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Application of the spatial multi-criteria evaluation (SMCE) method for landslide susceptibility mapping in Son La province, Vietnam

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Abstract: *The purpose of this study is to carry out landslide susceptibility mapping at 1:50,000 scale for Son La Province by applying the Spatial Multi-Criteria Evaluation (SMCE) method. Seven landslide triggering factor maps related to slope, drainage, deap cleavage, lineament, water holding capacity, weathering crust and land cover were used as input data. One landslide inventory map, which one was investigated by field-surveys, was used to check the reliability of the susceptibility map and the SMCE method. The susceptibility map shows that the susceptibility zones of Very High, High, Medium, Low and Very Low cover the area of 2578.26 km^2 (18.26% of the total area in the province), 4,517.79 km^2 (31.99%), 2,028.47 km^2 (14.37%), 2,518.03 km^2 (17.84%), and 2,468.34 km^2 (17.54%), respectively. The comparision of the susceptibility map with the landslide inventory map points out that more than 65% of the identified landslides are located in the Very High and High susceptibility zones. This proves the accordance between the susceptibility map and the landslide inventory map. Therefore, the susceptibility map is reliable, and the SMCE method is suitable for the study area and can be applied to other areas with similar setting.*

Introduction

In most of the mountainous areas of Vietnam, landslides are occurring with increasing frequency and scale. The damage to people, infrastructure and the environment caused by landslides is, however, often overlooked by society. In general, the studies on the landslides so far have usually only been applied on a large extent, at a small scale and with qualitative predictive zoning. There have not been enough detailed research studies about landslide susceptibility mapping to more effectively assist the prevention and mitigation of damage (Lê Quốc Hùng (chủ biên) và nnk., 2014). In order to overcome those limitations, it is necessary to build a synchronous investigation and analysis program, apply an advanced and appropriate method system to evaluate landslide susceptibility so that planners and local authorities can use for disaster prevention in the context of climate change (Lê Quốc Hùng (chủ biên) và nnk., 2014; Nguyễn Thành Long (chủ biên) và nnk., 2009; Nguyễn Xuân Khiển (chủ biên) và nnk., 2012; Tran Tan Van (editor) et al., 2002).

An area become highly susceptible to landslides when its natural - social factors are in favorable conditions for this hazard (such as geology, topography, geomorphology, petrology, lithology, meteorology, hydrology, land cover, traffic, human activities...). Therefore, assessing and analysing these

factors can help evaluating how susceptible a region is to landslides (Fell et al., 2008).

In most of the mountainous areas of Vietnam, and in Son La province in particular, spatial data sources, especially historical data on the landslide inventory, are often incomplete, or inconsistent in terms of projection grids, structure, properties, etc. Therefore, it is difficult to apply many advanced methods to study landslides.

The Spatial Multi-Criteria Evaluation (SMCE) is a quantitative evaluation method commonly used to evaluate the landslide susceptibility index (LSI). This method overcomes the limitations of the quantitative assessment methods (e.g. deterministic methods) which require a large amount of available and detailed inventory data set at national scale. Besides, the SMCE method can be deployed according to the semi-quantitative method. The difference between semi-quantitative and qualitative methods lies in the fact that the weighting is done under certain criteria. The advantage of the semi-quantitative method is evident when the time frame for the occurrence of identified landslides is not determinable and digital data is limited (Castellanos abella and Van westen, 2007).

To implement the semi-quantitative evaluation model, SMCE is often conducted as a module in ILWIS software, for example in the study of Castellanos Abella and Van Westen in Cuba (Castellanos abella and Van westen, 2007). However, it is not possible to use ILWIS to analyse high resolution maps in a short time. Therefore, the SMCE module has been integrated and used by the authors on ArcGIS software. This has made the analysis familiar, flexible and usable for large-scale, high-capacity maps with a shortened analysis time. Because the SMCE method was developed with a theoretical foundation from the Analytic Hierarchy Process (AHP) mothod developed by Saaty (Saaty t. l., 1977), the SMCE method has many similarities. However, the difference here is that SMCE uses semi-quantitative systematic tree analysis as described above. The advantage of this method has been published in the works of Koirala and Watkins (Koirala and Watkins, 1988), and Chowdhury and Flentje (Chowdhury and Flentje, 2003).

With the above advantages, in this study, the authors applied the SMCE Multi-Criteria Evaluation method, on the basis of applying expert knowledge, to perform landslide assessment and susceptibility zoning for the whole Son La province.

Research area and landslide triggering factors

Son La, a mountainous province in the North of Vietnam, has an area of 14,125 km^2. Son La lies between 20^{0}39' – 22^{0}02' N and 103^{0}11' – 105^{0}02' E (Figure 1). Landslides are causing economic losses to Son La province. In 2020, Son La province suffered damage due to natural disasters up to 219 billion (Lưu Thanh Bình., 2017). *Therefore, studying landslides to serve sustainable development is crucial*.

From the results of data collection, and on the basis of the completeness of the component maps, the authors selected 7 layers of maps of landslide triggering factors as the main input for the landslide susceptibility assessment and zoning using SMCE method. These layers include: slope, deep cleavage density, river density, water holding capacity, weathering crust, land cover, and lineament density. Simultaneously, the inventory map of landslide points identified from field trips is used to check the accuracy of the assessment and zoning results.

These map layers are shown in Figure 2, Figure 3 và Figure 4, as follows:

- The *landslide inventory map* was produced from landslide point data identified from field trips conducted by the State-Funded Landslide Project (SFLP): "Investigation, assessment and warning zonation for landslides in the mountainous regions of Vietnam" chaired by Vietnam Institute of Geosciences and Mineral Resources (VIGMR). In Son La province, 1694 locations of landslides and related geohazards have been identified from the field survey (Table 1 and Figure 2).

- Three map layers, including slope map, river density map, and deep cleavage density map were generated from the free SRTM 1

Arc-Second 30m DEM provided by NASA.

- The *slope map* of Son La province was generated from DEM with a resolution of 30mx30m based on using the SLOPE module available in ArcGIS 10.0 software. Based on the natural topography of the province, the slope map of Son La can be classified into 6 classes: 0-3 º, 3-8º, 8-15º, 15-25º, 25-45º, and > 45º (Figure 3a).

