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Landslide susceptibility mapping using geographically-weighted principal component analysis

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ABSTRACT

Landslide susceptibility mapping (LSM) documents the extent of probable landslide events in a region to investigate the distribution, pattern, recurrence and statistics of slope failure and consequent mass movement. Similar to other analyses of quantitative sources of spatial data, LSM sometimes uses principal component analysis (PCA), a form of multivariate statistical analysis. This approach helps identify susceptibility by grouping locations or by measuring the variation between groups. The present study outlines the principles and examines the capability of the proposed methodology for landslide mapping, considers optimized shapes for spatial units, estimates an efficient kernel size using alternating least squares (ALS) analysis confirmed by cross-validation, and uses geographically-weighted principal component analysis (GWPCA) to calculate landslide susceptibility using a fuzzy gamma operator. *RMSE* and *PBIAS* statistical estimators were then used to assess operational efficiency of all LSMs using fuzzy gamma operators (0.1 to 0.9). ROC curves were drawn for the best result for LSM using a landslide inventory containing 82 landslide points, with an area under curve of 0.889. The new tools can improve the quality of landslide-related analyses, including erosion studies and landscape modeling, susceptibility and hazard assessments, and risk evaluation.

1. Introduction

Landslides are geologic hazards that occur on spatial and temporal scales in mountainous landscapes (McKean and Roering, 2004). They occur on all continents and represent serious hazards. They play an important role in the evolution of landscapes (Guzzetti et al., 2012). Although there has been increased understanding of slope instability mechanisms and mitigation techniques, landslides continue to cause human and financial loss. Landslide susceptibility mapping (LSM) is a solution to understanding and predicting hazards to mitigate their consequences (Feizizadeh and Blaschke, 2011). The degree of susceptibility is usually expressed cartographically using light-to-dark shades or three-, four- or five-class susceptibility maps (Shadman et al., 2014).

LSM is generally based on qualitative assumptions (Pourghasemi et al., 2012; Shadman et al., 2014), quantitative assumptions (Vahidnia et al., 2010) or hybrid approaches (Goetz et al., 2011) (Fig. 1). In a quantitative approach, past conditions are indicative of future conditions and regions with prior landslides are assumed to be susceptible to future landslide events because they maintain similar environmental characteristics including topography, lithology, hydrology, and land cover/use.

Quantitative or data-driven statistical models use bivariate and multivariate techniques for landslide susceptibility analysis (Carrara, 1983; Carrara et al., 1991; Dai and Lee, 2002; Donati and Turrini, 2002; Nandi and Shakoor, 2009; Neuhausev et al., 2012; Schicker and Moon, 2012). Principal component analysis (PCA) is an efficient multivariate method of decreasing dimensionality and identifying combinations of characteristics that delineate multivariate samples to identify spatial patterns. In this respect, PCA can be used to assess how far different landslide related variables affect the landslide susceptibility of a study area. It also assists researchers to find a proper answer for questions like: "Is the landslide susceptibility of the study region more affected by topographic or by lithologic characteristics?"

Geographically weighted principal component analysis (GWPCA) can be applied as a quantitative solution to LSM when there is no known priority for landslide-related variables in the area of interest. The present study extended a data-driven LSM method using GWPCA where there was no prior expert knowledge for evaluation and weighting of variables.

Tessellation is required for neighborhood analysis; in this case hexagons were selected from the regular tessellations on a plane (hexagon, square, and triangle) (Carr et al., 1992; Birch et al., 2007). Triangular tessellation uses triangles with two orientations, which makes it unpopular for neighborhood analysis. Hexagons are considered to be more efficient spatial structures than square grids for continuously dividing a two-dimensional space, but a rectangle or square grid (Moore

