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Landslide susceptibility mapping by combining the analytical hierarchy process and weighted linear combination methods: a case study in the upper Lo River catchment (Vietnam)

Abstract The purpose of this study is to carry out a regional landslide susceptibility mapping for the upper Lo River catchment (ULRC) in northern Vietnam, where data on spatial distribution of historic landslides and environmental factors are very limited. Two methods, analytical hierarchy process (AHP) and weighted linear combination (WLC), were combined to create a landslide susceptibility map for the ULRC study area. In the first step, 216 existing landslides that occurred in the study area were mapped in field surveys in 2010 and 2011. A spatial database including six landslide factor maps related to elevation, slope gradient, drainage density, fault density, types of weathering crust, and types of land cover was constructed from various sources. To determine the relative importance of the six landslide factors and their classes within the landslide susceptibility analysis, weights of each factor and each factor class were defined by expert knowledge using the AHP method. To compute the landslide susceptibility, defined weights were assigned to all factor maps in raster format using the WLC method. The result is a landslide susceptibility index that is reclassified into four susceptible zones to produce a landslide susceptibility map. Finally, the landslide susceptibility zonation map was overlaid with the observed landslides in the inventory map to validate the produced map as well as the overall methodology. The results are in accordance with the occurrences of the observed landslides, in which 47.69 % of observed landslides are located in the two most susceptible zones (very-high-susceptibility zone and high-susceptibility zone) that cover 40.96 % of the total area. As the approach is able to integrate expert knowledge in the weighting of the input factors, the actual study shows that the combination of AHP and WLC methods is suitable for landslide susceptibility mapping in large mountainous areas at medium scales, particularly for areas lacking detailed input data.

Keywords Landslide susceptibility · Geographical information system · Analytical hierarchy process · Weighted linear combination

Introduction

Landslide susceptibility is defined as "the proneness of the terrain to produce slope failures" (Yalcin 2008). Landslide susceptibility mapping is the task of ranking areas in different degrees of landsliding potential by combining some critical factors (landslide factors) that contributed to the occurrences of inventoried landslides in the past (Chalkias et al. 2014). For land use planning and management, landslide susceptibility mapping can provide a basic tool for the decision-makers to make appropriate development plans (Gorsevski et al. 2006a; Feizizadeh et al. 2013). The process of landslide susceptibility mapping depends largely on the data availability, the scale of investigation, and the analysis methods (Fell et al. 2008). Landslide susceptibility mapping has been widely done for about 40 years (Nielsen et al. 1979; Brabb 1984; Varnes 1984; Wagner et al. 1988; Soeters and van Westen 1996), in which many researches have applied integrated approaches to analyze the spatial distribution of landslides and environmental factors as important indications of slope instability. Geographical information system (GIS) and remote sensing (RS) techniques are considered as advanced techniques to improve and update the quality and quantity of these factors. With the advanced technology development in the range of GIS and RS, more sophisticated and accurate spatial models have been increasingly used worldwide, especially for the landslide susceptibility mapping as reviewed by Gorsevski et al (2006a).

In Vietnam, mountainous regions have recently played an important role in national economic development; however, they are prone to a number of disastrous phenomena such as flash floods, landslides, and debris flows. Particularly, the frequency and magnitude of landslides in those regions have increased in the past 20 years, causing disastrous losses and damages to people, properties, economics, and the environment (Saro and Dan 2005; Bui et al. 2011; Duc 2013). Landslide susceptibility mapping is an urgent task for the government to find proper and effective strategies in land use planning and management for landslide-prone regions. Several studies on landslide susceptibility mapping have been conducted in other mountainous areas in Vietnam with consideration of the complex interactions among controlling factors (Saro and Dan 2005; Bui et al. 2012b). Some others applied modeling approaches, for example, frequency ratio, weight of evidence, probabilistic approach, and neural networks, to evaluate the susceptibility of landslides in relation to tectonic fracture, slope gradient, slope aspect, slope curvature, soil type, types of vegetation and land cover, etc. (Hung et al. 2005; Saro and Dan 2005; Long and De Smedt 2008; Bui et al. 2011, 2012a). However, those methods were mainly conducted in large regions (more than 1000 km^2) at medium scales (1:100,000 to 1:50,000), while they were only applied for critical areas at large scales (1:50,000 to 1:10,000), for example, in the surroundings of a hydroelectric plant of Da River in the northwest part of Vietnam (Khien et al. 2012).

Despite those recent achievements, landslide susceptibility mapping in Vietnam is still a challenge for scientists because the required data are unavailable or, if available, they are of poor quality, which is a common problem worldwide as remarked by Malczewski (2000), van Westen et al. (2006), and Fell et al. (2008). Even if the necessary data are available, they are often collected from various sources with different levels of uncertainty. Therefore, it is difficult to adequately conduct a regional landslide susceptibility mapping in Vietnam, and as a consequence, the resulting susceptibility maps reveal low accuracy and reliability.

Among several GIS-multicriteria decision analysis methods, the analytical hierarchy process (AHP) and weighted linear combination (WLC) have been considered the most simple approaches in regional landslide susceptibility mapping (Ayalew et al. 2004; Yoshimatsu and Abe 2006; Ladas et al. 2007; Akgun et al. 2008; Long and De Smedt 2008; Yalcin 2008; Wu and Chen 2009; Intarawichian and Dasananda 2010; Feizizadeh and Blaschke 2013; Feizizadeh et al. 2013; Tazik et al. 2014). These two methods are able to integrate expert knowledge in the weighting of the input factors. To solve the problem of mapping landslide susceptibility in a large area where data on spatial distribution of historic landslides and environmental factors are very limited, this study uses a combination of the AHP and WLC methods in the Vietnamese context. The case study refers to the upper Lo River catchment (ULRC) in northern Vietnam.

Study area

The ULRC is located in Ha Giang, one of the northern mountainous provinces in Vietnam (Fig. 1). This is a tectonically active area where landslides often occur as one of the most common natural hazards (Khien et al. 2012). The ULRC covers an area of approximately 4528 km^2 with strongly dissected and inclined terrain. It comprises high mountains in the north and the west, in which karst landscapes are the particular features of the north. The Lo River is the main channel system in these regions. It originates from the China territory and flows to the Vietnam territory with a northwest–southeast direction. The Lo River and its tributaries form a rather dense drainage network, with an average density of approximately 1 km/km^2; especially, it gets the highest density of about 6 km/km^2 in the southern part (Bac Quang District). Land cover in the ULRC varies according to the topography, weathering thickness of the substrate, and human activities, which have impact on the distribution of different types of forest and plantation. The ULRC is characterized by a tropical climate with four seasons: the winter period starts from November and ends in April, with an average temperature ranging from 10 to 20 °C, but highly different between day and night; the summer period starts from May and ends in October, with an average temperature of around 27 °C; and spring and autumn seasons are short with moderate temperatures. In the study area, rainfall is considered as the main trigger that has