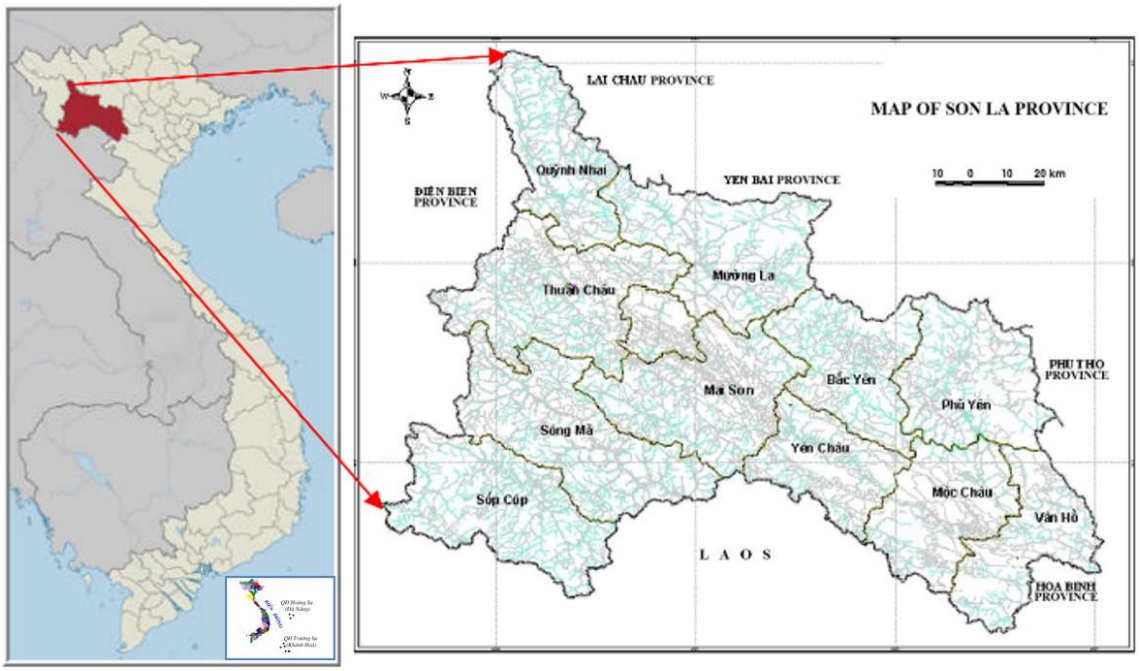


Figure 1: Map of the study area of Son La province.

Table 1. Distribution of landslides and related geohazards in districts of Yen Bai province.

District	Landslide points	Flash flood points	River bank erosion points
Bac Yen	210	9	7
Mai Son	177	5	4
Moc Chau	268	8	3
Muong la	96	3	2
Phu Yen	182	7	3
Quynh Nhai	74	6	2
Song Ma	260	7	9
Sop Cop	202	5	4
Son La City	27		
Thuan Chau	136	4	2
Yen Chau	62	6	5
Total	**1694**	**57**	**40**

- The *river density map* layer is extracted from the digital elevation model (DEM) at the scale of 1:10,000, calculated using the flow density method. Therefore, the river density map layer represents the density of rivers and streams per unit area (km/km^2), in which the higher the density value, the better the ability to conduct water along the tributaries on a

given area. Based on natural topography of the province, the river density map of Son La can be classified into four classes: 0-0.3 km/km^2, 0.3-0.6 km/km^2, 0.6-0.9 km/km^2, and > 0.9 km/km^2 (Figure 3c).

- The *deep cleavage density map* layer is extracted from the DEM at the scale of 1:10,000, representing the difference in terrain elevation per unit area (m/km^2). Therefore, the higher the value of the deep cleavage density is, the larger the terrain elevation difference in that area is. Based on natural topography of the province, the deep cleavage density map of Son La can be classified into five classes (m/km^2): 0-100 m/km^2, 100-200 m/km^2, 200-300 m/km^2; 300-400 m/km^2; and >400 m/km^2 (Figure 3d).

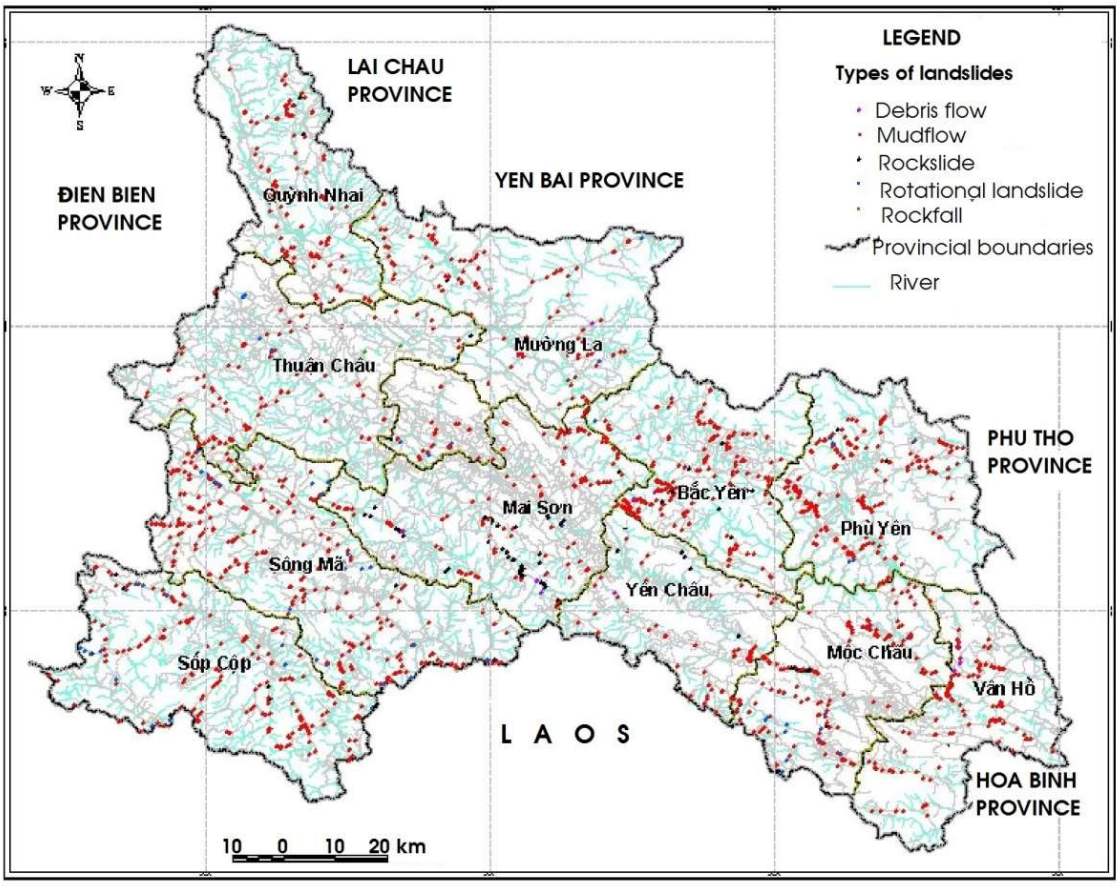


*Figure 2. **The inventory map of landslide points identified from field survey.***

