1 Point-by-point response

1.1 Referee 1

For the point-by-point response, please see https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2019-8/nhess-2019-8-AC1-supplement.pdf.

1.2 Referee 2

For the point-by-point response, please see https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2019-8/nhess-2019-8-AC2-supplement.pdf.

1.3 Editor

We thank you for your comments that will help us improve our manuscript. Here we reply point-by-point to the issues raised by the Editor. Our answers are highlighted in green colour.

(1) English has to be strongly revised with the help of some native English-speaker.

We have proof read the paper carefully and revised the grammar errors in this revision.

(2) The structure of the work must be improved according to the suggestions of Referee #2. Carefully separate Introduction from area description, methods, results and discussion of results in separate and self-contained sections.

Thanks. The structure of this manuscript has been reorganised.

(3) Modify the writing and the approach so as to support each statement with proofs and/or references to published papers.

In the revised manuscript, we checked and rephrased the related sentences.

(4) Greatly improve the references to previous work of similar type (most of the widely known work on landslide susceptibility is not cited).

According to your suggestions, some descriptions and references were added in the revised manuscript.

(5) Please try to modify the approach of the study to highlight the relevance to a susceptibility study which deals with the specific problem of an M7 trigger, as also underlined by referee #2.

In this revision, we modified some sentences related to the approach.

(6) Please add a reference to tables and figures in the text, when needed.

Thanks for your kind reminding. We checked and revised the related sentences.

(7) Please improve and enlarge the methodology section, by providing more details on the procedure and on the methods used.

According to your and referee's suggestions, we reorganised the methodology section of the study. The flowchart was added in the revised manuscript. Now, we think it's clear and easy to understand.

(8) Please also revise and answer to each minor comment provided by the referees as well.

Thanks for your kind reminding. We have read each comment carefully. In this revision, we have made substantial improvements to the paper according to each comment. We rephrased each sentence mentioned in the referees' comments and improved the writing of the whole article carefully.

2 List of relevant changes

We have:

(1) reorganised the structure of the manuscript,

(2) improved the writing of the whole article,

(3) more clearly stated the objectives and framework,

(4) completely reorganised and expanded the methodology section,

(5) modified and deleted some useless sentences as suggested,

(6) improved the quality of the figures as suggested,

(7) added some references as suggested,

(8) revised the results and improved the discussions.

GIS-based earthquake-triggered landslide susceptibility mapping with an integrated weighted index model in Jiuzhaigou region of Sichuan Province, China

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Abstract. A ~~Ms 7.0~~ Mw 6.5 earthquake struck the Jiuzhaigou region of Sichuan Province, China at 21:19 pm on Tuesday, 8 August 2017, ~~which~~ and triggered a large number of landslides. For mitigating the damages of earthquake-triggered landslides to individuals and infrastructures of the earthquake affected region, a comprehensive landslide susceptibility mapping was attempted with an integrated weighted index model by combining the frequency ratio and the analytical hierarchy process approaches under GIS-based environment in the earthquake heavily attacked Zhangzha town of the Jiuzhaigou region. For this purpose, a total number of 842 earthquake-triggered landslides were visually interpreted and located from Sentinel-2A images acquired before and after the earthquake at first, and then the recognized landslides were randomly split into two groups to establish the earthquake-triggered landslide inventory, among which 80 % of the landslides was used for training the integrated model and the remaining 20 % for validation. ~~Nine landslide controlling factors, namely slope, aspect, elevation, lithology, distance from faults, distance from rivers, land-use/cover, normalized difference vegetation index and peak ground acceleration, were considered with an integrated weighted index model for determination of the weighted index through analysing their relationships with occurrence frequency ratios of landslides with analytical hierarchy process approaches.~~ Nine landslide controlling factors were considered including slope, aspect, elevation, lithology, distance from faults, distance from rivers, land-use/cover, normalized difference vegetation index and peak ground acceleration. The frequency ratio was utilized to evaluate the contribution of each landslide controlling factor on landslide occurrence, and the analytical hierarchy process was used to analysis the mutual relationship between landslide controlling factors. Finally, the landslide susceptibility map was produced by using the weighted overlay analysis. Furthermore, an area under the curve approach was adopted to comprehensively evaluate the performance of the integrated weighted index model, including the degree of model fit and model predictive capability. The results demonstrated the reliability and feasibility of the integrated weighted index model in earthquake-triggered landslide susceptibility mapping at regional scale. The generated map can ~~be served as the scientific basis~~

~~to~~ help engineers and decision makers assess and mitigate hazards of the earthquake-triggered landslides to individuals and infrastructures of the earthquake affected region.

Keywords

Earthquake-triggered landslide susceptibility mapping; An integrated weighted index model; Frequency ratio; Analytical hierarchy process; The Jiuzhaigou region

1 Introduction

Recent natural disasters and their associated death tolls and financial costs have put mitigation of natural hazards at the forefront of societal needs. Landslides are the most common natural disasters (geological hazards) that cause ~~damages to people's lives and property~~ heavy human casualties and damage to property every year in many areas of the world (Saha et al., 2010; Su et al., 2015). ~~Landslides are more likely to occur when the slope becomes unstable. Slope instability can be caused by several factors, such as geological, meteorological and anthropogenic factors, especially the earthquake and rainfall~~ Landslides can be caused by several factors, such as strong earthquakes, intense or prolonged rainfall and multiple human actions (Guzzetti et al., 2012; Sato et al., 2007).

On August 8, 2017, a catastrophic earthquake of magnitude ~~7.0~~ 6.5 struck the Jiuzhaigou region of Sichuan Province, China. The epicentre of this earthquake with a depth of 20 km was located latitude 33.20° N and longitude 103.82° E close to the Jiuzhaigou National Nature Reserve, about 39 km West ~~from~~ to the city of Jiuzhaigou. According to China Earthquake Administration, the epicentre of the Jiuzhaigou earthquake was located near the Minjiang, Tazang and Huya faults (as can be seen in Fig. 1), and this earthquake was caused by tectonic movement of an NW-SE-oriented left-lateral strike-slip fault (Wang et al., 2018a). Although the intense rainfall was not observed after the earthquake, numerous landslides were triggered yet by strong seismic vibration of ground (Zhao et al., 2018). ~~Many tourists were trapped in the region due to numerous landslides blocking the roads.~~ Many scenic spots in the Jiuzhaigou National Nature Reserve were destroyed, as presented in Fig. 2(b), the Sparkling Lake was damaged. Due to numerous landslides blocking the roads, many tourists were trapped in the region, as can be seen in Fig. 2(d), the S301 highway was severely obstructed by a significant number of small-scale landslides. Based on field investigation, most of these landslides were small-scale rock slides, rock falls and debris slides (Fan et al., 2018; Zhao et al., 2018). As China Earthquake Administration reported, this earthquake caused 25 deaths and 176,492 injured or affected (Lei et al., 2018; Wang et al., 2018b). Landslides seriously threaten the anthropogenic activities, as well as tourist facilities of

the region. Comprehensive earthquake-triggered landslide susceptibility mapping in the earthquake affected area, therefore, is essential to assess landslide hazard and mitigate landslide damages through the proper prevention actions for the future.

