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Evaluation of key parameters in rainfall-induced shallow landslide analysis: Are Di Village Case

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Abstract: Are Di Village experienced a devastating landslide in September 2020. This research utilized the transient rainfall infiltration and a grid-based regional slope stability model (TRIGRS) to assess the causes of slope instability. Input parameters such as soil properties, rainfall data, slope geometry, and soil thickness were integrated into the analysis. The models were validated using landslide scars from the event. The analysis results indicate that soil thickness significantly influences landslide susceptibility. In this study, the empirical equation utilized to estimate soil thickness considered the influence of topography on the distribution of soil thickness. The results calculated from TRIGRS showed that the model with a maximum soil thickness input of 3.5 m produced the most reliable landslide susceptibility map with an %LSclass of 40% and %LRclass of 65%.

1. Introduction

Rainfall-induced slope failure is one of the most challenging natural hazards and commonly occurs after intense rainfall events in mountainous regions. Rainfall intensity, soil/rock properties, and slope configuration have been widely accepted as key parameters that control rainfall-induced slope failure [1–4]. Landslides and debris flows have caused significant damage in various regions of Thailand. A devastating landslide occurred after a heavy rainfall event in Are Di Village in Chiang Rai Province on September 8, 2020, which damaged buildings, houses, and public utilities. This landslide was evaluated in the present study. As shown in figure 1, the study area covers 10 km² with elevations ranging from 400 to 1,200 masl. The annual rainfall in this area is approximately 1500 mm. The area comprises granite and the Mae Chan fault, which moves approximately 3.0 mm annually [5]. The Geotechnical Engineering Research and Development Center (GERD) mapped landslide scars using aerial photos of the area. Figure 2 illustrates the distribution of scars and debris flows (red and orange polygons, respectively) from the September 8, 2020 event. A public newspaper reported that 55 landslides and debris flows occurred at approximately 6:00 A.M. on the September 8, 2020, and damaged 13 structures. Figure 3 shows the monitoring results for rainfall amounts obtained from weather stations around the study area. Figure 3 also shows that landslides and debris flows occurred immediately after heavy rainfall events.

This study focused on utilizing a geotechnical model to analyze landslide susceptibility in the study area, by utilizing geotechnical soil parameters, rainfall distribution, and soil thickness



distribution. The reliability of the susceptibility map was assessed by comparing the predicted unstable areas with actual landslide scars. The analysis methodology and results are presented in the following section.

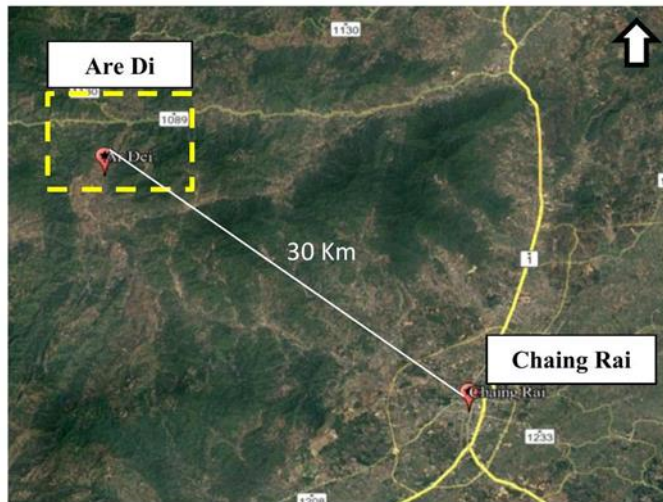


Figure 1. Location of Are Di Village.