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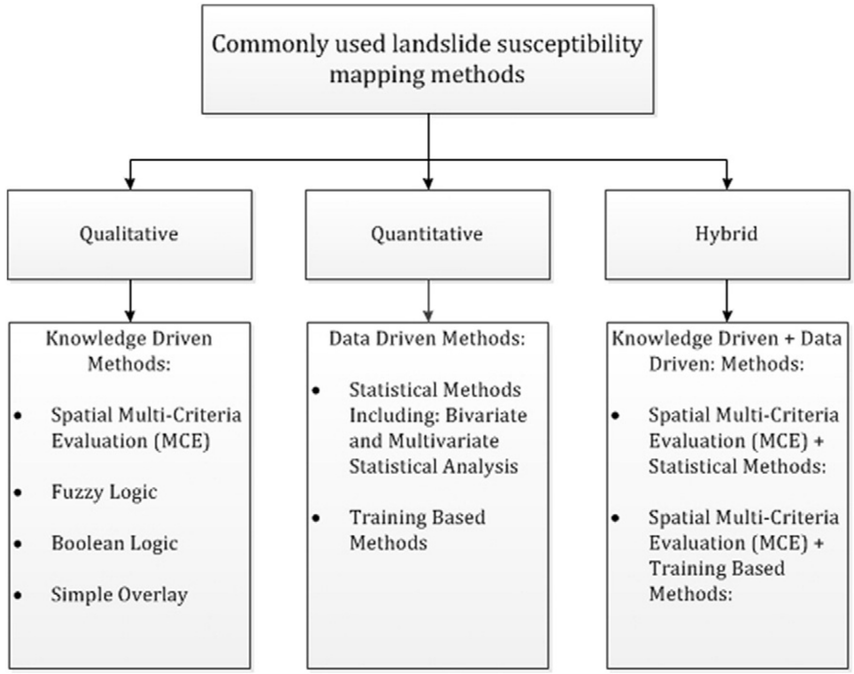

Fig. 1. A schematic illustration of commonly used LSM methods.

neighborhood) is more often used for LSM. Hexagonal shapes yield an isotropic neighborhood and result in better neighborhood analysis; however, the visual advantages of hexagonal shapes may be greater than their accuracy (Carr et al., 1992; Birch et al., 2007) (Fig. 2). We assume that GWPCA susceptibility maps using hexagonal grid neighborhood analysis tend to be less ambiguous and more accurate than those using a rectangular grid. We evaluate 12 landslide-related raster-based layers for LSM generation using an objective method with GWPCA.

2. The study region

The study region is the Chehelchay Basin in central Golestan Province in northeastern Iran (Fig. 3). It is one of the most landslide-prone areas of Iran (Pourghasemi, 2008; Shadman et al., 2014). It lies between 36°59′ and 37°13′ N latitude and 55°23′ to 55°38′ E longitude and covers a surface area of 34,300 km^2. The minimum elevation is 770 m and the maximum elevation is 2550 m. The climate at higher elevations is temperate and mountainous, whereas a temperate semi-humid climate prevails in the plains. The Alborz Range to the west, the Kopedagh Range to the east, and the Caspian Sea to the north provide climatic diversity. The average annual precipitation in the basin is 766.5 mm and mainly consists of rainfall (≈90%). The heaviest rainfall typically occurs between September and December because strong onshore winds blow from the Siberian High toward the Caspian Sea, although rainfall occurs throughout the year. The least rainfall occurs from April to July.

There are about 15 types of lithological outcrops throughout the study region within which fine-grained sedimentary rocks prevail. The general lithological properties of the Chehelchay Basin are shown in Fig. 4 and a detailed description is provided in Table 1. The prevailing

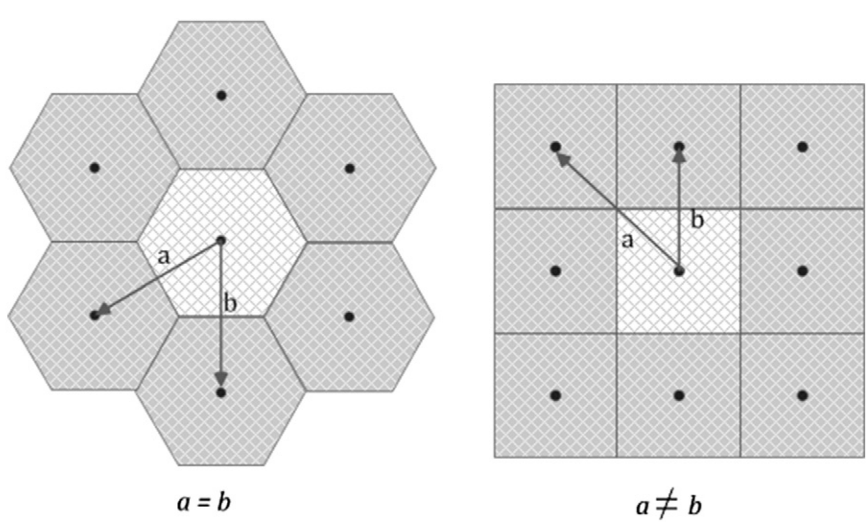

Fig. 2. Hexagonal versus rectangular (Moore) neighborhood for GWPCA based LSM.