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Landslide hazard and risk assessment using semi-automatically created landslide inventories

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ABSTRACT

Landslide inventories prepared manually from remote sensing data or through field surveys have shown to be useful for preparation of landslide susceptibility and hazard maps. Recent literatures show several studies have been carried out to prepare landslide inventories from satellite data by automatic methods. However, almost no attempt has been made to validate the effect of such inventories on landslide hazard and risk assessment. In this paper we have shown how landslide inventories prepared by semi-automatic methods from post-event satellite images can be used in the assessment of landslide susceptibility, hazard and risk in the High Himalayan terrain in India. A susceptibility map was made using the weights-of-evidence method, wherein weights were derived using the semi-automatically prepared historical landslide inventories combined with a series of pre-disposing factor maps. Seven evidence layers were used for the calculation of weights, selected in such a way that the majority could be derived from satellite data. Validation was done using the test data created through a temporal subsetting of the inventories. Temporal probability was calculated through Gumbel frequency distribution analysis using daily rainfall data of a 13 year period for which landslide inventories were prepared from satellite data. Spatial probability was determined by calculating landslide density for the inventories per susceptibility class that represent a given return period. Elements at risk, such as buildings and roads, were interpreted from a high resolution Cartosat-1 (2.5 m) image. Absolute vulnerability of the buildings and roads were multiplied with landslide spatial probability to derive the total loss for different return-period scenarios and shown in a risk curve. This study has shown that the inventories prepared semi-automatically can be used for landslide hazard and risk assessment in a data-poor environment.

1. Introduction

The availability of landslide hazard and risk maps is essential to identify the potential areas of landslide losses and to minimise their societal impact. One of the first steps in this direction is the preparation of a landslide susceptibility map, indicating the relative susceptibility of the terrain for the occurrence of landslides. When combined with temporal information, this can be converted into a landslide hazard map, which can be used in combination with elements at risk information for estimating potential losses due to landslides, and aid long-term landslide risk management in mountainous areas.

A landslide inventory is the basis for any landslide hazard and risk assessment (Carrara and Merenda, 1976; Guzzetti et al., 2000; Brardinoni et al., 2003). A typical landslide inventory map gives information about the type, volume, magnitude, date and place of occurrence. Landslide inventories can be used for the calculation of weights of the pre-disposing factor maps during landslide susceptibility mapping as well as for performance and reliability analysis in prediction modelling (Carrara and Merenda, 1976; Guzzetti et al., 2000; Brardinoni et al., 2003) and in magnitude and frequency analysis for the hazard mapping. However, preparation of landslide inventories by manual methods is a substantial challenge, as it requires time and a team of experienced people. According to an estimate by Galli et al. (2008), preparation of a landslide inventory required is on average one month per interpreter to cover a 100 km^2 area in the Umbria region of Italy. Alternatively, landslide inventories can be prepared through automatic methods by incorporating expert knowledge in image analysis (Barlow et al., 2006; Moine et al., 2009; Martha et al., 2010).

Preparation of semi-automatic landslide inventories can be fast, unbiased and data driven in comparison to manual methods. Particularly with object-oriented analysis (OOA), the outputs are also visually consistent. Recently, Martha et al. (2010) updated landslide diagnostic features using high resolution satellite data and a digital elevation model (DEM), and synthesised them using OOA for landslide detection. They

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not only detected landslides accurately but also classified them into translational rock slide, rotational rock slide, shallow translational rock slide, debris flow and debris slide using a semi-automatic method (Martha et al., 2010, 2011). Recent literatures show that many attempts have been made around the globe to prepare landslide hazard maps using manually identified landslides (van Westen et al., 2003; Guzzetti et al., 2005; Pradhan, 2010). Several attempts were made for automatic detection of landslides (Nichol and Wong, 2005; Rosin and Hervas, 2005; Barlow et al., 2006; Borghuis et al., 2007; Martha et al., 2010; Lu et al., 2011). Although it is implicit that the semi-automatic detection of landslides has great potential for short-term goals such as damage assessment after a disaster, evaluation of the applicability of using semi-automatic detection to achieve long-term goals, such as hazard and risk assessment, is worth doing. This research aims to investigate the potential of semi-automatically detected landslides for the preparation of landslide susceptibility and hazard map using statistical methods, which could not be achieved so far in many developing countries due to lack of systematic landslide inventories.

The objective of this paper is to use the multi-temporal landslide inventories, created using OOA, in assessing landslide susceptibility, hazard and risk. In our previous studies (Martha et al., 2010, 2011), we have used time-series images from high-resolution Cartosat-1 (2.5 m), Resourcesat-1 LISS IV Mx (5.8 m) and IRS-1D panchromatic (5.8 m) sensors and prepared landslide inventories for a 13 year period (1997–2009). These multi-temporal inventories in combination with historical daily rainfall data for the same period were used to estimate the spatial and temporal probabilities for hazard assessment. The hazard map was then integrated with data for elements at risk prepared from a high resolution Cartosat-1 image to assess the landslide risk.

