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Research Article

Proposed procedure of survey and model application for forecasting flow landslide susceptibility and hazards – A case study in Tam Chung commune, Thanh Hoa province

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Abstract: In this study, the main aim is to apply SMCE (Spatial Multi-Criteria Evaluation) and Flow-R models to predict flow landslide susceptibility and hazard in Tam Chung commune, Thanh Hoa province (Vietnam). For this, nine factor maps including slope, relief amplitude, elevation, drainage density, engineering geology, groundwater availability, land cover, lineament density, and weathering crust type were collected and prepared for generation of landslide susceptibility map using the weights generated from the SMCE model. Flow-R model was then used to forecast potential hazards related to the movement of flow landslide material. Landslde inventory collected from field survey was used to validate the landslide susceptibility and hazard maps. Results of this study showed that the susceptibility map, generated by applying the SMCE model, showed a high level of accuracy. By integrating detailed field surveys with the Flow-R model, the study identifies areas with low susceptibility to landslides but high vulnerability to material displacement. This study is helpful and supportive for better landslide hazard management in the study area, and facilitating informed decision-making in disaster prevention and mitigation.

Keywords: Flow landslide; Landslide susceptibility; Landslide hazard; SMCE model; Flow-R model.

1. Introduction

Landslides are prevalent natural disasters in mountainous regions, causing significant damage to human lives, infrastructure, properties, the environment, and socio-economic activities. According to United Nations statistics, since the beginning of the 21st century, landslide disasters have claimed the lives of over 50,000 people and caused property damage amounting to billions of dollars [1].

Landslides can occur in most mountainous and hilly regions, resulting from a combination of natural conditions such as geology, topography, and morphology, as well as human activities that alter the landscape, including the construction of buildings, roads, and mineral extraction. However, the occurrence of landslides is often associated with external triggers, with rainfall being the most common activating factor worldwide, including in Vietnam [2–4]. Moreover, a heavy rainfall event can trigger multiple landslide events simultaneously at different locations. With the influence of climate change, the frequency of intense rainfall events is projected to increase, leading to a higher occurrence rate and more severe intensity of landslide disasters [5–7].

Based on the characteristics of the movement, landslides can be classified into different types such as fall, topple, slide, lateral spread, and flow [8]. Among these types, predicting the potential hazards associated with flow landslides presents significant challenges due to their high velocity, unpredictability, large volume, and destructive potential. Flow landslides involve the movement of saturated or semi-fluid material down a slope and can be further classified into debris flows, mudflows, and earthflows, depending on the composition of the flowing material. The complex and dynamic behavior of flow landslides leads to rapid and nonlinear responses to triggering factors, resulting in unpredictable paths and magnitudes. Therefore, when implementing measures for prevention, mitigation, and settlement planning in areas prone to flow landslides, the identification of landslide susceptibility alone is insufficient. It is also crucial to forecast potential hazards in advance [9]. Landslide susceptibility refers to the relative probability of future landsliding, primarily determined by the inherent characteristics of a specific location, while landslide hazard represents the potential occurrence of landslides within a designated area, encompassing both source areas and runout zones [10].

Globally, as well as in Vietnam, landslide susceptibility maps are typically generated at small or medium scales with the objective of identifying areas that are prone to landslides for urban planning purposes and focused detailed investigations [11–15]. These maps are commonly constructed using various methods, such as statistical approaches (e.g., WoE - Weight of Evidence, FR- Frequency Ratio) or expert-based methods (e.g., AHP - Analytic Hierarchy Process, SMCE). Each method has its own advantages, and there is no universally recognized standard method due to the difficulty in comparing different methods with different datasets [16]. However, in situations where data are incomplete or insufficiently detailed, the use of expert opinions is often considered more effective [17].

To forecast potential hazards from flow landslides, numerial models such as LS-RAPID, DAN3D, and Debris 2D are commonly utilized [18–22]. These models have been found to provide high accuracy results but are typically suitable for small-scale applications, such as slopes or small catchments, due to their demanding data, time, and economic requirements. The Flow-R model, on the other hand, is an empirical GIS-based model that has been successfully applied in simulating flow landslide events in various locations worldwide [23–24]. It is one of the few models capable of forecasting flow landslide hazards on a broader scale (e.g., commune, district) without the need for detailed data such as soil analysis, geophysical measurements, etc.

The mountainous provinces of Vietnam are characterized by diverse geological features, steep topography, and high rainfall intensity, resulting in numerous landslide-prone areas. However, economic constraints limit the feasibility of conducting detailed surveys and applying complex material flow simulation models to all highly susceptible landslide zones. This is especially true in sparsely populated areas where warning about the potential impact of material flow is essential but employing complex models may exceed the budget allocated for relocating households. Therefore, in order to effectively support the work of warning and assessing the impact of material flow in the mountainous provinces of Vietnam, it is essential to develop a surveying process and apply appropriate models to provide forecasts of hazards in prioritized regions (residential areas and areas with frequent human activities).

This study introduces a procedure for predicting areas susceptible to and affected by flow landslides, applied, and tested in the Tam Chung commune - a mountainous region prone to flow landslides. The approach combines field surveys with the application of the SMCE and Flow-R models. Initially, susceptibility maps at a medium scale are generated using the SMCE model to identify susceptible areas of landslide occurrence. Subsequently, vulnerable areas deemed relevant to residential and human activities are further investigated in detail and analyzed using the Flow-R model to forecast the flow landslide hazards arising from flow landslide materials.

2. Methodological steps

The proposed procedure for investigating and forecasting high susceptibility areas and potential hazards by flow landslides is illustrated in Figure 1. The procedure involves the following primary steps:

- Data collection and compilation: Gathering and analyzing information on the current status of landslides, as well as relevant data and diagrams of factors influencing the landslide occurrence.