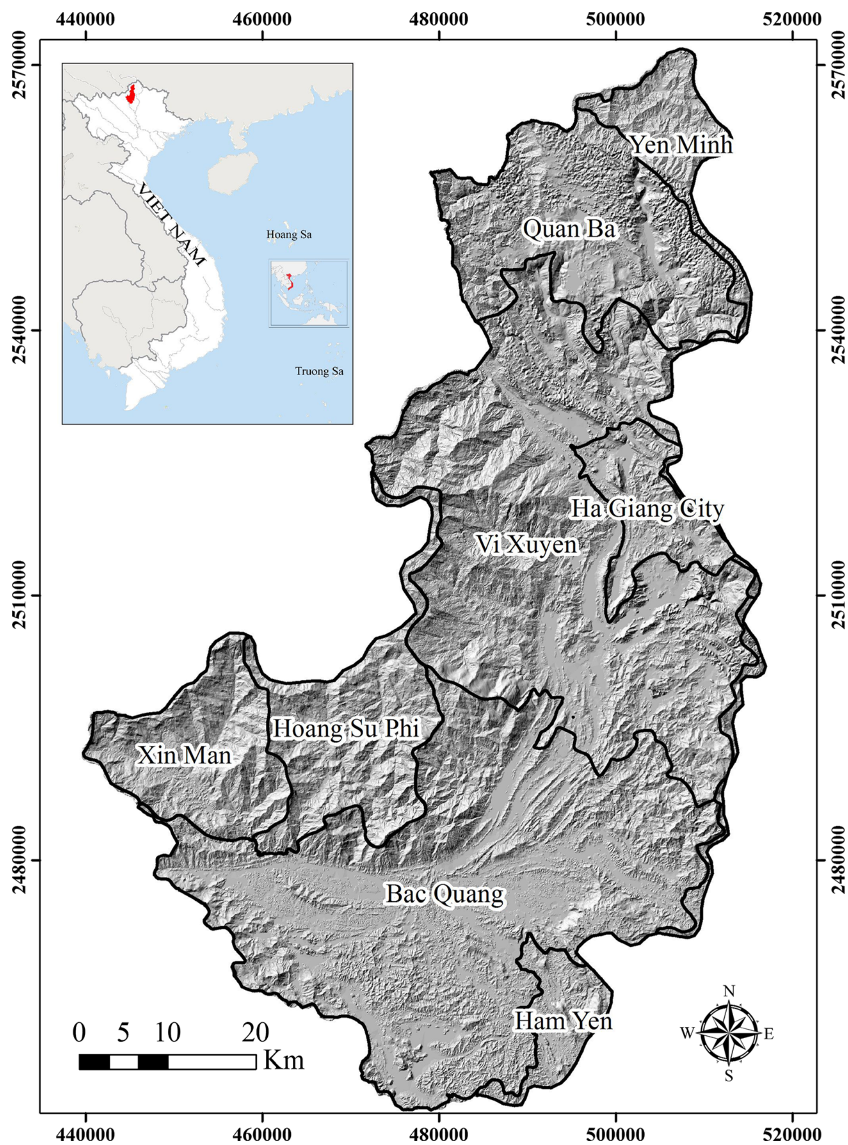


Fig. 1 Study area and shaded relief image showing the surface morphology. The *black line* indicates the boundaries of the administrative districts in the ULRC

caused a number of disastrous events including landslides (Khien et al. 2012). According to the 1976–2014 rainfall record database of the National Centre for Hydro-meteorological Forecasting of Vietnam, the ULRC has an average annual rainfall ranging from 2500 to 3200 mm/year, in which 90 % of the total rainfall occurs in the summer (from May to October every year). Locating in the central south part of the ULRC, Bac Quang District is one of the areas that have the highest rainfall in Vietnam. This district can get an annual rainfall up to 6000 mm in case of severe years.

In addition, as in many other mountainous areas in Vietnam, the ULRC is located in a tropical monsoon climate region, where weathering process has provided the most impacts on the rock mass of the slopes. When the weathering process takes place on natural slopes with steepness less than 20°, the weathering layers can be well conserved, therefore resulting in rather thick weathered layers. Under extreme weather conditions, such as rains with high density or long duration, landslides often occur on the natural slopes with highly weathered layers. The thicker the weathered layer is, the higher the volume of the landsliding mass will be. The field observations show that translational, rotational slides and rock fall are the most common types of landslides in the ULRC. The volumes/scales of landslides in this area are ranging from small to very large. Figure 2 shows some landslides that occurred in different places in which the soil and rock mass of slope surfaces were influenced by weathering process at different degrees.

Inside the ULRC, settlements are distributed with high densities in the lower terrain where rapid urbanization takes place in recent years (for example, Ha Giang City, Vi Xuyen Town), whereas they are sparsely distributed in the high terrain where ethnic minorities are the main inhabitants. In general, local people prefer to live along the Lo River and its tributaries in order to facilitate their daily lives. Along the river network, the development of transportation routes is of increasing importance.

In Vietnam, the ULRC is one of the mountainous regions that are threatened by many types of geohazards such as landslides, flash floods, debris flows, and river bank erosion that often occur during rainy seasons, in particular shallow landslides with high frequency. According to the Disaster Management Office of Ha Giang province, tens of shallow landslides were reported every year that caused deaths and injuries to people and damages and losses to properties and the environment throughout the whole catchment. Landslide phenomena are in many cases related to human activities, particularly to urban development and road constructions causing slope disturbance.

A regional landslide susceptibility mapping is required in order to support land use planning and management by improving knowledge on landslide evolution through scientific investigations. However, the reports on historic landslides were not systematically kept up-to-date in any form of disaster database. Scientists can only get disaster-related information through public media or annual reports of the local authorities, which contain mainly statistic summation of losses and damages rather than detailed observations that limits very much the availability and quality of historic landslide data as well as geodata on controlling and triggering factors in the study area. Therefore, it is not possible to apply statistical or deterministic methods to carry out an adequate landslide susceptibility mapping for the whole ULRC.

Methodology

In this study, the two methods, AHP and WLC, were combined in a GIS environment for regional landslide susceptibility mapping in the ULRC. The AHP was applied to define the relative importance of the landslide factors and their classes in landslide susceptibility

Fig. 2 a–d Common types of landslides were often observed in the ULRC (photos taken from the field in 2011)

a *Landslides occurred from moderately weathered materials of natural slopes in Vi Xuyen district, where is distributed with Siaferite-Sialite crust*

b *Landslides occurred from highy weathered materials of natural slopes in Yen Minh district, where is distributed with Siaferite*

c *Landslide occurred from completely weathered materials of a cut-slope in Quan Ba district, where is distributed with Ferosialite crust*

d *Landslides occurred from slightly weathered materials on cut-slopes in Vi Xuyen district, where is distributed with carbonate rock* by computing weights for each factor and each factor class. The WLC method was applied to assign on the one hand relative importance to the factor maps and to produce on the other hand raster datasets of similar resolution and format for subsequent overlay. A brief overview of these methods and detailed elaboration of the approach are described in the following sections.

General overview of the AHP and WLC methods

The AHP was introduced by Thomas Saaty (1980). The AHP is based on three principles: decomposition, comparative judgment, and synthesis of priorities (Malczewski 1999). The AHP is widely applied in many areas because of its simplicity and robustness in obtaining weights and integrating heterogeneous data (Gorsevski et al. 2006b). It is one of the multi-attribute techniques that can incorporate expert judgment into the GIS-based landslide susceptibility analysis to compute weights for different criteria (Intarawichian and Dasananda 2010; Feizizadeh and Blaschke 2013; Feizizadeh et al. 2013). It allows the active participation of decision-makers from disaster risk management and from other disciplines, which require disaster control and mitigation measures. It also provides a rational basis on which to allow evidence-based decisions (Feizizadeh et al. 2013). In landslide susceptibility mapping, AHP is applied to weight and rank the influence (the relative importance) of each landslide factor and its classes based on the occurrences of landslides in the study area. Therefore, this method has been used as the decision analysis technique for the evaluation of the relative importance to landslide activities in many areas in the world (Ladas et al. 2007) as well as in Vietnam (Long and De Smedt 2012). The following steps as adapted by Rajput and Shukla (2014) are involved in the AHP method:

(1) Decomposition of the complex problem into smaller ones.
(2) Construction of a decision matrix and determination of the priority score using a 9-point scale for pairwise comparisons as described in Table 1.
(3) Execution of the comparative judgment with the element in Table 1.
(4) Normalization of the comparison matrix by dividing each column by the sum of the entries of that column.
(5) Calculation of the eigenvector value of n normalized matrix to obtain the relative weight of the criteria. To calculate weights for each compared factor using the AHP approach, the comparison matrix means the weight matrix. Therefore, eigenvector values indicate weighted values of comparison factors.
(6) Checking the consistency of the comparison using the consistency index (CI), random index (RI), and consistency ratio (CR) as explained in Tables 2 and 3, in which the CR must be lower than 0.1 to accept the computed weights; otherwise, the pair comparison needs to be recalculated.
(7) Using the resulting evaluation scores to order the decision alternatives from the most to the least desirable.