Over the last decades, many approaches for landslide susceptibility mapping were proposed, among which the application of remote sensing associated with GIS modelling techniques became the most popular and effective ones (Alexander, 2008; Carrara et al., 1991; Dai and Lee, 2002; Guzzetti et al., 1999; Lee, 2005; Mantovani et al., 1996; Mansouri Daneshvar, 2014; Xu et al., 2012a). The most commonly used methods for landslide susceptibility mapping include logistic regression (Ayalew and Yamagishi, 2005; Bai et al., 2010; Manzo et al., 2013; Ozdemir and Altural, 2013), weights of evidence (Althuwaynee et al., 2012; Regmi et al., 2010), analytical hierarchy process (AHP) (Kayastha et al., 2013; Komac, 2006; Mansouri Daneshvar, 2014; Yalcin, 2008), frequency ratio (FR) (Guo et al., 2015; Lee and Pradhan, 2007; Li et al., 2017; Mohammady et al., 2012), support vector machine (SVM) (Marjanović et al., 2011; Su et al., 2015), decision tree (Nefeslioglu et al., 2010; Saito et al., 2009) and artificial neural network (ANN) (Caniani et al., 2008; Catani et al., 2005; Conforti et al., 2014; Ermini et al., 2005; Pradhan and Lee, 2009). These methods have been proved capable of mapping the locations that are prone to landslides, however, some shortcomings yet exist in these methods, which reduce the efficiency of these susceptibility methods when applied individually (Tien Bui et al., 2012; Umar et al., 2014). For example, the AHP can be used to identify the mutual relationship between landslide controlling factors and the landslide susceptibility, but the process and results mostly depend on the expert's knowledge, which are somehow subjective in practice (Youssef et al., 2015; Zhang et al., 2016). The FR is capable of representing the influence of the categories of each controlling factor due to landslide occurrences (Lee and Talib, 2005), however, the mutual relationship between the factors is mostly neglected (Zhang et al., 2016), and the same issue also exists in the modelled result. Logistic regression is good at analysing the relationships among the landslide controlling factors but is not capable to evaluate the impact of the categories of each factor individually on landslides (Umar et al., 2014). Fuzzy logic has also been employed in landslide susceptibility mapping, but the modelled results largely rely on the expert's knowledge, which often leads to a high degree of uncertainty (Tilmant et al., 2002). In addition, machine learning models (e.g. SVM, decision tree and ANN models) are very popular methods in landslide analysis, nevertheless, heavy dependence of a very high-speed computer along with large amounts of training data needed constrain their practical applications to some extent (Umar et al., 2014).

In addition, the combined approach has been gradually used for landslide susceptibility assessment (Ba et al., 2017; Boon et al., 2015; Dehnavi et al., 2015; Kadavi et al., 2018; Pham et al., 2018; Shrestha et al., 2017; Umar et al., 2014; Youssef et al., 2015). For instance, Umar et al. (~~Umar et al.,~~ 2014) used an ensemble method of FR and logistic regression to assess the landslide susceptibility in West Sumatera Province, Indonesia, and the similar integrated method was also applied by Youssef et al. (~~Youssef et al.,~~ 2015). Dehnavi et al. (~~Dehnavi et al.,~~ 2015) combined the step-wise weight assessment ratio analysis

method and adaptive neuro-fuzzy inference system to produce a landslide susceptibility map of Iran. Ba et al. (~~Ba et al.,~~ 2017) proposed an improved information value model based on grey clustering for landslide susceptibility mapping in Chongqing. Kadavi et al. (~~Kadavi et al.,~~ 2018) proposed a hybrid machine learning approach of AdaBoost, LogitBoost, Multiclass Classifier, and Bagging models for spatial prediction of landslides. Although those studies suggested effectiveness of the integrated method in some areas of the world, the universality and efficiency of the integrated method were yet remained as an important issue to be confirmed in different regions of the world (Reichenbach et al., 2018).

The main purpose of this study ~~was to apply an integrated weighted index model by combining FR and AHP for susceptibility mapping of earthquake-triggered landslides.~~ is to map the susceptibility of earthquake-triggered landslides by applying an integrated weighted index model by combining FR and AHP. The integrated model is capable of evaluating the contribution of each landslide controlling factor to landslide occurrence using FR method, meanwhile taking mutual relationships among controlling factors into account by the use of AHP. Such integration is capable to generate a complete model that largely restrains the shortcomings of these two individual methods and reduces the uncertainty and subjectivity resulted by the utilization of individual method. The experiment site was selected at the Zhangzha town of Jiuzhaigou, a region seriously affected by the Jiuzhaigou earthquake. An earthquake-triggered landslide susceptibility map was produced by using the integrated weighted index model along with the remotely sensed information, and a ~~detailed~~ validation analysis by using an area under the curve approach was conducted to the generated susceptibility map of the study area for evaluating the reliability and feasibility of the integrated model. This manuscript is structured as follows: Section 2 introduces the study area ~~and the basic information about the earthquake happened on August 8, 2017~~. Section 3 describes the data utilized and data preparing procedures. Section 4 gives the detailed explanation about the integrated weighted index model. Section 5 presents the results and discussions focusing on validations on the generated earthquake-triggered landslide susceptibility map of the study area followed by the conclusions drawn in Section 6 at the end.

2 Study area

The study area with an area of ~~about~~ 1345.19 km^2, as shown in Fig. 1, is located in the Zhangzha town of Jiuzhaigou County between 33.03° N – 33.35° N Latitude and 103.63° E – 104.05° E Longitude in the Min Shan Mountains ~~on~~ to the north of the Sichuan basin, eastern margin of the Tibetan Plateau. As pointed out in Deng (2011), the geological conditions of this region are extremely complex, and the tectonic movement strongly uplifted the entire western region of Jiuzhaigou, while the eastern region had different fault block movements along the early faults. Regional tectonic movements are intense (Wang et al., 2018b), as summarized in Fan et al. (2018), more than 50 earthquake events with magnitude 5.0 or greater occurred in the Jiuzhaigou area in the past century. Active regional tectonic uplift and tilting cause the elevation of the study area to vary from

1624 m to 4855 m above mean sea level. ~~The soluble carbonate rocks are widely distributed along with tufa deposition of karst developed, and regional tectonic movements are intense here (Wang et al., 2018b). The topography of the region is characterized by alpine karst terrain where the elevation varies from 1624 m to 4855 m above mean sea level.~~ The Jiuzhaigou County belongs to a cold sub-humid and cold semi-arid monsoon climate with the annual precipitation about 550 mm (Li et al., 2014). ~~The geomorphology of the study area is jointly formed by the climatic, geotectonic, lithological conditions under the effect of topography of the region.~~ The topography of the region is characterized by alpine karst terrain formed by glacial, hydrological and tectonic activity, and with karstification in travertine deposits, many travertine dikes and shoals appeared in the study area. Soluble carbonate rocks are widely distributed along with tufa deposition of karst developed. Due to abundant recharge supply of groundwater in this region, many lakes and streams develop over extensive alpine karst developed region, which favours the hill slope erosion processes, and results in frequent occurrence of rock slides, debris flows, and rock falls there (Florsheim et al., 2013).

~~The Jiuzhaigou National Nature Reserve, approved as the UNESCO World Biosphere Reserve, is just located in the study area. Many scenic spots in the Jiuzhaigou National Nature Reserve were destroyed in 2017 by the Jiuzhaigou earthquake, as presented in Fig. 2(b), the Sparkling Lake was damaged. A significant number of small-scale landslides, as shown in Fig. 1, were triggered by this earthquake along roads and river valley where many residents and infrastructures are located. Landslides seriously threaten the anthropogenic activities, as well as tourist facilities of the region, as can be seen in Fig. 2(d), the S301 highway was severely obstructed by rock falls and rock slides, which drawn great attentions extensively.~~

3 Data

In order to map the landslide susceptibility of the study area, we designed and developed a spatial database with the help of ArcGIS (version 10.2) software. This database contained two primary parts: (1) the landslide inventory dataset for earthquake-triggered landslides; and (2) the datasets of background condition representing the landslide controlling factors. The data layers used in the landslide susceptibility mapping were briefly described ~~as presented~~ in ~~the~~ Table 1.

3.1 Landslide inventory

Landslide inventory is essential for ~~analysing the relationships between controlling factors and the landslide occurrences, and also useful for~~ assessing landslide hazard or risk on a regional scale (Pellicani and Spilotro, 2015). The Jiuzhaigou earthquake ~~on August 8, 2017 with a magnitude of 7.0~~ triggered numerous landslides in the study area. ~~For deriving~~ To derive landslide inventory containing detailed and reliable information on landslide distribution, location, etc., Sentinel-2A images ~~acquired~~ on July 29, August 13 and September 7, 2017 were used to recognize and locate the earthquake-triggered landslides. Sentinel-2A image has 13 spectral bands (from ~~the~~ blue to ~~the~~ shortwave infrared) with the spatial resolution of 10 m, 20 m and 60 m,

respectively. In this study, three visible bands (red, green, blue) with the spatial resolution of 10 m were adopted to ~~establish the image feature sets of earthquake-triggered landslides based on the visual interpretation of the landslide image characteristics.~~ analysis the image characteristics of earthquake-triggered landslides. With the aid of ~~computer-aided GIS tools~~ ArcGIS and ENVI tools, the landslide information of the study area was extracted using on-screen visual interpretation on pre- and post-earthquake Sentinel-2A images~~, as examples presented in Fig. 2~~. In order to ensure the quality of visual interpretation, GF-1 images with spatial resolution of 2 m ~~acquired~~ on January 15, 2017, were used to verify the results. Consequently, a total number of 842 earthquake-triggered landslides were recognized and positioned. Smaller landslides with total pixels less than 20 were not included as they were not clear enough in visual features. We assumed that the distribution of the earthquake-triggered landslides was reasonably accurate and complete at regional scale in order to make the problem tractable. For earthquake-triggered landslide susceptibility mapping, the landslide inventory dataset was randomly split into two groups, among which 80 % (673 landslides) of the recognized landslides was used for training the integrated weighted index model and the remaining 20 % (169 landslides) for validation.