- Field investigation: Surveying locations where debris flow has occurred and constructing small- or medium-scale landslide inventory maps. Identifying common characteristics of past landslide events to determine the associated factors in the study area, to generate spatial factor maps (input for SMCE model) at a small- or medium-scale.

- Applying the SMCE model to construct the landslide susceptibility map (at small- or medium-scale).

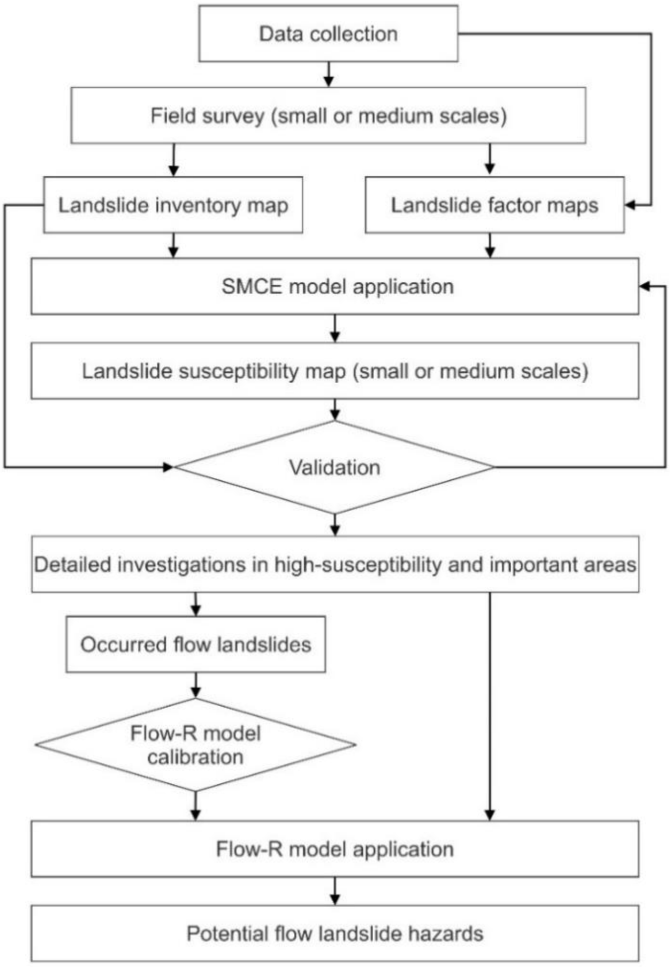

Figure 1. Process diagram of the combined application of field investigation and SMCE and Flow-R models to forecast flow landslide hazards.

To carry out the task of delineating landslide susceptibility areas, the authors propose the adoption of the Spatial Multi-Criteria Evaluation (SMCE) method [25]. The SMCE method is an extension of the AHP coupled with statistical methods. It facilitates multi-criteria analysis (multi-standard evaluation) within a spatial model [26]. This method overcomes the limitations of quantitative evaluation methods that require a large amount of available and detailed data, as well as a comprehensive inventory dataset of landslides.

In the SMCE model, factors contributing to landslide occurrence are represented as spatial maps and evaluated based on expert knowledge [27]. The input data for the method consist of a set of component maps that serve as representative spatial criteria classified into groups, standardized, and assigned weights. The component map layers are considered primary "criteria", and the attributes of each component map layer are secondary "criteria". The sensitivity to landslides of each "criteria" is expressed by weight values, denoted as W. The weight values of W are constrained within the range of 0 to 1, where the total weight value of all primary "criteria" (component map layers) or the total weight value of all secondary "criteria" within each primary "criteria" (attribute layers within each component map layer) equals 1. More detailed information regarding the SCME model can be found in reference [25].

The output data consists of a "composite index map" that represents the simulation results within the model, with areas classified into different landslide susceptibility index (LSI) groups [25].

- Verification and calibration of the susceptibility map with the landslide inventory map.

The susceptibility map derived from the SMCE method will be compared to the existing landslide inventory map in order to evaluate its accuracy. The application of the SMCE model needs to be performed and calibrated until the best verification results are obtained.

- Detailed investigations in high-susceptibility and important areas.

Based on the results of applying the SMCE model, detailed investigations are required for areas with high or very high landslide susceptibility. Depending on the available manpower, budget, and time constraints of each locality, the detailed investigation can be conducted in all high- susceptibility areas or prioritized in significant areas (e.g., densely populated areas, infrastructure, transportation). The objectives of this detailed investigation are: (1) to identify the locations where flow landslides have occurred and (2) to delineate the areas with high potential for future flow landslide occurrences.

- Application of the Flow-R model in the identified flow landslide locations for calibration and determination of model parameters.

The Flow-R model, an acronym for "Flow path assessment of gravitational hazards at a regional scale" [28], is built on the Matlab platform and primarily aims to simulate the flow propagation of materials in a 2D space based on empirical methods. The input data required for the Flow-R model predominantly comprise terrain-related maps, such as slope, curvature, and flow accumulation. The algorithms and parameters for flow direction, inertia, and friction loss used in the Flow-R model are determined through calibration with past flow landslide events within the same region or under similar conditions. More detailed information regarding the Flow-R model can be found in reference [28–29].

- Application of the Flow-R software (with calibrated parameters) to forecast the potential hazards associated with material flow in areas identified as susceptible to flow landslides.

