Susceptibility investigation of debris flow using topographic index in the Uttaradit Province

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Abstract

Uttaradit Province, situated in Thailand's lower northern region, faces significant risks from geohazards such as debris flows, landslides, and flooding. These hazards pose a serious threat to both people and property. The area's susceptibility to debris flows is influenced by several topographic factors, including steep mountain slopes and numerous mountain-front outlets. This study used the Frequency Ratio (FR) method to identify and map areas susceptible to debris flows in Uttaradit Province. We analyzed topographic indices related to debris flow activity using terrain data from a 12.5-meter resolution Digital Elevation Model (DEM). The FR was calculated using ten parameters indicative of areas vulnerable to debris flows. These parameters included: i) Distance to the road, ii) Plan curvature, iii) Terrain ruggedness index, iv) Profile curvature, v) Slope, vi) Melton ruggedness number, vii) Topographic wetness index, viii) Stream power index, ix) Elevation, x) Lithology. The results allowed us to categorize the debris flow susceptibility in Uttaradit Province into five levels. Areas with high and very high susceptibility are mainly located in the plains of the southwest and the Khao Phi Pan Nam region, covering 40.58% of the area. In contrast, the northeastern, northwestern, and northern parts of the province were identified as having medium and low susceptibility, covering 59.42% of the area.

Keywords: Uttaradit Province, Debris Flow, Topographic Index, Mass Wasting

1. Introduction

Mass wasting is a geological term referring to the downward movement of rocks, soil, mud, and snow along a slope. It can be classified into several categories based on i) Type of mass (e.g., rocks, soil, snow), ii) Amount of water, and iii) Movement patterns (e.g., drop, collapse, avalanche, slip, flow).

These factors result in different mass migration patterns regarding speed, size, area, and disaster potential, including rockfalls, landslides, rockslides, debris avalanches, and debris flows.

Uttaradit is a province in the lower northern region of Thailand, covering 7,838 km². Geographically, Uttaradit is located between latitudes 17°8’-18°11’ N and longitudes 99°54’-101°11’ E. It is bordered by Phrae and Nan to the north, Phitsanulok to the south, Laos to the east, and Sukhothai to the west. The regional topography of Uttaradit Province is composed of three types:

i) Nan River Basin, approximately 20% of the total area, ii) Plains between the valleys and foothills, approximately 20% of the total area, iii) Mountainous and high areas, part of the Phi Pan Nam Mountain, approximately 60% of the total area. The Sirikit Dam is also a significant feature in the region.

In 25 May 2006, a severe debris flow occurred in Laplae District, Uttaradit Province, resulting in over 75 fatalities, 28 missing persons, and damage to more than 697 houses. This disaster was due to abnormal rainfall over several days, causing the soil to be unable to retain the rain, leading to flooding, landslides, and falling debris.

The study has been structured around objectives to conduct an exhaustive examination of debris flow susceptibility in Uttaradit and subsequently produce a debris flow susceptibility map.

ArcGIS software was used for these analyses, while SAGA software was employed to calculate the topographic wetness index (TWI), stream power index (SPI), Melton ruggedness number (MRN), and terrain ruggedness index (TRI).

After analyzing all topographic indices for debris flow recognition, the FR approach was used to compute all indices in terms of score. Following this, the FR scores were classified according to their susceptibility to debris flows.

Table 1. Classification of debris flow susceptibility in this study

Class of debris flow susceptibility	Interval of debris flow susceptibility
Very low	0.16 to 0.36
Low	0.36 to 0.48
Medium	0.48 to 0.76
High	0.76 to 1.02
Very high	1.02 to 1.19

To assess the debris-flow hazard areas in Uttaradit Province, we utilized topographic analysis, remote sensing, and GIS to determine and zone potential risk areas. The Frequency Ratio (FR) method, widely used for landslide susceptibility assessment, was employed in this study due to its good performance (Regmi et al., 2014). This statistical method simulates environmental conditions using factors related to the dependent variable, aligning all obtained topographic indices with the FR score, representing debris-flow susceptibility. The results of this study could significantly contribute to debris-flow hazard mitigation planning.

For analyzing debris-flow sensitive areas (Figure 1), we used base data from a digital elevation model (DEM) with a resolution of 12.5 meters. We then spatially analyzed 12 topographic index factors across Uttaradit Province, including slope, aspect, distance to road, plan curvature, and profile curvature.

According to Table 1, the FR in this study was classified into five categories: very low, low, medium, high, and very high. Finally, debris flow susceptibility was mapped using the method described (Meinhardt et al,2015). The maps obtained in this study were validated against recorded debris flow hazards in Uttaradit Province, as available in the database of the Department of Mineral Resources (Figure 2).

2. Topographic Index

2.1. Distance to road

The distance to road (Figure 3a) infrastructure is most densely concentrated in the central, southern, and eastern regions of Uttaradit Province. The distances to the nearest roads can be categorized into five distinct classes, defined as follows: Class 1 (0 - 100 meters), Class 2 (100 - 500 meters), Class 3 (500 – 1,000 meters), Class 4 (1,000 – 1,500 meters), and Class 5 (1,500 – 40,000 meters). It is worth noting that Mueang Uttaradit District exhibits the highest road density within the province.