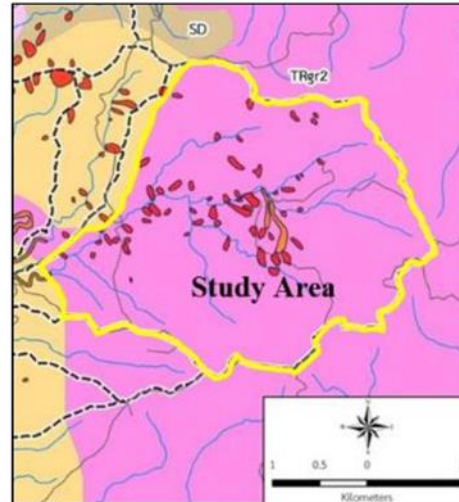


Figure 2. Landslide inventory map

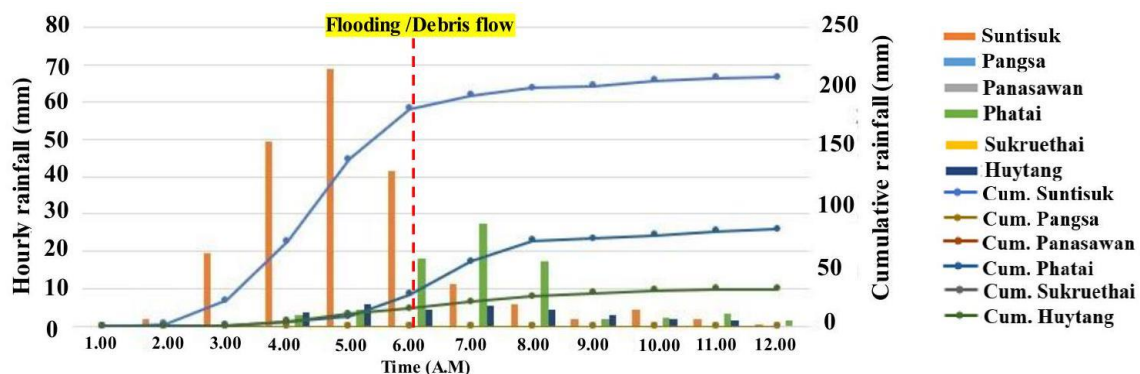


Figure 3. Monitoring of rainfall on September 8, 2020.

2. Transient rainfall infiltration and grid-based regional slope-stability model

Modeling water migration on slopes with unsaturated soils, while accounting for the influence of climatic conditions, poses a significant challenge [6]. The transient rainfall infiltration and grid based regional slope-stability model (TRIGRS) proposed by Baum et al. [7] is a program developed in the FORTRAN language, and incorporates an infiltration model, runoff water analysis, and infinite slope stability analysis. The TRIGRS model employs a simplified analytical solution of Richard's equation to evaluate pore pressure reaction and utilizes an infinite-slope approach to estimate the stability of shallow soil layers under storm conditions.

The failure of an infinite slope is determined by examining the relationship between the resisting basal Coulomb friction and gravitational force that drives the slope downslope. Figure 4 presents a conceptual infinite slope model for the TRIGRS. The factor of safety (FS) at a certain depth, Z, for the infinite slope shown in figure 4 can be calculated using equation (1).

$$FS(Z, t) = \frac{\tan \phi'}{\tan \delta} + \frac{C' - \gamma_w \psi(Z, t) \tan \phi'}{\gamma_s Z \sin \delta \cos \delta} \tag{1}$$

where:

- C' = Soil cohesion for effective stress
- ϕ' = Soil friction angle for effective stress
- Z = Depth of failure surface
- $\psi(Z, t)$ = Groundwater pressure head as a function of depth (Z) and time (t)
- δ = Slope angle
- γ_w = Unit weight of water
- γ_s = Unit weight of soil

Figure 5 shows the functions of the TRIGRS program. The required input parameters for the program included slope angle, flow direction, soil thickness, and hydraulic and mechanical properties of the soils. For a comprehensive understanding of the technical aspects of the model, further elaboration is provided by Baum et al. [7].

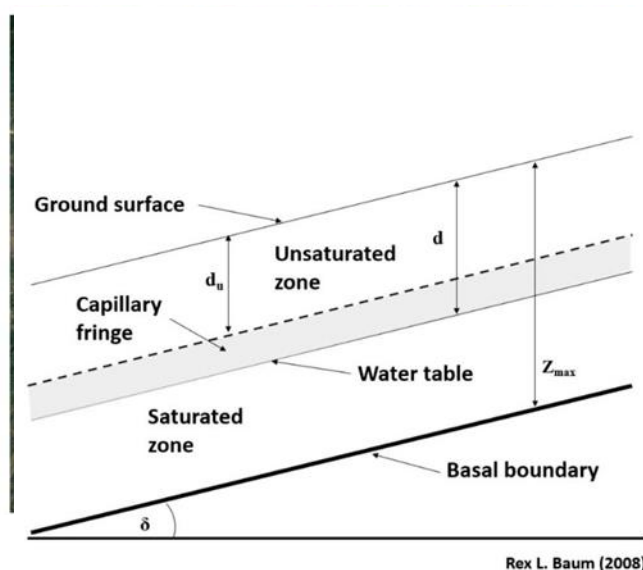


Figure 4. Conceptual diagram of the TRIGRS model.

