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Quantitative assessment of landslide susceptibility along the Xianshuihe fault zone, Tibetan Plateau, China

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ABSTRACT

The Xianshuihe fault (XSF) zone is a sinistral-slip fault system on the eastern margin of the Tibetan Plateau, with high Quaternary activity and frequent historic earthquakes. Large landslides along the fault zone have caused substantial damage and are the second-most important regional hazard after earthquakes. A landslide inventory in a 7339-km^2 area along the XSF zone documented 415 landslides and evaluated landslide distribution characteristics using frequency ratio (FR) and weight-of-evidence (WOE) models to map landslide susceptibility. A total of 11 variables were analyzed as input variables: slope angle, slope aspect, altitude, planform curvature, topographic wetness index, distance from active faults, lithology, annual rainfall, distance from rivers, distance from roads, and the NDVI of the study area. Among these factors, the distance from active faults, altitude, slope angle, aspect, lithology, and rainfall were the dominant influencing factors. Assessment of six susceptibility mapping schemes with FR and WOE models using the ROC method showed that, while all six of the model schemes produced good results, on the whole, the FR model performed better than the WOE model. The landslide susceptibility map of the FR model with six variables performed as well as the WOE model with the full 11 variables. Inclusion of more variables did not necessarily translate into a better predictive capability. Several factors typically associated with susceptibility to rainfall-triggered landslides—topographic convergence, rainfall, and topographic wetness index—either did not follow expected patterns (rainfall) or were not good general predictors of landslide locations (topographic convergence and wetness index). In contrast, distance to active faults, slope aspect, and topographic divergence were the best predictors as measured by the FR method. This combination points to earthquakes rather than rainfall as the dominant landslide-triggering mechanism in the study area.

1. Introduction

Landslides are one the most common natural hazards as unstable areas influence settlements and engineered structures around the world. Because of rapid urbanization in mountainous regions, landslides increasingly affect human beings; and the associated risks need to be taken into account in land management and construction. After earthquakes, landslides are the second-most important natural cause of damage to man-made structures in China. The Xianshuihe fault (XSF) zone is located at the southeast margin of the Tibetan Plateau (Fig. 1) in western Sichuan Province, China. It is surrounded by high mountains, with complex geologic structure, strong fault activity, and frequent historical earthquakes along the fault zone. Landslides are very common along the XSF because of the complex geology of tectonically sheared rock with weak mechanical properties and adverse climate (Chen et al., 2007; Wang et al., 2013; Li et al., 2014). Periodic landslides along roads and construction sites result in loss of life and property damage (Li et al., 2014), and major landslides along the XSF zone have seriously affected project planning and construction (Yao et al., 2012). To date, however, no landslide susceptibility mapping has been conducted along the XSF.

During the last several decades, the development of Geographical Information Systems (GIS) and remote sensing techniques facilitated the preparation of landslide susceptibility and hazard maps (e.g., Montgomery and Dietrich, 1994; Montgomery, 2003; van Westen and Getahun, 2003; Lan et al., 2004; Lee and Pradhan, 2007). Many studies have now been carried out on landslide hazard evaluation using GIS and geo-information related techniques based on probabilistic models (Gokceoglu et al., 2000; Clerici et al., 2006; Lee and Pradhan, 2006; Akgun et al., 2008; Pradhan and Lee, 2010; Yilmaz, 2010; Pourghasemi et al., 2012; Youssef et al., 2014), and logistic regression for landslide hazard mapping (e.g., Guzzetti et al., 1999; Lee and Sambath, 2006; Lee and Pradhan, 2007; Pradhan et al., 2008; Tunusluoglu et al., 2008; Bai et al., 2010; Oh and Lee, 2011; Akgun, 2012; Felicisimo et al., 2012). Most of the studies cited above have been conducted using regional landslide inventories derived from aerial photographs. Recently, other new methods have been applied for landslide hazard evaluation

