Susceptibility assessment of debris flow from Baoxing River basin in Lushan earthquake zone, China

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Abstract. As one of the prevalent natural disasters, debris flow often occurs in mountainous areas and causes severe property losses. This study primarily focuses on describing the spatial distribution of debris flow in the Baoxing River basin in the Lushan earthquake zone, Sichuan Province, and then a susceptibility index map. Geographic information systems (GIS) and certainty factor (CF) method were used to establish the relationship between debris flow sub-basins and six predisposing parameters: elevation, slope angle, slope aspect, geologic periods, lithology, and NDVI (normalized difference vegetation index). The results show that elevations above 2400m, slopes from 20° to 45°, slope aspects of east, south-east, and south, geologic periods of Sinian, Ordovician, and Carboniferous, NDVIs of -1 to 0.2, lithology areas such as pyroclastic and carbonate of sedimentary rock, and metamorphic rock containing mafic and magnesian are the special conditions that cause debris flows. Furthermore, it has higher susceptibility potential for the combination of topography and geologic parameters, including these predisposing parameters of elevation, slope angle, slope aspect, geologic periods, and lithology, than other combinations. The debris flow susceptibility assessment results show that the moderate and above susceptibility area accounts for around 94% of the total basin area or 51.5% of the study area; more than half of the study area is debris flow-prone, indicating that debris flows are quite active in the study area.

1. Introduction
Debris flow often causes enormous casualties and economic losses within a few minutes after their occurrence (Kappes et al. 2011; Di et al. 2008; Metternicht et al. 2005; Wieczorek et al. 2004; Pareschi et al. 2002). The Wenchuan earthquake in the upper tributaries of the Minjiang River triggered the debris flow disaster group, which resulted in a total of $96.6$ billion in direct economic losses as a result of 16 deaths, 20 missing people, 34 injured people, and severely damaged road transportation, power communications, and municipal facilities. Unfortunately, many landslides had been triggered since the Lushan Ms7.0 earthquake in 2013, China, which caused extremely rich landslide deposits to be deposited on the hillside (Xu & Xu 2014; Xu 2013). Extremely rich landslide deposits would increase debris flow susceptibility, especially during the rainy season (Baum et al. 2005; Frattini et al. 2004). Susceptibility assessment of debris flow can provide a reference for disaster...
prevention projects. It can also supply reasonable planning for urban construction and land resource rational utilization of disaster areas.

The geomorphic information entropy method, artificial neural network method, multi-factor comprehensive method, gray relational analysis, and fractal theory method are often used for susceptibility assessment of debris flow. Generally speaking, these methods can be roughly divided into two categories: based on the evolution of the debris flow development environment and the debris flow activity. The former considers the susceptibility of debris flow mainly through quantitative analysis of some factors that could express geomorphology, geology, and valley conditions of debris flow basins (Melelli & Taramelli 2004; Chevalier et al. 2013). However, the latter is a comprehensive method of susceptibility assessment of debris flow, which usually combined some environmental predisposing factors (Aronica et al. 2012; Liu et al. 2009; Gentile et al. 2008).

The occurrence of debris flow in the earthquake zone is characterized by sustainability, speediness, and difficulties in monitoring or forecasting. There is no doubt that challenges in susceptibility assessment of debris flow will increase if only the traditional field survey methods are used for debris flow occurrence statistics. Geographic information system (GIS) technology is a powerful tool used for susceptibility assessment of debris flow because it can obtain more detailed and complete information and even accurately express and analyze the entire debris flow basin system (Tang & Zhu 2002). Up to now, the successful application of GIS technology to the assessment of debris flow susceptibility has gone through the following processes: from the late 1980s to the mid-1990s, GIS and remote sensing (RS) technology were still not fully developed, though some scholars had explored debris flow susceptibility assessment by combining them (Mejianavarro et al. 1994; Mckeaw et al. 1991); and since the late 1990s, GIS technology has combined the powerful advantages of spatial analysis (Blahut et al. 2010; Tie and Tang 2010; Zhang et al. 2009; Li et al. 2004; Liu et al. 2004; Tang 2004; He et al. 2003; Huggel et al. 2003; Lin et al. 2002) and mathematical statistics module to simplify and optimize the process of debris flow susceptibility assessment (Liang et al. 2012; Cannon et al. 2010; Chang et al. 2010; Tunusluoglu et al. 2008; Carrara et al. 2004; Chau & Lo 2004; Delmonaco et al. 2003).