3.2 Landslide controlling factors

The occurrence of landslides is a consequence of geological, meteorological, anthropogenic and triggering factors, commonly referred to as landslide controlling factors (Bai et al., 2010). Standard guidelines for choosing the optimal landslide controlling factors are unavailable, but the scale of ~~the~~ analysis, the nature of the study area, the data availability and the quasi-empirical and statistical criterions in literatures can be referenced (Romer and Ferentinou, 2016; Zhou et al., 2016). In ~~present~~ this study, slope, aspect, elevation, lithology, distance from faults, distance from rivers, land-use/cover (LULC), normalized difference vegetation index (NDVI) and peak ground acceleration (PGA) were selected as the landslide controlling factors, as shown in Fig. 3~~, for analysis~~.

Among all landslide controlling factors, slope, aspect and elevation have been recognized as the most important topographic factors closely related to landslides (Ayalew and Yamagishi, 2005; Chalkias et al., 2016). Slope directly affects the velocity of both surface and subsurface flows (Su et al., 2015). ~~Pioneer studies suggested that~~ Landslides become more possible once the slope gradient is higher than 15° (Lee and Min, 2001). In the study area, the slopes were generally steep, with an average slope angle of about ~~29.92~~ 30°. Aspect, referred to the direction of slope faces, is related to ~~the~~ soil moisture, surface runoff and vegetation ~~growing conditions~~, which indirectly affects ~~the~~ landslide development (Zhang et al., 2016). The elevation, as the measure of the land surface height, is a key factor determining gravitational potential energy of terrain and ~~was~~ is often considered in relevant studies (Conforti et al., 2014; Peng et al., 2014). ~~In the study area, the rugged terrain makes the slope very unstable.~~ Topographic factors can be calculated with DEM. The DEM from SRTM database was used to extract slope (0°–78°), aspect and elevation (1624--4855 m ~~in the study area~~) in the study area.

Lithology is directly related to the slope stability, which plays an important role as one of landslide controlling factors (Guo et al., 2015, Saha et al., 2002). Ten geological formation units including Quaternary (Q, Qh), Triassic (T1, T2, T3), Permian (P, P2), Carboniferous (C), and Devonian (D) outcrop in the study area (Wang et al., 2018a). ~~For~~ During the Jiuzhaigou earthquake, most landslides in the study area occurred in the carboniferous formations which is mainly composed of metamorphic quartzite sandstones, limestone and slate (Fan et al., 2018). In addition, the Permian limestone and Triassic sandstone also exhibited a large number of landslides. In this study, the lithological data was obtained from the geological map at 1: 500,000 scale and was digitized in ArcGIS for further analysis. The distances of a slope from faults as well as from the river channels are also important factors in terms of slope stability (Kanungo et al., 2006). In addition, earthquake-triggered landslides ~~usually~~ are usually found in the vicinity of active faults. Hence, the distances of a slope from geological tectonic zone were often taken into account in slope stability analysis. ~~According to the China Earthquake Administration, the epicentre of the Jiuzhaigou earthquake was located near the Minjiang, Tazang and Huya faults. Some studies~~ Fan et al. (2018) had revealed that this earthquake occurred along a previously unknown blind fault probably belonging to a south branch of the Tazang fault or north part of the Huya fault ~~(Fan et al., 2018)~~. However, due to its great uncertainty, this blind fault was not taken into account in the study area. In this study, the faults were digitized from the geological map at 1: 500,000 scale, and the river channels were interpreted from remote sensing images. ~~Streams also have an impact on the slope stability because soil water erosion is prone to take place next to the rivers on slopes.~~ And the LULC map is one of controlling factors that pose direct impact on the occurrence of landslides (Song et al., 2012; Mansouri Daneshvar, 2014). ~~For the Jiuzhaigou earthquake, most landslides in the study area occurred in the wood land.~~ In this study, ~~the lithological data was obtained from the geological map at 1: 500,000 scale and was digitized in ArcGIS for further analysis.~~ the LULC map was downloaded from the Geographical Information Monitoring Cloud Platform.

Vegetation coverage poses effect on soil water erosion, which indirectly affects the occurrence of landslides. NDVI, as the measure of vegetation coverage, ~~was~~ is usually adopted in landslide susceptibility analysis (Siqueira et al., 2015). The NDVI ~~was~~ is calculated from these individual measurements as follows:

$$NDVI = \frac{DN_{NIR} - DN_R}{DN_{NIR} + DN_R}, \quad (1)$$

Where, DN_{NIR} stands for the spectral reflectance derived from the measured radiances in the near-infrared regions (NIR), and DN_R stands for the spectral reflectance derived from the measured radiances in the visible (Red) regions.

In this study, the NDVI map was generated from the Landsat-8 image acquired on April 8, 2017 over the study area.

~~As an important dynamic factor, earthquake~~ Earthquake as an important dynamic factor, often triggers slope failures (Xu et al., 2012a). Usually, the impact of earthquake on landslides ~~was~~ is measured and quantified by recording the absolute maximum

amplitude of ground acceleration (PGA) (Chalkias et al., 2016). In this study, the PGA map of the study area was downloaded from the USGS website (https://www.usgs.gov).

~~Landslide controlling factors, i.e., (a) slope, (b) aspect, (c) elevation, (d) lithology, (e) distance from faults, (f) distance from rivers, (g) LULC, (h) NDVI, (i) PGA, as illustrated in Fig. 3, were generated as described above.~~ To ensure the consistency and easy process of these data, all factor layers were converted into raster data format (GeoTIFF) with an identical spatial projection (WGS84 datum) and resampled to a resolution of 30 m by ENVI 5.3 and ArcGIS 10.2.

4 Methodology

In this study, an integrated weighted index model was developed as a complete landslide susceptibility model by combining AHP and FR approaches. ~~The assumption behind the integrated weighted index model was that future landslides will occur under similar environmental conditions as historical landslides (Guzzetti et al., 1999; Pourghasemi and Rahmati, 2018), and the susceptibility can be evaluated from the relationship between the controlling factors and the landslide occurrence area (Zhu et al., 2014). In the present study,~~ As shown in Fig. 4, the integrated weighted index model was run through three general steps: (1) determining the relative importance of landslide controlling factors using AHP method, (2) characterizing the relationships between controlling factors and landslide locations using FR and GIS techniques, and (3) predicting landslide susceptibility using ~~weighted overlay analysis~~ Weighted Overlay Analysis tool of ArcGIS. ~~The integrated model can assess the correlation between the controlling factors and also the influence of each landslide controlling factor on landslide occurrence.~~

~~The integrated weighted index was calculated as follows:~~

~~$I = \sum_i^m (W_i \times FR_i)$, (2)~~

~~Where, m stands for number of controlling factors, W_i is the weight of each controlling factor calculated by the AHP method, FR_i is the FR value of the controlling factor calculated by the FR method.~~

4.1 Analytical hierarchy process (AHP)

The AHP method, developed by Saaty (Saaty, 1977), is an important multiple criteria decision-making method (Vaidya and Kumar, 2006), which has been applied for landslide susceptibility assessment for many years (Akgun, 2012; Barredo et al., 2000; Kayastha et al., 2013; Komac, 2006; Pourghasemi et al., 2012; Yalcin, 2008).