The great advantage of this approach is that it rearranges the complexity of a dataset by the hierarchy with a pairwise comparison between two landslide factors or between two classes within one landslide factor. This comparison allows reducing subjectiveness in weighting and thus creates coherence in processing different data. Another advantage of the AHP is that it allows validating pair consistency. From eigenvector values, one consistency value is determined, which is used to recognize the inconsistency or dependency between two factors. The transitive of factors in the AHP is understood as, for example, if factor A is more preferred than factor B, and factor B is more preferred than factor C, then factor A should be more preferred than factor C. From that, the CI, RI, and CR are calculated in order to validate the consistency of the comparison (Saaty 2000). All these indices and ratios are arranged in a range from 0 to 1. The CR is a ratio between the matrix's consistency index and random index. The random index is the

Table 1 Adopted scale of absolute numbers for pairwise comparison (Saaty 2008)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to objectives
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor 1 activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor 1 activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is very strongly favored over another; its dominance is demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring 1 activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has 1 of the above non-0 numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

Table 2 List of equations adopted in this study

Equation number	Equation expression	Explanation of parameters
Equation 1	$CI = \frac{(\lambda_{max} - n)}{n-1}$	CI, consistency index n, number of elements to be compared λ_{max}, maximum eigenvector
Equation 2	$CR = \frac{CI}{RI}$	CR, consistency ratio that should be lower than 0.1; otherwise, the pair comparison needs to be recalculated RI, random index (Table 3)
Equation 3	$LSI = \sum_{j}^{n} W_j w_{ij}$	LSI, landslide susceptibility index W_j, weight of landslide factor j w_{ij}, weight of class i in landslide factor j n, number of landslide factors

average consistency index obtained by generating large numbers of random matrices (i.e., 500 matrices, as in the publication of Saaty (2000)). If CR is less than 0.1, the consistency of the model is acceptable; if it is greater than 0.1, the pairwise comparison needs to be recalculated.

However, the disadvantage of the AHP, as remarked by Gorsevski et al. (2006b), is that it does not adequately solve the ambiguity and imprecision associated with the conversion from qualitative categorical data into ordinal variables used in the comparison matrix. The AHP also shows some uncertainties in the selection of priorities, measurement scale, and ranking. For example, the measurement scale is still not agreed among scientists: although Saaty (1977) originally proposed a scale with measures from one to nine (1–9), other scientists such as Dodd and Donegan (1995) have criticized the absence of a zero in the scale. In the selection of priorities, in general, AHP pairwise comparison provides an ability to rank all parameters in order; however, if there is a small difference in weight value between two parameters, it is not able to decide which one is preferable to another (Banuelas and Antony 2004). More details about uncertainties in the measurement scale of the AHP are discussed in the publication of Jiří Franek and Aleš Kresta (2014).

Despite those disadvantages, the AHP method has been widely used for practical applications, particularly in combination with other methods to take into account expert assessment. The combined methods often involve expert judgments to improve inconsistencies in susceptibility mapping in the areas that have non-systematic input data, as remarked by Banuelas and Antony (2004). Experts from different disciplines related to landslide research are grouped to judge and break down the robust landslide factors to hierarchy; then, supplemented by observations in the field, the analyses of each expert are grouped and taken into account for the factor comparison of the AHP.

The WLC was first introduced by Voogd (1983). This aggregation method is one of the most often used decision models in GIS to derive composite maps for landslide susceptibility assessment and mapping (Malczewski 2000; Ayalew et al. 2004). After the relative weights are generated by other methods such as AHP, the weights are aggregated by the WLC to form a single score of evaluation (Gorsevski et al. 2006b). This method can be taken as a hybrid between qualitative and quantitative methods. In the spatial database prepared for the study, each thematic map, which represents a landslide factor, comprises a number of classes according to different homogeneous areas distributed in the territory. Using the WLC method, the classes of the landslide factors are standardized to a common numeric range and then combined by means of a weighting (Ladas et al. 2007). After the relative weights are generated by other methods such as the AHP, the weights are aggregated by the WLC to form a single score of evaluation (Gorsevski et al. 2006b). Each criterion is multiplied by its weight from the pairwise comparison, and the results are summed to form the final score, as expressed by Equation 3 in Table 2. There are six steps involved in the WLC procedure (Malczewski 2000) including:

(1) Defining the set of landslide factors, which depend largely on the availability of georeferenced data in digital form.
(2) Defining the set of factor classes (feasible alternatives), into which each landslide factor is classified.
(3) Generating landslide factors and their classes as thematic maps in GIS.
(4) Assigning weights to thematic maps, in which weights are generated by the AHP method.
(5) Combining maps and weights to produce a new combined map using Equation 3 in Table 2.
(6) Classifying the values (combined weights) of the new combined map into landslide susceptibility categories (the alternatives) to establish a landslide susceptibility zonation map. The assessment of priorities on score ranking can express the degree of landslide susceptibility adequately. A ranking scale is used with the following principle: one end of the scale is labeled with an expression and the other end of the scale is labeled with an opposite expression. Below is an example of the ranking scale:

The workflow for landslide susceptibility mapping of ULRC

The procedure of applying the combination of the two methods, AHP and WLC, for landslide susceptibility mapping in the ULRC is shown in Fig. 3. In the beginning, the 216 historic landslide locations were inventoried and mapped by field surveys in 2010 and 2011. This landslide inventory map was used in the final stage to validate the reliability of the result map. A spatial database was constructed in a GIS environment that includes six landslide factor maps related to elevation, slope gradient, drainage density, fault density, types of weathering crust, and types of land cover. Those factors were compiled from various sources according to the available data for the study area. Later, the AHP method was used

Table 3 Random indices (RI) for a matrix of n elements (Saaty 1977)

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

to define weights for the landslide factors and for the classes of each factor. The weights were assessed according to expert knowledge and studies from the field surveys. Then, the WLC method is used to compute weighted factor maps to assess the landslide susceptibility using a landslide susceptibility index (LSI). The LSI is calculated by summation of the weighted value of each factor multiplied by the weighted value of each factor class, as expressed by Equation 3 in Table 2. In this equation, the values of W_j and w_{ij} are determined based on pairwise comparison and calculation of eigenvectors by applying the AHP approach, in which W_j is the eigenvector value of the matrix describing the landslide causal factor relations, while w_{ij} is the eigenvector value of the matrix describing the relationship of classes of one landslide factor. The LSI values characterize the comparative susceptibility for landslide occurrence; hence, if the index is higher, the area will be more prone to landslides. When the LSI map is produced by the WLC method, it is then reclassified to produce a landslide susceptibility zonation map as a result of the landslide susceptibility mapping process. Finally, a sensitivity analysis was performed to validate the produced map as well as the overall study methodology by overlaying the landslide susceptibility zonation map with the landslide inventory map.

Input data and factor mapping

In this study, a spatial database was constructed in a GIS environment (e.g., ArcGIS 9.2) that includes a landslide inventory map and six landslide factor maps. Details of the landslide inventory and landslide factor mapping are described in the following sections.

Landslide inventory mapping can be defined as the task of recording "the location and, where known, the date of occurrence and the types of mass movements that have left discernible traces in an area" (Guzzetti et al. 2012). It can be used as a preliminary step towards landslide susceptibility, hazard, vulnerability, and risk assessment and mapping. In this study, an inventory of 216 existing landslides in the ULRC was mapped by two field surveys in 2010 and 2011. The landslide inventory, as shown in Fig. 4, indicates that landslides were mostly found in the central parts of the ULRC, especially densely populated areas such as Ha Giang City, Vi Xuyen Town, and some surrounding communities. There are also a number of landslides distributed along the main roads where many slopes were cut for house and road constructions such as Highway No. 2, No. 4, and local roads. Those landslides occurred on cut slopes (made by construction activities), but they were still triggered by rainfall; therefore, all landslides on natural slopes and cut slopes were integrated into the inventory of this study.

The landslide factors can be defined as controlling (or causal) factors and triggering factors. The controlling factors determine the initial favorable conditions for landslide occurrence while the triggering factors determine the timing of landsliding (Ladas et al. 2007). A landslide in any location usually has several controlling factors but only one triggering factor. In the ULRC, heavy rainfall is the main landslide triggering factor; however, the detailed rainfall data and maps were not available. Therefore, only the controlling factors are incorporated to establish the landslide susceptibility mapping.