2.2. Plan curvature

Plan curvature (Figure 3b) corresponds to the curvature at right angles to the direction of the steepest slope. It is classified into three categories: i) Concave, ii) Plain, and iii) Convex.

These categories may indicate the inward or outward flow of the surface based on negative to positive values. According to the results, the concave areas, identified by negative values, covered the smallest portion of Uttaradit Province, with only 1,022 km². The majority of the province was covered by plan areas, amounting to 5,283 km². Additionally, the convex areas, identified by positive values, covered 1,496 km² (Table 2).

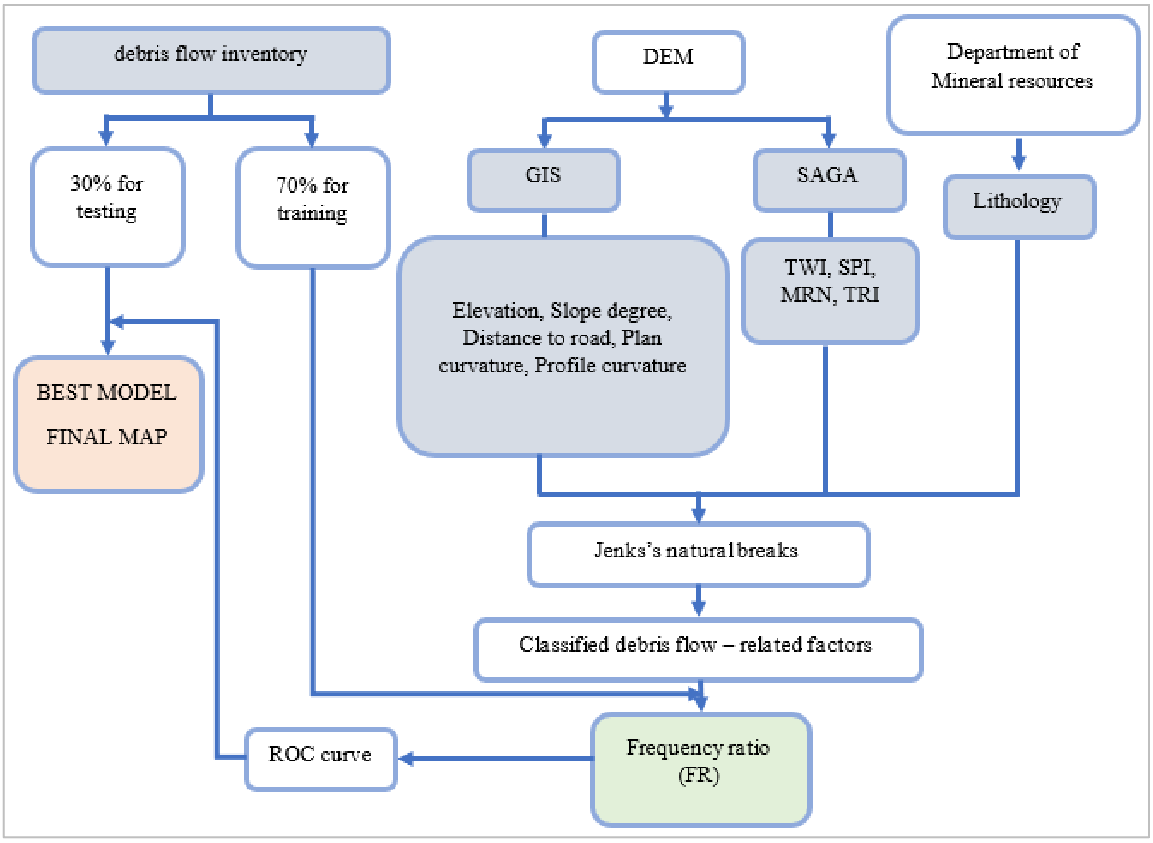

Figure 1. Flowchart showing methodology to analyze debris flow susceptibility in this study.

