

MAPPING LANDSLIDES: RECENT DEVELOPMENTS IN THE USE OF DIGITAL SPATIAL INFORMATION

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Abstract: The aim of this paper is to discuss a number of issues related to the use of spatial information for landslide mapping over larger areas. The last few decades have shown very rapid development of the application of digital tools such as Geographic Information Systems, Digital Image Processing, Digital Photogrammetry and Global Positioning Systems. In landslide risk assessment at scales of 1:10,000 or smaller, GIS has become the standard tool. Much progress has been made in the generation of Digital Elevation Models obtained from different sources, ranging from SRTM to LIDAR, and these are used to generate landslide inventories. Landslide inventories can now make use of a variety of approaches, ranging from digital stereo image interpretation to automatic classification, based either on spectral or altitude differences, or a combination of both. Landslide inventory databases are becoming available to more countries and several are now also available through the Internet. A comprehensive landslide inventory is a basic requirement in order to be able to quantify both landslide hazard and risk.

INTRODUCTION

The first extensive papers on the use of spatial information in a digital context for landslide susceptibility mapping date back to the late seventies and early eighties of the last century. