation measures. Since rainfall is commonly recognized as main temporal factor causing landslides, landslide rainfall threshold is commonly used as one of the vital components of landslide early warning system (Aleotti, 2004; Salee et al., 2022; Chinkulkijniwat et al., 2022). The most common parameters used to define the rainfall threshold are those based on characteristic of triggering landslide rainfall event (Caine, 1980; Aleotti, 2004; Guzzetti et al., 2008; Vennari et al., 2014; Vessia et al., 2014; He et al., 2020; Gariano et al., 2019; Peruccacci et al., 2017). Other than rainfall characteristics, a landslide can be influenced by many spatial factors, such as slope aspect, gradient, relative relief, lithology, degree of weathering, depth, permeability, porosity, etc. Incorporating these spatial factors to the rainfall threshold might enhance the efficiency of the landslide prediction. A landslide susceptibility map caries the relevant information; relating to geomorphology, geological, meteorological soil, land use, land cover and hydrologic conditions, of the terrain and classifies the terrain into zones with differing likelihoods that landslides may occur. Integration of the landslide rainfall threshold and the landslide susceptibility map would benefit the landslide prediction. In fact, number of recent works reported the succession of the joint use of the landslide rainfall thresholds and the landslide susceptibility maps (Segoni et al., 2015; Jemec Auflic et al., 2016; Segoni et al., 2018). Recently, the Department of Mineral Resources updated Thailand landslide susceptibility maps for the provincial level (https://gis.dmr.go.th/DMR-GIS/gis). These maps present five landslide susceptibility levels; including very high, high, moderate, low, and very low landslide susceptibility levels. This study used these susceptibility maps as a proxy to include the spatial factors carried by the landslide susceptibility map to the landslide rainfall threshold in the Southern Thailand. A contingency table and a set of skill scores were used to assess the performance of the threshold.

Data collection and rainfall characteristics in the study area

The authors gathered ninety-two landslide events that took place during 1988 to 2018 in the south of Thailand reported by the Department of Mineral Resources, Ministry of Natural Resources and Environment. Among ninety-two landslides, some landslides took place at the same time and their locations are close to each other. Under this condition, the largest landslide was chosen to represent the others. After this process, ninety-two landslides were reduced to eighty landslides. The Relevant rainfall data from the years when these eighty landslide events occurred were gathered from Thai Meteorological Department (TMD) rain gauge stations located in the catchment area (Figure 1) where the considered landslide is located. Inverse distance weighting (*IDW*) was employed to map the amount of rainfalls at the landslide locations.

To identify a rainfall event, a criterion that separates two consecutive rainfalls must be defined. The criterion is defined by a combination of the rainfall intensity threshold *A* and rainfall duration *B* and termed as inter-event criterion ($IEC_{A,B}$).