The landslide factor maps can be represented by relevant thematic maps and generated in a GIS environment. In this study,

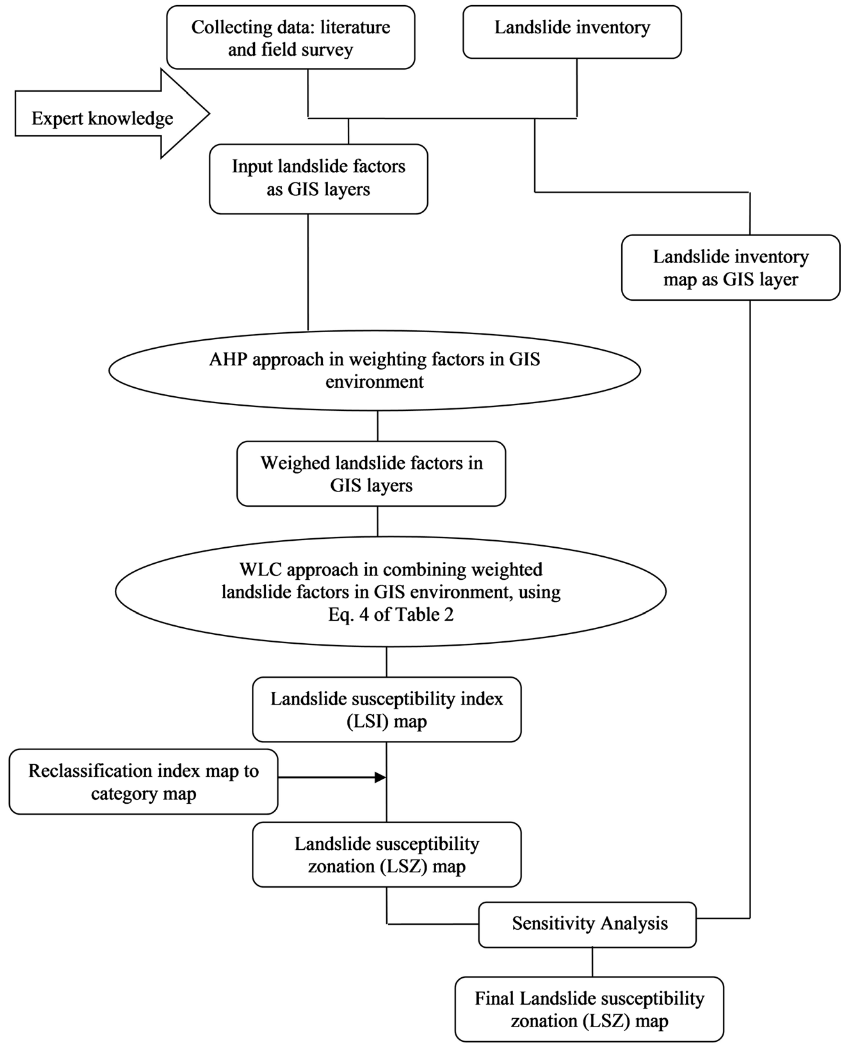
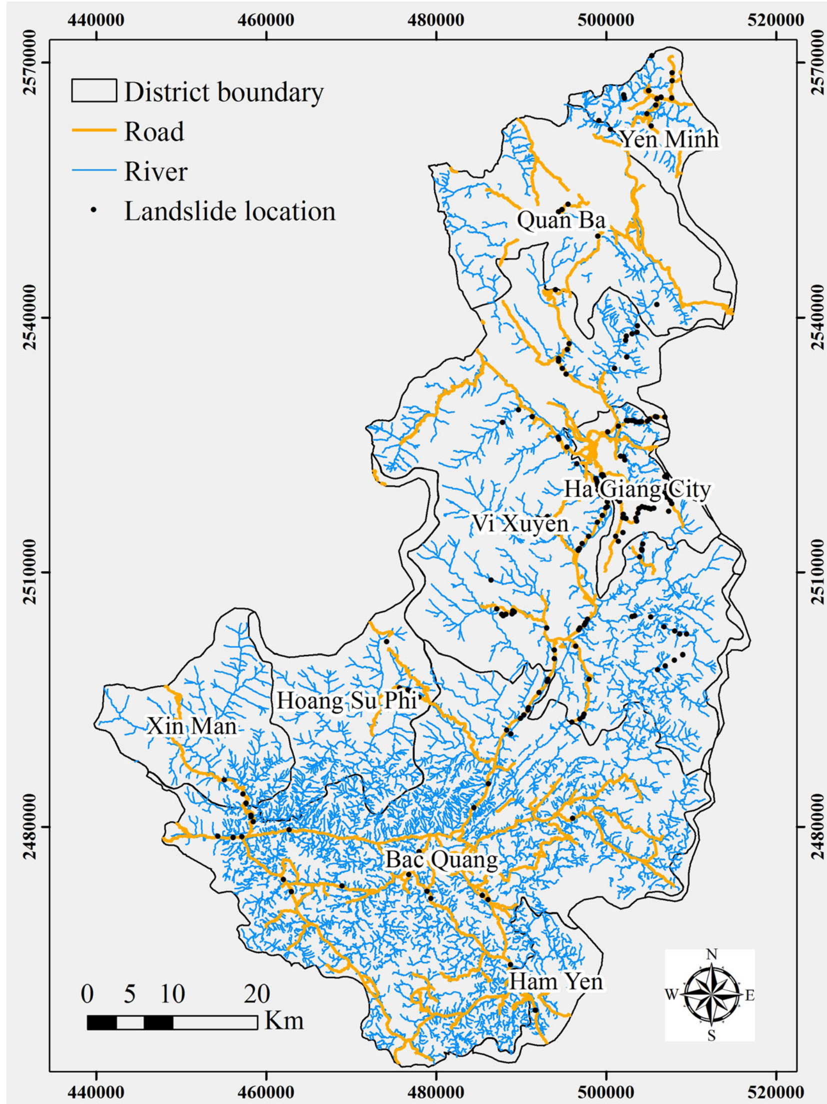


Fig. 3 Procedures of the landslide susceptibility mapping using the combination of AHP and WLC methods

six landslide factors in the ULRC at a scale of 1:100,000 were compiled from different available sources, including elevation, slope, drainage, fault, weathering, and land cover. Among them, three maps related to elevation, slope, and drainage were extracted from 1:50,000-scale topographic maps; two maps related to fault and weathering were constructed from 1:200,000-scale geological maps and field observations; and the land cover map was compiled from the 1:100,000-scale forest maps. The landslide factor maps of the ULRC are given in Fig. 5. To be employed for landslide susceptibility analysis in a later stage, the main attributes of those six maps were grouped into different classes using Jenks Natural Break classification in ArcGIS 9.2. Jenks Natural Break classification is used to define the best arrangement of values into different classes. This method seeks to reduce the variance within classes and maximize the variance between classes. Therefore, this classification was used instead of expert knowledge in order to keep in the classified maps the actual distribution of different homogeneous zones in the study area. A brief description of those six landslide factor maps is as follows:

- The *elevation map (E)* was derived from a digital elevation model (DEM) with a ground resolution of 20×20 m, which was interpolated from 1:50,000-scale topographic maps. The ULRC terrain altitude has an elevation ranging from 40 to 2420 m a.s.l. By the natural distribution of the terrain altitude, the elevation map is classified into five levels of elevation: (1) <313.6 m, (2) 313.6–633.4 m, (3) 633.4–981.3 m, (4) 981.3–1391 m, and (5) >1391 m. The elevation is chosen as the controlling factor based on field observations, and the occurrence of landslides is also changed corresponding with the change of elevation. The study area is determined as a mountainous region, with the lowest elevation at 40 m a.s.l. The elevation map is shown in Fig. 5a.
- The *slope map (S)* was derived from the same DEM that produced the elevation map. It has a maximum steepness of up to 83°. By the natural distribution of the terrain slope, the slope map is classified into five levels of gradients: (1) <8.3°, (2) 8.3°–19.9°, (3) 19.9°–29.3°, (4) 29.3°–40.3°, and (5) >40.3°. This classification is almost equivalent to terrain division for agriculture in the mountainous regions of Vietnam, which is based on the agriculture slope classification criteria of the Ministry of Agriculture and Rural Development. The slope map is shown in Fig. 5b.