Based on GIS technology and the CF method, this study aimed to describe the spatial distribution of debris flow in Baoxing River basin in Lushan earthquake zone, Sichuan Province, and formulate a susceptibility index map. Six predisposing parameters such as elevation, slope angle, slope aspect, geologic periods, lithology, and NDVI were used only to assess debris-flow susceptibility. The relationship between the spatial distribution of debris flow and six predisposing parameters was calculated using GIS technology and the CF method. The accuracy of susceptibility assessment and the susceptibility potential of debris flow of different predisposing parameter combinations will be determined by the AUC (area under curve) value. A susceptibility index map of debris flow was formulated based on various predisposing parameters with a higher susceptibility potential by utilizing GIS technology as the operating platform.

2. Description of the Study Area
The study area is a mountainous county with a total area of 4723km². In this study area, the maximum and minimum elevations are 5298m and 603m, respectively. The average elevation and the average slopes are 2860.74m and 36.17°, respectively. Length is about 110km from north to south, and width is about 90 km from east to west, measured, as shown in Figure 1. Baoxing River, as one of the main water sources of Qingyijiang, originates in the southern foot of Jiajinshan.

In this study area, neotectonic movement activities are intense because some major faults like Shuangshi-dachuan fault, Yanjing-Wulong fault and Jintang arc fault all go through the study area the trend of these faults is mostly NE. Meanwhile, some relatively complete strata from Paleoproterozoic to Cenozoic have been formed in the study area. The study area presents two characteristics of miraculous vertical differences in climatic elements and quite obvious tridimensional climate as a subtropical monsoon climate. Moreover, the annual average temperature is approximately 15°C, and the annual rainfall can reach up to 1000–1750mm. The forest coverage rate in the study area is greater
than 60%, and it is mainly composed of the subtropical evergreen broad-leaved forest. In recent years, the farming area has been declining, which may be related to the rapid development of infrastructure in the study area. The urbanization rate of the study area is fast and has now reached about 30%.

![Figure 1](image.png)

**Figure 1.** The location map of the study area and debris flow inventory map of Baoxing River basin in Sichuan Province, China.

### 3. Data and Methodology

#### 3.1 Data sources and database

The primary data, including digital elevation model (DEM), geological maps in 1:250,000 scale, and Landsat8 RS imagery (15m×15m), were prepared to extract the six environmental parameters of debris flows: elevation, slope angle, slope aspect, geologic periods, lithology, and NDVI. Meanwhile, debris flow sub-basins inventory map and detailed co-seismic landslide deposits data of the study area were provided. The debris flow sub-basins area is 2664km² (Figure 1); the 2013 Lushan Ms7.0 earthquake triggered at least 22528 landslides, generally distributed in a similar ellipse area of 5400km² with 18.88km² landslide areas (Xu et al. 2015), and the data of landslide volume was obtained from the more extensive power-law formula of landslide area-volume conversion (Larsen 2010).

The following is an example of data collecting based on the six predisposing parameters: The DEM used in this study was derived from SRTM DEM with a resolution of about 90 meters and ASTER GDEM with a resolution of about 30 meters; the ASTER GDEM had more noise and local information distortion, so SRTM DEM was chosen as the source of the study area's digital elevation model. The SRTM DEM was re-sampled to a DEM in 10m resolutions to avert significant errors of the subsequent statistical analyses (Liu et al. 2015). Slope angle and aspect were extracted from the DEM based on the GIS spatial analysis module. Geological parameters were represented by geologic periods and lithology, derived from the geological map in 1:250,000 scale.

The NDVI primary data was obtained by Landsat 8 RS imagery (Chen et al. 2016) and was calculated using the band calculation formula, namely

\[
NDVI = \frac{P(NIR) - P(R)}{P(NIR) + P(R)}
\]

Where \(NDVI\) was defined as the NDVI; \(P(NIR)\) was defined as a reflectance obtained by the RS channel located in the near-infrared band; and \(P(R)\) was defined as a reflectance obtained by the RS channel located in the visible light band. Here NDVI values change from -1 to 1. Moreover, a negative NDVI value represents the ground is covered with clouds, water, snow, etc.; 0 indicates the presence of bare rock soil; a positive NDVI value indicates vegetation cover.
Based on its hydrology analysis module and Google Earth RS imagery, 290 debris flow sub-basins were acquired by human-computer interactive interpretation (catchment threshold is set to 500) using GIS technology as the operating platform. The process includes DEM flow direction analysis, depression calculation and determination, depression filling, flow accumulation analysis, drainage network extraction, and extraction sub-basins.

3.2 Certainty factor model

CF method uses as a probability method for analyzing the sensitivity of a particular event occurrence. The susceptibility potential of a debris flow can be determined according to the relationship between past mountain disasters and environmental factor data sets, and the CF method is based on this assumption. Shortliffe and Buchanan first proposed the CF method (1975), later improved by Heckerman (1985). The expression is

\[
CF = \begin{cases} 
\frac{PP_a - PP_s}{PP_a(1 - PP_s)} & PP_a \geq PP_s \\
\frac{PP_s - PP_a}{PP_s(1 - PP_a)} & PP_a < PP_s 
\end{cases}
\]

Where \(PP_a\) is defined as the conditional probability of debris flow events occurred in the class unit a; \(PP_s\) is defined as the prior probability of debris flow events occurred throughout the study area. In the actual study, \(PP_a\) was considered as the ratio of debris flow sub-basins area existed in-class unit with this class unit area; \(PP_s\) was considered as the ratio of debris flow area with the entire study area.