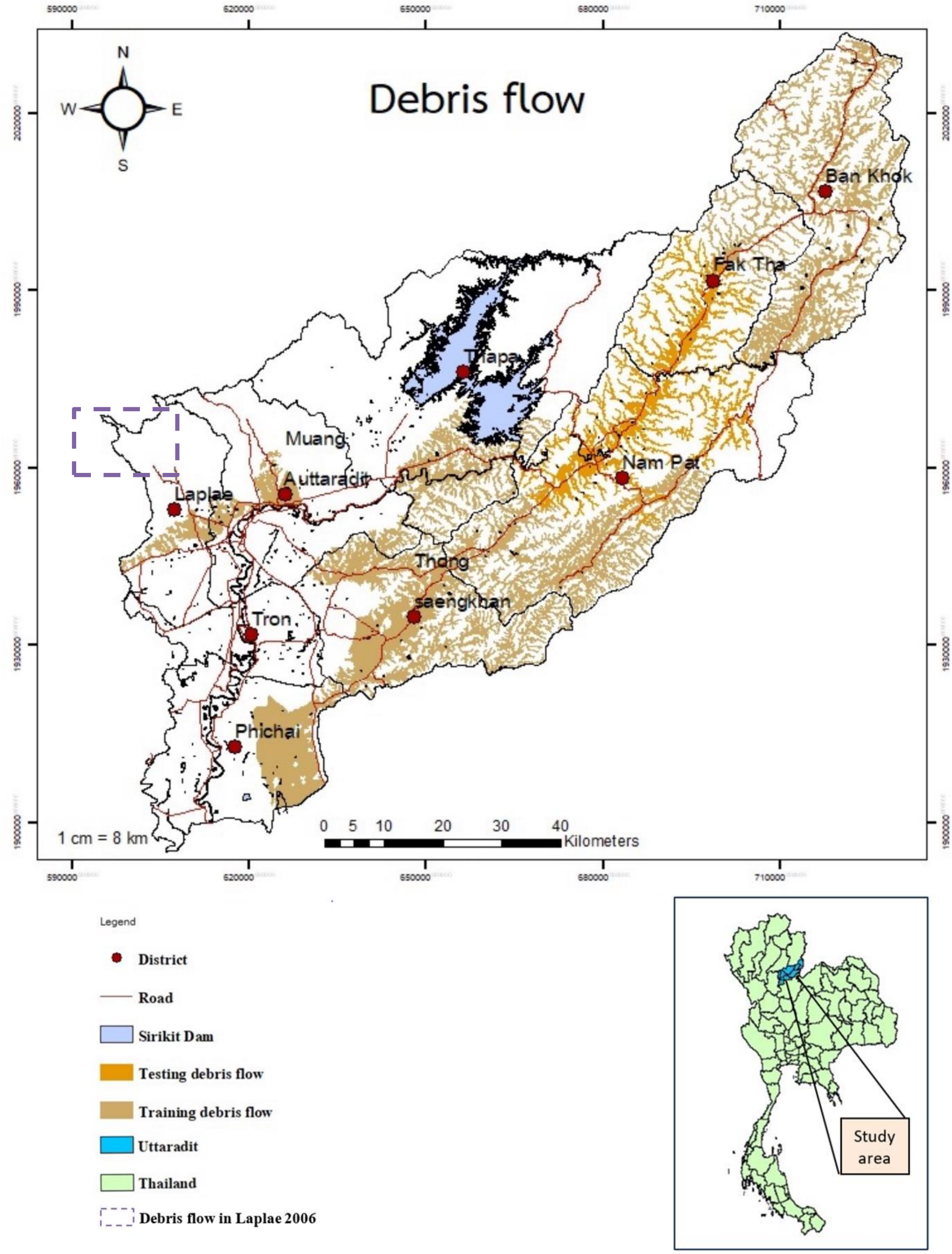

Figure 2. Map of Uttaradit Province showing the location of the debris flow has been posed previously. All data reported and recorded by the Department of Mineral Resource and Showing the study area, Sirikit Dam Road in Uttaradit Province. and the area where debris flow occurred In 25 May 2006, in Laplae District.