3. Study area and data collection

Tam Chung commune is situated in Muong Lat district and is characterized as a highland area encompassing a natural land expanse of approximately 123.89 km^2. Geographically, it is bounded by coordinates ranging from 20^{o}29'54" to 20^{o}39'12" latitude North and from 104^{o}34'02" to 104^{o}41'58" longitude East. The administrative borders of Tam Chung commune are shared with Muong Ly commune to the east, Ten Tan commune to the west, Nhi Son commune and Muong Lat town to the south, and Tan Xuan commune (Moc Chau-Son La) and Hua Phan district (Laos) to the north. As of the statistical records until 2019, the commune is home to a total population of 4,070 individuals residing in 852 households, resulting in an average population density of approximately 13 people/km^2 [30].

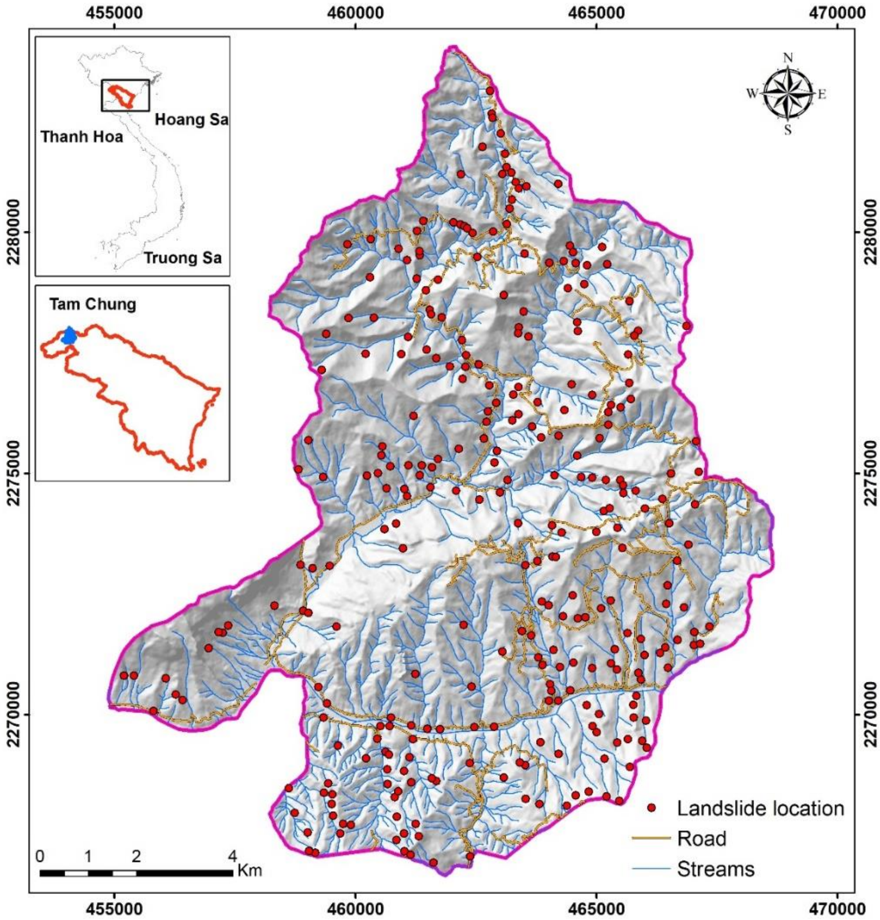

Figure 2. The location of Tam Chung commune and the landslide inventory.

The topography of Tam Chung commune is highly diverse and complex. It mainly consists of interconnected high mountains forming mountain ranges, which are divided by streams, creating distinct regions. The overall terrain has a basin-like shape sloping in three directions: northeast, northwest, and southeast. The average absolute elevation ranges from 650–700 m, with steep slopes averaging from 25^o to 35^o and some areas exceeding 35^o. The lowest point is located in the area near the mouth of the Ma river in the southeast of the commune, with an absolute elevation of approximately 135 m, while the highest point is in the mountainous region in the northwest of the commune, with an absolute elevation of approximately 1,574 m. The average annual rainfall in Tam Chung commune is 1,266 mm, with the highest recorded rainfall at 1,969 mm and the lowest recorded rainfall at 1,014 mm. However, the majority of rainfall is concentrated during the rainy season from April to October, with heavy rain events typically occurring in July and August.

Geohazards, particularly landslides, are observed in most of the villages within Tam Chung commune, with the highest occurrence in Suoi Long, on followed by Poong, Lat, Pom Khuong, Cha Lan, and Sai Khao. Flow landslides are a common type of landslide in the area, often occurring on naturally eroded slopes, predominantly in areas of reforestation and agricultural land.

Based on the data collected from the 2019 landslide field investigation conducted by the State-Funded Landslide Project (SFLP) "Investigation, Assessment, and Zoning of Landslide Hazard in the Mountainous Provinces of Vietnam" and the Google Earth satellite imagery interpretation results, the research team identified 296 landslide occurrences within the Tam Chung commune. The field surveys revealed that the highest concentration of landslide occurrences is observed in areas characterized by natural slope gradients ranging from 25.74° to 42.26°, elevations varying between 135 and 608.98 meters, cross-section cutting densities ranging from 1.93 to 4.16 km/km^2, and deep section cutting densities ranging from 144.88 to 442.15 m/km^2. Certain locations exhibited a pattern of recurrent landslides, particularly during periods of heavy rainfall, which have been documented in recent years. The corresponding landslide inventory is presented in Figure 2.