Fig. 4 Observed landslides in the inventory map of the ULRC



– The *drainage density map (D)* was derived from the same DEM that produced the elevation map and combined with the river system that was extracted from 1:50,000-scale topographic maps. Both permanent and temporary runoffs were taken into account because the temporary runoffs are closely related to slope erosion degree while the permanent runoffs are closely related to rainfall. The features of drainage density play an important role in inducing landslide phenomena in this area. The drainage network of the ULRC has a rather high density and concentrates in the south with a maximum of up to 6 km/km^2. By the natural distribution of the drainage network, the drainage density map is classified into five levels of density: (1) <0.5 km/km^2, (2) 0.5–1.3 km/km^2, (3) 1.3–2.1 km/km^2, (4) 2.1–3 km/km^2, and (5) >3 km/km^2. The drainage density was used instead of distance to drainage lines according to the geomorphology of the area. The ULRC is characterized by various types of terrains with different densities of runoffs that cause different numbers of landslides. Figure 2a shows occurrences of several landsides close to a main stream in a commune of Vi Xuyen District that has a moderately high density of drainage. The drainage density map is shown in Fig. 5c.

– The *fault density map (F)* was extracted from the 1:200,000-scale geological maps. The highest density of up to 0.78 km/km^2 mainly distributes in the central part of the ULRC. By the natural distribution of the fault system, the fault density map is classified into five levels of density: (1) <0.175 km/km^2, (2) 0.175–0.3 km/km^2, (3) 0.3–0.42 km/km^2, (4) 0.42–0.57 km/km^2, and (5) >0.57 km/km^2. The fault density map is shown in Fig. 5d.

– The *weathering crust map (W)* was produced from the 1:200,000-scale geological maps and field surveys. Weathering crusts have been considered as an important controlling factor regarding the landslide phenomena not only in the ULRC but also in most of the mountainous areas of Vietnam. The impact of weathering process on geological formations has been considered to result in different types of "weathering crusts." The crust types are recognized by the mineral and chemical compositions and types of bedrocks from which the weathered

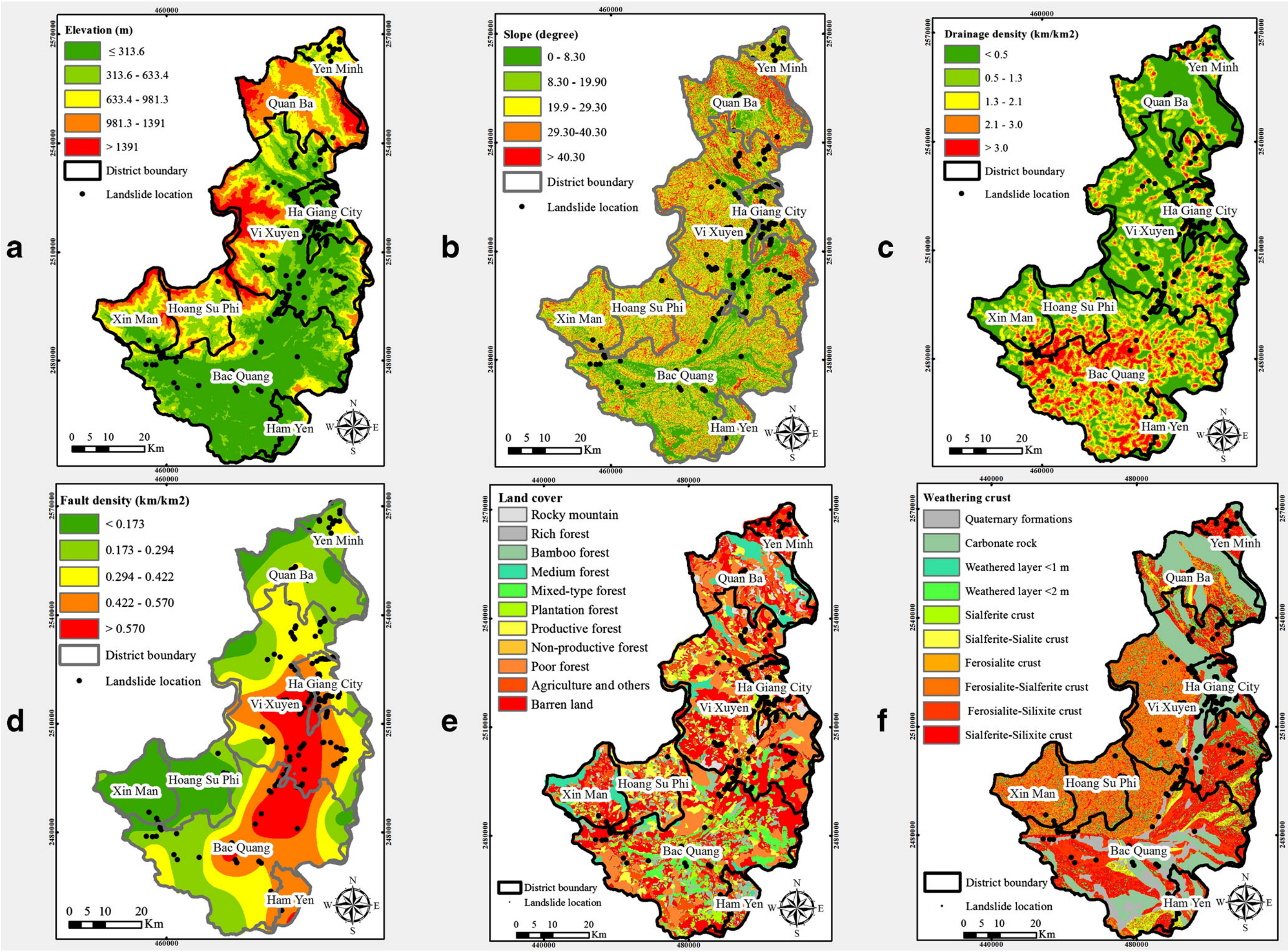


Fig. 5 Landslide factor maps: **a** elevation (E), **b** slope (S), **c** drainage density (D), **d** fault density (F), **e** weathering crust (W), and **f** land cover (L)

products are formed. There are seven main types of weathering crusts as follows:

(1) Quaternary formations that are composed of loose sediments
(2) Carbonate rocks that are composed of carbonate minerals
(3) Bedrock, slightly weathered rock, or areas with a small weathered layer
(4) Sialferite crust that is weathered on acid igneous rocks, neutral igneous rocks, sedimentary rocks, and metamorphic rocks
(5) Sialite crust that is weathered on acid igneous rocks, neutral igneous rocks, and eruptive sedimentary rocks
(6) Ferosialite crust that is weathered on ultramafic igneous rocks, mafic igneous rocks, sedimentary rocks, and metamorphic rocks
(7) Silixite crust that is weathered on quartz sandstone, quartzite, and schist

In addition to those seven main types, there are many other subtypes of weathering crusts, which are derived from the crust type (3) with different thicknesses of weathered layers or which are the mixture of the above four main crusts (4), (5), (6), and (7).

In the ULRC, there are ten types of crusts: (1) Quaternary formations distributed in low areas, which are little prone to landslides; (2) carbonate rocks distributed in rocky mountains; (3) bedrock, slightly weathered rock, or areas with a weathered layer less than 1 m; (4) slightly weathered rock or areas with a weathered layer less than 2 m; (5) sialferite crust; (6) sialferite-sialite crust that is a mixture of sialferite and sialite crusts; (7) ferosialite crust; (8) ferosialite-sialferite crust that is a mixture of ferosialite and sialferite crusts; (9) ferosialite-silixite crust that is a mixture of ferosialite and silixite crusts; and (10) sialferite-silixite crust that is a mixture of sialferite and silixite crusts. Among those ten crusts, three types—(2), (3), and (4)—have little conservation of weathering materials. The weathering crusts in the ULRC normally have thicknesses ranging from 2.5 to 10 m. In some parts such as Hoang Su Phi District, the thicknesses of weathering crusts are from 5 m up to tens of meters. The weathering crust map is shown in Fig. 5e.