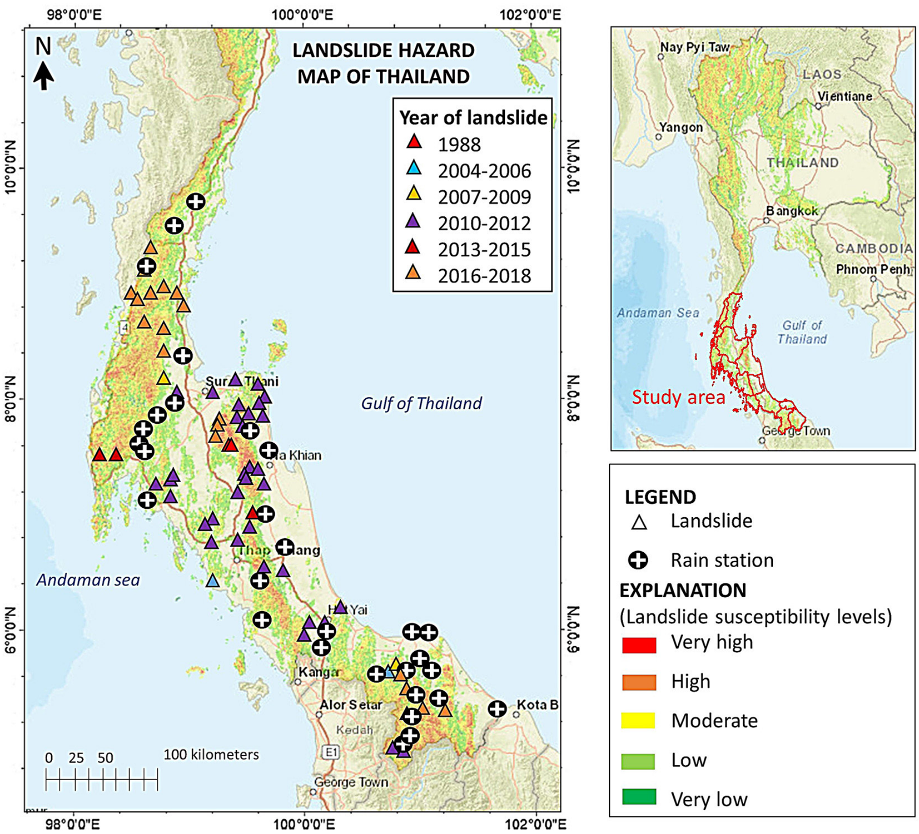

Figure 1. Locations of landslides and TMD rain gauge stations in the study area

The condition that distinguished two consecutive rainfall events had to satisfy the combined criterion. On the basis of an assumption that inter-event times have an exponential distribution for which the mean equals the standard deviation (Bonta and Rao 1988), the suitable *IEC* was identified on the basis of a variation coefficient (*CV*) of inter-event times equal to 1.0. Salee et al. (2022) reported that the inter-event criterion of $IEC_{2,1}$ can be used to distinguish two consecutive rainfalls in Southern Thailand. Accordingly, a criterion $IEC_{2,1}$ was used as the inter-event criterion to distinguish two consecutive rainfalls collected in this study. Distinction of two consecutive rainfall events is a condition that satisfied the combined criterion. As depictured in Figure 2, if rainfall intensity is no greater than 2 mm/day for at least 1 day, two consecutive rainfall events are considered to have occurred.

Regarding to the landslide susceptibility maps published by the Department of Mineral Resources, there are five susceptibility levels of landslide; very low susceptibility (green color), low susceptibility (light green color), moderate susceptibility (yellow color), high susceptibility (orange color), and very high susceptibility (red color). Eighty landslide locations were mapped to the corresponding susceptible maps for the provincial level to identify the landslide susceptibility level at those locations. Figure 3 presents three landslides took placed in Krung Ching subdistrict,

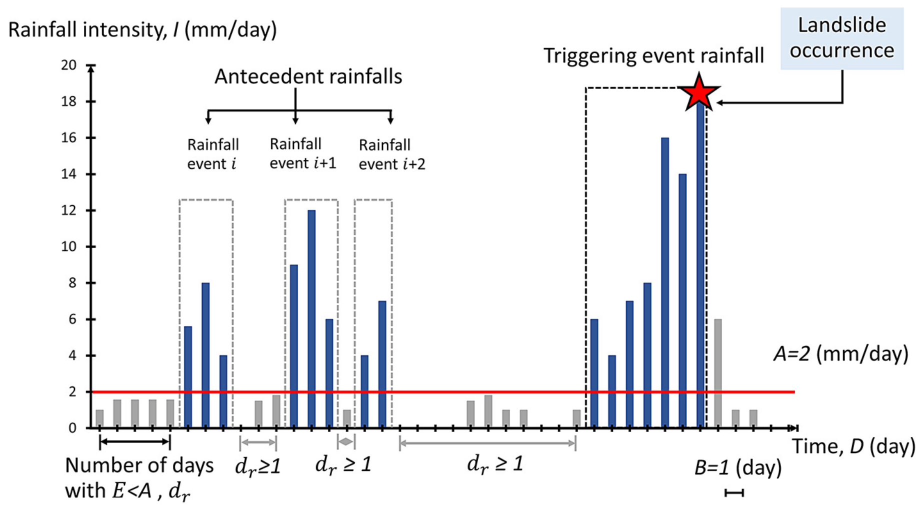

Figure 2. Definition of inter-event criteria used to separate two consecutive rainfalls in this study