CF values change from -1 to 1. CF value is close to zero, indicating that the prior probability and conditional probability is very close, implying that this class unit is uncertain whether it is a debris flow prone area; CF value of 0 to 1 suggests high susceptibility to debris flow, and CF value is closer to 1, denoting that this class unit is more prone to debris flow; CF value of -1 to 0 signifies low susceptibility to debris flow, and CF value close to -1, indicates low susceptibility to debris flow. However, CF boundary value -1 and 1 only represents an ideal state, which becomes less frequent in the actual study.

4. Results

4.1 Predisposing parameters analysis

The difference in elevation classification is directly related to river system development and soil topology, indicating that elevation predisposing parameter as a predisposing indirect parameter controls debris flow occurrence. Figures 2A and 3a depicted the study area's elevation classification. Figure 3a showed that CF values were positive at 2400m and above elevations, indicating that these elevation ranges, particularly 3900m to 4200m, were more susceptible to debris flow. Generally speaking, a steep area is more prone to debris flows; however, some specific slope ranges are more susceptible to debris flows. The slope aspect affects slope dryness, illumination angle, and vegetation growth status, and thus it impacts debris flow. Figures 2B and 2C show slope angle and slope aspect classification of the study area. CF values were positive when the slope angle was 20º to 45º, which indicated slope angle was an enabling factor for debris flow occurrence (Figure 3b). Meanwhile, Figure 3c presented these slope aspects of east, south-east, and south were more prone to debris flow.

There may be some correlations between debris flow and geologic periods, implying that the distribution of seismic landslides and geologic periods are related (Wang et al. 2007). For example, lithology significantly impacts the slope's structural strength, and weak strata are more likely to cause slope instability (Table 1). Figure 2 shows geologic periods and lithology at D and E, respectively. Results in Figure 3d show that the debris flow was more susceptible in Sinian, Ordovician, and Carboniferous geologic periods. But unfortunately, the statistical characteristic of Devonian–Carboniferous was not obvious because of a highly trivial grading area. Figure 3e shows that pyroclastic and carbonate of sedimentary rocks, and metamorphic rocks containing mafic and magnesian, were more prone to debris flow.
Figure 2. Different classifications of predisposing parameters.

NDVI is extensively used because it can adequately represent vegetation coverage. The distribution of NDVI was illustrated in Figure 2F. When NDVI values ranged from -1 to 0.2, it was more prone to debris flows (Figure 3f).
**Figure 3.** Spatial distribution statistics of debris flow.

**Table 1.** Lithology classes and their description.

| Rock types          | Classes | Description of lithology                                      |
|---------------------|---------|--------------------------------------------------------------|
| Sedimentary rock    |         | Terrigenous clastic rock (conglomerate and breccias, sandstone, siltstone, quartz sandstone, etc.) |
|                     | 1       | Clay rock (mudstone, shale, etc.)                           |
|                     | 2       | Pyroclastic (volcanic, etc.)                                |
|                     | 3       | Carbonate (limestone, dolomite, etc.)                       |
| Metamorphic rock    | 5       | Argillaceous series (sericite-phyllite, mica schist, etc.)  |
|                     | 6       | Felsic rock series (feldspar schist, quartzite, sandy slate, etc.) |
|                     | 7       | Carbonate series (marble, etc.)                             |
|                     | 8       | Containing mafic and magnesian, etc.                        |
| Magmatic rock       | 9       | Plutonic rock (granite, peridotite, diorite, etc.)          |
|                     | 10      | Hypabyssal rock (diabase, etc.)                             |
|                     | 11      | Extrusive rock (basalt, etc.)                               |
| Others              | 12      | Quaternary terrace wash-pluvial material                    |

**4.2 Predisposing parameters analysis**

CF values can be used as the weight value, and the total weight can reflect the susceptibility potential of debris flow. If the CF value is positive, the predisposing parameter classification is conducive to debris flows occurrence; on the contrary, it shows that it is not conducive to debris flow occurrence.
Furthermore, the CF value is near zero, indicating that predisposing parameter classification plays a smaller role in the occurrence of debris flows. The superposition of each parameter layer obtained debris flow susceptibility index maps of the study area. Superposition formula is

\[ DFI = \sum Recl_i \times CF_i \]  

Where \( DFI \) is defined as the susceptibility coefficient of debris flow; \( CF_i \) is defined as is the CF value of each predisposing parameter based on their different grading; \( Recl_i \) is defined as the reclassified thematic layer of different predisposing parameters.

