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# Object-oriented mapping of landslides using Random Forests

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A B S T R A C T

Landslide inventory mapping is an indispensable prerequisite for reliable hazard and risk analysis, and with the increasing availability of very high resolution (VHR) remote sensing imagery the creation and updating of such inventories on regular bases and directly after major events is becoming possible. The diversity of landslide processes and spectral similarities of affected areas with other landscape elements pose major challenges for automated image processing, and time-consuming manual image interpretation and field surveys are still the most commonly applied mapping techniques. Taking advantage of recent advances in object-oriented image analysis (OOA) and machine learning algorithms, a supervised workflow is proposed in this study to reduce manual labor and objectify the choice of significant object features and classification thresholds. A sequence of image segmentation, feature selection, object classification and error balancing was developed and tested on a variety of sample datasets (Quickbird, IKONOS, Geoeye-1, aerial photographs) of four sites in the northern hemisphere recently affected by landslides (Haiti, Italy, China, France). Besides object metrics, such as band ratios and slope, newly introduced topographically-guided texture measures were found to enhance significantly the classification, and also feature selection revealed positive influence on the overall performance. With an iterative procedure to examine the class-imbalance within the training sample it was furthermore possible to compensate spurious effects of class-imbalance and class-overlap on the balance of the error rates. Employing approximately 20% of the data for training, the proposed workflow resulted in accuracies between 73% and 87% for the affected areas, and approximately balanced commission and omission errors.



## 1. Introduction

During the last century (1903–2004) approximately 16,000 people were killed by landslides in Europe (Nadim et al., 2006), while in other parts of the world even single events can have comparable dimensions (20,000 in Peru, 1970, 29,000 in China, 2008)(Kjekstad & Highland, 2009; Petley, 2009). The mean annual costs of landslides in Italy, Austria, Switzerland and France are estimated between USD 1–5 billion for each of the countries (Kjekstad & Highland, 2009). The assessment of associated risks, a prerequisite for disaster mitigation, is still a difficult task, with comprehensive landslide inventories being the most commonly used source for quantitative landslide hazard and risk assessment at regional scales (van Westen et al., 2006).

Landslide inventories have traditionally been prepared combining the visual interpretation of aerial photographs and field work, which to date remains the most frequently followed approach for the elaboration of inventory maps in scientific studies and by administrative bodies (Hervás & Bobrowsky, 2009). Despite its time-consuming and labor intensive nature, however, results still include a large degree of subjectivity (Galli et al., 2008), and incur the risk of omissions due to limited site access or aerial survey campaigns only being mounted with some delay, when landslide traces are starting to disappear.

Notable advances are being made in the detection of surface-displacements from active (e.g. Cascini et al., 2010) and passive (e.g. Debella-Gilo & Kääb, 2011) spaceborne sensors, allowing for detailed monitoring of ground-deformations. Those techniques depend on a coherent signal over time and are applicable for the mapping of slow to extremely slow moving landslides (<13 m/month after Cruden & Varnes, 1996) with a sparse vegetation cover. For the automated mapping of dormant landslides under forest high-resolution surface models from airborne laser scans provide new opportunities (e.g. Booth et al., 2009). However, most hazardous landslides reach considerable velocities and can typically only be mapped in a post-failure stage, for which optical airborne and satellite images are the commonly chosen data sources. Large events with thousands of individual landslides such as recently in China (earthquake, 2008),

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Haiti (earthquake, 2010) and Brazil (rainfall, 2011) illustrate the immense challenges posed for any non-automated mapping approach.

The large fleet of existing and planned very high resolution (VHR) satellites allows to record inexpensive imagery within days or even hours after a given landslide event, and a number of studies have already addressed the development of more automatic techniques for landslide mapping with VHR images (Barlow et al., 2006; Borghuis et al., 2007; Hervás & Rosin, 1996; Joyce et al., 2008; Lu et al., 2011; Martha et al., 2010; Nichol & Wong, 2005; Rau et al., 2007; Whitworth et al., 2005). Most of them targeted the mapping of fresh features after rapid slope failures, but a few works also demonstrated the potential of optical data for the identification of slow-moving and dormant landslides (Hervás & Rosin, 1996; Whitworth et al., 2005).

Proposed approaches may be generally classed into pixel-based and object-based techniques, both including methods for the analysis of monotemporal and multitemporal imagery, and often making use of ancillary datasets such as digital elevation models (DEMs). Pixel-based approaches include unsupervised (Borghuis et al., 2007) and supervised classification (Joyce et al., 2008), as well as change detection techniques (Hervás et al., 2003; Nichol & Wong, 2005; Rau et al., 2007). Although those techniques consider to some extent additional geometric constrains, such as minimum size, minimum slope or non-rectangular shapes, they rely mainly on the spectral signal of individual pixels. To exploit better the information content of local pixel neighborhoods, Hervás and Rosin (1996) conducted a systematic statistical evaluation of texture measures for landslide mapping and found texture features after Haralick et al. (1973) especially useful to highlight hummocky surfaces often associated with landslides. Similarly, more recent studies concluded that the integration of texture improves the image classification and may yield more accurate maps (Carr & Rathje, 2008; Whitworth et al., 2005).