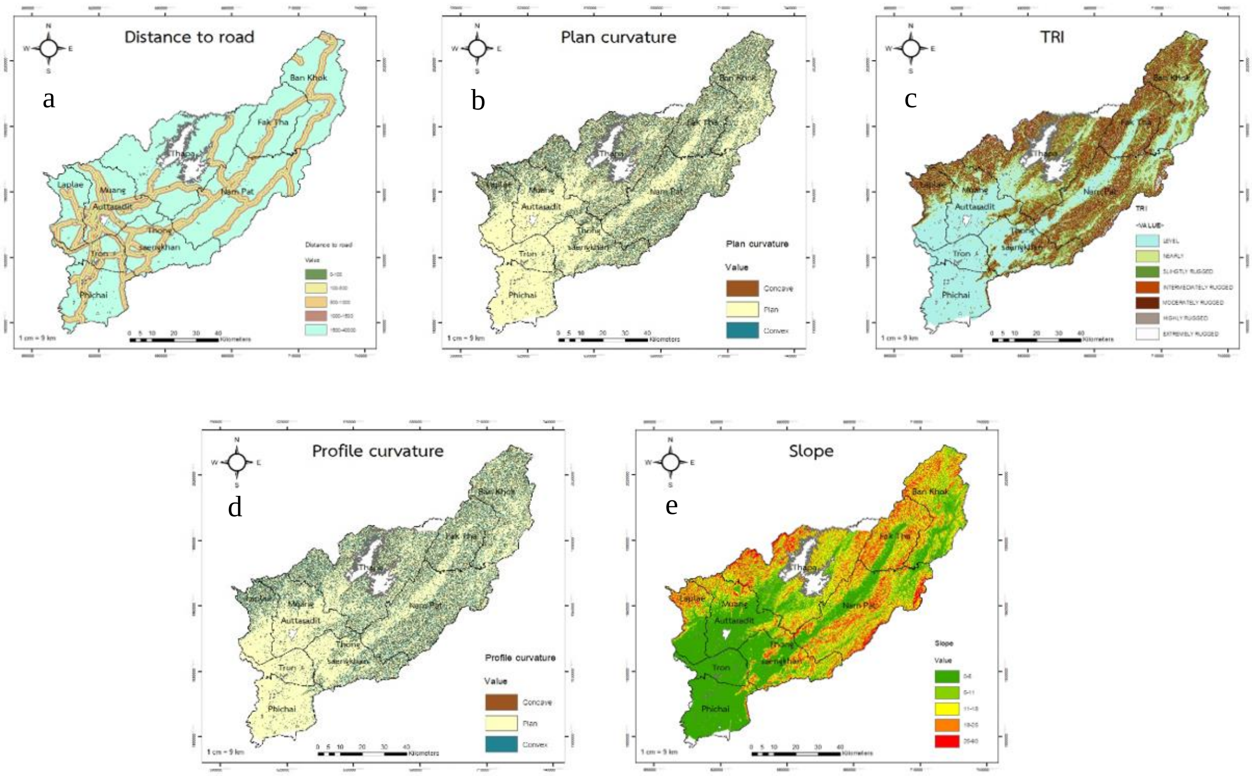

Figure 3. Map of Uttaradit Province showing the topographic index related to the debris flow susceptibility. (a) distance to road, (b) plan curvature, (c) TRI, (d) profile curvature, (e) slope.

2.3. Terrain ruggedness index

The Terrain Ruggedness Index (TRI) (Figure 3c) was grouped into seven classes following the classification (Riley et al,1999): i) Level, ii) Nearly level, iii) Slightly rugged, iv) Intermediately rugged, v) Moderately rugged, vi) Highly rugged, and vii) Extremely rugged.

According to the assessment, the majority of the study area is classified as level and slightly rugged, covering 6,644 km² and 3,811 km², respectively. Additionally, the classifications include: i) Nearly level (1,221 km²), ii) Intermediately rugged (1,160 km²), iii) Moderately rugged (3,098 km²), iv) Highly rugged (604 km²), and v) Extremely rugged (52 km²). Extremely rugged is the area with the least number of pixels in Uttaradit Province. TRI analysis revealed that debris primarily forms on Level terrain.

2.4. Profile curvature

Profile curvature (Figure 3d) represents the vertical curve parallel to the steepest direction of the slope. It is categorized into three classes: i) Concave, ii) Plain, and iii) Convex. These classes are associated with flow speed, ranging from slow to fast, and are represented by negative and positive values, respectively. According to the analysis, the concave zones with negative values cover the smallest region in Uttaradit Province, totaling 1,006 km². The plain zones cover the majority of Uttaradit Province, encompassing 5,326 km². The convex zones, identified by positive values, cover 1,661 km² (Table 2).