2. Materials and methods

2.1. Study area

Countries in the Himalayan region, which is a global hotspot for landslide hazards, frequently face the dangerous outfall of landslides (Nadim et al., 2006). About half a million km^2, i.e. 15% of India's land area is susceptible to landslide hazard. Out of this, 0.098 million km^2 is located in the northeastern region, while the remaining 80% is spread over the Himalayas, Nilgiris, Ranchi Plateau, and Eastern and Western Ghats (GSI, 2006). An area covering 81 km^2 around Okhimath in the Rudraprayag district of Uttarakhand State, including the Garhwal Himalayas along the Rishikesh–Kedarnath tourist and pilgrimage route, was selected for hazard and risk mapping (Fig. 1).

The presence of landslides of different sizes and different types, such as rock slides (rotational and translational), debris slides and debris flows offers a good opportunity to test automatic landslide detection techniques for landslide inventory preparation, and the effect of these inventories on subsequent landslide susceptibility and hazard mapping. Okhimath is situated at an average elevation of 1300 m on the confluence of the Mandakini (originating from Kedarnath) and Madhyamaheshwar rivers. Two major rainfall events, the downpours on 9, 12, 17 and 19 August 1998, and the cloud burst on 16 July 2001 in this area, triggered 466 and 200 landslides, and claimed 103 and 27 lives, respectively (Naithani, 2001; Naithani et al., 2002). Unfortunately, no maps are available showing the spatial distribution of these landslides, and of the damage caused.

2.2. Data

Both multispectral and panchromatic data (Table 1) were used to prepare annual landslide inventories from 1997 to 2009 by OOA. The data sources used for the preparation of evidence layers, which were considered as the most important contributing factors for the occurrence of landslides in the Himalayas, are provided in Table 2. The available geological map prepared by the Geological Survey of India on 1:250,000 scale (Rawat and Rawat, 1998) was used to refine the boundary between different rock types using a break-in-slope criteria (Fig. 2a). This area is traversed by two major thrusts, namely the Main Central Thrust (MCT-II) that passes just south of Okhimath, and the Vaikrita Thrust (also known as MCT-I) that passes north of Okhimath (Fig. 2a). The MCT is a nearly 10 km wide shear zone, inclined at 20° to 45° northward. Foliations dip at moderate angles in NE to NNW directions (Naithani, 2001; Naithani et al., 2002). While thrusts and faults were derived from the available geological map, lineaments were interpreted from LISS-IV Mx and hillshade images (Fig. 2a). Finally, linear geological structures (lineaments, faults and thrusts) were converted to a polygon layer using a variable buffer criterion, since a lineament has a very narrow zone of influence on the strength of the rock in comparison to a thrust, which has larger zone of influence.

The slope angle derived from a 10 m DEM extracted from the stereoscopic Cartosat-1 data, was classified into 10 classes using a quantile classification system. Slope aspects have a significant role for the occurrence of landslides in the Himalayas. South facing slopes support more anthropogenic activities in comparison to other slope directions due to maximum availability of sunlight in a day, leading to the destabilisation of slopes. Therefore, slope aspects derived from the DEM were used for the creation of susceptibility map. Relative relief is another important parameter for the initiation of landslides. It was derived from the DEM using the zonal statistics tool of ArcGIS, wherein slope facets were used as zones (Fig. 2b). Slope facets or terrain units, which have more or less similar characters of slope showing consistent slope direction and inclination, and are generally delimited by ridges, spurs and gullies (Anbalagan, 1992), were prepared manually with the help of the hillshade, slope angle and aspect maps.

The landslides in this area are mainly due to excessive rainfall and less related to the change in land use/cover (Naithani, 2001). As land use has not changed a lot over the period of study, we selected the first available multispectral image in the observation period, i.e. a LISS-IV Mx image of 2004, to prepare the land use/cover map of this area (Fig. 2c). The soil in this area is mostly transported and composed of sub-angular rock fragments with a high proportion of sandy to sandy–silty matrix (Naithani, 2001; Naithani et al., 2002). Soil depth, which is an important parameter for the creation of landslide susceptibility map, was prepared using an available soil map (Fig. 2d) (Atlas, 2001).

2.3. Methodology

The methodology adopted in this chapter for landslide susceptibility, hazard and risk assessment is briefly explained in Fig. 3. The details of the methodology are explained in the following sub-sections.

2.3.1. Preparation of multi-temporal landslide inventories by a semi-automatic method

The knowledge-based semi-automatic method used to create landslide inventories is explained in detail by Martha et al. (2010, 2011). However, for clarity and completeness, the methodology is explained in brief here. All 13 images (Table 1), one corresponding to each year, were processed separately. Multiresolution segmentation of the satellite images was carried out to generate objects, which were used subsequently as image primitives for classification by OOA. A typical effect mostly observed after the occurrence of landslides is loss of vegetation and exposure of bare rock and soil. Therefore, landslide candidates were identified using an NDVI threshold for multispectral images and brightness threshold for panchromatic images. Subsequently, false positives (roads, barren rocky and non-rocky lands, built-up areas, shadows and river sands) were detected. The DEM and its derivatives