Figure 4. Conceptual diagram of the TRIGRS model

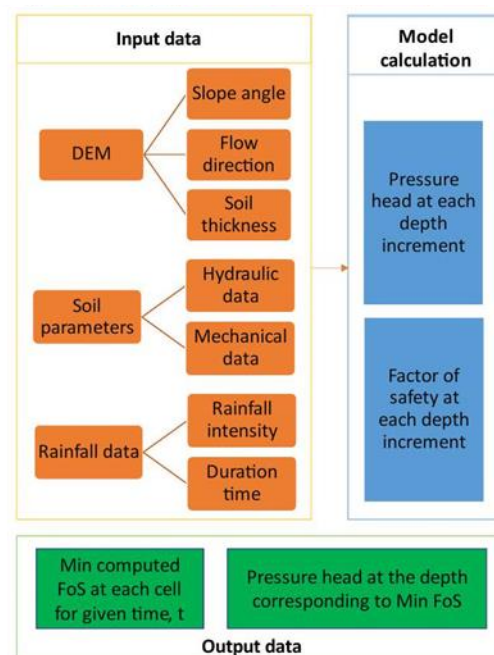


Figure 5. Function of the TRIGRS

3. Methodology

This study comprised three main phases: (1) data collection, (2) modeling phase, and (3) model validation. Initially, a literature review, site investigation, laboratory testing, and landslide scar distribution were conducted. Once all the necessary data were gathered, the modeling of rainfall and

soil thickness maps was conducted to generate the input maps. The soil mechanics parameters, soil thickness map, and rainfall distribution map obtained were subsequently utilized to run the TRIGRS program, resulting in the generation of an FS map. In the model validation phase, the predicted landslide areas were compared with actual landslide scars. The percentage of landslide sites (%LS) and landslide ratio of each predicted FS class (%LR) were used as performance indicators to select the most reliable map. The %LS class is the proportion of actual landslide sites contained in each FS class, whereas the % LR class is the proportion of actual landslide sites contained in each FS class relative to the total number of landslide sites.

4. Analysis

4.1. Field investigations

Based on site observations, a triangular facet and a beheaded stream were identified, which could be interpreted as the fault running along the stream in the study area. Soil thickness varied across the study area, with highly fractured rock outcrops commonly observed along the creek. Landslide scars in the study area were characterized as shallow landslides, primarily occurring on steep slopes along the creek.

Resistivity and seismic surveys were conducted in areas where landslide scars were observed. The results of the resistivity survey showed that the soil material had resistivity values of $>1,500 \Omega.m$, and the soil thickness ranged from 1 to 10 m. The results of the seismic survey indicated that the soil layer had a velocity of <300 m/s, and the soil thickness ranged from 1 to 6 m.

4.2. Landslide scar distribution

The distribution of landslide scars was analyzed according to their elevation, slope gradient, aspect, and flow direction. The results of the analysis are presented in figures 6–9. Figure 6 shows that most scars (32%) occurred within an elevation range of 700–800 m. Figure 7 shows that slopes with a gradient of 30° – 40° exhibited the highest concentration (55%) of scars. Slopes facing 315° to 360° were identified as the predominant locations (25%) for scars, as shown in figure 8. The highest concentration of scars was observed in the north direction (22%), as indicated in figure 9.

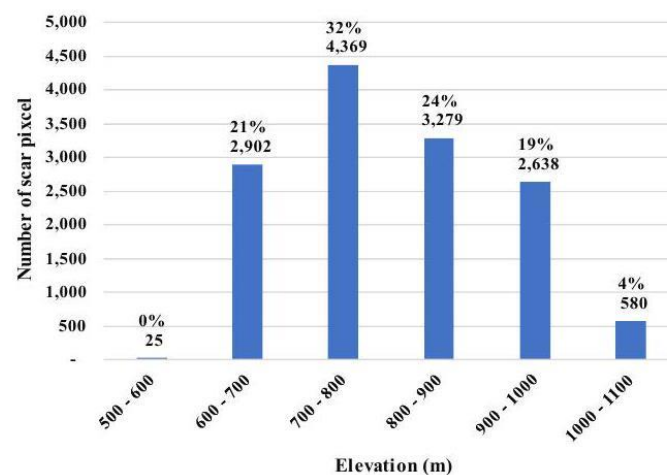


Figure 6. Landslide distribution in relation to elevation.