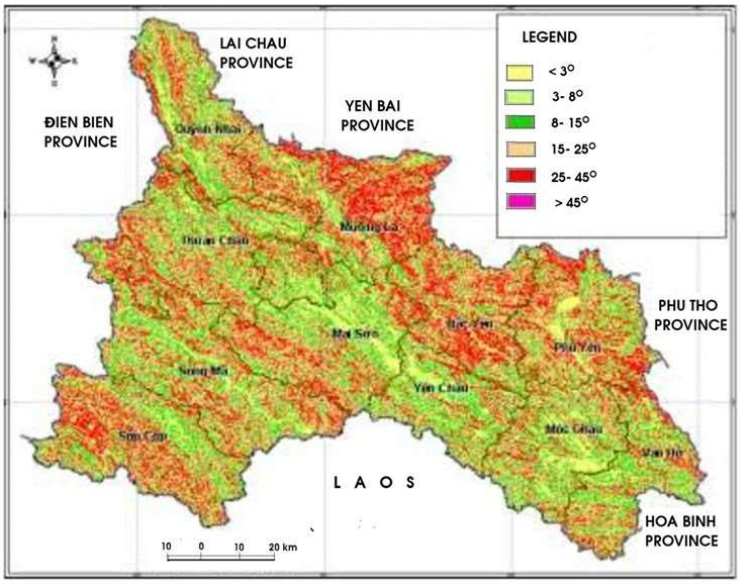
- The *crust of weathering map* is produced from data collection and field survey (Nguyễn Chí Thực (chủ biên) và nnk., 2014). From the geological map, geological formations are grouped into bedrock groups based on the principle that geological formations with similar weathering characteristics are classified into the same group. Then, based on the results of weathering crust classification and distribution rules of weathering crust types, the distribution areas of weathering crust types on the map are delineated according to the same principle. The results show that the weathering crust in Son La province can be classified into 14 classes as follows:: (1) Unconsolidated sediments; (2) No weathering crust; (3) Carbonate; (4) Sialite-Sialferite (SL-SAF); (5) Feroalite-Ferosialite (FA-FSA); (6) Sialite-Ferosialite (SL-FSA); (7) Sialferit-Sialit (SAF-SA); (8) Sialferite (SAF); (9) Ferosialite-Sialferite (FSA-SAF); (10) Ferosialite (FSA) (Figure 3b).

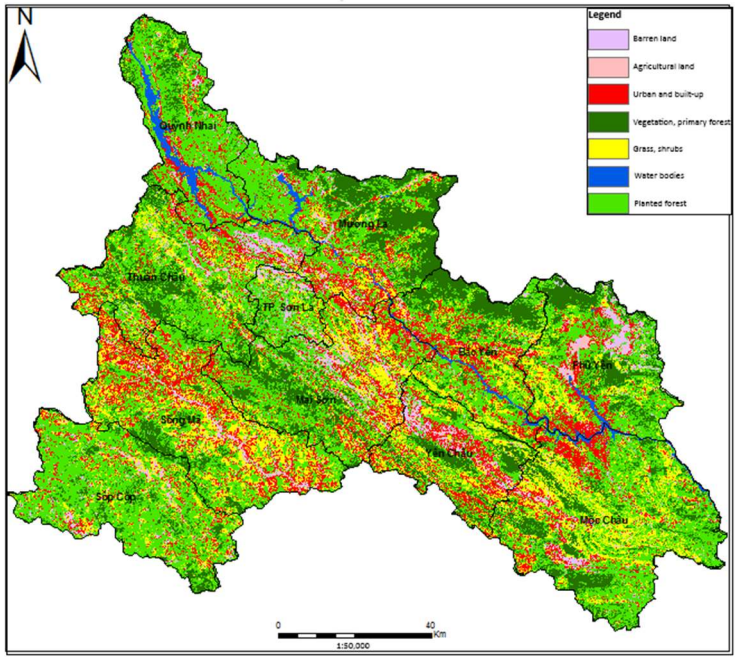
- The *soil water holding capacity map* layer is edited and normalized from the hydrogeological map (Nguyễn Quốc Khánh

(chủ biên) và nnk., 2014). The results show that the water holding capacity of aquifers in Son La province can be classified into 4 classes: very poor, poor layer, medium and rich (Figure 3e).

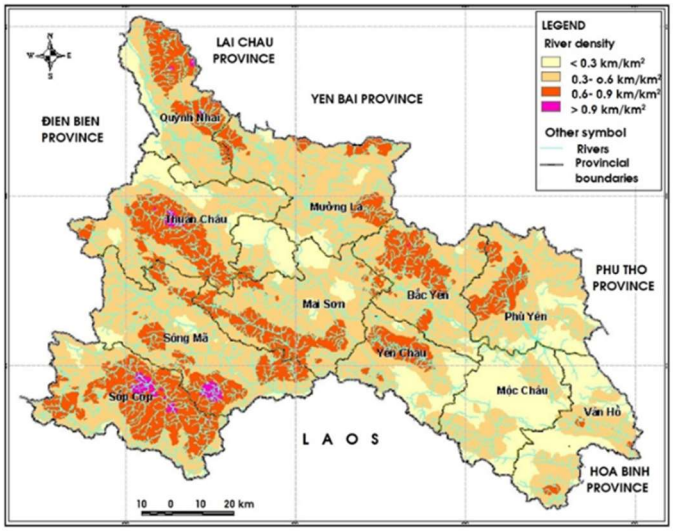
- The *lineament density map* layer is created based on the application of remote sensing technology, through analysising and processing Landsat 7 ETM+ satellite images. The results show that the lineament density in Son La province ranges from 0.028 to 4526.178 (m/km^2) (Figure 3f).

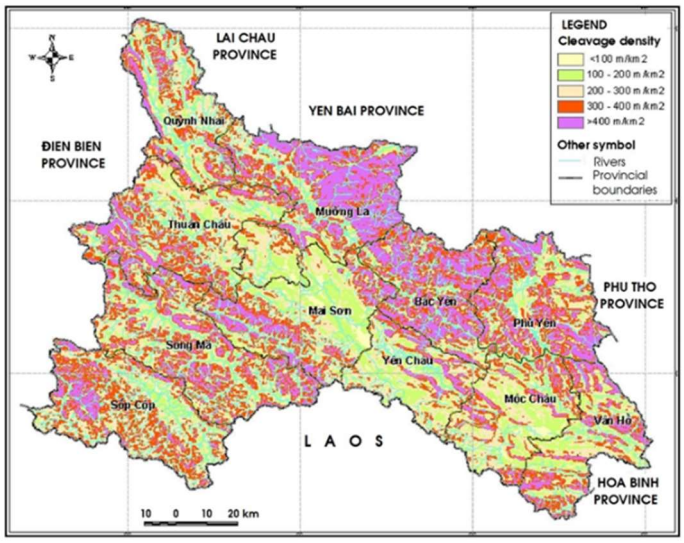
- The *land cover map* is the result of analysis and assessment of the types of land cover in Son La province in 2021. The land cover map was created using the application of remote sensing technology. Accordingly, the land cover of Son La province includes: barren land, agricultural land, urban and built-up, primary forest, grassland and shrubland, water bodies, and planted forest. In which, the barren land, urban and built-up, and grassland and shrubland are the classes with high landslide susceptibility (Figure 3g).