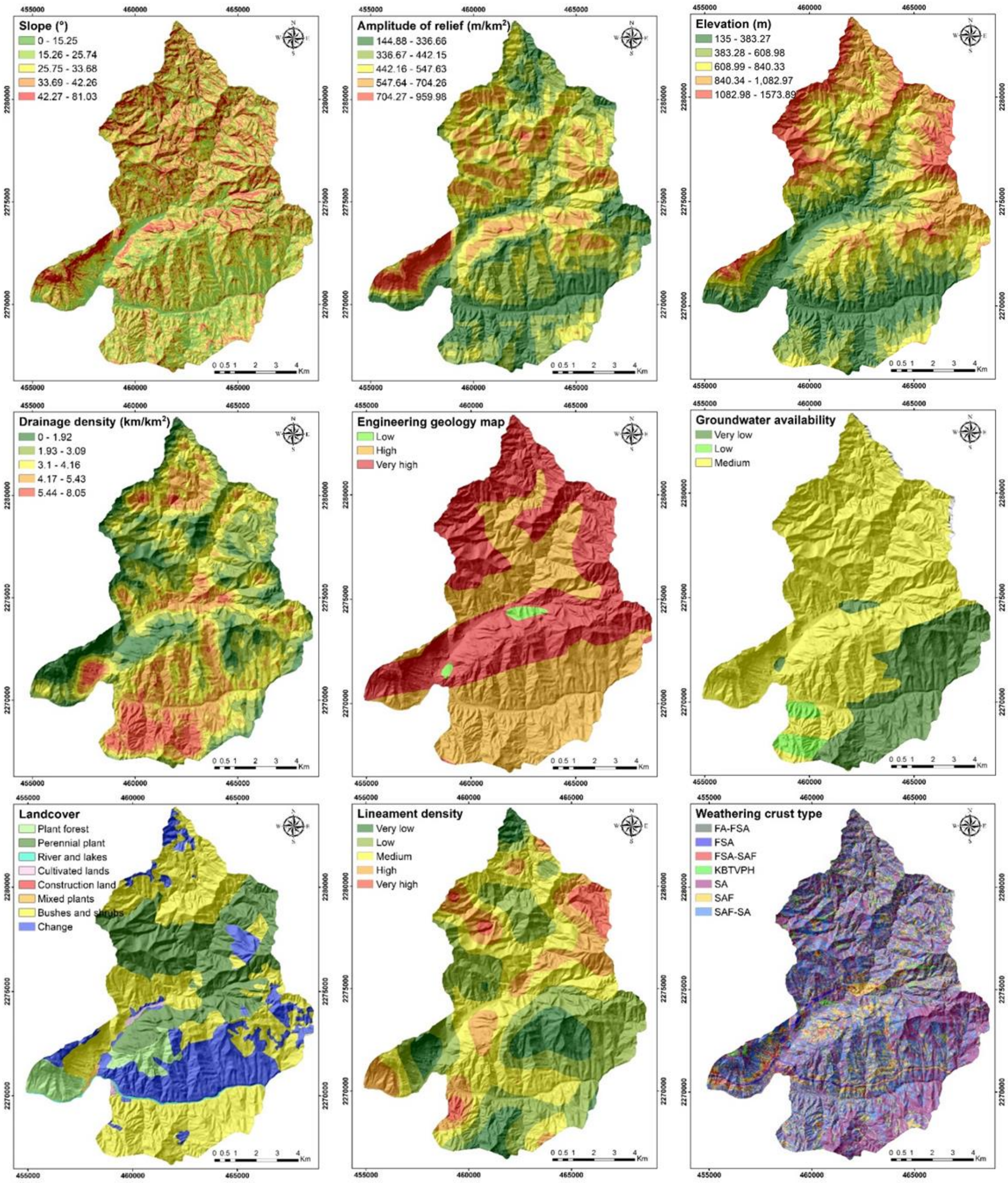

Figure 3. The landslide factor maps in Tam Chung commune.

The analysis and evaluation of the factors influencing landslide susceptibility in the Tam Chung commune, including the determination of their weights, were conducted by summarizing the assessment opinions of three groups: field survey personnel, landslide research experts, and model implementation personnel. Nine factors have been identified as crucial in the formation of landslides within the Tam Chung commune: slope, relief amplitude, elevation, drainage density, engineering geology, groundwater availability, land cover, lineament density, and weathering crust type. Therefore, these nine landslide factor maps have been selected as the primary input data for the SMCE model to assess and zoning landslide susceptibility areas. Therefore, mentioned maps were obtained from the SFLP project, utilizing scales of 1:10,000 and 1:50,000, and featuring a precise resolution of 20 meters (Figure 3).

The criteria weights (W) of each landslide factor map and their attributes are summarized in the “criteria tree” depicted in Figure 4.