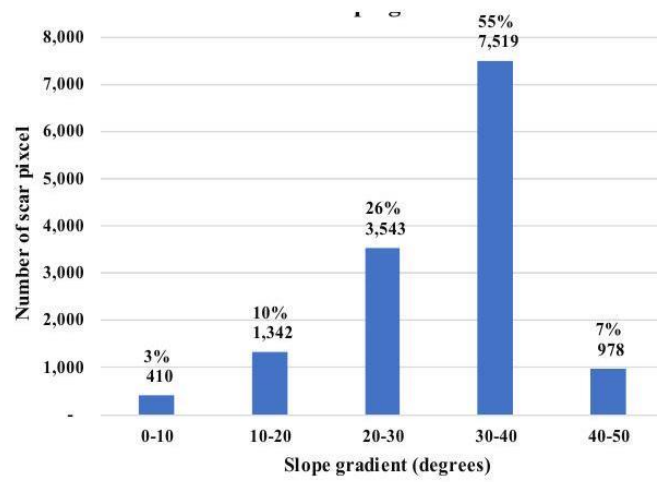


Figure 7. Landslide distribution in relation to slope gradient.

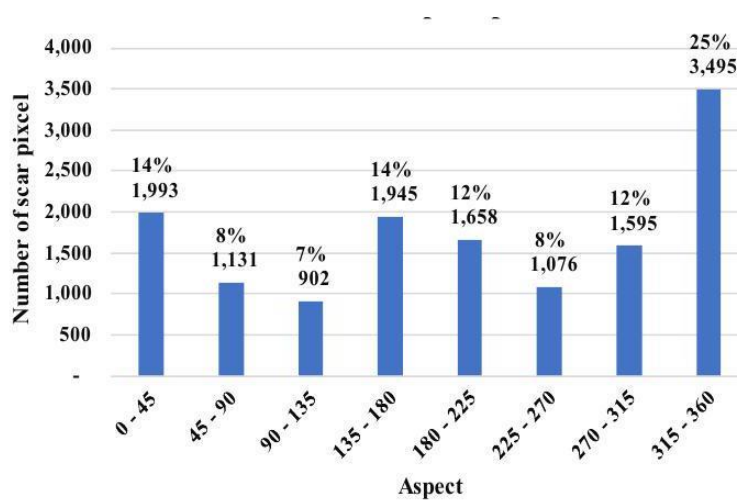


Figure 8. Landslide distribution in relation to aspect.

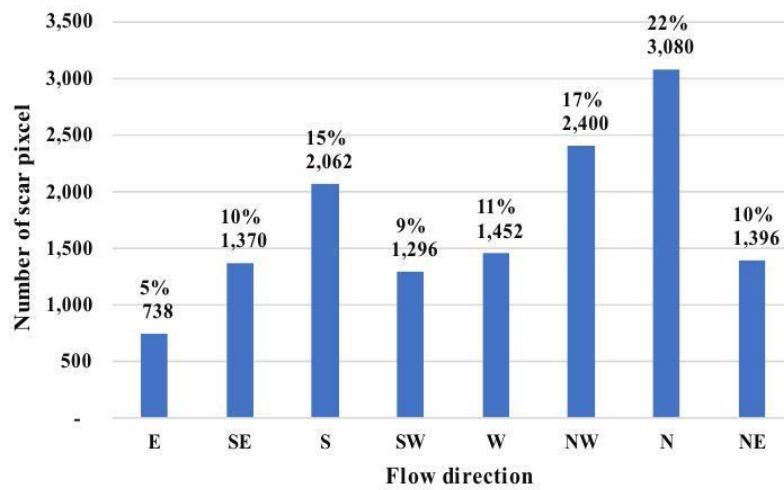


Figure 9. Landslide distribution in relation to flow direction.

4.3. Rainfall distribution

This study used rainfall data recorded at six weather stations located around the site. The data were employed for inverse distance weighting (IDW) interpolation to generate a rainfall distribution map. A rainfall distribution map of the study site is shown in figure 10.