– The *land cover map (L)* was extracted from the 1:100,000-scale forest maps, which were constructed in 2010. This factor map presents 11 types of land cover that distribute in the ULRC including (1) rocky mountain, (2) rich forest, (3) bamboo forest, (4) medium forest, (5) mixed-type forest, (6) plantation forest, (7) productive young forest, (8) non-productive young forest, (9) poor forest; (10) agricultural and other land, and (11) settlements and barren land. The land cover map is shown in Fig. 5f.

Factor weighting and susceptibility index

The analyses for weighting and ranking of the landslide factors and their classes are mainly based on expert knowledge about the natural features that distribute over the whole region. The weighting and ranking scale is defined in a range of 0–1. Six landslide factors are evaluated using pairwise comparison in the AHP method. The weights are presented by the eigenvalues as given in Table 4, in which the slope factor has the highest eigenvalue (0.3310) while the elevation factor has the lowest value (0.0463). From the results of pairwise comparison, the eigenvalues were assigned as weighting values W_i corresponding to individual landslide factors. The obtained consistency ratio (CR) of 0.0218 indicated an adequate degree of consistency in the comparison; thus, all values were taken into the WLC model in the GIS environment. From the results of these pairwise comparisons as given in Table 5, the eigenvalues were assigned as weighting values w_{ji}, corresponding to classes of each landslide factor. All CR smaller than 0.1 indicate the weights of all factor classes are accepted. Using the WLC method, Equation 3 as given in Table 2 was applied to all landslide factors to produce the landslide susceptibility index (LSI) map (Fig. 6).

From Equation 3 in Table 2, the applied equation is expressed as follows:

$$\mathrm{LSI} = 0.0463{*}\mathrm{E} + 0.0705{*}\mathrm{D} + 0.1116{*}\mathrm{F} + 0.1785{*}\mathrm{L} + 0.2621{*}\mathrm{W} + 0.3310{*}\mathrm{S}$$

in which variables E, D, F, L, W, and S are abbreviations of the landslide factors: elevation, drainage density, fault density, land cover, weathering crust, and slope, respectively. LSI represents the relative susceptibility of a landslide occurrence; therefore, the higher the LSI, the more susceptible the area is to landslides. The LSI values were normalized to the range 0–1 in order to perform the consistency in comparison and classification across all factors.

The final landslide susceptibility map and discussion

The landslide susceptibility zonation map as shown in Fig. 7 represents the final susceptibility map of the study area. It was established by reclassifying the LSI map using natural breaks in the cumulative frequency histogram of LSI values, as presented in Fig. 6 and Table 6. The surfaces of the study area were classified into four landslide susceptibility zones, namely "low," "moderate," "high," and "very high," that account for 21.57, 37.46, 29.21, and 11.75 % of the total areas, respectively (Table 7).

To validate the final susceptibility map as well as the overall methodology, the landslide susceptibility zonation map was then overlaid with the observed landslides in the inventory map. As presented in Table 7, out of 216 observed landslides, 50 landslides (~23.15 %) fall within the low-susceptibility zone, 63 landslides (~29.17 %) fall within the moderate-susceptibility zone, 83 landslides (~38.43 %) fall within the high-susceptibility zone, and 20 landslides (~9.26 %) fall within the very-high-susceptibility zone. The results are in accordance with the occurrences of the observed landslides, in which 47.69 % of observed landslides are located in the two most susceptible zones (very-high-susceptibility zone and high-susceptibility zone) that cover 40.96 % of the total area. This simple type of validation based on spatial cross-checking of the mapping results serves as a first indicator for the plausibility of the landslide susceptibility map. A true validation of the overall methodology, however, is only supported to some extent by now.

In this study area, landslides have been observed in two types of slopes: natural slopes that are not influenced by human activities and cut slopes that are influenced by human activities such as excavation of slopes for road and house constructions. But those inventoried landslides were all triggered by rainfall. Landslides that were triggered by human activities (such as mining and excavating) were not registered in the inventory map and therefore not taken into account for the analysis of landslide susceptibility. Such anthropogenic interventions were considered as the driving factor that accelerates the landsliding process, not as the triggering factor that plays as a final cause to landslides. In the weighting of the input factors, the authors mainly took into account the natural impacts of environmental factors to assess the natural potential of landsliding or natural landslide susceptibility. This explained why in the final landslide susceptibility zonation map, many inventoried landslides were found in the low-susceptibility zone. This information from the result map is valuable to recommend to the local authorities and communities for landslide hazard mitigation and risk reduction. They must take adequate measures for

Table 4 Pairwise comparison matrix, weights, eigenvector values, and consistency ratio (CR) of the landslide factors

Landslide factors	(1)	(2)	(3)	(4)	(5)	(6)	Eigenvector value
(1) Elevation	1						0.0463
(2) Drainage density	2	1					0.0705
(3) Fault density	3	2	1				0.1116
(4) Land cover	4	3	2	1			0.1785
(5) Weathering crust	5	4	3	2	1		0.2621
(6) Slope	5	4	3	2	2	1	0.3310
							CR=0.0218

Table 5 Pairwise comparison matrices, weights, eigenvector values, and consistency ratios (CR) of all classes of each factor

Landslide factors	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	Eigenvector value
Elevation (m)												
(1) ≤313.6	1											0.0694
(2) 313.6–633.4	2	1										0.1198
(3) 633.4–981.3	3	2	1									0.2121
(4) 981.3–1391	5	3	2	1								0.3865
(5) ≥1391	3	2	1	1/2	1							0.2121
												CR=0.0039
Fault density (km/km^2)												
(1) 0.173	1											0.0419
(2) 0.173–0.294	3	1										0.0836
(3) 0.294–0.422	5	3	1									0.1772
(4) 0.422–0.570	6	4	2	1								0.2728
(5) >0.570	7	5	3	2	1							0.4245
												CR=0.0307
Drainage density (km/km^2)												
(1) <0.5	1											0.0514
(2) 0.5–1.3	2	1										0.0780
(3) 1.3–2.1	4	3	1									0.1749
(4) 2.1–3.0	5	4	2	1								0.2717
(5) >3.0	6	5	3	2	1							0.4241
												CR=0.0219
Land cover												
(1) Rocky mountain	1											0.0163
(2) Rich forest	2	1										0.0225
(3) Bamboo forest	3	2	1									0.0338
(4) Medium forest	3	2	1	1								0.0338
(5) Mixed-type forest	3	2	1	1	1							0.0338
(6) Plantation forest	4	3	2	2	2	1						0.0520
(7) Productive young forest	5	4	3	3	3	2	1					0.0756
(8) Non-productive young forest	6	5	4	4	4	3	2	1				0.1064

Table 5 (continued)

Landslide factors	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	Eigenvector value
(9) Poor forest	7	6	5	5	5	4	3	2	1			0.1473
(10) Agriculture and other lands	8	7	6	6	6	5	4	3	2	1		0.2024
(11) Barren land	9	8	7	7	7	6	5	4	3	2	1	0.2761
												CR=0.0286
Weathering crust												
(1) Quaternary formations	1											0.0159
(2) Carbonate rock	2	1										0.0194
(3) Bedrock and slightly weathered rock or weathered layer <1 m	2	1	1									0.0241
(4) Bedrock and slightly weathered rock or weathered layer <2 m	3	2	2	1								0.0349
(5) Sialferite crust	7	6	5	4	1							0.0950
(6) Sialferite-sialite crust	7	6	5	4	1	1						0.0950
(7) Ferosialite crust	8	7	6	5	2	2	1					0.1413
(8) Ferosialite-sialferite crust	8	7	6	5	2	2	1	1				0.1413
(9) Ferosialite-silixite crust	9	8	7	6	3	3	2	2	1			0.2165
(10) Sialferite-silixite crust	9	8	7	6	3	3	2	2	1	1		0.2165
												CR=0.0105
Slope (°)												
(1) ≤8.3	1											0.0472
(2) 8.3–19.9	2	1										0.0713
(3) 19.9–29.3	4	3	1									0.1565
(4) 29.3–40.3	5	4	2	1								0.2362
(5) >40.3	7	6	4	3	1							0.4888
												CR=0.0314