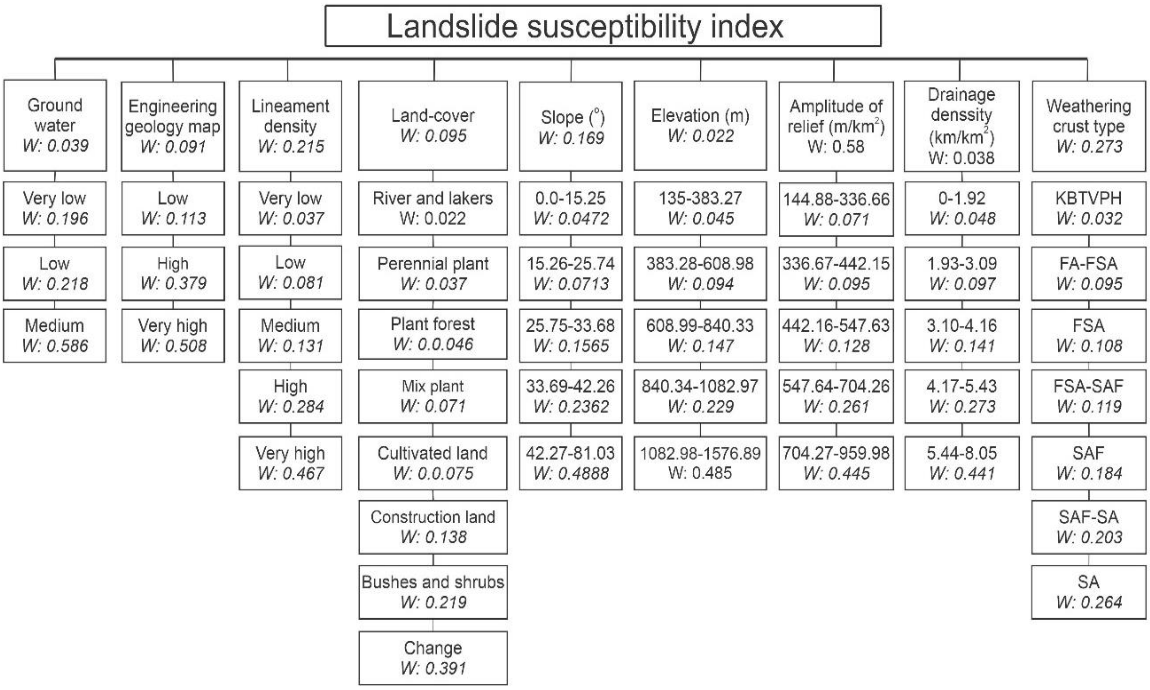

Figure 4. Criteria tree for criteria weight (W), showing the influence on landslide occurrence of nine factors.

4. Results and discussion

4.1. SMCE model application

By analyzing the natural distribution (Jenks natural breaks classification method [31]) of the Landslide Susceptibility Index (LSI) across all pixels on the susceptibility index map, four threshold values have been established. These thresholds are used to classify the area of the Tam Chung commune into five distinct zones, each representing different levels of susceptibility: very low, low, moderate, high, and very high (Table 1).

Table 1. LSI thresholds for generating landslide susceptibility map in Tam Chung commune.

Landslide susceptibility index (LSI)	Landslide susceptibility class
0–0.0872	Very Low
0.0873–0.1158	Low
0.1159–0.1432	Moderate
0.1433–0.1802	High
0.1803–0.2975	Very High

- The zone exhibiting a significantly high susceptibility to landslides covers an estimated area of 24.23 km^2, accounting for approximately 15% of the total natural area. This area of heightened susceptibility is primarily concentrated in the northwestern portion of Lat village, Tam Chong village, and the eastern region of Hin Phang village.

- The high susceptibility zone spans an area of approximately 30.22 km^2, accounting for approximately 29% of the total natural area. This zone is characterized by a scattered and interspersed distribution, often adjacent to areas exhibiting a very high susceptibility to landslides.

- The zone characterized by moderate susceptibility to landslides covers an area of approximately 44.74 km^2, representing approximately 36% of the total natural area. It is primarily concentrated in the eastern and southeastern regions of Tam Chung commune, while the remaining portion is scattered across areas with low-lying topography.

- The low susceptibility and very low susceptibility zones cover an approximate area of 24.54 km^2, comprising approximately 20% of the total natural area. These zones are primarily concentrated along the floodplains of the Lat stream, specifically in Pong Ngoai village.