Different parameter combinations were shown in Table 2 based on avoiding predisposing parameters being affected by artificial selection and considering interaction among parameters. The AUC value will be used to determine the accuracy of susceptibility assessment and the susceptibility potential of debris flow of various predisposing parameter combinations. Area under curve is a percentage cumulative test curve of forecast and actual debris flow susceptibility area. Therefore, it can evaluate the accuracy of debris-flow susceptibility potential results by the area percentage under the curve. Here, the study is based on some special assumptions, wherein 290 debris flow sub-basins are treated as the actual data because of the shortage of accurate data in the current. As shown in Table 2, the AUC value of the combination of topography and geological parameters reaches about 89%, which means that it has a higher susceptibility potential than other combinations.

**Table 2.** Predisposing parameter combinations and AUC test results.

| Combinations | Parameter combinations | Detailed list of parameter combinations | AUC/\% |
|--------------|------------------------|------------------------------------------|--------|
| I            | Terrain & geomorphologic | Elevation; slope angle; slope aspect; NDVI | 77     |
| II           | Terrain & geologic      | Elevation; slope angle; slope aspect; geologic periods; lithology | 89     |
| III          | Terrain, geomorphologic & geologic | Elevation; slope angle; slope aspect; NDVI; geologic periods; lithology | 82     |
| IV           | Three kinds independent factors | Slope angle; NDVI; lithology | 68     |

### 4.3 Susceptibility assessment of debris flow

There are three major conditions for a debris flow: loose-rich deposits, steep terrain, and sufficient burst water. Among them, loose-rich deposits (primarily landslides) must be highlighted because they are an essential factor in debris flows in earthquake zones. (Xu & Xu 2014). Susceptibility assessment mapping and zoning of debris flow considering landslide deposits could be obtained by: First, with GIS technology as the operating platform, the best index map was masked by 290 debris flow sub-basins polygon data to obtain the index map of debris flows sub-basins. The average value of all grid cells in these basins was invoked as the value of each basin by using the zone statistic tools. Next, to obtain the raster map of provenance sensitivity, 290 debris flow sub-basins polygon data and landslides volume data of similar ellipse areas were superimposed (Figure 4) using the response rate of seismic slope mass movements (RRSSMM) (Xu & Xu 2013). RRSSMM represents the average thickness of the material accumulation in per 1 km² grid cells, and its unit is the millimeter.

A susceptibility index map of debris flow was formulated based on a combination of predisposing parameters with a higher susceptibility potential by utilizing GIS technology as the operating platform, namely combination II (elevation, slope angle, slope aspect, geologic periods, and lithology). The best susceptibility potential index map of debris flow and the raster map of debris flow provenance sensitivity were multiplied to get the susceptibility assessment result of debris flow based on landslide deposits. Using the raster reclassify tool and the natural breaks method, the susceptibility potential index map of debris flow was divided into five zones: very high, high, moderate, low, and very low (Figure 5). In this case, the natural breaks method is a more objective classification method that keeps
internal categories consistent and distinguishes between them. The smallest difference between internal categories and the remarkable difference between categories are the principles of the natural breaks method.

The debris flow susceptibility assessment results show that the moderate and above susceptibility area accounts for around 94% of the total basin area, or 51.5% of the study area; more than half of the study area is debris flow-prone, indicating that debris flows are quite active in the study area.

**Figure 4.** Provenience sensitivity level of debris flow sub-basins.

**Figure 5.** Susceptibility assessment map of debris flow based on landslide deposits.

5. Conclusions and Prospect
The relationship between the predisposing parameters and the spatial distribution of debris flows was shown. The elevation above 2400m, the slope from 20° to 45°, slope aspects of east, south-east, and south, geologic periods of Sinian, Ordovician, and Carboniferous, NDVI of -1 to 0.2, and lithology areas such as pyroclastic and carbonate of sedimentary rock, metamorphic rock containing mafic and magnesian, were more likely to trigger debris flows. The AUC curve tested susceptibility index maps of debris flows of different predisposing parameters combinations. The AUC value of the combination of topography and geological parameters reaches about 89%, which means that it has a higher susceptibility potential than other combinations.

The debris flow susceptibility assessment results show that the moderate and above susceptibility area accounts for around 94% of the total basin area, or 51.5% of the study area; more than half of the study area is debris flow-prone, indicating that debris flows are quite active in the study area.

Loose-rich deposits, steep terrain, and sufficient burst water (namely enough rainfall and rainfall intensity in a short time) are three important conditions that trigger debris flows. The study was mainly based on landslide deposits, steep terrain, and geomorphology, but the precipitation parameter was not considered. Therefore, the susceptibility assessment of debris flow with heavy rainfall will be the focus of future research.

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