~~For the AHP, a complex non structural problem was broken into its component parameters which were considered as the factors of this study. Then, the contribution of factors was converted into numerical values with the help of a pair wise comparison matrix generated through comparing the relative importance of each factor based on the expert's prior experience and knowledge (Vargas, 1990). In addition, it also provided a methodology to judge the relative importance of factors by~~

~~scoring. When a factor is more important than another, the score varies between 1 and 9. Conversely, the score varies between 1/2 and 1/9. The higher the score, the greater the importance of the factor. Finally, weights of factors were determined in the process of a pair-wise comparison matrix using Python software, and the weights with the Consistency Ratio (CR) less than 0.1 were accepted.~~

In the AHP, a complex non-structural problem is first broken down into several component factors. Then, based on the expert's prior experience and knowledge, a pair-wise comparison matrix can be constructed through comparing the relative importance of each factor (Vargas, 1990). An underlying 9-point recording scale is used to rate the relative importance of factors (Mansouri Daneshvar, 2014). Specifically, when a factor is more important than another, the score varies between 1 and 9. Conversely, the score varies between 1/2 and 1/9. The higher the score, the greater the importance of the factor. With the help of a pair-wise comparison matrix, the contribution of factors can be converted into numerical values. Note that a consistency check of comparison matrix needs to be carried out, and the Consistency Ratio (CR) of less than 0.1 is generally accepted.

In this study, the relative importance of landslide controlling factors was determined from the prior experience and knowledge of experts. Since the knowledge source varies from person to person, the best judgment always comes from an individual who has good expertise (Ayalew et al., 2004). To find the appropriate correlation between controlling factors, we investigated some related literatures (Shahabi and Hashim, 2015; Xu et al., 2012b; Zhang et al., 2016) and consulted with some professional experts. Finally, the pair-wise comparison matrix was determined by means of discussion (Table 2) and a general consensus achieved by experts. Weights of factors were determined in the process of a pair-wise comparison matrix using Python software, as shown in Table 2. The Consistency Ratio (CR) for this study was 0.017, which showed that the pair-wise comparison matrix satisfied the consistency requirement.

4.2 Frequency ratio (FR)

The FR method is one of the most widely used approaches to assess the landslide susceptibility at regional scale (Guo et al., 2015; Li et al., 2017; Mohammady et al., 2012), which is based on the observed spatial relationship between landslide locations and controlling factors (Lee and Pradhan, 2007; Poudyal et al., 2010). The assumption behind the FR is that future landslides will occur under similar environmental conditions as historical landslides (Guzzetti et al., 1999; Pourghasemi and Rahmati, 2018), and the susceptibility can be evaluated from the relationship between the controlling factors and the landslide occurrence area (Zhu et al., 2014). The definition of FR is the ratio of the probability of the occurrence to the non-occurrence for given properties (Lee and Talib, 2005). The spatial relationship between landslides and controlling factors can be investigated ~~through~~ by using the FR method. Therefore, the FR values of each controlling factor category were calculated from their relationship with landslide occurrence locations as illustrated in Table 3. The average value of FR is 1 so that a value larger than one represents a higher correlation and those less than it, a lower correlation (Romer and Ferentinou, 2016).

The FR value can be calculated as follows (Ghobadi et al., 2017):

$$FR_i = \frac{Ncell(S_i)/Ncell(N_i)}{\sum Ncell(S_i)/\sum Ncell(N_i)} \quad (3)(2)$$

Where, $Ncell(S_i)$ represents number of grid cells recognized as landslides in class i, and $Ncell(N_i)$ represents total number of grid cells belonging to class i in the whole area; while $\sum Ncell(S_i)$ stands for the total number of grid cells recognized as landslides in the whole area, and $\sum Ncell(N_i)$ represents total number of grid cells in the whole area.

4.3 Integrated weighted index

The integrated weighted index is considered to measure the probability of slope failures. By combining FR and AHP methods, the integrated weighted model can assess the correlation between the controlling factors and also the influence of each landslide controlling factor on landslide occurrence.

The integrated weighted index can be calculated as follows:

$$I = \sum_i^m (W_i \times FR_i) \quad (3)$$

Where, m stands for number of controlling factors, W_i is the weight of each controlling factor calculated by the AHP method, FR_i is the FR value of the controlling factor calculated by the FR method.

In this study, the values of W_i and FR_i were used to obtain the integrated weighted index of each grid cell in the study area, and the final landslide susceptibility map was generated by using Weighted Overlay Analysis tool of ArcGIS.

5 Results and discussions

5.1 Landslide susceptibility mapping

~~In this study, the relative importance of landslide controlling factors was determined from the prior experience and knowledge of experts. Since the knowledge source varies from person to person, the best judgment always comes from an individual who has good expertise (Ayalew et al., 2004). To find the appropriate correlation between controlling factors, we investigated some related literatures (Shahabi and Hashim, 2015; Xu et al., 2012b; Zhang et al., 2016) and consulted with some professional experts. Finally, the pair-wise comparison matrix was determined by means of discussion (Table 2) and a general consensus achieved by experts.~~ The AHP method was used to assign the weights for each controlling factor ~~(Table 2)~~. The higher the weight was, the more impacts on landslide occurrence could be expected. ~~In the~~ As shown in Table 2, the ~~weights for the nine controlling factors were estimated as follows: slope – 0.222, aspect – 0.043, elevation – 0.058, lithology – 0.116, distance from faults – 0.197, distance from rivers – 0.080, LULC – 0.083, NDVI – 0.043 and PGA – 0.158. The Consistency Ratio was 0.017, which showed that the pair-wise comparison matrix satisfied the consistency requirement. The higher the weight, the more~~

impacts on landslide occurrence could be expected. The weight of slope was highest, implying the most significant influence of slope on the landslide occurrence, and the weights of aspect and NDVI were the lowest, which indicated that these two factors played the least role in the landslide occurrence.

Thus, the FR was considered as a measure for the spatial relationship between landslides and controlling factors. Through analysing the relationship between each controlling factor and the landslide occurrence, the FR values were calculated by using the Eq. (3) (as shown in Table 3). The higher the FR was, the closer the relationship between the landslide controlling factor and the landslide occurrence would be. The FR values of each controlling factor category were calculated by using the Eq. (2) (as shown in Table 3). Table 3 clearly shows the relationship between each controlling factor and the landslide occurrence. In the term of the relationship between landslide occurrence and slope, landslides mostly occurred in the slope ranging from 40° to 60°. For the elevation, landslides mostly occurred below the elevation of 3400 m, which implied that the probability of landslide occurrence was higher in moderate steep mountainous region. In terms of the aspect, the FR value was very high for the class of E, N, SE and NE, and it was lowest for the class of Flat. For the lithology, the highest FR value was achieved for Permian System which influenced the landslide occurrence. For the factor of distance from faults, the highest FR value belonged to the area higher than 2000 m. The distance from rivers with the highest FR value for frequent landslide occurrence was found usually between 0 and 600 m, and landslides mostly occurred in the region with low vegetation cover of less NDVI value. In the case of PGA, the value of 0.26 g had the highest FR value, which indicated the significant influence of the earthquake on the landslide occurrence. In general, our results were basically consistent with the previous study (Fan et al., 2018), which found that most of the landslides mainly occurred in proximity of rivers and the epicentre, with an elevation of 2600 m to 3200 m and a slope of 35° to 55°.

Finally, the weighted index was calculated by using the Eq. (2). The landslide susceptibility map of study area was generated by using Weighted Overlay Analysis tool of ArcGIS, and the study area was classified into seven categories of landslide susceptibility levels as presented in Fig. 45: very high, high, relatively high, moderate, relatively low, low and very low by using Natural Breaks (Jenks) method with ArcGIS, respectively.

According to the landslide susceptibility map, the location close to the epicentre and rivers was classified as the most susceptible areas for landslides, and the high and very high landslide susceptible areas mostly located in the middle central mountainous region accounting for 10.99 % of the study area. The low and very low susceptibility areas far from the epicentre and less affected by the earthquake, mainly distributed in the North and South-West parts of the study area, accounting for approximately 35.06 % of the study area. Generally, the landslide susceptibility map generated by the integrated weighted index model can reflect the potential area of the landslide occurrence in the study area. Table 4 presented the distribution of seven landslide susceptibility levels. As indicated in Table 4, the very low susceptible area covered 9.72 % of the whole area,

whereas low, relatively low, moderate, relatively high, high and very high susceptible areas covered 25.34 %, 22.92 %, 17.76 %, 13.27 %, 7.97 % and 3.02% of the whole area, respectively. A total of 61.76 % of the landslides were observed in the high and very high susceptibility areas, and only 3.08 % of the landslides were observed in the low and very low susceptibility areas. For the landslide density, the values for very low, low, relatively low, moderate, relatively high, high and very high were 0.03, 0.06, 0.11, 0.37, 0.96, 3.03 and 4.79, respectively. The landslide density for the very high susceptible area was significantly larger than for the other susceptible areas.