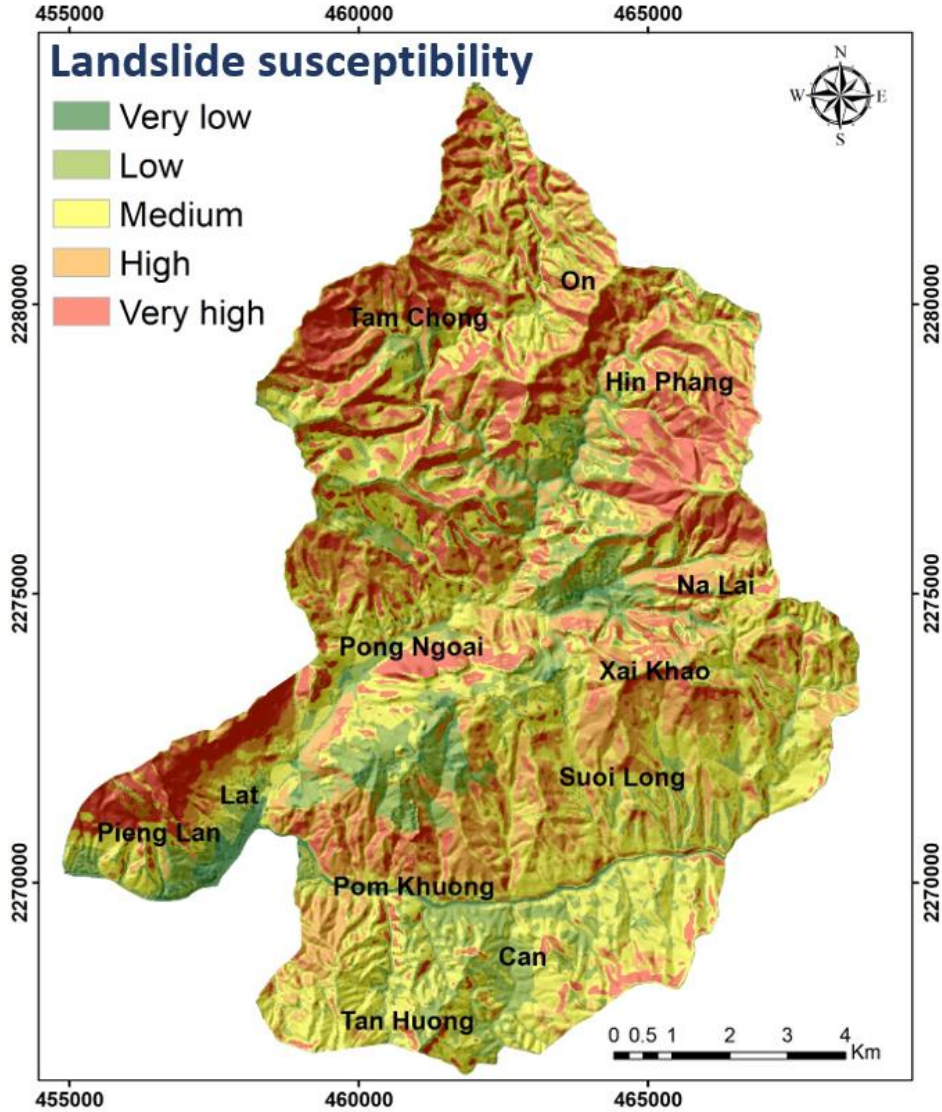

Figure 5. The landslide susceptibility map was constructed using the SMCE model.

The comparison between the landslide susceptibility zoning results obtained using the SMCE method and the findings from the field investigation (Table 2) reveals a high level of conformity and reliability. The majority of observed landslides occurred in areas identified as high and very high susceptibility zones (78%) and no landslide events were reported in locations designated as very low susceptibility.

Although the SMCE model heavily relies on expert opinions, it has successfully addressed the requirement for extensive data collection to identify high susceptibility landslide areas. However, a notable observation from comparing the landslide susceptibility map with the landslide inventory map is that a significant number of landslides (67 landslide locations or 22%) occurred in areas assessed as having moderate to low susceptibility. Upon further investigation, these landslides were predominantly small-scale events, occurring along roads and within residential areas. Two main factors could explain this issue: the terrain data used in this study was not updated to reflect rapid changes in reality (construction activities), and the resolution of the data (20 m) was not detailed enough to capture small-scale slopes.

Table 2. The results of the landslide susceptibility classification using the SMCE method were compared with the landslide inventory map.

Landslide susceptibility class	Predicted landslide susceptibility classes		Observed landslides	
	Area (km^2)	Percentage (%)	Number	Percentage (%)
Very Low	2.81	2%	0	0%
Low	21.73	18%	12	4%
Moderate	44.74	36%	55	18%
High	30.72	29%	84	29%
Very High	24.23	15%	145	49%

4.2. Flow-R model application

To calibrate the algorithms and parameters of Flow-R for suitability in the Tam Chung commune area, two locations that experienced flow landslide events in August 2018 were chosen for calibration. Location 1 corresponds to the Tam Chung Ethnic Secondary School in Lat village (as depicted in Figure 6), while Location 2 is situated in Suoi Long village (Figure 7). The flow landslide that occurred at Location 1 resulted in significant devastation to several structures within the school premises, leading to an estimated economic loss exceeding 6 billion VND. Initially, the landslide encompassed three distinct sliding masses, spanning a total area of approximately 6 hectares, and affecting an additional area of approximately 16 hectares. The debris involved in the flow consisted of a mixture of boulders, gravel, soil, sand, and water, which cascaded from the source areas towards the secondary school and the residential zone of Lat village, covering a distance of approximately 1.2 km.

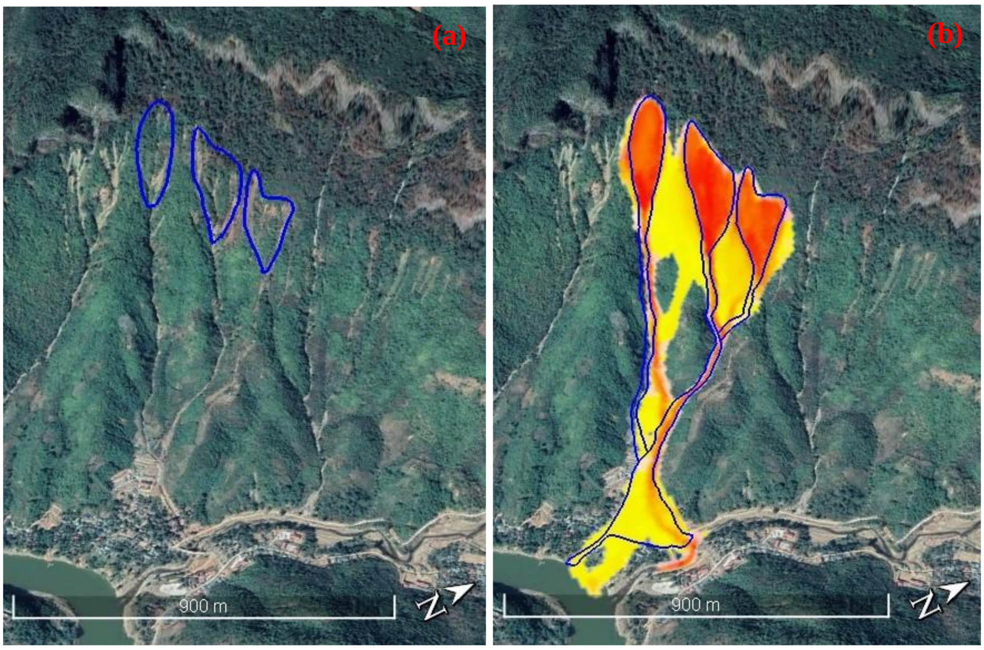

Figure 6. (a) The initial area (blue area); (b) The observed hazard (blue) and the simulation result (yellow to red) in location 1 by the Flow-R model.