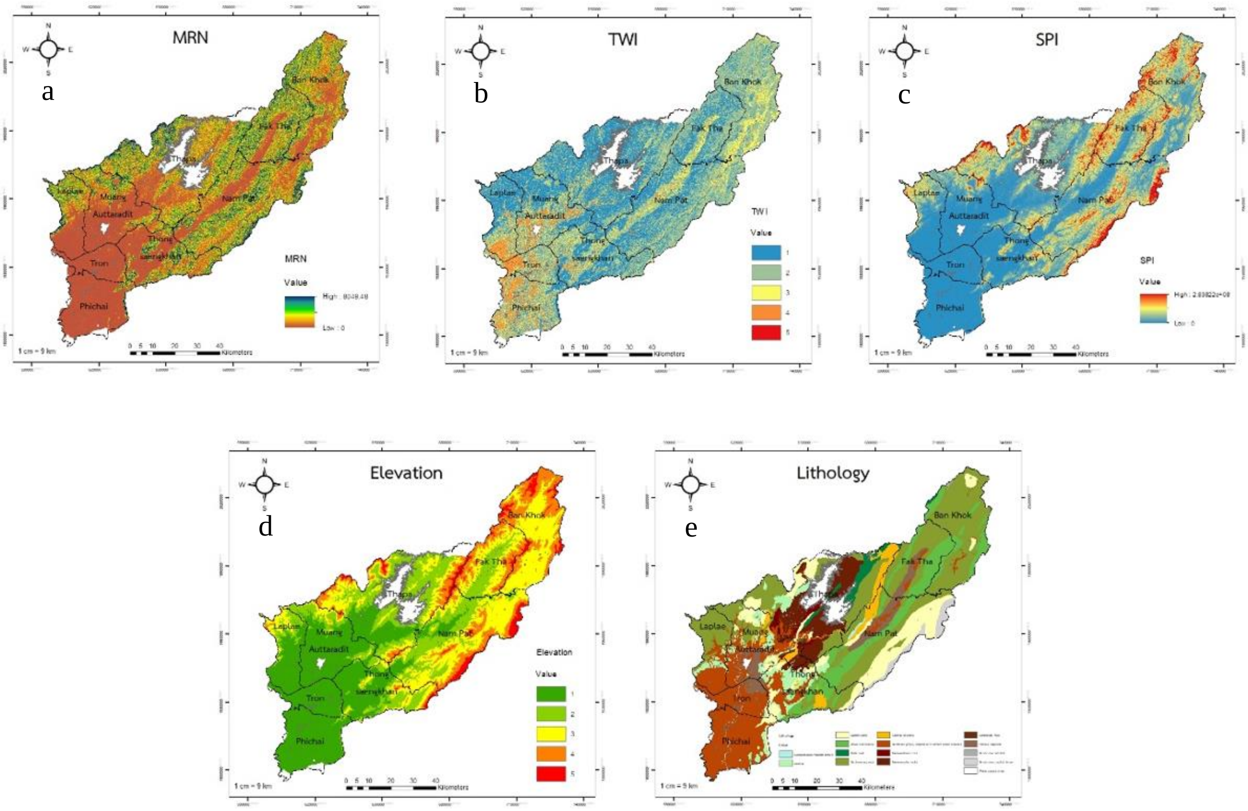

Figure 4. Map of Uttaradit Province showing the topographic index related to the debris flow susceptibility. (a) MRN, (b) TWI, (c) SPI, (d) Elevation, (e) Lithology.

2.5. Slope

Slope is the most commonly used factor in assessing debris flow susceptibility. The slope of Uttaradit Province (Figure 3e) ranges from 0° to 70°. The average gradient in most regions is between 0° and 5°, with the maximum values found in the Phi Pan Nam area, located in the center of Uttaradit Province, where slopes range from 25° to 60°.

Before calculating susceptibility, this investigation categorizes the slope gradient into five classes: Class 1: 0° - 5°, Class 2: 5° - 11°, Class 3: 11° - 18°, Class 4: 18° - 25°, Class 5: 25° - 60°. Class 1 slope are primarily found in the middle to lower parts of Uttaradit Province and the Phi Pan Nam Valley. The other classes are located in the upper parts of Uttaradit Province.

2.6. Melton ruggedness number

The Melton ruggedness number (MRN) in Uttaradit Province (Figure 4a) ranges from 0 to 8049.47. Before calculating debris flow susceptibility, MRN is divided into 5 classes: Class 1: 0 – 284.09, Class 2: 284.09 – 820.73, Class 3: 820.73 – 1483.62, Class 4: 1483.62 – 2493.76, Class 5: 2493.76 – 8049.47

The maximum value of 2493.76 to 8049.47 is located on the eastern ridge and northwest of Uttaradit Province, which constitutes a mountain range. The lowest value of 0.00 to 284.09 is situated along the mountain ridge and the lower part of Uttaradit Province, representing a flat area.

2.7. Topographic wetness index

In Uttaradit Province, Topographic wetness index (TWI) values ranged between 2.61 and 20.8, as illustrated in Figure 4.3. Most of the zone exhibits an average TWI within the range of 2.61 to 3.92. The highest TWI value of 20.80 is observed in the southwestern part of Uttaradit Province. Additionally, areas along the eastern ridge and around Sirikit Dam depict minimum TWI values ranging from 0 to 2.61 (Figure 4b).

Before calculating debris flow susceptibility, TWI is divided into 5 classes: Class 1: 0 – 2.61, Class 2: 2.61 – 3.92, Class 3: 3.92 – 7.10, Class 4: 7.10 – 13.70, Class 5: 13.70 – 20.80. Class 1 is found predominantly in the northwestern area and around the ridge of Khao Phi Pan Nam. Class 2 is mainly located in the northeastern and southwestern regions. Classes 3, 4, and 5 are situated along the mountain ridge from the northeast to the southwest and in the lower flat areas of Uttaradit Province.

2.8. Stream power index

In Uttaradit Province, the Stream power index (SPI) ranges from 0 to 2,838, as depicted. Most zones exhibit an average SPI ranging from 0 to 67. The lowest SPI was observed in the lower part of Uttaradit Province. Moreover, the maximum SPI is displayed in the southeastern area along the mountain ridge of Uttaradit Province, reaching a peak value of 2,838.

Before calculating debris flow susceptibility, the SPI can be categorized into five classes (Figure 4c), including: Class 1: 0 – 67, Class 2: 67 – 189, Class 3: 189 – 356, Class 4: 356 – 712 and Class 5: 712 - 2,838. Class 1 found in the northwest area. southeast and around the ridge of Khao Phi Pan Nam Furthermore, the remaining classes are situated in the middle to lower parts of Uttaradit Province.

2.9. Elevation

The elevation within Uttaradit Province is categorized into five distinct levels as follows: Class 1: 34.57 - 168.97 meters, Class 2: 168.97 - 350.40 meters, Class 3: 350.40 - 551.99 meters, Class 4: 551.99 - 800.62 meters, Class 5: 800.62 - 1,748.11 meters (Figure 4d).