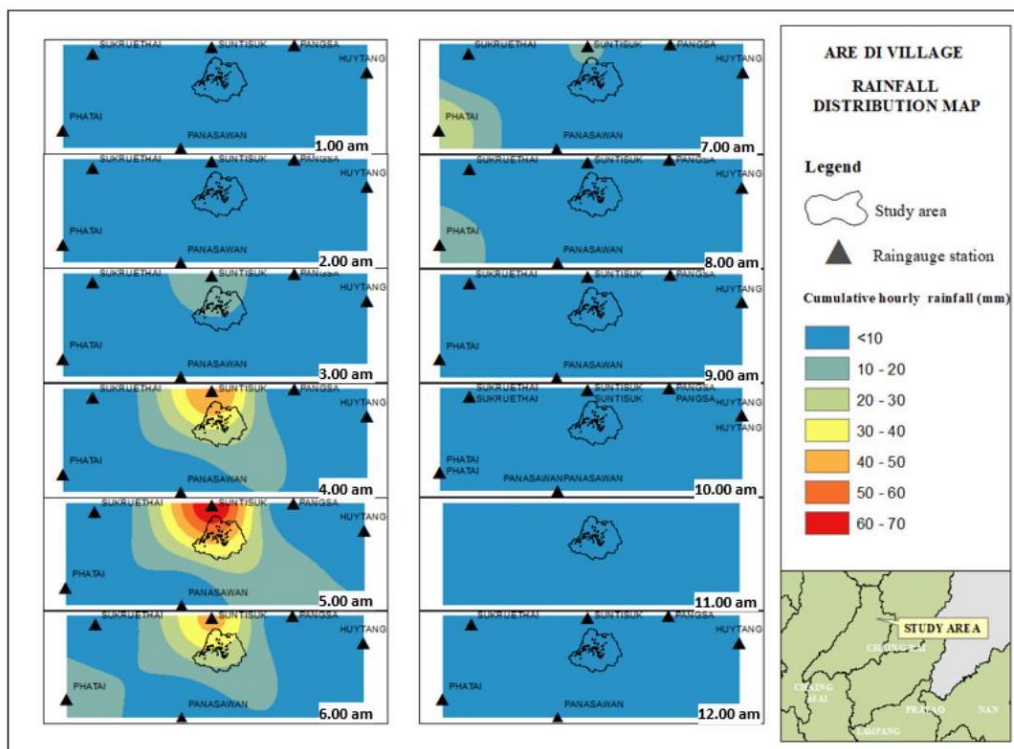


Figure 10. Rainfall distribution map.

4.4. Soil thickness distribution

In this study, the estimation of soil thickness distribution was performed using a combination of site observation, topography analysis, and empirical equations. The following assumptions were made regarding soil thickness distribution: Fractured rocks are susceptible to weakening, allowing water to

seep in, thereby increasing weathering and erosion; additionally, rocks with more exposed fractures are likely to have thicker residual soil. Saulnier et al. [8] proposed a soil thickness model based on the assumption that erosion tends to produce shallower soils at higher elevations. The initial effective soil thickness values were predicted to decrease linearly with the elevation, as shown in equation (2):

$$m_i = m_{\max} \left[1 - \frac{m_{\max} - m_{\min}}{Z_{\max} - Z_{\min}} (Z_i - Z_{\min}) \right] \quad (2)$$

Figure 11 shows the general conditions of the site. The input parameters of the soil thickness model are listed in table 1. The calculated soil thickness maps are shown in figure 12.

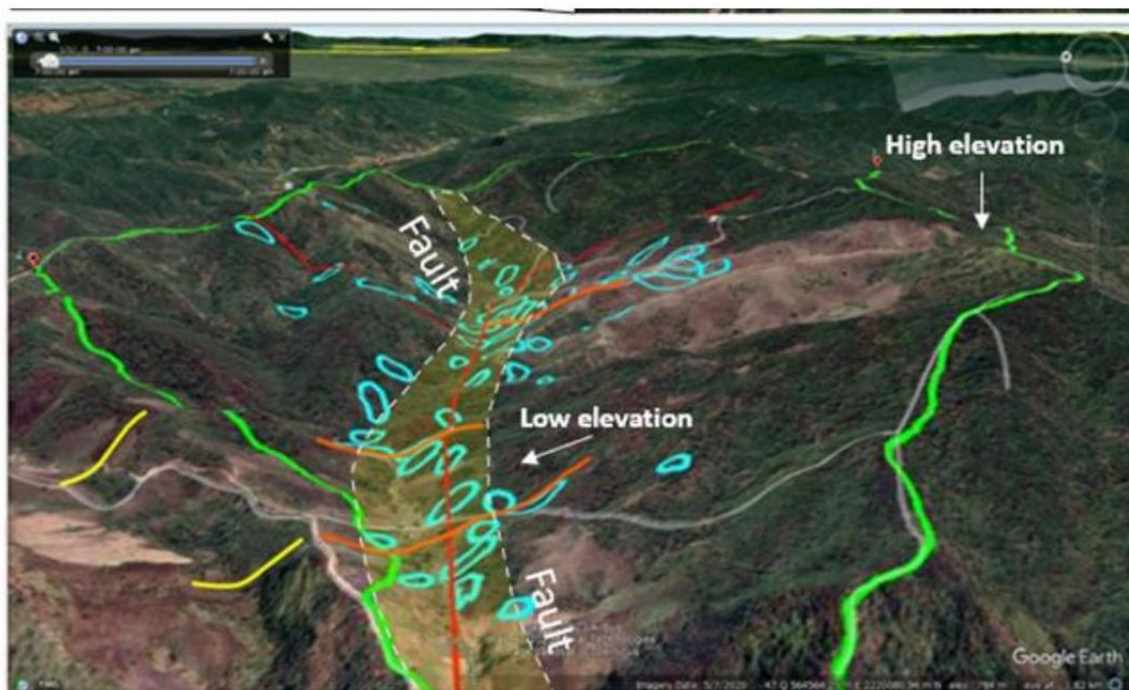


Figure 11. General site condition.