5.2 Validations

For landslide susceptibility mapping, ~~detailed~~ validation of the modelled results is essential. A simple procedure of validation can make a comprehensive and reasonable interpretation of the future landslide hazard (Chung and Fabbri, 2003).

In this study, operating characteristics curve (ROC) approach (Brenning, 2005; Bui et al., 2016) was adopted to evaluate the performance of the integrated weighted index model, including the degree of model fit and model predictive capability. The ROC curve was obtained by calculating the area under the curve (AUC) and the AUC value varied from 0.5 to 1.0 (Umar et al., 2014). The AUC value of 1.0 implied a perfect performance of the model, whereas a value close to 0.5 indicated that the model performed not so well. To assess the fitting performance of the integrated weighted index model, five sub-datasets containing 20 %, 40 %, 60 %, 80 % and 100 % of training dataset (i.e., 673 landslides) respectively, were used to obtain the fitting curves ~~(Fig. 5(a))~~. Figure ~~5~~6(a) shows a quantitative measure of the ability of integrated weighted index model to describe the known distribution of landslides. The AUC values of five sub-datasets were 82.57 %, 84.52 %, 84.99 %, 86.08 % and 85.65 %, respectively, which suggested the effective fitting capability of the integrated weighted index model developed in this study.

To investigate the prediction performance of the integrated weighted index model, we also adopted five sub-datasets containing 20 %, 40 %, 60 %, 80 % and 100 % of validation dataset (i.e., 169 landslides) respectively, to estimate the prediction rates. Note that the validation dataset (i.e., 20 % of the landslide inventory dataset) was not used in the training process. The AUC values of five sub-datasets, as presented in Fig. ~~5~~6(b), were 78.71 %, 81.66 %, 84.27 %, 86.09 % and 87.16 %, respectively. With the increase of input data, the performance of the integrated weighted index model was significantly improved, which indicated a reliable predicting capability of the integrated weighted index model adopted in this study.

In addition, the landslide density distribution of each susceptibility level was computed by associating landslides with the classified landslide susceptibility map (as shown in Table 4). There was a clear trend that the increase in the level of landslide susceptibility was highly correlated with the density of landslides. The high and very high susceptibility levels had the significant high landslide density values, while the low susceptibility categories were just the opposite, which also implied the effectiveness of the generated landslide susceptibility map of the study area.

5.3 Discussions

Landslide susceptibility is defined as the likelihood of landslides occurring in an area under local environmental conditions (Fell et al., 2008; Reichenbach et al., 2018). ~~The susceptibility can be evaluated from the relationship between the environmental conditions and previous landslides (Zhu et al., 2014). There are numerous methods that have been proposed to model this relationship.~~ There are numerous methods that have been proposed to evaluate the susceptibility. The main purpose of this study ~~was~~ is to assess the spatial probability of landslide occurrences by using an integrated weighted index model in association with the utilization of FR and AHP approaches ~~to generate an earthquake-triggered landslide susceptibility map. To achieve this objective, nine controlling factors (slope, aspect, elevation, lithology, distance from faults, and distance from rivers, LULC, NDVI and PGA) were taken into consideration~~. The FR is a data-driven statistical approach which can derive spatial relationship between landslide locations and controlling factors. However, the FR method does not consider the mutual relationships between controlling factors. The AHP method is an important multiple criteria decision-making method, which can overcome this shortcoming. To some extent, the integrated method preserves the advantages of FR and AHP methods and restrains their weak points. Some similar studies have also pointed it out (Reichenbach et al., 2018; Youssef et al., 2015; Zhou et al., 2016).

The implementation of the integrated weighted index model revealed that landslide susceptibility levels were basically consistent with the distribution of earthquake-triggered landslides. The high susceptibility areas were concentrated in the central mountainous region close to the epicentre of the earthquake of the study area, which indicated the significant influence of the Jiuzhaigou earthquake on the landslide occurrence. From the landslide susceptibility map (as shown in Fig. 5 and Table 4), the “very high” and "high" susceptibility areas covered 10.99 % of the whole area ~~a significant part of the study area (10.99 % of the whole area)~~ and most of the Jiuzhaigou National Nature Reserve was classified as the most landslide susceptible areas. Even though, some limitations yet existed in the proposed method. Firstly, the accuracy of FR method is highly depended on the quality of dataset, especially the landslide inventory (Zhou et al., 2016). Nevertheless, the landslide inventory is generally incomplete (Fell et al., 2008), and is affected by many factors, such as the quality and scale of remote sensing images, the tectonic setting complexity of study area, and the expertise of the interpreter involved (Malamud et al., 2004). In this study, we mainly focused on the interpretation of earthquake-triggered landslides, and interpretation results were basically consistent with the previous studies (Fan et al., 2018; Wang et al., 2018a; Wang et al., 2018b). We didn’t accurately identify the landslides before the Jiuzhaigou earthquake due to the limitations of historical images, and smaller landslides were also not completely identified. Future work should focus on the preparation of more detailed landslide inventories. Secondly, in this study, as the proposed method was applied to medium-scale datasets, the results may not be suitable for specific analysis of large or detailed scale. At large or detailed scales, more detailed landslide inventory dataset and controlling factor layers ~~were~~ are required.

Additionally, the assumption behind much of the landslide susceptibility mapping is that future landslides will occur under similar environmental conditions as historical landslides (Guzzetti et al., 1999; Pourghasemi and Rahmati, 2018). However, results obtained in the past environmental conditions are not a guarantee for the future (Guzzetti et al., 2005). In this study, we used a weighted index model by integrating the AHP and FR approaches to map the earthquake-triggered landslides susceptibility and the generated susceptibility map of the study area was made for the present situation. The susceptibility results need to be adapted as soon as environmental conditions or their causal relationships obviously change in the future~~, such as urban sprawl (van Westen et al., 2008)~~. Despite its limitations, the integrated method can generate a reliable landslide susceptibility map at regional scale which can provide the ~~scientific basis~~ rapid assessment for reconstruction of tourism facilities, regional disaster management etc.

6 Conclusions

Earthquake is one of the dynamic causes in landslide occurrence. Earthquake-triggered landslides can cause extensive and significant damages to both lives and properties. In this study, given the main motivation to adopt an integrated weighted index model based on FR and AHP methods for earthquake-triggered landslide susceptibility mapping at the Zhangzha town of the Jiuzhaigou County where a ~~Ms 7.0~~ Mw 6.5 earthquake struck on Tuesday, 8 August 2017, nine factors such as slope, aspect, elevation, lithology, distance from faults, distance from rivers, LULC, NDVI and PGA as landslide controlling factors were adopted in the integrated weighted index model for generating the landslide susceptibility map of the study area with reclassification of seven levels of landslide susceptibility areas within a GIS environment. The ROC approach was used to comprehensively evaluate the performance of the integrated weighted index model, including the degree of model fit and model predictive capability. The results demonstrated the reliability and feasibility of the integrated weighted index model in landslide susceptibility mapping at regional scale.

Even some limitations do exist, the integrated weighted index model can generate a reliable landslide susceptibility map at regional scale that is useful for~~ serving the scientific basis for disaster mitigation and management.~~ engineers and decision makers to understand the probability of landslides and mitigate hazards. Furthermore, the integration of some machine learning techniques should be taken into account in the integrated weighted index model for advancement in future studies.

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Figures

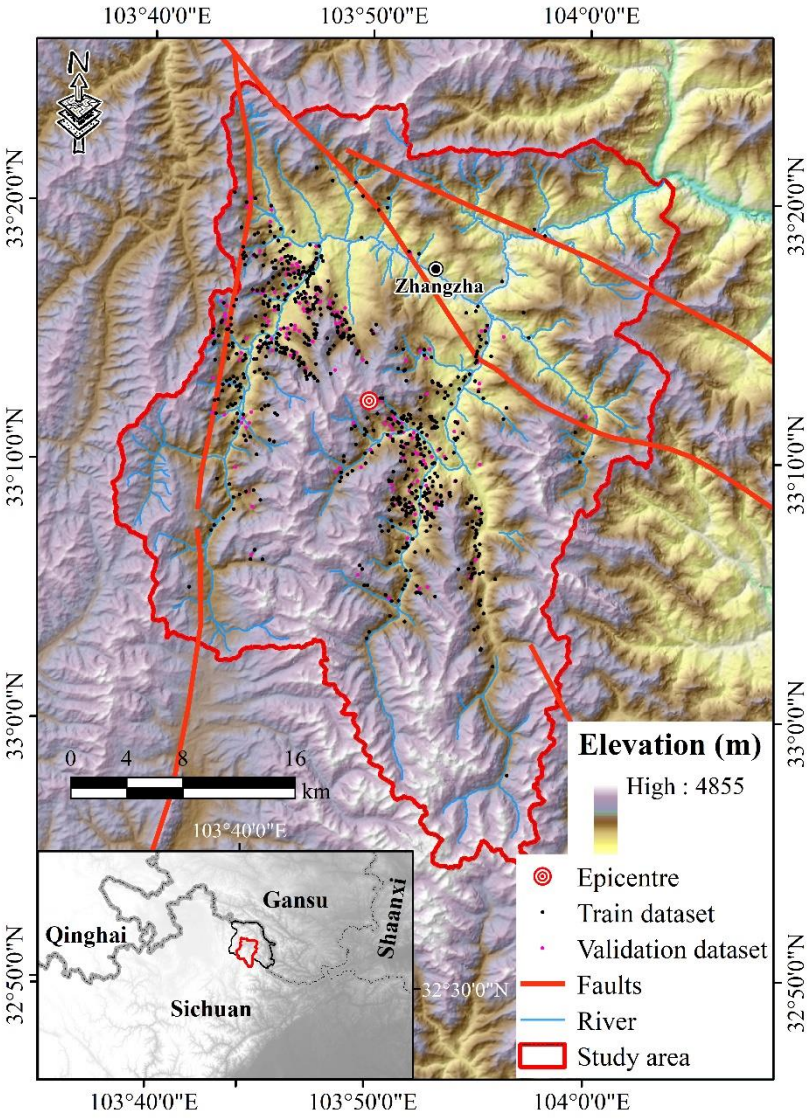

Figure 1: The digital map showing the location, topography, river networks, faults, epicentre of the Jiuzhaigou earthquake, as well as the locations of earthquake-triggered landslides for training and validation over the study area.

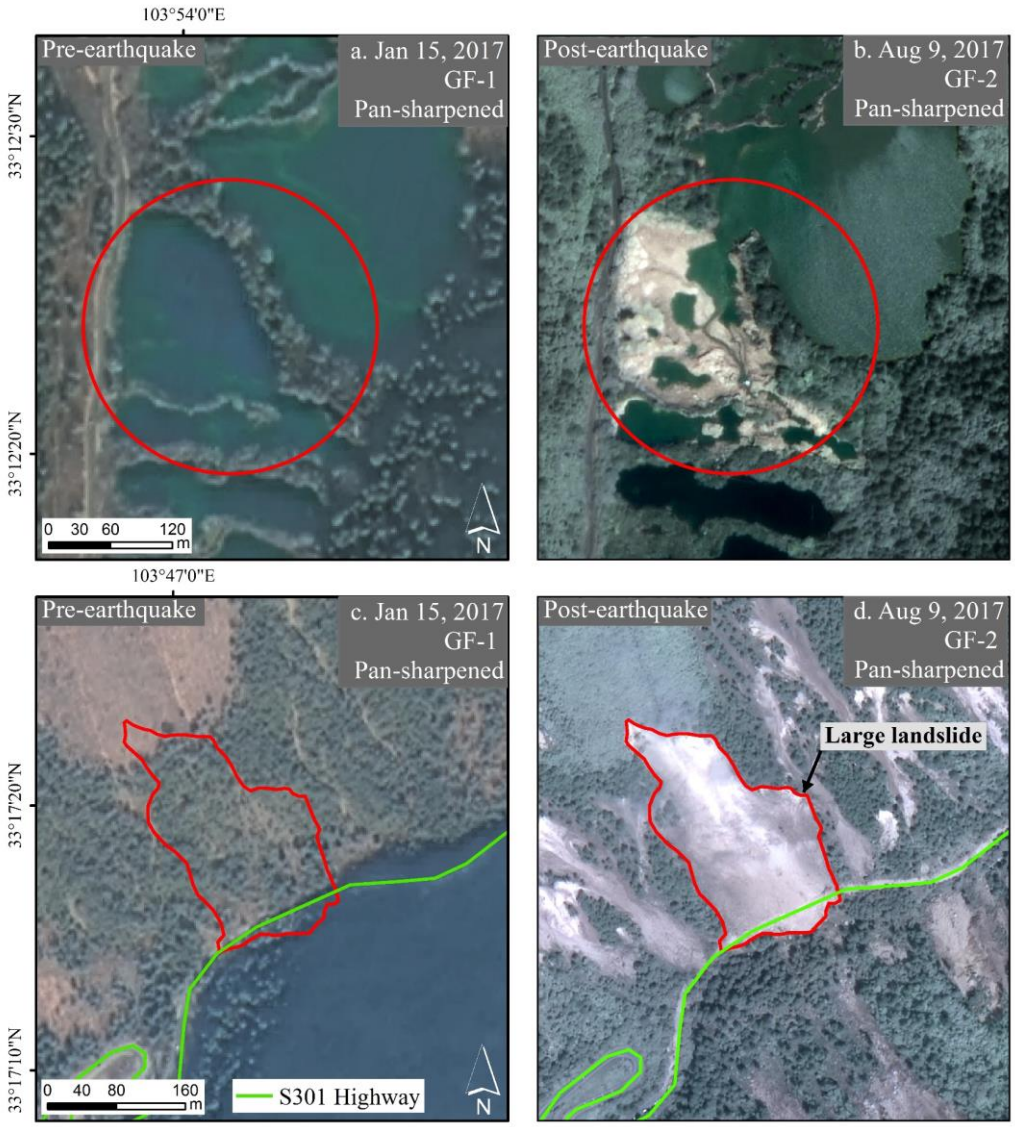

Figure 2: Remote sensing interpretation for earthquake disaster of the study area. a) 2 m spatial resolution GF-1 remotely sensed image ~~acquired~~ on January 15, 2017 before the earthquake compared with b) 1 m spatial resolution GF-2 remotely sensed image ~~acquired~~ on August 9, 2017 after the earthquake, clearly revealed the dried up of the Sparkling Lake after the Jiuzhaigou earthquake; c) 2 m spatial resolution GF-1 remotely sensed image ~~acquired~~ on January 15, 2017 before the earthquake compared with d) 1 m spatial resolution GF-2 remotely sensed image ~~acquired~~ on August 9, 2017 after the earthquake, illustrated the damage of the S301 highway in the Jiuzhaigou earthquake.