According to the analysis, Class 5 covers the smallest region in Uttaradit Province. Has the least number of pixels, totaling 281 km², while Class 1 Found a lot in the area middle to lower part of the province, It has the highest number of pixels, totaling an area of 2,879 km² (Table 2).

2.10. Lithology

The information about rock type and its extent, sourced from the Department of Mineral Resources, are classified into 15 distinct categories (Figure 4e): Class 1: Reddish-brown Conglomerate, Class 2: Granite, Class 3: Quartz Sand, Class 4: Arkos Sandstone, Class 5: Mafic Rock, Class 6: Sedimentary Rock, Class 7: Volcanic Granite, Class 8: Sediment Group, Original and Current Water Sources, Class 9: Metasediment Rock, Class 10: Metamorphic Rocks, Class 11: Carbonate Rock, Class 12: Terrace Deposits, Class 13: Red Brick Sandstone, Class 14: Purple-brown Sandstone, Class 15: Water Source Area

According to the analysis, Class 6 (sedimentary rock) has the highest pixel count, totaling 2,436 km². This class is predominantly distributed in the northeast and west of Uttaradit Province. Conversely, the class with the smallest number of pixels is Class 13 (red brick sandstone), which encompasses 4 km² (Table 2).

3. Debris-Flow Susceptibility

3.1. Frequency Ratio (FR)

The FR model was employed to calculate the weighting factors of debris flow susceptibility using ten parameters: i) Distance to road, ii) Plan curvature, iii) Terrain ruggedness index, iv) Profile curvature, v) Slope, vi) Melton ruggedness number, vii) Topographic wetness index, viii) Stream power index, ix) Elevation, and x) Lithology.

The FR method has been widely used for debris flow susceptibility assessment (Li et al., 2017) based on the observed relationship between the scattering of debris and individual debris flow-related variables. This method demonstrates the relationship between the location of the debris flow and the variables in the study area.

The FR can be calculated using the equation below (1).

$$F_r = \frac{N_i}{N} / \frac{S_i}{S} \qquad \text{Equation (1)}$$

In the equation, S represents the total number of pixels, N represents the number of pixels in a class where debris occurrences are observed, S_i represents the number of pixels in a specific variable, and N_i represents the number of pixels in the i variable. A value greater than 1 indicates a stronger correlation, while a value less than 1 suggests weaker correlations, on average (Lee et al, 2004a, 2004b).

The FR values for each factor were summed for each pixel. Consequently, a higher FR indicates higher sensitivity, while a lower FR indicates lower sensitivity to debris flow (Das and Raja, 2015).

The computed FR can be divided into five categories using the natural Jenks division: very low, low, medium, high, and very high susceptibility (Das and Raja, 2015).

The AUC (Area under the ROC Curve) method was used to assess the accuracy of the FR results. It evaluates the accuracy of the model's predictions regardless of the classification threshold used. In this study, the AUC was 79.6% (Figure 5), indicating that the debris flow susceptibility map is highly precise.

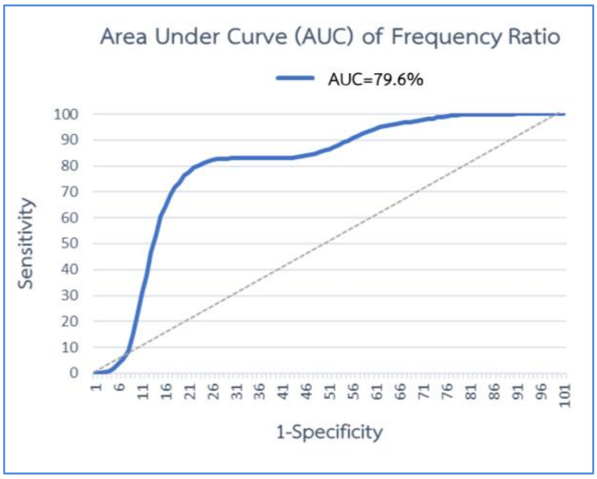

Figure 5. Showing area under curve (AUC) of frequency ratio (FR)

Table 2. Debris flow susceptibility of 10 parameters in this study.

Index	Class	Area (km²)	Area (pixel)	Debris flow in class (pixel)	Fr
Distant to road	0-100	187	207,955	40,560	0.2
	100-500	699	776,871	142,199	0.18
	500-1,000	766	850,667	125,651	0.15
	1,000-1,500	667	741,541	91,451	0.12
	1,500-40,000	5,586	6,207,210	440,279	0.07
Plan curvature	Concave	1,022	1,135,297	66,125	0.06
	Plan	5,283	5,870,403	749,790	0.13
	Convex	1,496	1,662,496	24,045	0.01
TRI	1	2,852	3,168,973	664,392	0.20