Table 1. Input parameters for the soil thickness model

Input parameter	Value	Unit	Source
Max soil thickness, m_{\max}	1.0 – 10.0	meter	Geophysics, Site observation
Min soil thickness, m_{\min}	1.0	meter	Geophysics, Site observation
Max elevation, Z_{\max}	1,218	meter	DEM
Min elevation, Z_{\min}	573	meter	DEM

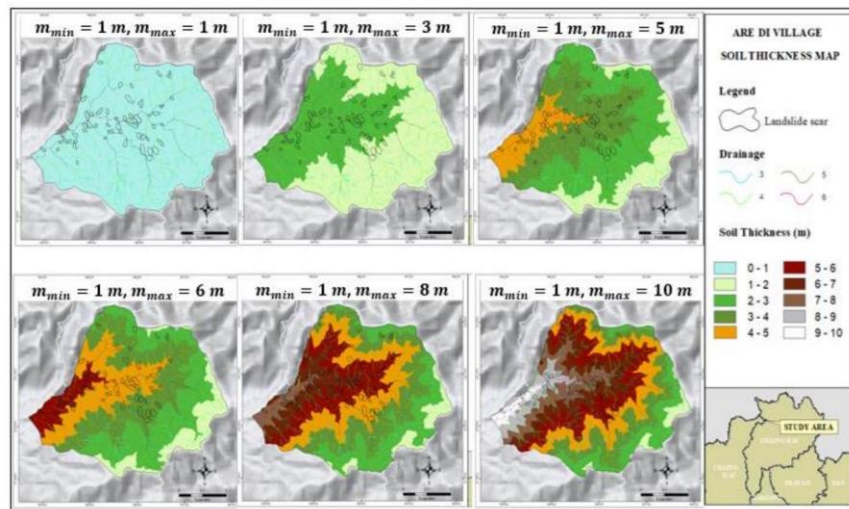


Figure 12. Soil thickness distribution map.

4.5. Landslide susceptibility modeling

The input parameters for the landslide susceptibility modeling are listed in table 2. The soil parameters, including the strength parameters, unit weight of soil, permeability, saturated volumetric water content, residual volumetric water content, hydraulic diffusivity, and steady infiltration rate, were established through a combination of laboratory testing and literature review. The alpha parameter of the Gardner model was estimated by recalibrating the Soil–Water Characteristic Curve (SWCC) of the Book and Corey model. The groundwater level was assumed to be at the same depth as that of the soil at each location. The IDW was used to prepare the input rainfall raster. The input soil-thickness maps were estimated using Eqs. (2). To validate the models, the predicted landslide areas were compared with actual landslide scars.

Table 2. Input parameters for landslide susceptibility modeling

Parameters	Input Values	Parameters	Input Values
Soil cohesion (N/m ²)	15,691	Alpha parameter (1/m)	0.17
Soil friction angle (Degrees)	27	Hydraulic diffusivity (m ² /s)	1.47E – 04(150Ks)
Unit weight of soil (N/m ³)	18,437	Steady infiltration rate (m/s)	9.78E – 09(0.01Ks)
Permeability, Ks (m/s)	9.78E – 07	Soil thickness (m)	Varies: 1–10
Residual volumetric water content	0.098	Groundwater table (m)	Varies: 1–10
Saturated volumetric water content	0.42		