In general there is an emerging agreement in the remote sensing community that unsatisfactory results of per-pixel analysis can often be attributed to the fact that geometric and contextual information contained in the image is largely neglected (e.g. Blaschke, 2010). This is especially true at higher resolutions, with a higher spectral variance leading to increased intra-class variability and typically lower classification accuracies (Woodcock & Strahler, 1987). Further challenges arise due to the typically lower number of spectral bands of modern VHR sensors and a higher sensitivity to co-registration errors at higher resolutions. To address such issues object-oriented analysis (OOA), also often referred to as object-based image analysis (OBIA), became a widely spread concept for many geoscientific studies to exploit geometric and contextual image information of multi-source data (Blaschke, 2010).

Image segmentation and classification resemble human cognition to some degree and have inspired a number of researchers to transfer existing knowledge in machine executable rule sets. Such rule sets have already been used for landslide mapping as a self-contained classification scheme (Barlow et al., 2003), prior to supervised classification (Barlow et al., 2006), for the post-processing of pixel-based classification (Danneels et al., 2007), and for change detection with multi-temporal images (Lu et al., 2011). Martha et al. (2010) emphasized the importance of exploiting a range of features as widely as possible, and developed a complex set of decision rules, including 36 particular thresholds, to detect and classify landslides of 5 different types in the High Himalayas.

Expert rule sets are a very transparent solution for the exploitation of domain knowledge but comprise two main limitations: (i) the difficulty to decide which descriptive features are actually significant, and (ii) their restricted generic applicability for different input data types and under variable environmental conditions. Professional OOA software solutions readily provide hundreds of potentially useful object metrics, and further customized features enrich this great variety. They allow the user high flexibility in setting up efficient automated processes, but the selection of significant features remains a challenging and time-consuming task.

Feature selection in high-dimensional datasets is an important task in many fields such as bioinformatics (Saeys et al., 2007) or hyperspectral remote sensing (e.g. Guo et al., 2008), and typically targets a better performance of the algorithm classifying the data and/or the investigation of causal relationships. A few object-oriented studies already addressed statistical feature selection for land cover mapping from VHR imagery (e.g. Laliberte & Rango, 2009; Van Coillie et al., 2007), but no such efforts have been in the context of landslide mapping. Little is known about the robustness, efficiency, scale-dependency and generic applicability of the object-features and thresholds proposed in individual studies. Considering the great variety of landslide types, environmental conditions and available imagery this largely prevents the transferability of proposed methods and the development of operational workflows.

Machine learning algorithms, such as Random Forests (RF, Breiman, 2001), have demonstrated excellent performance for the analyses of many complex remote sensing datasets (Gislason et al., 2006; Lawrence et al., 2006; Watts et al., 2009). RF is based on ensembles of classification trees and exhibits many desirable properties, such as high accuracy, robustness against over-fitting the training data, and integrated measures of variable importance (Diaz-Uriarte & Alvarez de Andres, 2006). However, like many other statistical learning techniques RF is bias-prone in situations where the number of instances is distributed unequally among the classes of interest. Under class-imbalance in fact most classifiers tend to be biased in favor of the majority class, and vice versa may underestimate the number of cases belonging to the minority class (He & Garcia, 2009). Experiments on synthetic datasets suggest that such biases are combined effects of class imbalance and an overlap of the classes in feature space (e.g. Denil & Trappenberg, 2010). As landslides typically cover only minor fractions of a given area, class-imbalance is an inherent issue that affects the probabilistic assessments of slope susceptibility (Van Den Eeckhaut et al., 2006), and may complicate the application of machine learning algorithms for image-based inventory mapping.

The objective of this study was to investigate the applicability and performance of the RF learning algorithm in combination with OOA to reduce the manual labor in landslide inventory mapping with VHR images. Assuming that a sample-based framework combining both techniques could be a flexible and efficient solution for many real-world scenarios, VHR imagery recorded by state-of-the-art systems (Geoeye-1, IKONOS, Quickbird, and airborne) at four different sites was analyzed. To achieve an accurate and robust image classification it was of particular interest to determine which image object metrics efficiently distinguish landslide and non-landslide areas. Training and testing samples were derived from existing landslide inventories, and a RF-based feature selection method (Diaz-Uriarte & Alvarez de Andres, 2006) was adopted to evaluate the capability of a broad set of object metrics (color, texture, shape, topography) and their sensitivity to changing scales of the image segmentation. Class-imbalance and -overlap were expected to be critical points for the application of the RF, and we further investigated if an iterative resampling scheme could be used to design training sets that lead to a balance between commission and omission errors. The efficiency of this approach was evaluated at each test site with different segmentation scales and in scenarios where 20% of the image objects would be available for training.

## 2. Study sites and data

VHR images collected in the immediate aftermath of two recent major earthquakes, as well as from two sites affected by non-seismic landslides, were used in this study (Table 1). The areas are characterized by a great diversity of environmental settings, landslide processes and image acquisition conditions, and in this manner