Index	Class	Area (km²)	Area (pixel)	Debris flow in class (pixel)	Fr
	2	1,343	1,492,377	122,098	0.08
	3	1,328	1,475,128	38,112	0.03
	4	1,116	1,240,262	11,604	0.01
	5	757	841,163	3,098	0
	6	347	385,468	604	0
	7	58	64,827	52	0
Profile curvature	Concave	815	905,108	4,158	0
	Plan	5,326	5,918,000	682,808	0.12
	Convex	1,661	1,845,088	152,994	0.08
Slope	1	3,115	3,460,745	703,642	0.2
	2	1,497	1,663,063	103,143	0.06
	3	1,485	1,650,511	26,416	0.02
Index	**Class**	**Area (km²)**	**Area (pixel)**	**Debris flow in class (pixel)**	**Fr**
Slope	4	1,213	1,347,288	6,045	0
	5	492	546,589	714	0
MRN	1	4,289	4,765,868	679,884	0.14
	2	1,712	1,902,372	104,959	0.06
	3	1,154	1,282,284	42,682	0.03
	4	530	589,179	11,183	0.02
	5	116	128,495	1,252	0.01
TWI	1	2,675	2,972,508	82,356	0.03
	2	3,467	3,852,715	370,526	0.1
	3	907	1,007,572	215,821	0.21
	4	734	815,145	165,987	0.2
	5	18	20,258	5,270	0.26
SPI	1	4,174	4,637,676	786,313	0.17
	2	1,899	2,110,413	45,022	0.02
	3	1,159	1,287,631	7,622	0.01
	4	453	502,912	875	0
	5	100	111,039	126	0
	6	17	18,527	2	0
Index	**Class**	**Area (km²)**	**Area (pixel)**	**Debris flow in class (pixel)**	**Fr**
Elevation	1	2,879	3,199,334	576,435	0.18
	2	1,761	1,957,088	141,060	0.07
	3	1,860	2,067,019	103,458	0.05
	4	1,019	1,132,403	17,889	0.02
	5	281	312,352	1,118	0
Lithology	Conglomerate reddish brown	11	12,416	639	0.05
	granite	425	472,625	123,164	0.26
	Quartz sand	832	924,475	45,254	0.05

Arkos Sandstone	797	885,563	36,988	0.04
Mafic rock	150	166,684	1,000	0.01
sedimentary rock	2,436	2,706,435	141,974	0.05
granite volcanic	273	303,504	5,904	0.023
Sediment group	1,530	1,700,203	332,825	0.2
Metasediment rock	83	92,277	2,314	0.03
Metamorphic rocks	562	624,411	26,510	0.04
Carbonate rock	13	14,345	1,142	0.08
terrace deposits	311	345,170	55,643	0.16
Sandstone redbrick	4	4,476	67	0.015
Sandstone purplish brown	132	146,661	1,765	0.01
Water source area	295	327,790	64,951	0.2