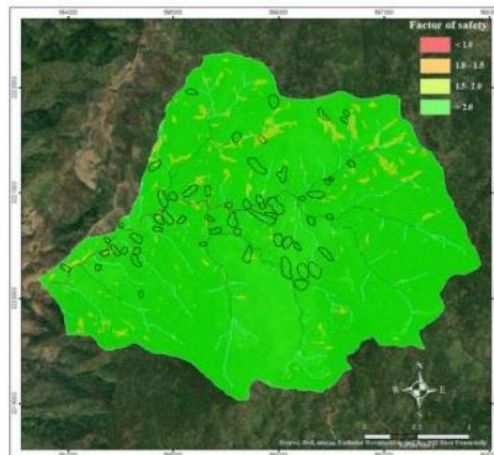
5. Results and discussion

The main output of the TRIGRS is the safety factor value for every grid cell. Figure 13 shows a graphical representation of the FS map predictions obtained for various maximum soil thicknesses. The FS map depicts the estimated distribution of the safety factors at 12:00 on September 8, 2022. In figure 13, the areas where the calculated safety factor was less than unity are highlighted in red, and the scar areas mapped at the study site are indicated by open solid lines. Figure 14 illustrates the correlation between the predicted unstable area percentage and maximum soil thickness input. The graph shows that soil thickness is a crucial factor in model prediction. As the maximum soil thickness increases, the calculated unstable area percentage also increases, leading to an overestimation of the landslide area. Moreover, when the maximum soil thickness input exceeded 3 m, an unstable area appeared. In addition, if the maximum soil thickness input exceeded 6 m, the model predicted that approximately 25% of the total area would remain unstable.

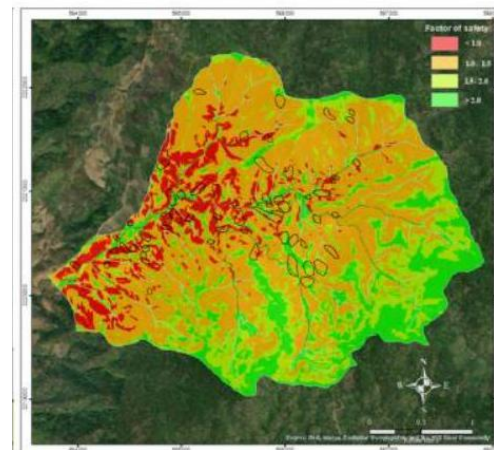
For comparison and validation, scar areas were used to calculate the %LS and %LR classes to evaluate the performance of the predicted model. The reliabilities of the susceptibility map, %LS class, and %LR class were evaluated by examining the relationship between the predicted landslide and landslide scar areas. The FS map, estimated from a maximum soil thickness input of 3.0 m, achieved the highest %LR class of approximately 70%, while the 3.5-m input map had the highest %LS class of approximately 40%. Based on these results, a susceptibility map created with a maximum soil thickness input of 3.5 m was selected for this study, because it had the highest %LS class of 40% and a relatively high %LR class of 65%. The details of the %LR class calculations are listed in table 3. Figure 15 shows the selected landslide susceptibility map of the study area, created using the 3.5-m maximum soil thickness input.

Table 3. Detailed calculations of %LS class and %LR class (example: input 3.5 m of the maximum soil thickness)

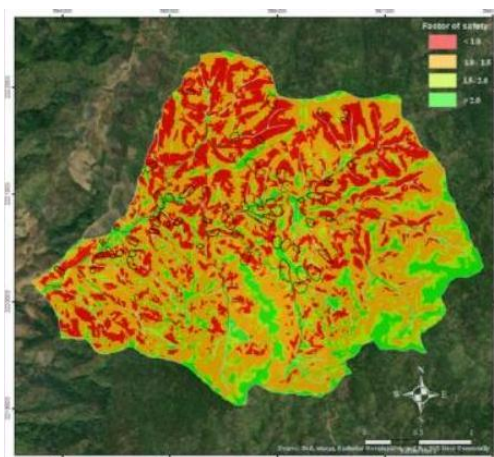
FS class	Landslide site (a)	% of Landslide site (c) = a/b	% of Predicted area (d)	LR class (e) = c/d	% of LR class = e/f
FS ≤ 1.0	22.0	40.0	9.9	4.04	64.8
1.0 < FS <= 1.5	15.0	27.3	50.1	0.54	8.7
1.5 < FS <= 2	10.0	18.2	23.0	0.79	12.7
2.0 < FS <= 10	8.0	14.5	16.9	0.86	13.8
Sum	55.0 = (b)	100.0	100.0	6.23 = (f)	100.0



Input soil thickness: min 1.0 m; max 1.0 m



Input soil thickness: min 1.0 m; max 3.5 m



Input soil thickness: min 1.0 m; max 7.0 m

Figure 13. FS map analyzed from different maximum soil thickness inputs.

