Catena 140 (2016) 125–139

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Evaluation of a combined spatial multi-criteria evaluation model and deterministic model for landslide susceptibility mapping

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ARTICLE INFO

Article history:
Received 5 September 2014
Received in revised form 26 November 2015
Accepted 24 January 2016
Available online 2 February 2016

Keywords:
Combined model
Deokjeok-ri Creek
GIS
Landslide susceptibility
SHALSTAB
SMCE

ABSTRACT

This study evaluated the application of a combined spatial multi-criteria evaluation model and deterministic model for landslide susceptibility mapping in Deokjeok-ri Creek, located in the northeastern part of Korea. This region has frequent shallow landslides often caused by intense rainfall on weathered granite soil slopes. This study compared the predictive capability of two different models: a spatial multi-criteria evaluation (SMCE) model, which is a semi-quantitative model, and a shallow landslide stability (SHALSTAB) model, which is a deterministic model used to produce shallow landslide susceptibility maps. For the SMCE model, input layers of landslide causative factors (i.e., topographic, hydrological, soil, forest, and geological factors) were prepared for pairwise comparison to obtain susceptibility weightage. For SHALSTAB, a digital elevation model was used to calculate slope and wetness indices. Field inventories were used to validate and combine the two models. A comparison of the susceptibility map obtained from the SMCE method with that obtained with the SHALSTAB method revealed that the total mismatch area between the two maps for all three susceptibility classes was about 53%. Therefore, the two results were combined to improve the reliability of the susceptibility map. The performance of the combined map was determined using the receiver operator curve (ROC). The area under curve (AUC) revealed a success accuracy of 79.56%, and the predictive accuracy was 83.6%. These results demonstrate that the combined model was more accurate than either individual model at delineating landslide-prone areas of weathered granite soil slopes.

1. Introduction

Concern about climate change has been increasing worldwide, and localized high-intensity, short-duration rainstorms have been observed in Asia. Korea is also experiencing changes in climate parameters, including annual temperature and precipitation (Chung et al., 2004). Data on the frequency of torrential rain have revealed a 25% increase in torrential rain watches and a 60% increase in heavy rain warnings over the last 20 years. South Korea has also been affected by extreme rainfall events associated with typhoons: extreme rainstorms have caused major damage via landslides and debris flows in the South Korean mountains.

Typhoon Ewiniar in 2006 brought particularly heavy rains that triggered many landslides, especially on soil-covered slopes over weathered granite. Slope saturation due to infiltration of rainfall was the primary cause of the landslides. In Korea, approximately 228 people were killed by landslides from 2002 to 2011 (Pradhan and Kim, 2014).

Determining which areas are prone to landslides is important to preserve human lives and avoid negative effects on regional and national economies. Landslide susceptibility assessment is a primary tool for understanding the basic characteristics of slopes that are prone to landslides, especially during extreme rainfall events (Dahal et al., 2012).

Researchers have developed various methods to assess landslide susceptibility and landslide hazards and risk. Landslide susceptibility is the likelihood of landslide occurrence in an area on the basis of local terrain conditions (Brabb, 1984). To date, many techniques have been developed and applied to produce landslide susceptibility maps. Soft computing techniques such as artificial neural networks (Gomez and Kavzoglu, 2005; Lee and Pradhan, 2007; Pradhan and Pirasteh, 2010) and fuzzy approaches (Pourghasemi, 2008; Tangestani, 2009; Pradhan and Lee, 2009; Akgün et al., 2012) have been used extensively for landslide susceptibility assessment, and semi-quantitative, spatial, multi-criteria evaluations have also been used for this purpose (Abella and van Westen, 2007; Armas, 2011; Akgün et al., 2012; Neuhauser et al., 2012).

Deterministic models have also been used extensively since the 1990s (Montgomery and Dietrich, 1994; Dietrich and Sitar, 1997; Dietrich and Montgomery, 1998; Wilcock et al., 2003). Several researchers have proposed different deterministic approaches based on an infinite-slope stability model and rainfall infiltration models (Montgomery and Dietrich, 1994; Dietrich et al., 1995; Terlien et al., 1995; Crosta et al., 2003).

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http://dx.doi.org/10.1016/j.catena.2016.01.022
0341-8162/

Most previous research has involved a GIS technique applied to an individual susceptibility model or compared with maps resulting from different susceptibility models. Recently, Goetz et al. (2011) used generalized additive models (GAMs) to improve landslide susceptibility models by combining the SHALSTAB model and a factor of safety (FS) derived from an infinite-slope model with statistical and machine-learning techniques; however, variables representing physically based models did not significantly improve the empirical models, although they may allow for better physical interpretation of the empirical models. Choi et al. (2012) combined three landslide susceptibility maps using frequency ratio (FR), logistic regression (LR), and artificial neural network (ANN) models to make three different improved susceptibility maps, based on six landslide conditioning factors, and then combined these maps. Prediction accuracy increased slightly as a result of this combination. Rossi et al. (2010) highlighted that the combined models resulted in a reduced number of errors and in less uncertain predictions; the combination of landslide susceptibility zonation can provide "optimal" susceptibility forecast.

Although comparative studies of multiple forecasts for landslide susceptibility assessment are available, a method for combining different geographical forecasts into an optimal prediction is still to be established (Chen et al., 2014). Rossi et al. (2010) and Choi et al. (2012) adopted landslide susceptibility forecasting approaches similar to those applied to determining optimal weather forecasting (Molteni et al., 1996, 2001; Marsigli et al., 2001). They used different models that made separate results, then evaluated these results independently and combined them into best performance optimal forecast.