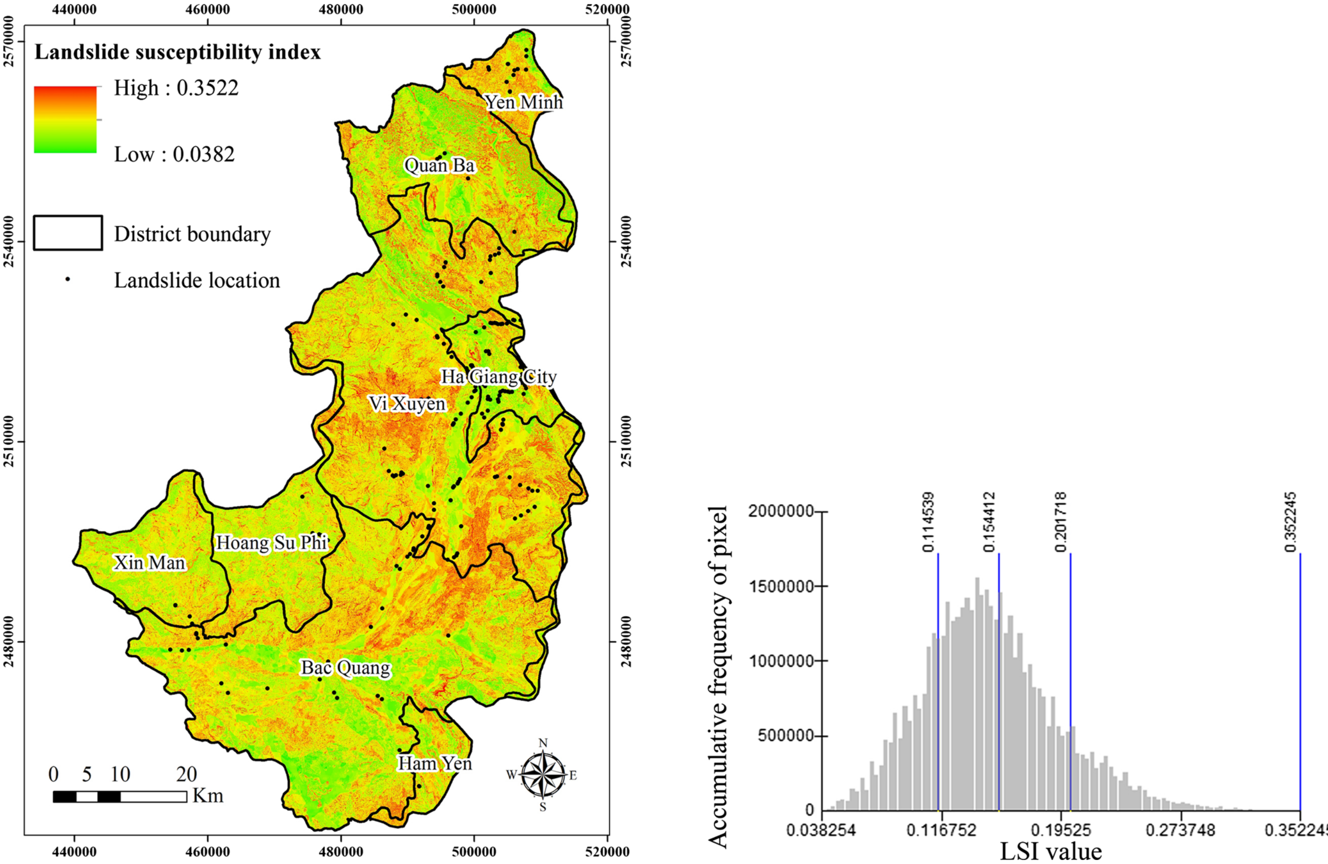


Fig. 6 Landslide susceptibility index (LSI) map of the ULRC (*left*) and the cumulative frequency histogram of LSI values (*right*) that breaks naturally into four classes of LSI values

land use planning or carrying out any construction work even if they settle in the lower elevation or lower slope gradients.

In the low-susceptibility zone, people often excavate natural slopes for house and road constructions and make stable slopes become susceptible to landslides during the rainy season. That explains why many existing landslides (50 locations, equivalent to 23.15 % of the total inventory) were found in the low-susceptibility zone. On the other hand, as shown in the final landslide susceptibility zonation map (Fig. 7), the very-high- and high-landslide-susceptibility zones (>40 % of the total area) are located largely in Vi Xuyen District, and partly in Bac Quang District, where landslide factors contribute the most favorable conditions to landsliding potential: (1) highest fault density (>0.422 km/km^2) because they locate in the center of the Lo River fault zone; (2) rather dense drainage system (from 0.5 to 3 km/km^2); (3) slope gradients of lower than 40° with conserved thick weathering layers (2–20 m); (4) distribution of the four weathering crust types—sialferite-silixite, ferosialite-silixite, ferosialite-sialferite, and ferosialite—which are the most susceptible to landsliding; (5) lithology comprises of shales, shale-serixites, siltstones, and sandstones, which are easily weathered and then swollen in wet condition, inducing slope instability during or after raining; and (6) barren land that distributes over areas influenced by human activities. Thus, the final predicted map (landslide susceptibility zonation map) shows reliable results.

The fact shows that many existing landslides were found inside or close to areas related to human activities such as settlements, transportation routes, terraced fields, mining sites, deforestation land, and barren land; therefore, the occurrences of landslides in the moderate- or low-susceptibility zones are attributed to local impacts. Those susceptibility zones are often characterized by natural features such as lowland, gentle slope, low density of drainage and faulting, and loose sediment. Therefore, these places are theoretically favorable for human settlements and unfavorable for landsliding. From field observations in 2010 and 2011, together with studies on available literatures (topographic maps, geological maps, and forest maps), in summary, landslides in the ULRC often occur in the areas with the following characteristics:

(1) Steepness of the natural slope is greater 20° and/or steepness of the cut slope is greater than 45°
(2) Bare land or less vegetation cover (such as young forest, poor forest)
(3) Place close to residential areas, where many cut slopes are created that foster landslide occurrences as the result of inadequate designs of cut slopes or due to the weathering process on the slope surface
(4) Slope surface easy to store water/rich in water that weakens the strength of slope materials