Although the flow landslide at Location 2 did not cause damage to infrastructures, it severely affected agricultural land, rendering it unsuitable for cultivation. The initial area of the flow landslide 2 was estimated to be around 2.5 hectares, with a total impacted area of approximately 10 hectares. The materials involved in the flow, including boulders, gravel, soil, sand, and water, followed the stream course and crossed the National Highway 16, extending a distance of about 2 km.

The results of applying the Flow-R model to the two locations 1, 2 were compared with the actual field conditions and presented in Figure 6 and Figure 7. The blue areas represent the initial parts of landslides (determined based on field surveys and remote sensing analysis), while the yellow to red areas indicate the results from the Flow-R software, with increasing probabilities of being affected by landslide materials. Regarding flow direction and length, the implementation of the Flow-R model in the two calibrated areas exhibited a notable resemblance to the field observations. Furthermore, the accuracy of the predicted hazard areas was relatively high, with 93% and 79.5% of the actual hazard areas (in location 1 and location 2, respectively) overlapping with the simulated hazard areas.

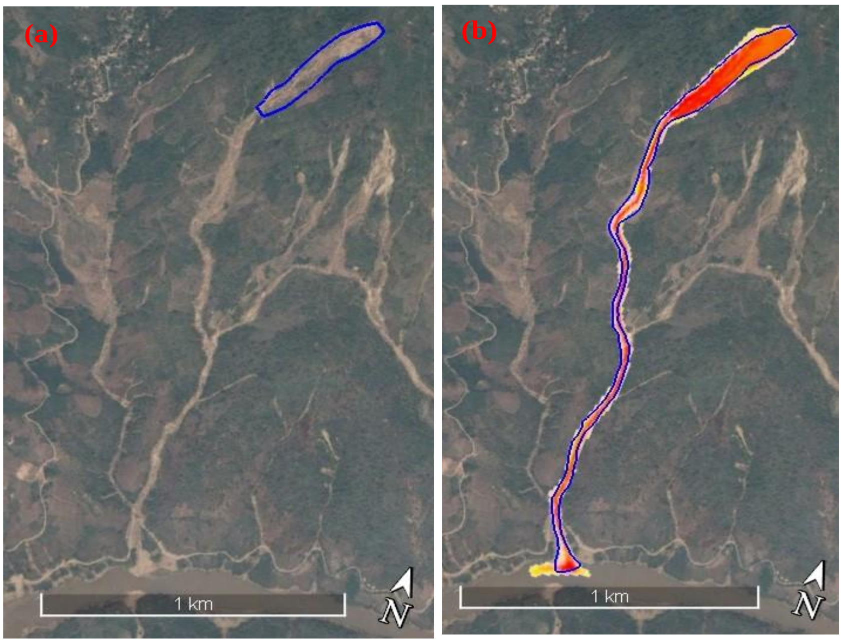

Figure 7. (a) The initial area (blue area); (b) The observed hazard (blue) and the simulation result (yellow to red) in location 2 by the Flow-R model.

Based on the results obtained from the SMCE model for landslide susceptibility zoning, focused investigations and surveys were conducted in areas exhibiting high susceptibility and posing potential risks to the population and public infrastructure. A total of 17 areas prone to flow landslides were identified, primarily concentrated in Suoi Long, Lat, Pieng Lan, and Pong Ngoai villages. Subsequently, these areas were subjected to the calibrated Flow–R model to predict the potential extent of material impact in the event of flow landslide occurrences. The results of applying the Flow–R model to these areas are presented in Fig. 8, where increasing probabilities of being affected by flowing material are represented by varying shades from yellow to red. The predicted material flows were found to potentially travel significant distances, ranging from 0.7 km to over 2 km, posing a significant threat to residential areas and potentially causing extensive damages.

The Flow-R model is employed for simulating the spatial extent of flow landslides and exhibits remarkable simulation capabilities. It stands out among global software programs by allowing material impact forecasting without the need for detailed geotechnical parameter determination, thereby eliminating the requirement for soil and rock sampling and analysis. The primary advantage of the Flow-R software lies in its suitability for large-scale areas, such as entire watersheds, with basic input data requirements. However, due to its reliance on basic input data, the Flow-R model can only provide preliminary predictions regarding the areas susceptible to material impact, without being able to forecast the velocity or thickness of the material.

The calibration results of the model reveal that certain discrepancies in the primary flow directions between the simulated and actual conditions can be attributed to the inaccuracies in representing the terrain in the digital elevation model (DEM) data. According to [23], the performance of the Flow-R model is highly dependent on the accuracy of the DEM. The use of a DEM with a resolution of approximately 10 m (or finer) yields the best results, whereas employing a DEM with a resolution of around 25 m significantly reduces accuracy. Due to data limitations in this study, the authors were unable to experiment with more detailed DEMs for comparison. However, it is recommended to apply the Flow-R model using a maximum DEM resolution of 20m.