The main objective of this study was to identify landslide-prone areas with weathered granite soil using a combined approach involving different susceptibility models. It evaluated landslide susceptibility mapping using a semi-quantitative spatial multi-criteria evaluation (SMCE) model and a shallow landslide stability model (SHALSTAB). SMCE based models generally function under the principle that landslides are more likely to occur under similar ground conditions to previous events and such model of susceptibility does not usually take into account triggering factors, such as earthquakes and precipitation (Dai et al., 2002; Sidle and Ochiai, 2006). On the other hand, SHALSTAB model utilizes the physical properties and hydrological properties that control geomorphological processes spatially. Various susceptibility mapping methods from different models such as quantitative or qualitative techniques have always advantages and disadvantages. In quantitative and qualitative techniques, critical rainfall as a thematic layer is always missing. The combination of SMCE model with SHALSTAB can incorporate the rainfall triggering factor in semi-quantitative model. The main difference between the present study and previous approaches is its combination of a semi-quantitative SMCE and deterministic critical rainfall based models, which helps to incorporate with critical rainfall scenario and improves accuracy and reduces model variance. However these two models did not depend on each other. This study has two strands: firstly, the susceptibility class comparison and validation of two models, and secondly, the susceptibility maps were subsequently combined into one map using the normalized frequency ratio (NFR) method to assess the maximum likelihood of future landslide occurrences.

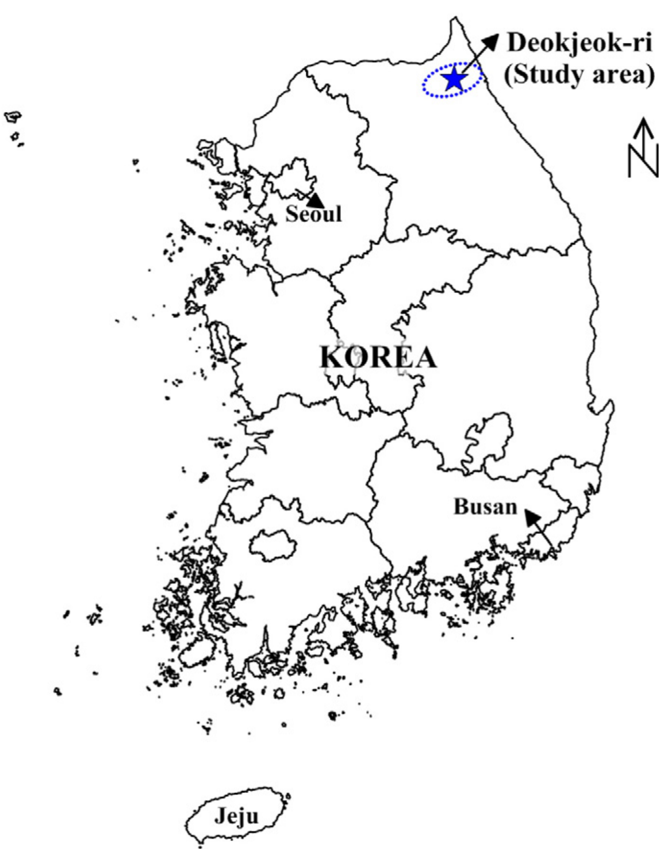

Fig. 1. Location map of Deokjeok-ri.

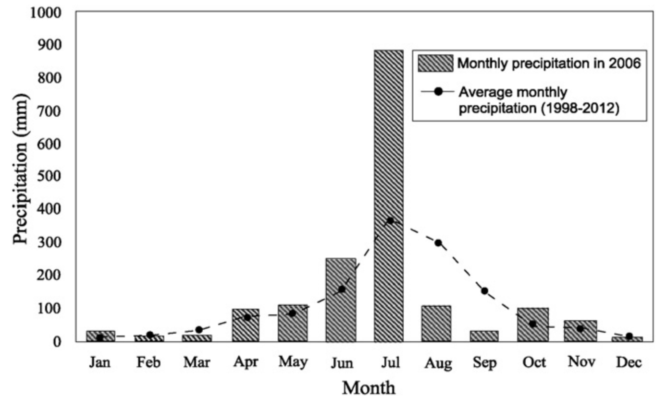

Fig. 2. Mean monthly rainfall in Inje area.

2. Study area

Deokjeok-ri Creek in Inje County, Korea, which suffered a great deal of damage following heavy rain in 2006, was selected as a suitable site for evaluating landslide susceptibility models. Deokjeok-ri Creek is located in the northeastern part of Korea, as shown in Fig. 1. Its area is 33.4 km^2, and it is surrounded by steep mountains. The lithologies of this area include Precambrian gneisses and Mesozoic granites.

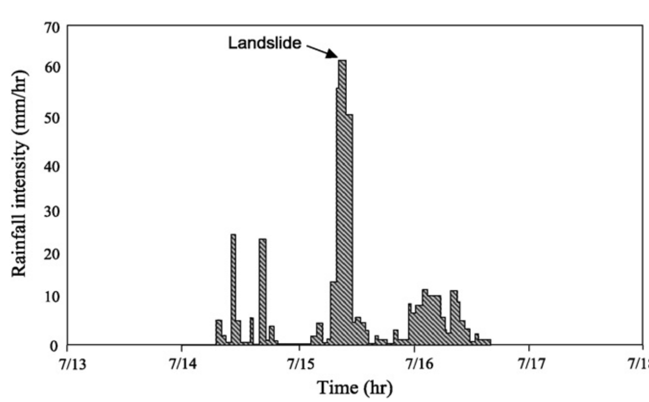

Fig. 3. Extreme rainfall on July 14 to 17 in Inje area.