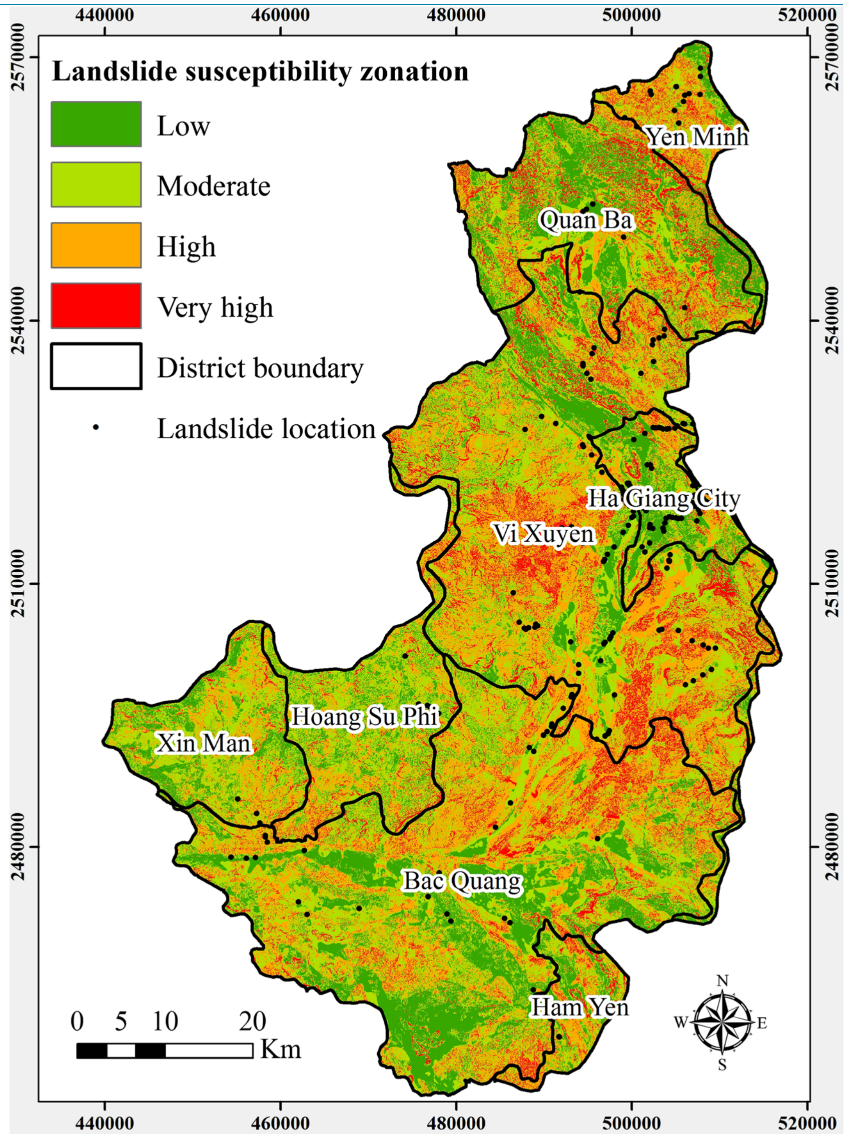


Fig. 7 Landslide susceptibility zonation map of the ULRC

(5) Loose weathering crusts, which contain silts, sandstones, and siltstones, on top of the bedrocks clay schist, clay schist-serixite (as with ferrosillite crust)
(6) High annual rainfall and high rainfall frequency (as in Bac Quang District)
(7) Complex geological structures, mostly with high density of faults as in the central part of Vi Xuyen District

To analyze the final susceptibility map in relation to the controlling factors in the ULRC, the distribution of the observed landslides over the landslide factor maps was assessed by calculating the percentage of areas and the observed landslides distributed per landslide factor class over the ULRC. The percentage of area is calculated as the ratio of class area per total area, for each landslide factor. The percentage of observed landslide is calculated

Table 6 Reclassification of LSI values to produce the landslide susceptibility zonation map

Cumulative frequency of LSI values (%)	Susceptibility index (LSI)	Landslide susceptibility classes
22	LSI<0.11582	Low
59	0.11582<LSI<0.1564	Moderate
88	0.1564<LSI<0.2032	High
100	LSI>0.2032	Very high

Table 7 Summary of the distribution of the predicted landslide susceptibility classes in the landslide susceptibility zonation map compared with the observed landslides in the landslide inventory map

Landslide susceptibility class	Predicted landslide susceptibility classes		Observed landslides	
	Area (km^2)	Percentage (%)	Number	Percentage (%)
Low	977	21.57	50	23.15
Moderate	1696	37.46	63	29.17
High	1323	29.21	83	38.43
Very high	532	11.75	20	9.26
Total	4528	100	216	100

as the ratio of the number of landslides that occurred within one factor class per the total number of observed landslides that occurred in the research area, i.e., the dataset of 216 landslides in the inventory map. The calculation results are shown in Table 8.

As presented in Table 8:

- 74.54 % of observed landslides distribute in the elevations of less than 313.6 m; subsequently, the higher the elevation is, the lower the number of landslides that occurred.
- More than 80 % of observed landslides distribute in the slopes with gradients less than 29.3°; particularly, 34.72 % of observed landslides distribute in the gradients of less than 8.3°. The slopes having this range of gradients often contain thick layers of weathered soils that are still well conserved on those slope surfaces.
- More than 55 % of observed landslides distribute in the drainage densities of higher than 1.3 km/km^2. Particularly, during heavy rainfall, landslides often occur in the areas with high drainage density which are prone to shallow-seated landslide or in the areas with low drainage density which are prone to large-scale landslides.
- About 80 % of observed landslides distribute in the areas having fault densities of higher than 0.3 km/km^2; particularly, 28.70 % of observed landslides distribute in the areas having fault densities of less than 0.5 km/km^2.
- About 54 % of observed landslides distribute in barren land or land with less vegetation cover (such as poor forest, young forest).
- About 21 and 30 % of observed landslides distribute in the ferosialite crust and weathered carbonate rock, respectively. That was in accordance with the fact that ferosialite crust is rich in clay mineral and very easy to be weathered, while landslides on carbonate rock are mainly related to human activities (road constructions, mining).

The fact shows that development of landslides in mountainous areas in the ULRC is closely related to weathering layers, where rock and soil mass of the slopes have been deteriorated over time due to the weathering process, which results in different types of weathering crusts with different thicknesses. Having the same natural conditions (such as the same slope gradient, land cover, and weathering thickness), the ferosialite crust is the most susceptible to landslides and the silixite crust is the least susceptible to landslides. The mixed types of crusts are more susceptible to landslides than the single types. That is in accordance with the fact that landslides often occur on the sialferite or ferosialite crusts that contain loose materials with thickness from 1 m up to tens of meters. It could be argued that, even though the thickness of the weathering layer may be deep to tens of meters, the weathering materials are very weak and easily saturated in heavy rainfall.

Conclusions

The frequency of landslides in the ULRC in northern Vietnam has increased with the rapid urbanization and the economic development of the ULRC in the last 10 years. A regional landslide susceptibility mapping is required to provide a foundation for a long-term land use planning that includes landslide mitigation measures in the region. The lack of historical landslide data in the region has made the landslide susceptibility assessment difficult. In this study, 216 historic landslides were mapped by field surveys.

Among many available techniques worldwide, the integrated analytical hierarchy process (AHP) and weighted linear combination (WLC) approach in landslide susceptibility mapping was applied. The results revealed the effectiveness of the combination of AHP and WLC for landslide susceptibility mapping in a region with limited data on spatial distribution of landslides and environment factors. Therefore, this approach can quickly result in the final maps in order to provide the local authority and community better strategies for disaster mitigation and management. However, this approach still depends very much on the experience and knowledge of individual experts.

The final susceptibility map of the ULRC is established based on six factors: the elevation (E), slope (S), drainage density (D), fault density (F), weathering crust (W), and land cover (L). Among these factors, the slope and weathering crust are of utmost importance. The result shows that 77 % of the area of the ULRC is in the moderate-susceptibility zone to the very-high-susceptibility zone. This is important for the local government since human activities are the cause of many landslides that occur in the low-susceptibility zone (23 % of the ULRC).

Table 8 Percentage of area and observed landslides that distribute per landslide factor class over the ULRC

Landslide factors and their classes	Distributed area (%)	Observed landslides (%)
Elevation		
<313.6	39.78	74.54
313.6–633.4	20.77	17.59
633.4–981.3	18.30	6.48
981.3–1391	14.29	1.39
>1391	6.85	0.00
Slope		
<8.3	21.50	34.72
8.3–19.9	20.25	21.76
19.9–29.3	28.17	25.46
29.3–40.3	21.66	15.28
>40.3	8.41	2.78
Drainage density		
<0.5	37.80	28.70
0.5–1.3	21.46	16.67
1.3–2.1	19.34	25.00
2.1–3.0	14.20	23.15
>3.0	7.21	6.48
Fault density		
0.175	18.20	6.02
0.175–0.300	27.32	14.35
0.300–0.420	23.61	29.17
0.420–0.570	19.06	27.78
>0.570	11.80	22.69
Land cover		
Agriculture and other lands	14.14	15.74
Rocky mountain	2.97	1.39
Barren land	32.92	54.17
Medium forest	6.10	0.00
Bamboo forest	5.48	0.93
Productive young forest	10.59	11.57
Mixed-type forest	4.71	3.24
Plantation forest	4.53	9.26
Poor forest	18.17	3.70
Rich forest	0.30	0.00
Non-productive young forest	0.09	0.00
Weathering crust		
Bedrock and slightly weathered rock or weathered layer <1 m	3.13	0.46
Bedrock and slightly weathered rock or weathered layer <2 m	14.40	8.33
Sialferite crust	20.43	18.52
Ferosialite crust	10.76	21.30
Ferosialite-sialferite crust	4.69	7.87
Sialferite-sialite crust	17.49	7.41
Sialferite-silixite crust	2.38	0.00
Ferosialite-silixite crust	1.40	0.46
Carbonate rock	19.70	30.09
Quaternary sediments	5.63	5.56

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