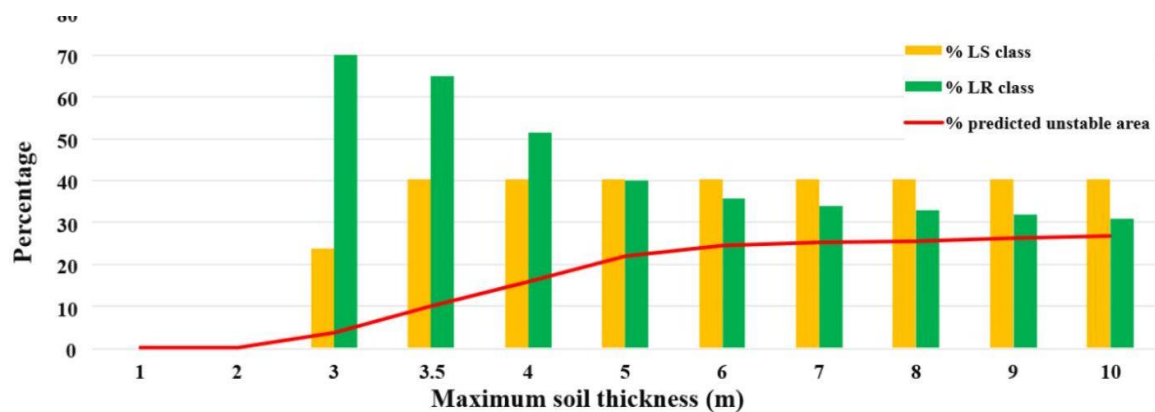


Figure 14. Relationship of maximum soil thickness, %predicted landslide area and performance of each map.

- %LS class is the percent of actual landslide sites contained in each FS class.
- %LR class is based on the ratio of landslide sites contained in each FS class in relation to the total number of actual landslide sites, according to the predicted percentage of each FS class.

$$LR_{\text{class}} = \frac{\% \text{ of contained landslide site in each class of FS}}{\% \text{ of predicted landslide areas in each class of FS}}$$

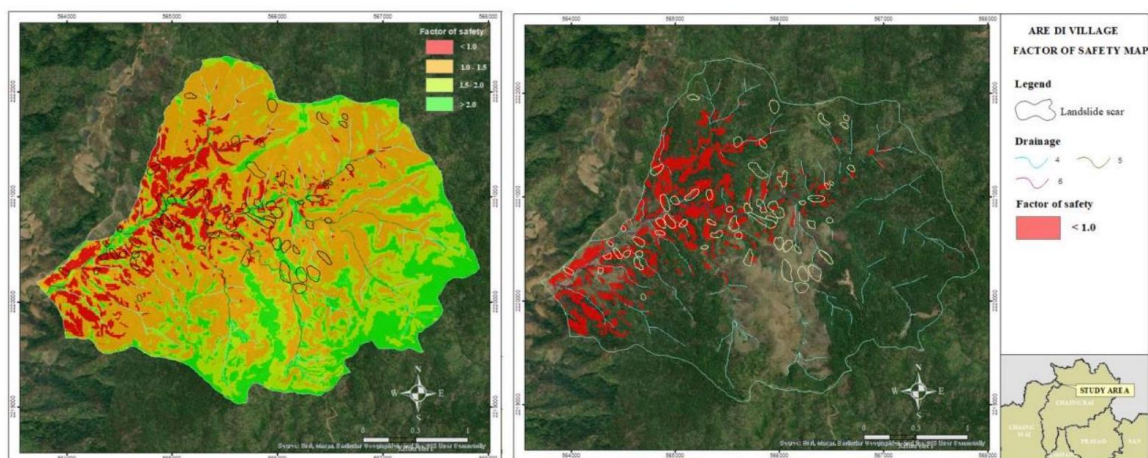


Figure 15. Selected landslide susceptibility map of the study area.

6. Conclusions and recommendations

This study investigated the factors contributing to landslide susceptibility in Are Di village, Chiang Rai Province, Thailand, and developed a reliable and accurate landslide susceptibility map using field investigations, TRIGRS, and GIS techniques. The results of our study show that the study area is composed mainly of Triassic granite, and that the major structural geology in the area is the Mae Chan Fault, which runs along the creek. Landslide scars are concentrated near creeks at elevations of 700–800 m and slopes of 30°–40°, particularly on the north-facing slopes. This pattern can be attributed to the increased exposure to rainstorms, which results in higher saturation levels and reduced shear strength, making these areas more susceptible to landslides.

According to the assessment of the shallow rainfall-induced landslides susceptibility analysis using the TRIGRS program, soil thickness was found to be one of the most critical input parameters for the

analysis. Consequently, assuming a homogeneous soil depth throughout the area could either overestimate or underestimate FS. The results calculated from TRIGRS showed that the model with a maximum soil thickness input of 3.5 m produced the most reliable landslide susceptibility map, with a %LS class of 40% and %LR class of 65%.

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