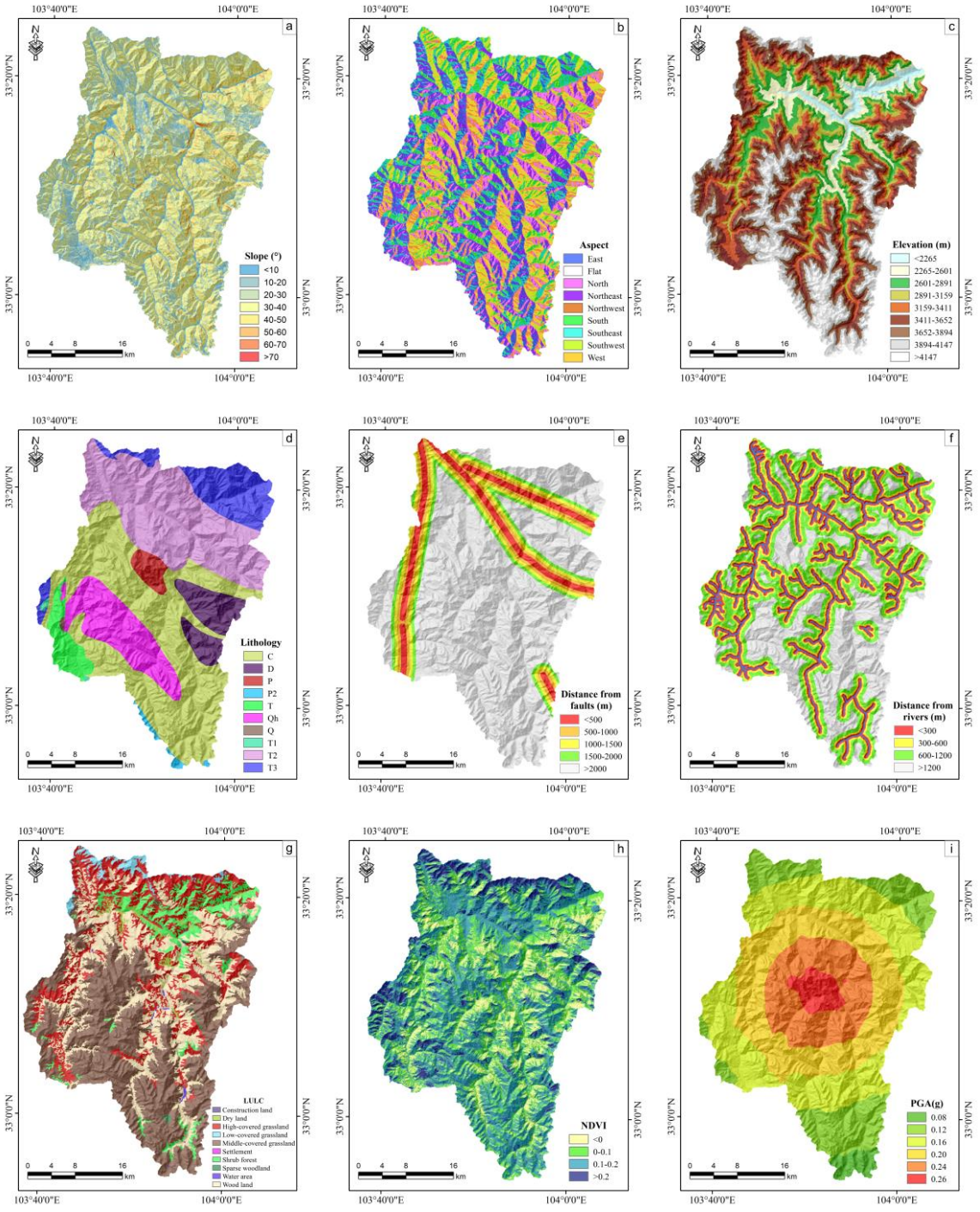

Figure 3: Landslide controlling factor layers used for landslide susceptibility mapping in the study area. (a) Slope, (b) Aspect, (c) Elevation, were all extracted from DEM data, (d) Lithology, digitized from the geological map at 1: 500,000 scale, (e) Distance from faults, calculated by ArcGIS 10.2 software, (f) Distance from rivers, calculated by ArcGIS 10.2 software, (g) LULC, collected from the Geographical Information Monitoring Cloud Platform, (h) NDVI, extracted from the Landsat-8 image, (i) PGA, downloaded from the USGS website.

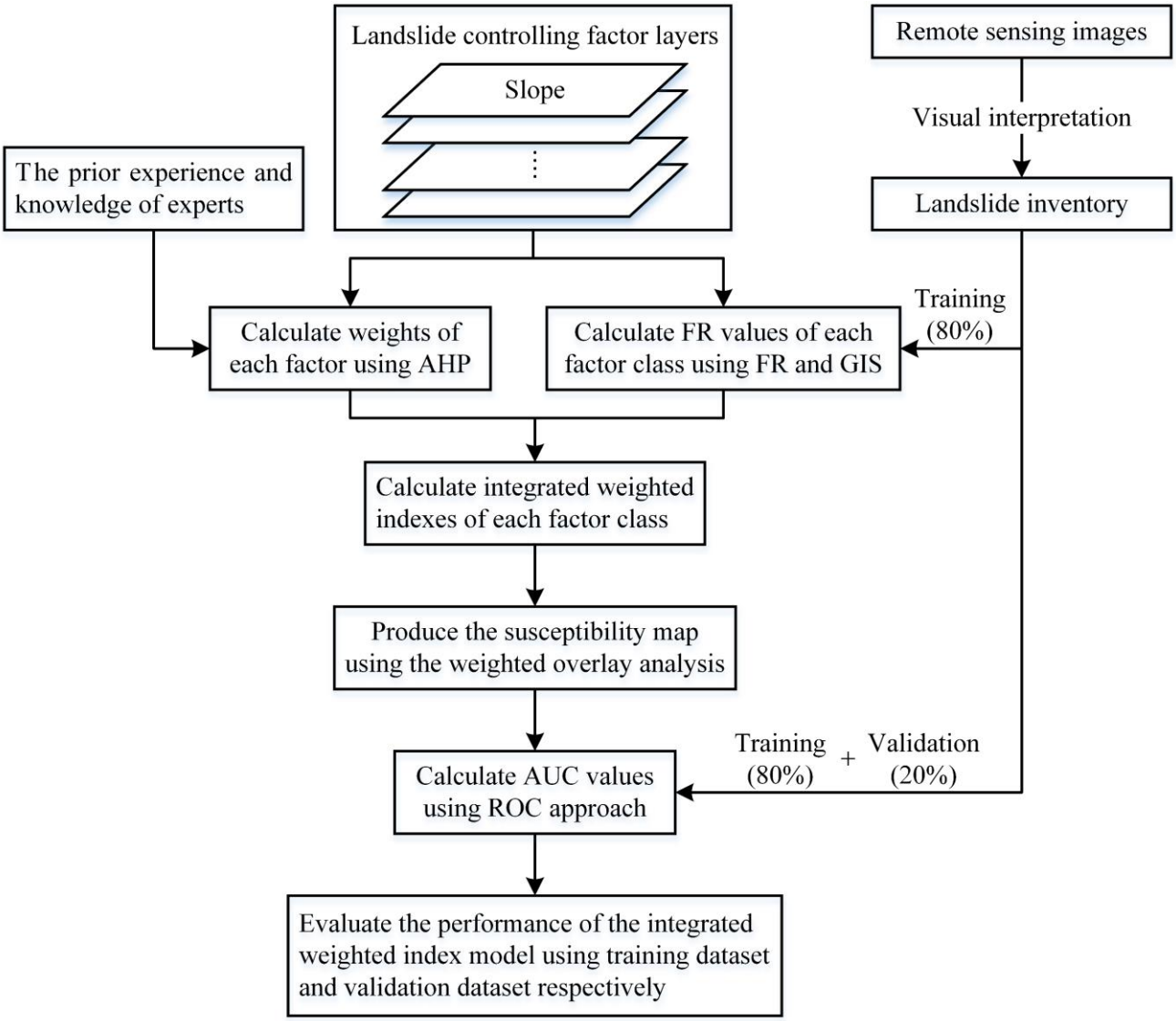

Figure 4: Flow chart of the landslide susceptibility mapping.