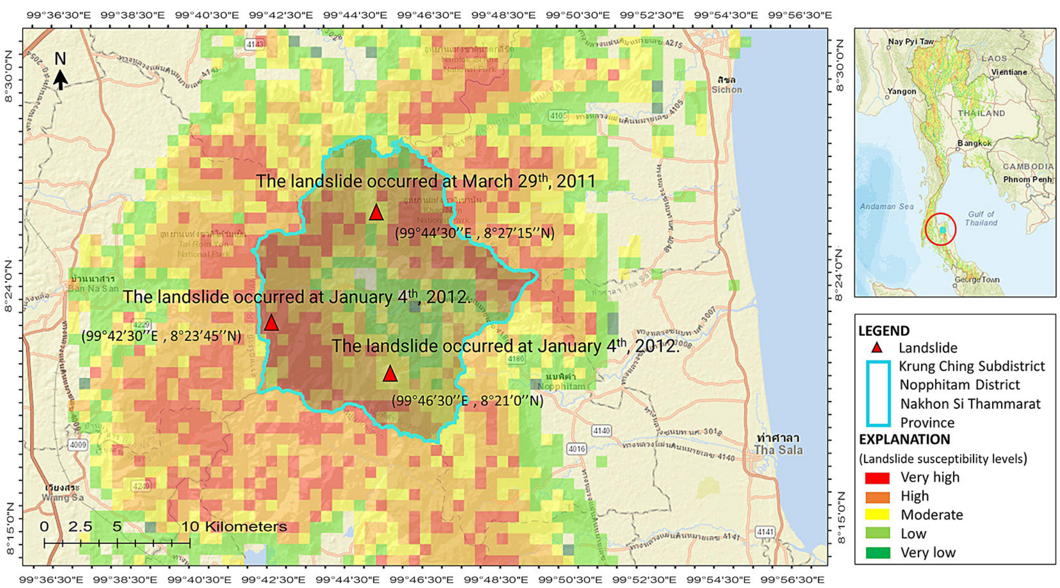

Figure 3. Landslide susceptibility map for Krung Ching subdistrict, Nopphitam district, Nakhon Si Thammarat and locations of landslide took place in this area (https://gis.dmr.go.th/DMR-GIS/gis)

Table 1. Duration of rainfalls that caused eighty landslides during 1988–2018 categorized by landslide susceptibility level

Duration (day)	Landslide susceptibility levels				
	Very high	High	Moderate	Low	Very low
1	7	1	0	0	0
2	1	2	0	0	0
3	2	10	0	0	0
4	0	5	7	0	0
5	1	5	0	0	0
6	0	3	0	0	0
7	0	5	6	0	0
8	0	2	0	0	0
9	0	3	0	0	0
10	0	0	1	3	0
11	0	0	4	7	0
12	0	0	1	1	0
13	0	0	0	3	0
Total	11	36	19	14	0

Nopphitam district, Nakhon Si Thammarat (the other landslides had been mapped to the corresponding susceptibility maps in a similar manner). Table 1 summaries, from eighty landslides, the number of landslide events took place for each landslide susceptibility level in the Southern Thailand. A greater number of landslides was found for the higher landslide susceptibility level. However, the number of landslides for very high susceptibility was small. It was because the places classified as very high susceptibility level were generally far from communities; hence, many landslides were neglected and not reported. Table 1 also presents, from the triggering rainfall events, distribution of duration for the rainfalls that triggered the landslides at the places of different susceptibility levels. There is no doubt that many of the landslides at the very high susceptibility places were caused by rainfall events that lasts for only one-day. In turn, no landslide at very low to moderate susceptibility places occurred with rainfall duration less than 4 days.

Landslide triggering rainfall thresholds and the assessment

Figure 4 presents the rainfall event (E) and rainfall duration (D) data points of non-triggering-rainfalls (open circles) and triggering-rainfalls (gray circles) plotted on a double logarithmic scale. On the basis of Eq. 1, the landslide rainfall threshold was analyzed from rainfall event (E) and duration (D) of triggering-rainfalls,

$$\log_{10}E = a + b\log_{10}D \tag{1}$$

where: a and b are regression coefficients.

With the above-mentioned relationship, the threshold gave a straight line in double logarithmic scale. Quantile regression (Koenker and Bassett, 1978; Koenker and Hallock, 2001; Koenker, 2009) was employed to fit the specified

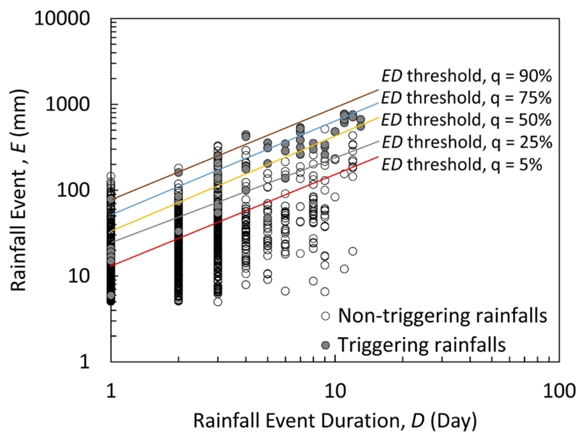

Figure 4. Relationship between rainfall event (E) and its duration (D) form triggering rainfalls and non-triggering rainfalls in the Southern Thailand. Gray circles represent the triggering rainfalls that caused landslides and open circles represent the non-triggering rainfall events. The *ED* threshold drawn from quantile regression at various probability levels of triggering rainfall events

Table 2. Threshold parameters *a* and *b* for the *ED*, ED^m, and ED^h thresholds at exceedance probabilities from 5 to 90%

Probabilistic level (%)	*ED* parameters		ED^m parameters		ED^h parameters	
	a	*b*	*a*	*b*	*a*	*b*
5	3.322	1.130	1.283	1.188	1.065	1.508
10	1.992	1.689	1.223	1.342	1.081	1.523
25	0.773	1.932	1.650	0.922	1.226	1.455
50	1.322	1.444	1.565	1.206	1.555	1.204
75	1.833	1.008	1.626	1.197	1.943	0.870
80	1.893	0.941	1.827	1.019	2.004	0.805
85	1.965	0.888	1.827	1.020	1.962	0.892
90	2.045	0.810	2.260	0.604	1.962	0.908

percentiles of the triggering events. The *ED* threshold given at various probability levels from 5–90% was presented in Figure 4. The corresponding magnitudes of parameters *a* and *b* for the *ED* threshold are given in Table 2.

For ease of incorporating the landslide susceptibility level to the rainfall threshold, the susceptibility level was re-categorized from five levels to two levels; termed as the modest susceptibility level and the huge susceptibility level. The modest level is the combination of the very low, low, and moderate susceptibility levels indicated in the landslide susceptibility maps. The huge level is the combination of the high, and very high susceptibility levels indicated in the landslide susceptibility maps. Among eighty events, thirty-three and forty-seven events occurred at the locations classified as the modest level and the huge level, respectively. Figure 5a presents rainfall event (*E*) and rainfall duration (*D*) data points of non-triggering-rainfalls (open circle) and triggering-rainfalls (colored circle) plotted on a double logarithmic scale. Indeed, this plot is Figure 4 modified by grouping the data with susceptibility levels (the modest level and the huge level). The green color plots are for the rainfalls that took place at the modest susceptibility places and the red color plots are for the rainfalls that took place at the huge susceptibility places. The *ED* threshold for the modest level places (ED^m threshold) and that for the huge level places (ED^h threshold) at various probability levels together with scatter plots, in double logarithmic rainfall event–duration plane, of non-triggering and triggering-rainfalls are given in Figure 5b. The threshold parameters *a* and *b* for exceedance probabilities from 5 to 90% of the ED^m and ED^h thresholds are given in Table 2.

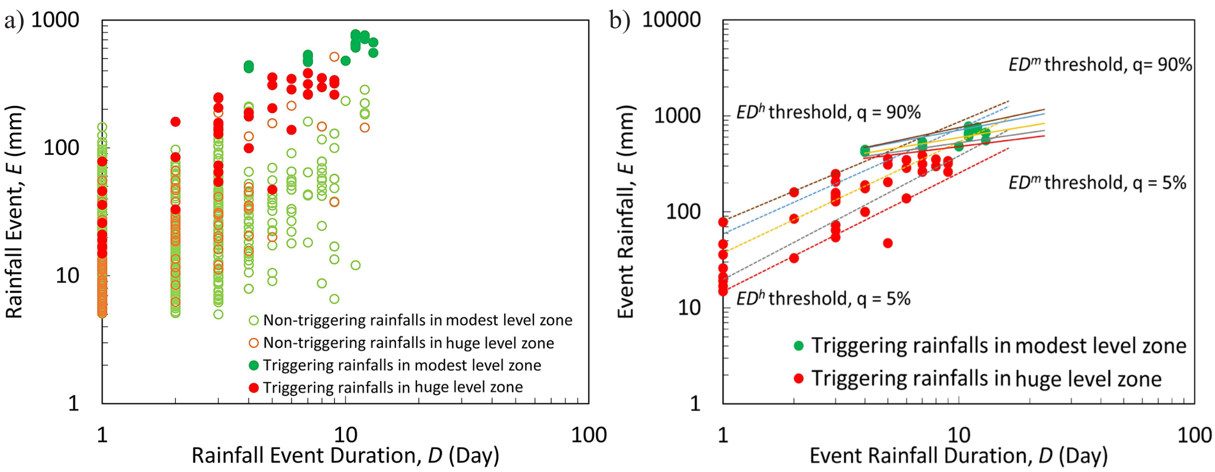

Figure 5. a) Relationship between rainfall event (*E*) and its duration (*D*) form triggering rainfalls and non-triggering rainfalls in the Southern Thailand. Red circles represent the triggering rainfalls that caused landslides at the huge susceptibility places and green circles represent that at the modest susceptibility places. In turn, open green circles and open red circles are for the non-triggering rainfalls in the modest and huge susceptibility places, respectively. b) The ED^m and ED^h thresholds drawn from quantile regression at various probability levels of triggering rainfalls at the modest and the huge susceptibility places, respectively

Assessment of the thresholds

The aforementioned thresholds were assessed through a contingency table and a receiver operating characteristic (*ROC*) curve. There are four scenarios in contingency table; including (1) true positives (*TP*), (2) true negative (*TN*), (3) false positive (*FP*), and (4) false negative (*FN*). Figure 6 presents *TP, FN, FP,* and *TN* defined from threshold value and distribution curve of triggering rainfall events and those of non-triggering rainfall events. *TP* indicated the cases in which landslides were correctly predicted, *FN* indicated the cases in which landslides took place without prediction, *FP* indicated the cases in which landslides were forecasted but did not take place, and *TN* stood for the correct prediction of a rainfall event without a landslide. These contingencies were employed to calculate the following skill scores; i) a hit rate (*HR*) which is defined as number of correct prediction per total number of event rainfall: $HR = TP / (TP + FN)$, ii) a false alarm rate (*FAR*) which is defined as number of false alarm per the total number of non-event rainfall: $FAR = FP / (FP + TN)$, and iii) Hanssen and Kuipers skill score (*HK*): $HK = HR - FAR$. *HK* is proportional to the frequency of events being forecast by equal emphasis on ability to forecast both events and nonevents. The receiver operating characteristic curves (*ROC* curve), *HR* against *FAR*, was plotted at various probabilistic levels of landslide threshold and the areas under the *ROC* curves (*AUC*) were determined. At each threshold probabilistic level, the Euclidean distance δ was calculated from the distance between the point corresponding to the threshold on the *ROC* curve and the perfect point of coordinate (0,1).

Assessment of the thresholds was conducted by considering triggering and non-triggering rainfall events that took place at the places corresponding to the established thresholds. For the *ED* threshold, the rainfall events that took place in the whole study area were employed for the assessment. In turn, for the assessment of the ED^m and ED^h thresholds, only the rainfall events at the places classified to the corresponding susceptibility levels were employed. Furthermore, the considered data indicated that the rainfall events that caused landslides at the modest level places had duration no shorter than 4 days; the authors of this paper implied that the rainfall events of their duration shorter than 4 days did not cause landslides at the modest level places. Hence, for the rainfalls at the modest level places, only the rainfall events having their duration no shorter than 4 days were used for the assessment of ED^m threshold.

RESULTS AND DISCUSSIONS

Table 3 summarizes the four contingencies (*TP, FP, FN, TN*) and the four skill scores (*HR, FAR, HK*, δ) for ten probabilistic levels (from 5 to 90%) from the *ED*, the ED^m and the ED^h thresholds. The best compromise between the minimum number of incorrect landslide predictions (*FP, FN*) and the maximum number of correct predictions (*TP, TN*), indicated by combination of the largest values for the *HK* and the smallest value of the δ, were obtained at 15%, 5%, and 10% for the *ED*, the ED^m, and the ED^h thresholds, respectively. Since the assessment of ED^m threshold was conducted by considering

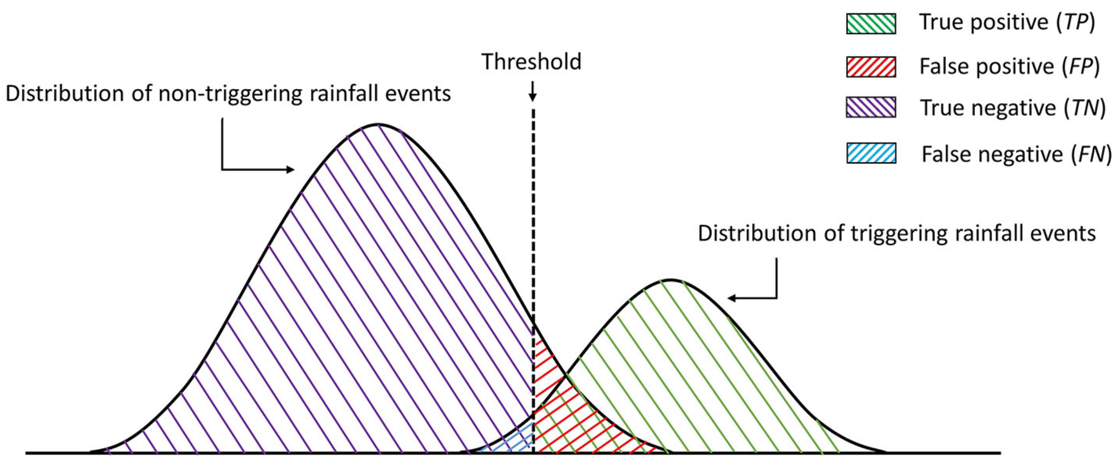

Figure 6. Distribution of triggering and non-triggering rainfalls and the threshold to define the meaning of true positive (*TP*), true negative (*TN*), false positive (*FP*), and false negative (*FN*)

only the rainfall events having a duration no shorter than 4 days, the number of rainfall in contingency table for the ED^m threshold was not as high as that reported in the contingency table for the ED^h threshold.

Figure 7 presents the *ROC* curves obtained from the *ED*, ED^m, and ED^h thresholds. The areas under the *ROC* curves (*AUC*), indicating prediction capability, are also reported in Figure 7. Incorporating landslide susceptibility into the threshold resulted in an improvement of the threshold performance. Even at very high and high landslide susceptibility places, the threshold established particularly these zones (ED^h threshold) which exhibited significantly better performance (AUC = 0.89) than the *ED* threshold (AUC = 0.71). Since there was no non-triggering rainfall event laid above the ED^m threshold, this threshold yielded *FAR* of 0.0 at every probabilistic level. This character was expressed through the *ROC* curve of the ED^m threshold that indicated perfect performance with *AUC* of 1.00. The years in which landslides occurred at very low to moderate landslide susceptibility places are presented in Table 4. Twenty landslides from thirty-three landslides took place in two periods (gray shaded rows in Table 4); 1) the period from the late 2010 to the early 2011, and 2) the year 2017. During the period from late 2010 to the early 2011, there were fourteen landslides were reported in this study. For late 2010, a tropical depression in November over Southern Thailand caused very heavy rain occupied widely over southern east-coast. Lastly, the daily maximum rainfall recorded 396 mm/day at Don Sak, Surat Thani. Thereafter in March 2011, an active low pressure cell caused intense rainfall over the Southern Region of Thailand,

Table 3. Summary of the four contingencies (*TP*, *FP*, *FN*, *TN*) and the four skill scores (*HR*, *FAR*, *HK*, δ) obtained from the *ED*, ED^m, and ED^h thresholds for nine probabilistic levels

Threshold	Probabilistic level (%)	Contingencies and skill scores							
		TP	*FN*	*TN*	*FP*	*HR*	*FAR*	*HK*	δ
ED	5	77	3	848	1312	0.96	0.61	0.36	0.61
	10	72	8	884	1276	0.9	0.59	0.31	0.6
	15	62	18	1299	861	0.78	0.4	0.38	0.46
	25	40	40	1358	802	0.5	0.37	0.13	0.62
	50	21	59	2026	134	0.26	0.06	0.2	0.74
	75	15	65	2046	114	0.19	0.05	0.13	0.81
	80	12	68	2091	69	0.15	0.03	0.12	0.85
	85	8	72	2123	37	0.1	0.02	0.08	0.9
	90	4	76	2149	11	0.05	0.01	0.04	0.95
ED^m	5	28	3	151	0	0.9	0	0.9	0.1
	10	26	5	151	0	0.84	0	0.84	0.16
	15	26	5	151	0	0.84	0	0.84	0.16
	25	23	8	151	0	0.74	0	0.74	0.26
	50	17	14	151	0	0.55	0	0.55	0.45
	75	8	23	151	0	0.26	0	0.26	0.74
	80	5	26	151	0	0.16	0	0.16	0.84
	85	6	25	151	0	0.19	0	0.19	0.81
	90	4	27	151	0	0.13	0	0.13	0.87
ED^h	5	46	1	800	301	0.98	0.27	0.71	0.27
	10	43	4	846	255	0.91	0.23	0.68	0.25
	15	41	6	859	242	0.87	0.22	0.65	0.25
	25	35	12	900	201	0.74	0.18	0.56	0.31
	50	24	23	1052	49	0.51	0.04	0.47	0.49
	75	11	36	1069	32	0.23	0.03	0.2	0.77
	80	11	36	1078	23	0.23	0.02	0.21	0.77
	85	6	41	1081	20	0.13	0.02	0.11	0.87
	90	3	44	1086	15	0.06	0.01	0.05	0.94

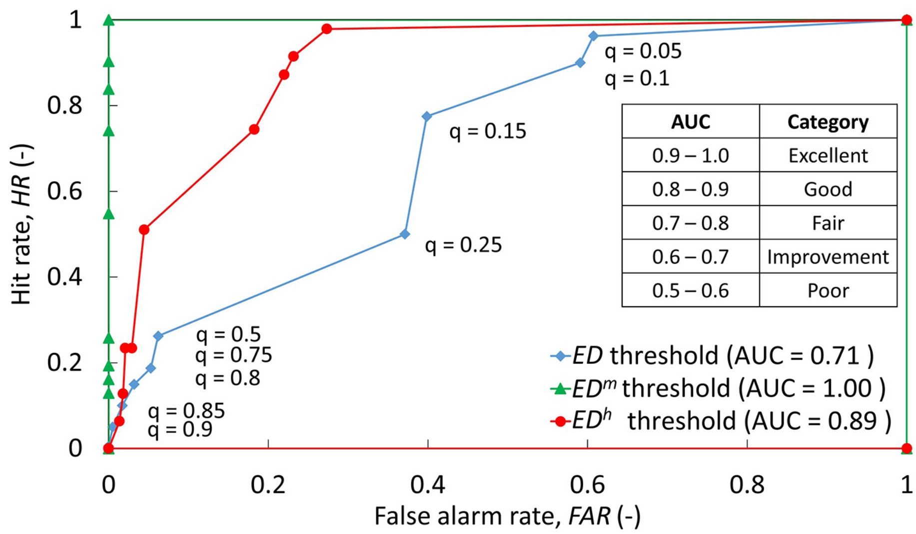

Figure 7. Receiver operating characteristic (*ROC*) and corresponding area under the *ROC* curve (*AUC*) of the *ED*, ED^m and ED^h thresholds

resulting in unprecedented flash floods and landslides in many provinces in Southern of Thailand. It was noted that in 2011, Thailand experienced the worst flood in over fifty years, as volume of flood water occupied more than half the country. For the 2017, there were six landslides reported in our study. In this year, a significantly strong southwest monsoon extended over Southern Thailand in January resulting in series of torrential rainfalls. The total amount of rainfall from December 30th to January 31st exceeded 1,000 mm in many provinces. According to Jin and Fu (2019), the maximum 24-h accumulated precipitation of up to 330 mm appeared around Nakhon Si Thammarat province on January 5th and the maximum 24-h accumulated precipitation of up to 420 mm appeared around the Pattani province on January 7th. In short, the locations classified to the zone of very low to moderate landslide susceptibility could suffer from landslide only if they experience unusual torrential rainfalls. The ED^m threshold established in this study laid above rainfall event of 400 mm which could represent unusual torrential rainfalls, and hence 100% of usual rainfalls were not predicted.

Table 4. Number of landslides with respect to time that landslide occurred at the very low to moderate susceptibility places

Month	Year	Number of landslide in modest susceptibility places		
		Moderate	Low	Very low
1988–2009		4	2	-
Nov.	2010	3	3	-
Mar.	2011	3	5	-
Jan.	2012	2	1	-
Jul.	2013	1	-	-
Nov.	2013	-	-	-
Oct.	2014	-	1	-
Jan.	2017	4	2	-
Jul.	2017	-	-	-
Sep.	2017	-	1	-
Nov.	2017	1	-	-
Dec.	2017	-	-	-
Mar.	2018	-	-	-
Jul.	2018	-	-	-
Aug.	2018	1	-	-

CONCLUSIONS

Landslide rainfall threshold based on rainfall event and rainfall duration (*ED* threshold) was proposed for landslide prediction in the Southern Thailand. Other than rainfall characteristic, a landslide can be influenced by various spatial factors, such as slope conditions, lithology, soil type, and hydrologic conditions. Incorporation of such factors to the rainfall threshold might enhance the predictability of the rainfall threshold. For this purpose, the landslide susceptibility maps at provincial level published by the Department of Mineral Resources (https://gis.dmr.go.th/DMR-GIS/gis) were used as a proxy to allow the connection between the *ED* threshold and the spatial factors. To facilitate the process, five susceptibility levels, ranging from very low to very high, indicated in the landslide susceptibility maps, were regrouped to two susceptibility levels (the modest and the huge susceptibility levels). The modest susceptibility level was a combination of very low, low, and moderate susceptibility levels indicated in the maps. The huge susceptibility level was a combination of high and very high susceptibility levels indicated in the map. Two *ED* thresholds, namely ED^m and ED^h thresholds, were introduced, each for different susceptibility level. The ED^m threshold was established for landslide warning at the places classified as very low to moderate susceptibility levels, while the ED^h threshold was established for the places classified as high and very high susceptibility levels. The following conclusions were drawn from this study:

1) On the basis of the rainfall event that triggered 99 landslides in Southern Thailand in 1988–2018, a rainfall event-duration (*ED*) threshold was introduced for landslide warning in the whole Southern Thailand. However, the predictability of the *ED* threshold was fair with an area under a receiver operating characteristic curve (*AUC*) of 0.71.
2) Integration of the landslide rainfall threshold and the landslide susceptibility map gave a new set of *ED* thresholds (ED^m and ED^h thresholds). These thresholds provided much better predictions than the original *ED* threshold. The *AUC* for the ED^h threshold was 0.89 comparing with *AUC* of 0.71 for the *ED* threshold. In turn, the ED^m threshold provided perfect prediction with *AUC* of 1.00.
3) For the landslides reported in this study, it was found that the landslides in very low to moderate landslide susceptibility level zones were triggered only by the rainfall events having duration no shorter than 4 days. Under these conditions, many rainfall events with their duration shorter than 4 days were filtered out before the assessment of the ED^m threshold. Furthermore, the cumulated rainfall of triggered events was found greater than 400 mm, indicating that landslides in such places would be triggered by unusual torrential rainfall.

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