a) *b)*


LEGEND
River density
< 0.3 km/km²
0.3- o.6 km/km²
0.6- 0.9 km/km²
> 0.9 km/km²
Other symbol
Rivers
Provincial boundaries
LAI CHAU PROVINCE
YEN BAI PROVINCE
ĐIỆN BIÊN PROVINCE
Quỳnh Nhai
Thuận Châu
Mường La
Mai Sơn
Bắc Yên
Phù Yên
Sông Mã
Yên Châu
Sốp Cộp
Mộc Châu
Vân Hồ
PHU THO PROVINCE
HOA BINH PROVINCE
L A O S
10 0 10 20 km


LEGEND
Cleavage density
<100 m/km2
100 - 200 m/km2
200 - 300 m/km2
300 - 400 m/km2
>400 m/km2
Other symbol
Rivers
Provincial boundaries
LAI CHAU PROVINCE
YEN BAI PROVINCE
ĐIỆN BIÊN PROVINCE
Quỳnh Nhai
Thuận Châu
Mường La
Mai Sơn
Bắc Yên
Phù Yên
Sông Mã
Yên Châu
Sốp Cộp
Mộc Châu
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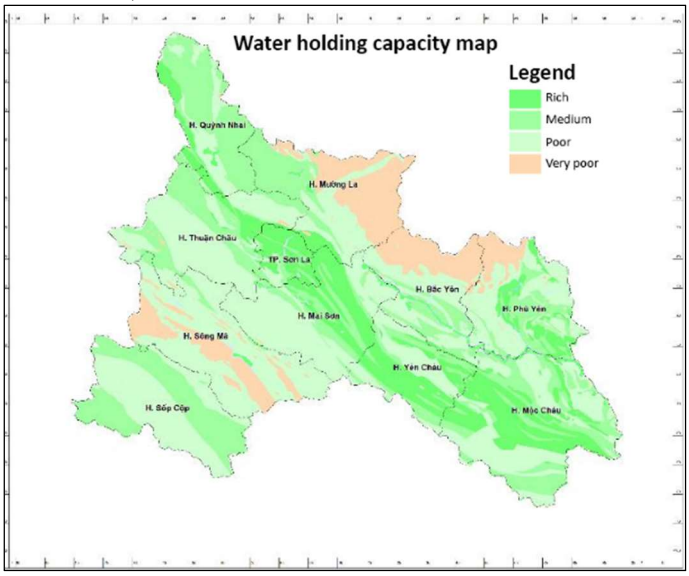
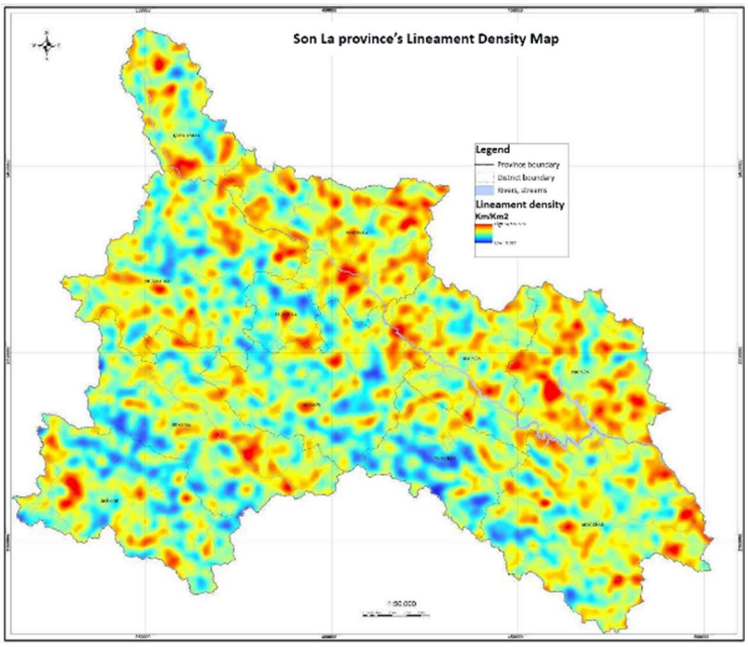
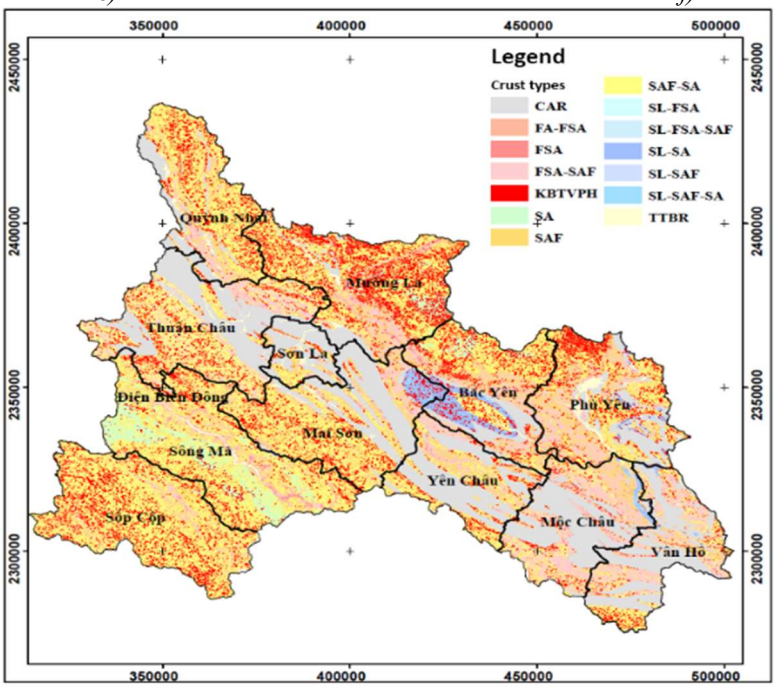
PHU THO PROVINCE
HOA BINH PROVINCE
L A O S
10 0 10 20 km

c) *d)*


Water holding capacity map
Legend
Rich
Medium
Poor
Very poor
H. Quỳnh Nhai
H. Mường La
H. Thuận Châu
TP. Sơn La
H. Bắc Yên
H. Phù Yên
H. Mai Sơn
H. Sông Mã
H. Yên Châu
H. Sốp Cộp
H. Mộc Châu



e) *f)*



g)

Figure 3. Factor map layers: a) Slope; b) Land cover; c) River density; d) Deep cleavage density; e) Water holding capacity; f) Lineament density; g) Weathering crust.

Methodology

Spatial Multi-Criteria Evaluation (SMCE)

The establishment of the landslide susceptibility map of Son La province at scale 1:50,000 was carried out according to the process shown in Figure 4, in which the expert-based Spatial Multi - Criteria Evaluation - SMCE method was used as the main research method.

The SMCE method was developed from the Analytic Hierarchy Process (AHP) method (Saaty t. l., 1977) combined with the

semi-quantitative method. The SMCE method can assist and guide the user to perform multi-criteria evaluation in a spatial model. The input data of the SMCE method is a set of maps, used as representative spatial criteria, grouped, normalized, and weighted in a "criteria tree".