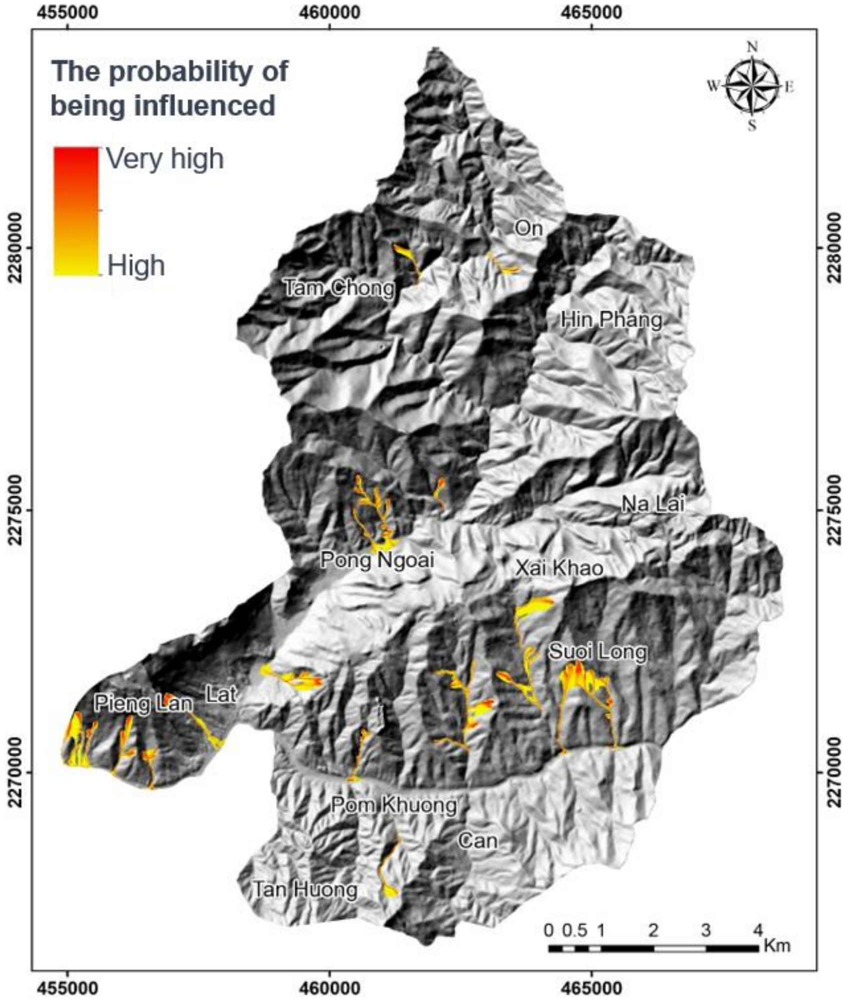

Figure 8. The potential hazards are identified through the application of the Flow-R model in Tam Chung commune.

Another limitation that may affect the simulation results of the Flow-R model is its inability to account for the presence of structures such as bridges, underground culverts, and buildings. The failure to represent the flow of materials beneath bridges or within underground culverts results in an overestimation of material flow in the surrounding areas compared to reality. Conversely, the absence of structures such as buildings leads to an underestimation or lack of prediction of material flow in the vicinity.

The results from applying the proposed procedure to Tam Chung commune clearly demonstrate the necessity of combining the SMCE and Flow-R models for forecasting flow landslide susceptibility and hazards. The application of the SMCE model has greatly assisted in identifying numerous landslide-prone areas, enabling focused detailed investigations. However, on-site surveys and the application of the Flow-R model have been limited to residential or inhabited areas, saving significant costs and time.

Residential areas tend to concentrate in flat areas, which are generally evaluated as having low or moderate landslide susceptibility. Consequently, residents and local authorities may become complacent and may not implement appropriate prevention measures. The results from the Flow-R model have highlighted the importance of simulating the flow of landslide materials to forecast potential hazard areas. With their extended reach and spread, the predicted flow materials from the 17 flow landslides have the potential to directly impact residential areas and transportation routes.

5. Conclusion

This study presents a comprehensive approach that integrates field surveys and the application of the SMCE and Flow-R models to forecast the potential extent of material impact during flow landslide occurrences. The use of the SMCE model at small to medium scales optimizes resource allocation by identifying priority areas for detailed investigations. This approach minimizes the time and cost associated with extensive field surveys and allows for targeted data collection in high-susceptibility areas. At larger scales, field surveys and the application of the Flow-R model are subsequently conducted to predict areas susceptible to material displacement.

The proposed procedure is successfully applied and validated in the Tam Chung commune, Muong Lat district, Thanh Hoa province, demonstrating its high reliability. Through field surveys and the application of the Flow-R model, several areas are identified with low landslide susceptibility but high susceptibility to material displacement. Thus, for geohazard events with prolonged impacts, such as flow landslides, the application of material flow simulation models is crucial for effective prevention and damage mitigation.

In areas already mapped with landslide susceptibility zoning, detailed investigations and the implementation of the Flow-R model can be conducted to delineate areas at risk of material displacement. For larger areas characterized by diverse geological conditions, the Flow-R model should be supplemented with additional geological maps. In areas of high significance, characterized by dense populations and critical infrastructure, the application of more precise models, such as detailed 3D models of the terrain, analysis of soil samples to determine geotechnical parameters, and geophysical surveys to estimate material thickness, should be considered.

Based on the forecasted displacement trends of sliding materials, local authorities should adopt a combination of structural and non-structural measures to minimize potential damage. Non–structural measures include raising awareness among the population, proactively evacuating residents in high-susceptibility areas during heavy rainfall and adjusting urban planning and infrastructure in the region. Proposed structural measures for densely populated areas include initiating landslide mass movements in a preemptive manner, constructing material barriers along the flow path of flow landslides, altering the direction of material flow, and reinforcing structures within the hazardous zone.

By integrating statistical analysis, expert knowledge, and model application, despite the existence of certain limitations in the results, this study contributes valuable insights into the assessment and zoning of landslide hazardss. The findings enhance the understanding and management of landslide hazards in the Tam Chung commune, facilitating informed decision–making for disaster prevention and mitigation efforts. These research findings will be integrated into a shared inter-sectoral database, serving the early warning system for geohazrds in the mountainous provinces of Vietnam in general, and specifically in Thanh Hoa province [32]. Furthermore, the presented results will serve as a scientific basis for the development of technical regulations and the management of geohazard investigative operations in Vietnam [33].

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Conflicts: The authors declare that this article was the work of the authors, has not been published elsewhere, has not been copied from previous research; there was no conflict of interest within the author group.

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