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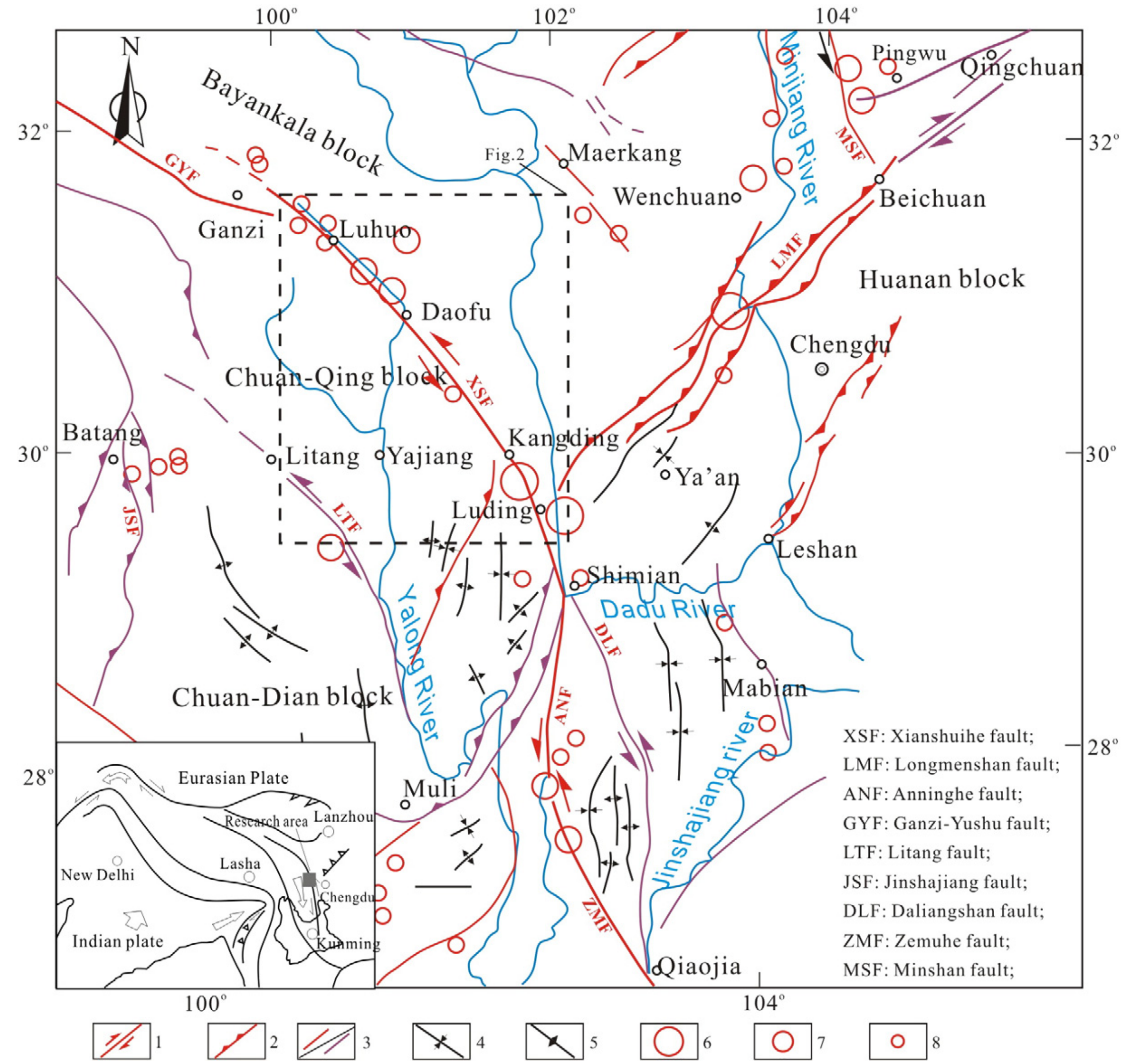

Fig. 1. Location of the study site in Southwest Sichuan, China. 1. Strike-slip fault; 2. thrust fault; 3. late Pleistocene active fault and early–mid-Pleistocene active fault; 4. syncline; 5. anticline; 6. earthquake of Ms ≥ 8.0; 7. earthquake of 7.0 ≤ Ms < 8.0; 8. earthquake of 6.0 ≤ Ms < 7.0.

using fuzzy logic (Ercanoglu and Gokceoglu, 2002; Pradhan, 2011; Akgun, 2012), weight-of-evidence (Dahal et al., 2008; Armas, 2012; Mohammady et al., 2012; Xu et al., 2012a,b), and knowledge-based artificial intelligence techniques (Ercanoglu and Gokceoglu, 2002; Lee et al., 2004; Yilmaz, 2010). Here we assess the most important factors for mapping landslide susceptibility in an active fault zone.

Because of the high elevation and difficult access in the XSF zone, landsliding in the region is poorly studied, particularly in the deeply incised valleys on the eastern margin of the Tibetan Plateau. We use field investigations and aerial photograph interpretation to map landslide distribution characteristics in this region and to produce a landslide inventory map for a part of the XSF zone in northwest Sichuan Province, China. We then use the frequency ratio (FR) and weight-of-evidence (WOE) models to produce a GIS-based landslide susceptibility map. We assess the performance of models based on 6 to 11 variables and show that the simplest model (FR with 6 prominent variables) performs almost as well as the most complicated (WOE with 11 variables).

2. Geologic background

Active faults in the eastern Tibetan Plateau are remarkably complex (Fig. 1), involving sinistral strike-slip, dextral strike-slip, and reverse faults (Zhang et al., 2009). The Xianshuihe fault (XSF) extends NW–SE from north of Donggu village of Ganzi County, crossing through Luhuo, Daofu, and Kangding counties to the south, and ends at Tianwan, Shimian County (Wen et al., 1988; Allen et al., 1991; Zhang et al., 2009) (Fig. 2). The XSF zone is about 350 km long (Wen et al., 1988) and controls the morphology of the Xianshuihe River valley. Previous researchers divided the XSF zone into eight segments according to its geometrical structure, spatial distribution, and activity (Fig. 2): ① the Luhuo fault (90 km), ② the Daofu fault (85 km), ③ the Qianning fault (62 km), ④ the Yalahe fault (31 km), ⑤ the Zhonggu fault (21 km), ⑥ the Kangding fault (80 km), ⑦ the Zheduotang fault (30 km), and ⑧ the Moxi fault (40 km). The total left-slip offset accumulated on this fault zone over at least the past 4 Ma has been estimated at 78–100 km along its northwestern segment (Wang and Burchfiel, 2000) and ~60 km along the southeast Kangding segment (Wang and Burchfiel, 2000; Su et al., 2012). Offset along the XSF is mainly sinistral strike-slip with a component of thrust movement, and offset rates of 10–20 mm/a northwest of Qianning town, <10 mm/a in the southeastern part of Kangding County, and an average of 5 mm/a between Kangding and Moxi (Li and Du, 1997).

The study area experienced a large number of landslides triggered by historical earthquakes, such as the Ms 7 3/4 earthquake of 1 June,