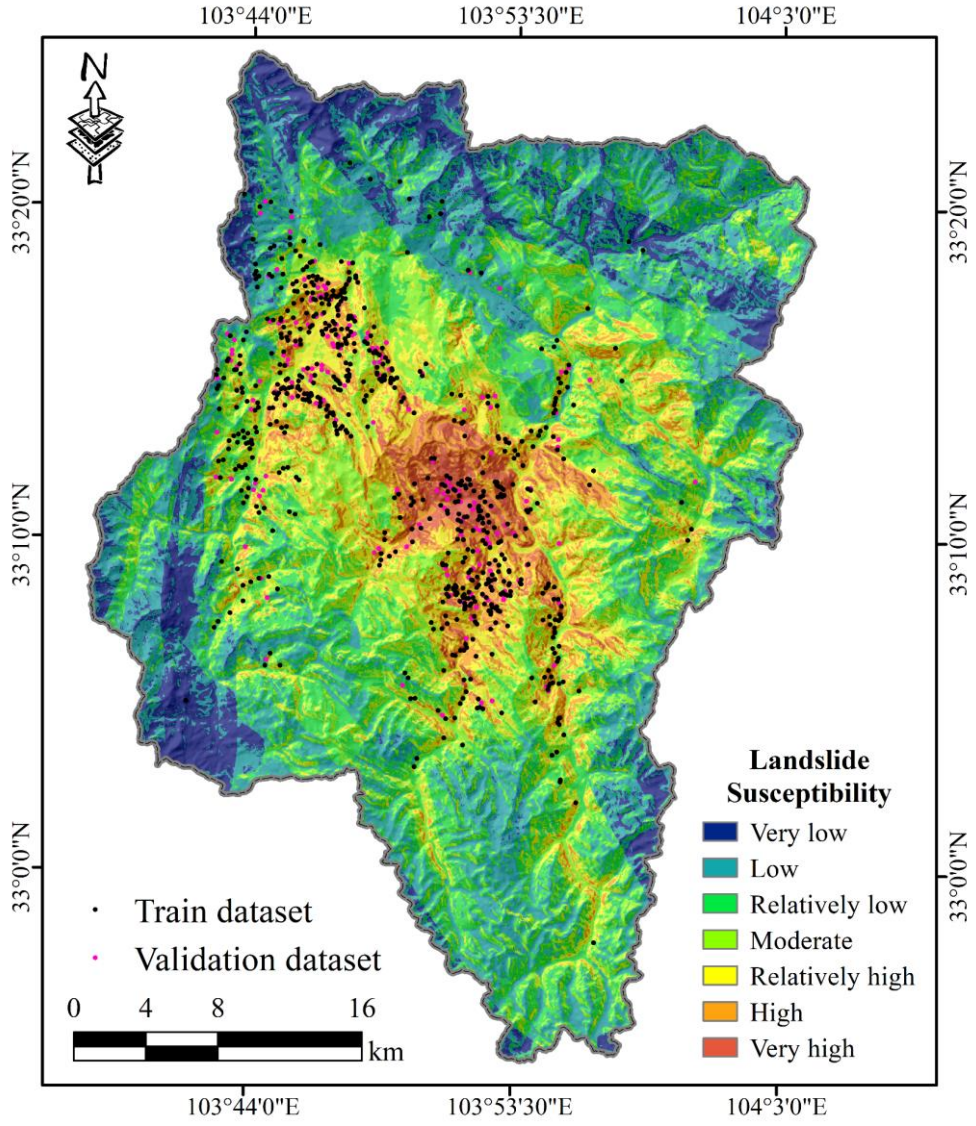

Figure 45: Landslide susceptibility map of the study area generated by using the integrated weighted index model.

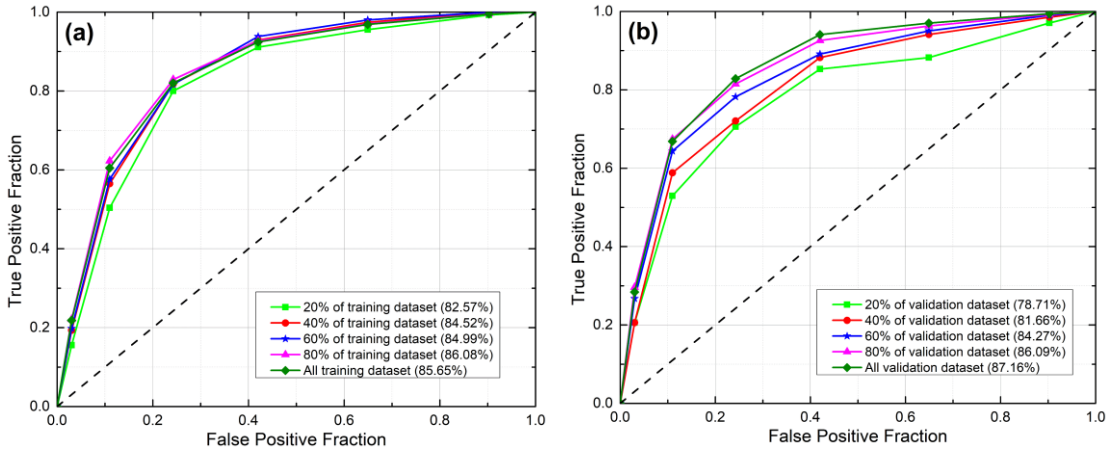

Figure 56: ROC curves of the Jiuzhaigou landslide susceptibility assessment. (a) Fitting performance of the integrated weighted index model; (b) Prediction performance of the integrated weighted index model.

Tables

Table 1: Data layers of the study area.

Data layer	Data format	Scale/resolution	Data source
DEM	Grid	30 m	Shuttle Radar Topography Mission (SRTM)
Sentinel-2A	IMAGINE image	10 m	European Space Agency
Landsat-8	IMAGINE image	30 m	United States Geological Survey (USGS)
GF-1/2	IMAGINE image	2 m/1 m	China Centre for Resources Satellite Data and Application
Lithology	Shapefile (polygon)	1:500,000	The geological map
Fault	Shapefile (line)	1: 500,000	China Earthquake Administration
River	Shapefile (line)	1:10,000	Remote sensing interpretation
LULC	Grid	30 m	Geographical Information Monitoring Cloud Platform
PGA	Shapefile (polygon)	1:25,000	United States Geological Survey (USGS)

Table 2: The pair-wise comparison matrix, factor weights, and consistency ratio obtained in present study.

Factor	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	Weight
Elevation (a_1)	1	1/4	2	1/3	1/4	1	1/3	1/2	2	0.058
Slope (a_2)		1	4	2	1	3	2	3	4	0.222
Aspect ($a_{3)}$			1	1/3	1/4	1/2	1/3	1/2	1	0.043
Lithology (a_4)				1	1/2	1	1/2	2	3	0.116
Distance from faults (a_5)					1	2	1	3	4	0.197
LULC (a_6)						1	1/2	1	2	0.083
PGA (a_7)							1	2	3	0.158
Distance from rivers (a_8)								1	2	0.080
NDVI (a_9)									1	0.043
Consistency Ratio: 0.017										

Table 3: The FR and weights for landslide controlling factors for the study area.

Factor	Class	FR	Weight	Factor	Class	FR	Weight
Slope (°)	<10	0.000	0.222	Elevation(m)	<2265	0.451	0.058
	10-20	0.106			2265-2601	1.153	
	20-30	0.431			2601-2891	2.411	
	30-40	1.270			2891-3159	2.437	
	40-50	2.330			3159-3411	1.496	
	50-60	2.807			3411-3652	0.819	
	60-70	1.804			3652-3894	0.177	
	>70	0.000			3894-4147	0.021	
Aspect	Flat	0.000	0.043		>4147	0.000	
	N	1.305		Lithology	T3	0.030	0.116
	NE	1.116			T2	0.528	
	E	1.662			P	3.431	
	SE	1.343			C	1.819	
	SE	0.965			D	0.544	
	SW	0.590			P2	0.000	
	W	0.646			T	0.039	
	NW	0.560			T1	0.000	
	N	0.819			Qh	0.471	
Distance from	<500	0.689	0.197		Q	0.000	
faults (m)	500-1000	0.482		Distance from	<300	1.302	0.080
	1000-1500	0.594		rivers (m)	300-600	1.162	
	1500-2000	0.606			600-1200	0.795	
	>2000	1.169			>1200	0.863	
NDVI	<0	1.211	0.043	LULC	Dry land	0.796	0.083
	0-0.1	1.199			Wood land	2.085	
	0.1-0.2	0.975			Shrub forest	0.164	
	>0.2	0.306			Sparse woodland	0.000	
PGA (g)	0.08	0.000	0.158		Water area	0.970	
	0.12	0.009			High-covered grassland	1.072	
	0.16	0.273			Medium-covered grassland	0.550	
	0.20	1.448			Low-covered grassland	0.000	
	0.24	2.194			Settlement	0.000	
	0.26	3.578			Construction	0.000	

Table 4: Landslide susceptibility levels and density of landslides in the study area.

Susceptibility level	Area (km^2)	Percentage of area	Number of landslide occurrences	Percentage of number	Density (no./km^2)
Very Low	130.81	9.72 %	4	0.47 %	0.03
Low	340.86	25.34 %	22	2.61 %	0.06
Relatively low	308.29	22.92 %	35	4.16 %	0.11
Moderate	238.84	17.76 %	89	10.57 %	0.37
Relatively high	178.52	13.27 %	172	20.43 %	0.96
High	107.20	7.97 %	325	38.60 %	3.03
Very High	40.67	3.02 %	195	23.16 %	4.79
Total	1345.19	100 %	842	100 %	--