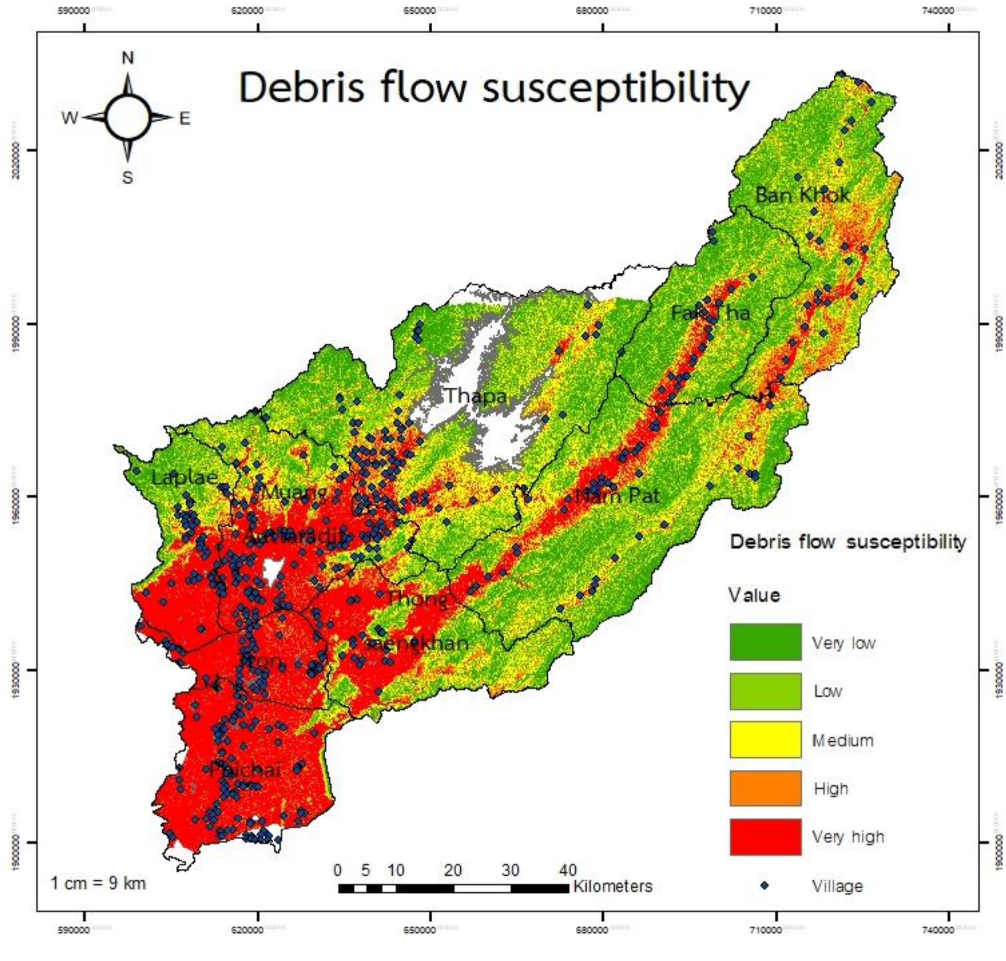

Figure 6. Map of Uttaradit Province depicting debris flow susceptibility levels obtained from this study. Green indicates areas with very low susceptibility, while red signifies areas with very high susceptibility. Blue dots represent village locations.

3.2. Susceptibility Mapping

The results of debris flow susceptibility in Uttaradit Province are illustrated in Figure 6, with color classifications indicating different sensitivity levels: Dark green indicates a very low debris flow susceptibility area. i) Green indicates a low debris flow susceptibility area, ii) Yellow indicates a medium debris flow susceptibility area, iii) Orange indicates a high debris flow susceptibility area, iv) Red indicates a very high debris flow susceptibility area, v) Debris flow susceptibility assessment is divided into five groups, as shown in Table 1: Class 1: Very low (0.16-0.36), Class 2: Low (0.36-0.48) Class 3: Medium (0.48-0.76), Class 4: High (0.76-1.02), Class 5: Very high (1.02-1.19). The area quantity for each class, sorted in descending order, is as follows: Class 5: 2,665 km², Class 1: 1,880 km², Class 2: 1,758 km², Class 3: 1,483 km², Class 4: 832 km².

According to the analysis, a large portion of Uttaradit Province has been designated as a very high susceptibility area, found mostly in the plains in the lower part of Uttaradit Province and the Phi Pan Nam valley area. This region also has a high density of villages.

Other areas not mentioned above are considered to have high to very low susceptibility, found mostly in the plains in the upper part of Uttaradit Province.

From this research, the indices that are significant in assessing debris flow susceptibility are SPI and TRI (Table 2).

Table 3. Summary of the area in each debris flow susceptibility class in Uttaradit Province.

Class of debris flow susceptibility		Area (Km^2)	village
(dark green)	Very low	1,880	13
(green)	Low	1,758	40
(yellow)	Medium	1,483	198
(orange)	High	832	304
(red)	Very high	2,665	447

4. Discussion

According to the results (Figure 6), the southwest, south, and Phi Pan Nam Valley regions of Uttaradit Province, characterized by flat terrain and high mountains, were classified as having very high to high debris flow susceptibility, encompassing a total of 523 villages. This classification likely stems from the furrowed and flat terrain, indicating the area's susceptibility to debris flow. The analysis method, employing terrain factors, reinforces this conclusion.

In contrast, the north and northeast regions of Uttaradit Province, categorized as Highland areas, exhibited medium to very low susceptibility classes, covering a total of 99 villages. Consequently,
the likelihood of debris flow occurrence in these areas is lower.

Upon comparing the research maps with the actual events (21 August 2022 at Nam Phai Subdistrict, Nam Pat District), it was found that the events occurred in areas classified as Very High and High risk on the maps in this study.

Areas with steep slopes are more prone to disasters than flat areas, representing a major factor contributing to debris flow occurrences.

There may be experimental uncertainties resulting from calculations involving different parameters. For instance, some areas may contain surface debris or landfills mistaken for potential debris flow sites, leading to calculation errors. However, the Frequency Ratio (FR) approach is widely acknowledged for identifying areas susceptible to debris flows with high precision.

The historical record of debris flow hazards aligns with the obtained results. It is evident that debris flows have previously occurred in areas identified as highly susceptible.

5. Conclusion

Geomorphological indices serve as effective tools for evaluating the impact of debris flow hazards. In this study, terrain analysis was conducted using DEM data with a resolution of 12.5 meters. The Frequency Ratio (FR) method was employed to assess and assign weights to factors influencing debris flow occurrences, considering ten parameters: distance to road, plan curvature, TRI, profile curvature, slope, MRN, TWI, SPI, elevation, and lithology. These parameters, termed debris flow susceptibility values, were categorized into five sensitivity levels.

The high and very high susceptibility classes (Class 4 and Class 5) are concentrated in the mountainous regions spanning from the east to the central and southern parts of Uttaradit Province, comprising a total of 523 villages. In contrast, the low and very low susceptibility classes (Class 1 to Class 3) are predominantly situated in the northwest area and southeast along the ridge of Khao Phi Pan Nam, encompassing a total of 99 villages.

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