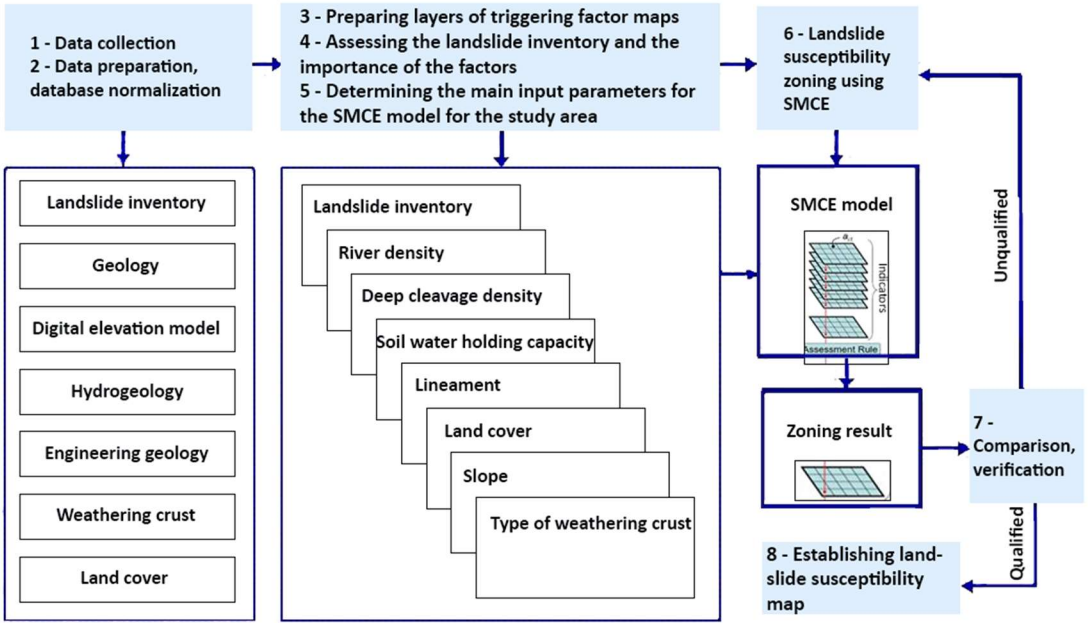
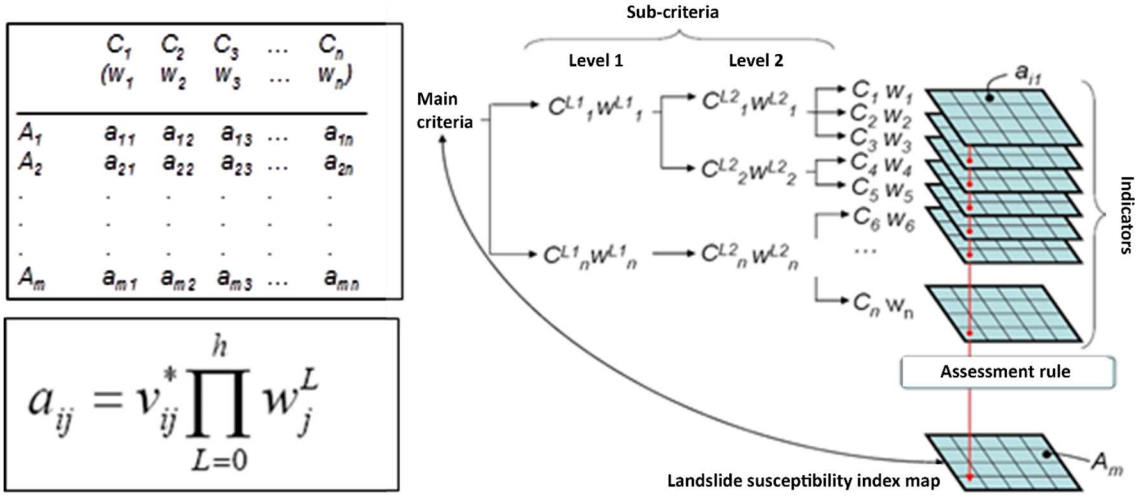


Figure 4. Flowchart of the establishment process of the landslide susceptibility map of Son La province at scale 1:50,000.



$$a_{ij} = v^{*}_{ij} \prod_{L=0}^{h} w_j^L$$

Figure 5. Simulation diagram of the mathematical basis of the spatial multi-criteria evaluation (SMCE) method, in which: C: criteria (or landslide triggering factors); W: weight; L: level; A: option; m: number of options; n: number of criteria; a_{ij}: selection of i^{th} option for j^{th} criterion (Castellanos abella and Van westen, 2007).

The output data is one or more "index map(s)" representing the results that have been simulated in the model (Castellanos abella and Van westen, 2007). The SMCE can be presented as a matrix as shown in the diagram in Figure 5, where:

- Matrix A consists of criteria (layers of landslide triggering factors) represented on an axis (C_1 to C_n) and a list of possible options (establishing a hierarchy, scoring, weighting, etc.). The decision is made from the set of criteria (the result of the matrix A) made on a different axis (A_1 to A_m).

- Each cell in the matrix (a_{ij}) represents a

particular selection for each particular criterion. The value of each cell in the matrix is the result of the multiplication between the value (normalized to values between 0 and 1) of each criterion for a particular choice, and the weight corresponding to each criterion (W_1 to W_n).

- Once the cells in the matrix have been filled (the criteria have been evaluated), the final value is equal to the sum of all the cell values of the different criteria for each particular choice (eg. A_1 is the sum of all cells from a_{11} to a_{1n}).

The SMCE method can be carried out in 12 steps as follows:

1. Identify the main goal(s) to be achieved *(e.g. landslide susceptibility mapping)*.
2. Define a system of main criteria and sub-criteria *(e.g. landslide triggering factors)*.
3. Determine the role and influence of each criterion *(e.g. ability to cause slope failure, etc.)*
4. Develop a criterion tree showing the hierarchy of the main - sub-criteria system in relation to the set goals.
5. Determine the result (selection) to be achieved after evaluating the criteria.
6. Determine the input map (classes) corresponding to each criterion *(e.g. the factor map layers for assessing and zoning landslide susceptibility)*.
7. Define weighting methods for each criterion *(e.g. pairwise comparisons, ranking; giving expected value of score for the criteria)*.
8. Weighting each criterion.
9. Create an index map *(e.g. landslide susceptibility index map)* from the results of multiplications between hierarchical levels.
10. Check the values in the index map.
11. Classification of the index map according to different index thresholds (e.g. corresponding to different susceptible classes).
12. Verify and validate the results to form the final map according to the set goals.

Results and discussion

Evaluation of the role of the factors and the degree of landslide susceptibility

The ability to cause slope failure in Son La province of 7 selected factors has been analyzed and evaluated on the basis of summarizing the evaluation opinions of 3 groups of experts: (1) field survey staff ; (2) professional research staff (geology, topography - geomorphology, hydrogeology - engineering geology, weathering crust and land cover); (3) zoning staff.

According to the evaluation results of the field survey team, landslides can occur on areas with low, medium and steep slopes. The landslides on low and medium slopes are mainly along traffic routes or near residential areas where the natural slope is low. Whereas, in areas with less human activities, natural landslides often occur on steep slopes. Besides, the survey team also observed that landslides often occur in areas with medium river density (0.86-3.18 km/km2) and medium deep cleavage density, on Sialferite-Sialite (SAF-SA), Sialferite (SAF), Feroalite-Ferosialite (FA-FSA) and Sialite-Ferosialite (SL-FSA) weathering crust types, in rocky areas with weak and medium shear strength.

According to the assessment results of the group of expert researchers, landslides often occur in areas with high slopes and high deep cleavage density, located in the distribution area of rocks belonging to the group of acidic - neutral eruption rocks and their tuff, metamorphic rock group with rich alumoslicate composition, intrusive rock group with acidic - neutral composition, or occurring on bedrock of shale, limestone shale - sericite, silty clay , sandstone, granite, are materials with weathering products that easily swell and become soggy when it rains, contributing to the increased landslide susceptibility in the area. Areas with high density of lineament are often distributed along faults and tectonic fault zones, which are places where landslides are likely to occur because these areas often have fracture zones with low consolidation. Areas with significant changes in land cover, or in residential areas,

bare land or grasslands, planted forest land are also highly susceptible to landslides because these are areas with highest human activities. In general, areas in the range of terrain elevation from 200-1,200 m are considered to be prone to landslides because this is the main distribution area of residential areas, constructions, traffic, and where the vegetation cover is significantly reduced due to anthropogenic activities.

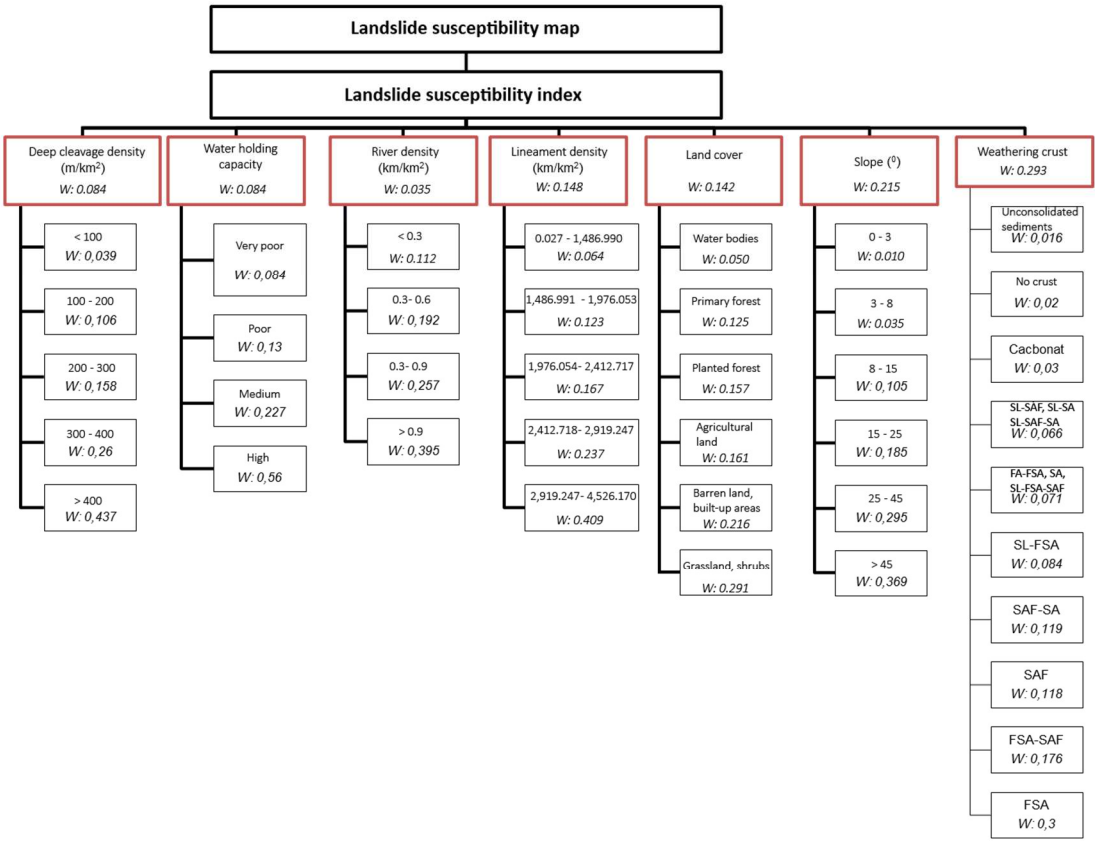


Figure 6. Criteria tree for criteria's weights (W), showing the influence on landslide occurrence of 7 factors and the classes each factor, to establish the landslide susceptibility map at scale 1:50,000 of Son La province.

According to the evaluation results of the group of zoning staff, the influence of 7 factors on landslides in the study area was synthesized from the evaluation opinions of the two groups of experts mentioned above. At the same time, combined with reference to related studies and actual observations from field surveys, the susceptibility of each factor was determined through the use of weights (abbreviated as W).

The evaluation of the influence of the input-factors for the SMCE model in Son La province, is summarized in the "criteria tree" shown in Figure 6. Here, the layers of factor maps are considered as the main "criteria", and the classes of each map layer are considered as "sub-criteria". The landslide susceptibility of each "criterion" is expressed by W. The W values are calculated according to the AHP hierarchical analysis method (Saaty t. l., 1977; Saaty t.l., 2000), on the basis of pairwise comparisons between the main "criteria" and between the "sub-criteria" within each main "criterion". The value of the weight W is limited in the range 0 to 1. The sum of the weighted values of all major "criteria" (factor map layers), or the sum of the weighted values of all "sub-criteria" in each of the main "criteria" (classes in each factor map), always equals 1.

Evaluating and zoning the landslide susceptibility in Son La province

By using SMCE module in ArcGIS 10.0 software to analyze and evaluate 7 layers of factor maps, an LSI map is established as shown in Figure 7. Then, based on the analysis natural distribution of sensitivity values of all pixels on the index map, 4 index thresholds have been determined to classify the index map into 5 different sensitivity classes (very low, low , medium, high and very high) as shown in

Table 2.

Table 2. Susceptibility index thresholds for the establishment of landslide susceptibility map in Son La province.

Landslide susceptibility index (LSI)	Landslide susceptibility
< 0.110	Very low
0.110 – 0.145	Low
0.145 – 0.162	Moderate
0.162 – 0.200	High
> 0.200	Very high

For validation, the susceptibility map is then crosschecked with the inventory map. The ratio of area of each class and the ratio of landslide points in each susceptible zone are shown in Table 3.

According to the comparison table (Table 3), the largest proportion of landslides identified from field survey (40.6%) is distributed in the zone with very high susceptibility (Table 3), although this zone only accounts for about 18% of the total area of the province. Notably, about 50% of the total area of the province is highly or very highly susceptible to landslides and 65% of the landslide points in the inventory map are located in these zones. In areas with very low and low susceptiblity, there are only nearly 25% of the landslide points identified from field survey.

The landslide inventory survey has shown that the restoration and re-determination of the historic landslides sites on natural slopes - in remote areas (in high to very high susceptible zones) is much more difficult than in low-altitude areas, with many artificial slopes, but convenient for surveying (belonging to very low and low susceptible zones). Therefore, the landslide inventory survey can make statistics of most of the landslide sites occurring in very low and low susceptible zones, but omit a lot of the landslide sites occurring in areas with high and very high susceptibility. Therefore, the distribution of susceptible zones are relatively close to the actual distribution of the landslide sites according to the survey results.

Landslide susceptibility map of Son La province

From the LSI map (Figure 7) and the thresholds (

Table 2), a landslide susceptibility map for Son La province was established as shown in Figure 8.

The zones with high and very high susceptibility are distributed with a very large area in the districts of Song Ma and Sop Cop. Particularly in Sop Cop district, although the natural area of the district is the second largest in the province (accounting for nearly 12% of the province's total area), the area of high and very high susceptible zones in this district account for nearly 16% of the total area of Son La province.

The districts with relatively large areas of high and very high susceptibility zones are Muong La (57% of the district), and Thuan Chau (51% of the district). The district with smallest area of high and very high susceptibility zones is Moc Chau district (27% of the district). This properly reflects the fact that most of the large-scale to particularly large-scale landslides mainly occur in areas with high

landslide susceptibility such as in Sop Cap and Song Ma districts. In urbanized areas such as Moc Chau district and Son La City, there are mainly small to medium-sized landslides, which are largely related to human activities.

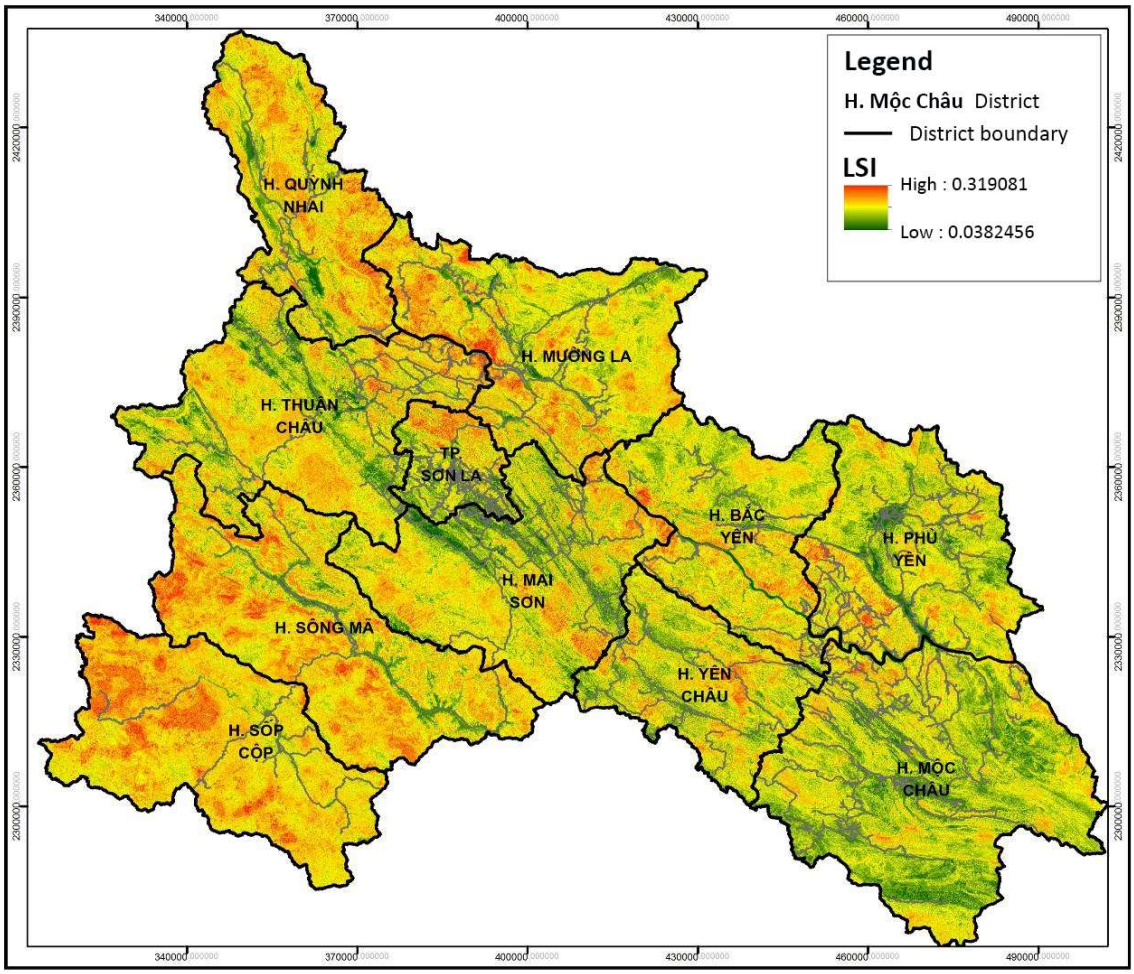


Figure 7. Landslide susceptibility index map of Son La province.

Table 3. Comparison of distribution of susceptible zones with the landslide inventory in Son La province.

Susceptible zones	Susceptibility area		Landslide points from inventory map	
	Area (km²)	*Ratio (%)*	*Number of points*	*Ratio (%)*
Very low	2477.20	17.54	169	11.89
Low	2520.22	18.84	227	12.37
Medium	2029.26	14.37	219	10.26
High	4518.54	31.99	410	24.88
Very high	2579.68	18.26	669	40.6
Total	14124.92	100	1694	100

The distribution of susceptible zones on the landslide susceptibility map is consistent with the distribution of natural landslide triggering factors in Son La province. The distribution area of areas with very high susceptibility increases gradually with the increase of the slope (common at slopes greater than 19°) and of the lineament density (commonly greater than 2919.247 m/km^2), and vice versa. This is completely consistent with the observed reality and the survey results of landslides inventory because in the hillsides with steep slopes, high fault density, soil and rock are more susceptible to weathering and become

weaker. The risk of landslides is even more serious when the areas with high lineament density are located in areas with strong weathering processes, as well as on steep slopes with low coverage of vegetation such as in Sop Cop district.

In addition, the areas with high to very high landslide susceptibility are widely distributed in areas with low to medium deep cleavage density and river density, on the hydrographic formations with very poor water holding capacity, and in areas with low vegetation coverage (such as shrubland, grassland, barren land), such as in Thuan Chau and Quynh Nhai districts. This shows that landslide occurrence does not depend much on: flow density, drainage capacity, deep cleavage density and water holding capacity of the geomorphological formation of the area. This result is consistent with the field survey results in Thuan Chau and Quynh Nhai districts. In areas where there are low river density and low deep cleavage density, the occurrence of landslides is still high due to other factors such as steep slopes, thick weathering crust, high lineament density, low vegetable coverage, etc.

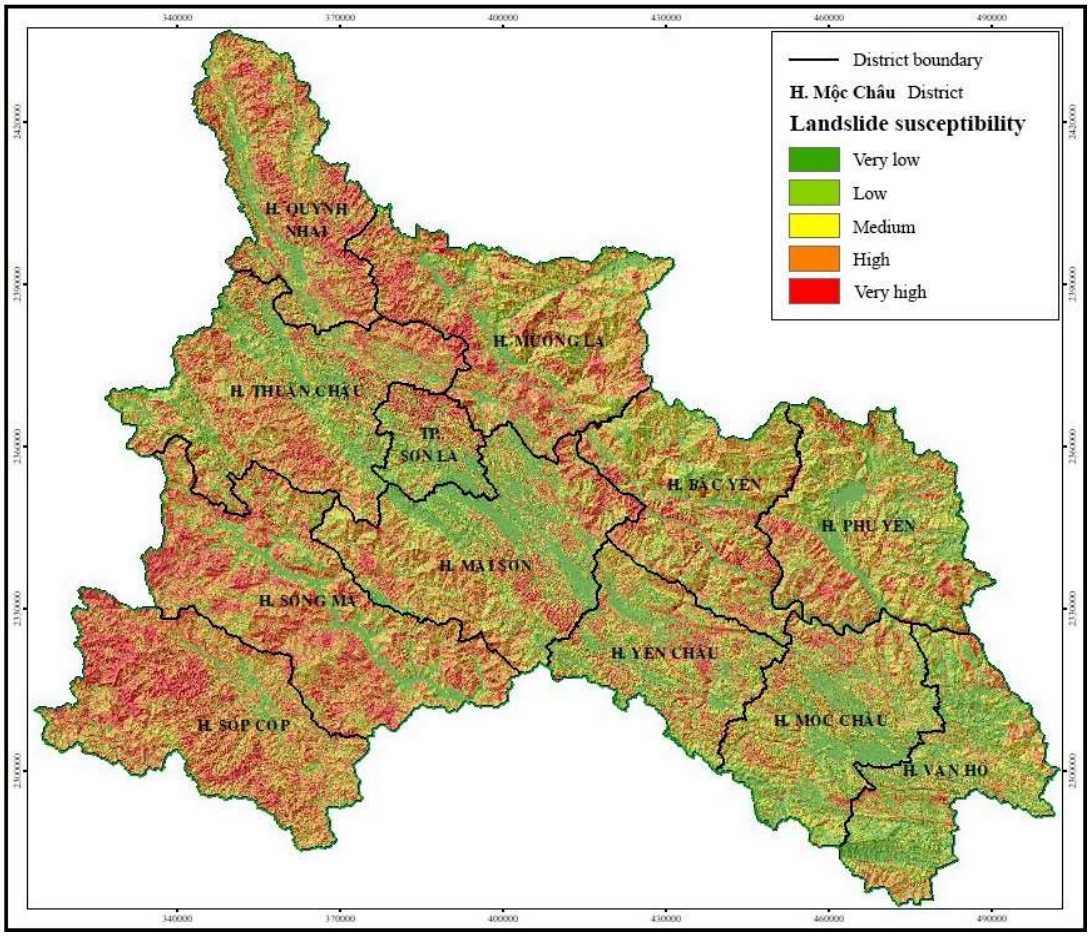


Figure 8. Landslide susceptibility map of Son La province.

Table 4. Distribution of susceptible zones in Son La province.

No.	District	Susceptible area (km^2)					Total area (km^2)
		Very low	*Low*	*Medium*	*High*	*Very high*	
1	Bac Yen	130.41	248.76	221.24	338.16	164.00	1,102.57
2	Mai Son	345.43	257.38	197.11	421.44	204.48	1,425.85
3	Moc Chau	604.75	546.64	338.86	414.79	140.50	2,045.53
4	Muong La	160.88	229.92	220.49	519.48	296.86	1,427.62
5	Quynh Nhai	145.83	148.57	116.46	388.55	256.68	1,056.09

No.	District	Susceptible area (km^2)					Total area (km^2)
		Very low	*Low*	*Medium*	*High*	*Very high*	
6	Song Ma	197.21	172.91	180.13	624.50	458.03	1,632.78
7	Sop Cop	101.79	95.63	145.61	657.80	472.57	1,473.40
8	Thuan Chau	263.35	291.94	195.24	510.86	274.22	1,535.60
9	Yen Chau	194.02	178.57	140.19	233.04	107.37	853.20
10	Phu Yen	226.04	285.89	229.80	343.73	149.20	1,234.66
11	Son La City	98.65	61.81	43.34	65.43	54.35	323.58
Total area (km^2)		**2,468.34**	**2,518.03**	**2,028.47**	**4,517.79**	**2,578.26**	**14,110.88**
Ratio of area (%)		**17.49**	**17.84**	**14.38**	**32.02**	**18.27**	**100**

Conclusion

The SMCE method can be simply integrated in ArcGIS software to process and analyze many map layers with large capacity, high pixel resolution. At the same time, SMCE is a quantitative assessment method, but can be implemented in a semi-quantitative way when combined with expert knowledge assessment, especially for research areas with limited quantity and quality of input data. Therefore, the SMCE method was selected to conduct the work of landslide susceptibility mapping at the scale of 1:50,000 for Son La province. Input data for the SMCE model in this study is 7 factor map layers representing 7 landslide triggering factors (river density, deep cleavage density, slope, hydrology, lineament density, land cover, water capacity) in the study area. Based on the analysis and evaluation of 3 groups of experts (field survey, expert researchers, and zoning staff), the landslide susceptibility of 7 factors are analyzed and evaluated using the SMCE module in ArcGIS to create the landslide susceptibility map.

The results show that the distribution area of 5 zoning levels namely very high, high, medium, low and very low are respectively 2578.26 km2, 4,517.79 km2, 2,028.47 km2, 2,518.03 km2, and 2,468.34 km2. In particular, Sop Cop and Song Ma are the districts with the highest distribution of areas with high and very high susceptibility, accounting respectively for nearly 16% and 15% of the areas with high and very high susceptibility in the whole province. Areas with high and very high landslide susceptibility are characterized by slopes (greater than 15o); lineament density from medium to high (greater than 2,919 m/km2); low to medium river density and deep cleavage density; areas with very poor water holding capacity; on weathering crust types SAF, SAF-SA, SAF and SAF-SA; and in areas with low vegetation coverage (e.g. shrublands, grasslands, barren land).

These results have shown consistency with landslide inventory in Son La province. It shows that the established susceptibility map is reliable, or in other words, the applied SMCE method is suitable for the study area. However, this method is still highly dependent on the experience and knowledge of experts. Therefore, by applying expert knowledge in evaluation and susceptibility mapping, the SMCE method can be applied in other mountainous areas in Vietnam, effectively serving the disaster management, control and mitigation of local authorities.

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