Remote Sens. **2013**, *5*, 5488-5492; doi:10.3390/rs5115488

OPEN ACCESS

Remote Sensing

ISSN 2072-4292

www.mdpi.com/journal/remotesensing

Editorial

Remote Sensing for Landslide Investigations: From Research into Practice

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Received: 18 October 2013 / Accepted: 18 October 2013 / Published: 25 October 2013

The relevant impact [1] that landslide geo-hazards may have on society in terms of human lives and economic losses, has resulted in great efforts to develop sustainable solutions to deal with their prediction and mitigation. To date, several aspects have been investigated involving geological and geo-statistical analysis, geotechnical modeling, design of effective mitigation and protection structures, and sensor development [2].

The impressive progress of remote sensing techniques has given a great contribution to research on landslides during the last two decades. According to the classification given in [3], applications of remote sensing can be grouped into three main categories: recognition and mapping, monitoring, spatial analysis and hazard prediction. Moreover, several studies reported in the literature demonstrate that in real applications different aspects should be closely integrated. Recognition may well provide precise information to help monitoring, and both are expected to furnish useful data for modeling and prediction.

The second important consideration is related to the impact that research on remote sensing techniques for landslide investigations may have on the practices of public bodies and institutions dealing with civil protection and management of natural hazards. Several scientific studies have focused on coping with high-risk situations and provided useful information to help mitigation or prediction of different landslide phenomena. Like global navigation satellite systems (GNSS), engineering geodesy techniques and geotechnical sensors, satellite and ground-based remote sensing have become the routine solutions adopted for assessment and monitoring of such geo-hazards.

This Special Issue is aimed at collecting papers describing how remote sensing for landslide investigations can be put into practice. Fourteen articles have been accepted for publication, reporting on different experiences carried out in several areas of the world (Austria [4,5], Brazil [6], China [7,8], Hungary [9], Iran [10,11], Iraq [11], Italy [9,12–14], Peru [15], Poland [9], Spain [9], Switzerland [9,16],

and Taiwan [17]). Three Feature Papers [4,9,14] are included from recognized authors at the request of the Guest Editor.

The problem of construction and application of landslide inventories [18] is mainly discussed in four papers. Mapping of shallow landslides on steep Alpine grasslands is the subject of paper [5]. In [11], a landslide inventory derived from high-resolution satellite imagery is used to study the effects of landslides on the drainage network. In [15], an inventory for the analysis of earthquake-induced landslides is created by using an object-oriented technique [19] applied with high-resolution satellite imagery [19]. This group of papers shows how images from spaceborne and airborne platforms can be used for landslide recognition and mapping at different scales. The use of unmanned aerial vehicles (UAV) is addressed as a promising tool to gather high-resolution images and to cover areas that are difficult to access from the ground. In [16], the geomorphological information collected from photo-interpretation is integrated with the outcomes of deformation analyses coming from Differential-InSAR (D-InSAR) and Persistent Scatterer-InSAR (PS-InSAR) techniques which are based on the processing of multiple SAR images.

InSAR techniques have also been widely used for the analysis of existing landslides and for monitoring surface displacements over time. In the former case, results of these analyses can help redefine the landslide borders and better understand the state of activity, as well as the deformation pattern and its relationship with the causative reasons of instability. In the latter case, the availability of continuous up-to-date SAR images can be used to detect changes on the slopes. This application is particularly important because of the growing capability of new spaceborne SAR sensors, featuring higher resolution and shorter revisiting time with respect to the first generation satellites. From the papers included in the Special Issue, it is possible to understand where the major limitations of advanced InSAR techniques are, and where future research efforts should be focused. The vegetation coverage on most mountain slopes may prevent the acquisition of coherent SAR images over time, this, however, works quite efficiently in the case of buildings and rocks [12]. Some suggested processing improvements have been published recently to extend the application of PS-InSAR to those areas with lower coherence [20,21]. The integration of InSAR techniques with other *in situ* sensors (like GNSS, geodetic and geotechnical sensors) is also important for validation and for completing data acquisition in low coherence regions [10,16]. Moreover, the integration of InSAR processing outputs with underground observations from local sensors allows the establishment of a link between surface and subsurface displacements [14]. A second relevant problem related to the use of InSAR, is the need of combining data from different orbits to achieve a more complete description of the spatial displacement components, as addressed in [8,14]. Outcomes of an FP7 research project also showed how large archives of C-Band SAR data have been exploited in different European regions for the analysis of subsidence and landslide phenomena [9].

The second group of papers concerning monitoring applications is based on the use of laser scanning techniques [22]. In [13], the comparison of multi-temporal terrestrial laser scanning data integrated with airborne photogrammetry allows to detect the velocity of surface displacements on the slopes of an Italian volcano. This paper demonstrates how useful multi-source remote sensing data is for the characterization of steep slopes where geodetic benchmarks cannot be installed. Similarly, in [4] integrated data from terrestrial and airborne laser scanning are exploited to study an active landslide in

Austria. Here a 3-D range-flow algorithm derived from computer vision applications has been originally applied to track 3-D displacements on a mountain slope.

The remaining papers can be classified into the category of spatial analysis and hazard prediction [23]. In [6], the combination of spatial data and two simulation models allows to map hazards in the occurrence of both shallow landslides and debris-flows. In [7], different aspects are highlighted. Susceptibility mapping based on an artificial neural network is adopted to locate failure-prone slopes in the 2008 Wenchuan earthquake area in China. Topography, river and road distributions turn out to be the most important factors for the localization of such landslides. A monitoring sensor network designed for deployment in a specific site has proven to be particularly critical because of the high geo-hazard risk. In [17], the problem of correcting the rainfall intensity on the basis of topographic data is addressed, being a crucial parameter in many models used for landslide prediction. These papers highlight how different approaches for modeling landslide behavior strictly depend on the quality of rheological, geotechnical, and geomorphological input parameters. On the one hand, remote sensing techniques have the capability to improve this knowledge, especially for aspects related to topography, land cover and surface displacement. Further, a great effort is required for collecting more information from the field. A better integration between modeling and Earth observations from different platforms is the key-point to ensure future research on landslides will be more effective in real applications.

A further general conclusion is evident from most of the papers. Successful solutions to cope with landslide prediction need to be based on data and sensor integration due to the absence of a technique which can be efficiently applied in all situations. In particular, the dream of investigating landslides with the sole use of remotely sensed data is quite utopic. However, many results of research activities described here (and from previous literature) confirmed that remote sensing techniques may provide a remarkable contribution to this field, but they need to be validated and complemented by *in situ* data. Remote sensing may provide an overview of problems over wide areas and help localize specific high-risk sites. These can be thoroughly investigated by deploying local sensor networks able to gather real-time and more extensive observations [7]. In a successive stage, remote sensing techniques are expected to provide wide-coverage data to be integrated with *in situ* observations in the modeling process. In this direction, terrestrial remote sensors (laser scanning, ground-based InSAR, image-based techniques) have demonstrated suitability because of the higher resolution and the opportunity to focus on specific problems.

Finally, I would like to thank all people who have contributed to this Special Issue: all the authors of submitted papers, the reviewers who gave valuable support, and the Remote Sensing Editorial Office for conducting a high-quality review and editing process for all the published papers. I hope that this Special Issue will further promote research on the application of remote sensing in landslide investigations, and that it will foster the process of technology and knowledge transfer from the scientific community to the institutions in charge of handling geo-hazards. Such an exchange will be beneficial to the sustainable development of society as a whole.

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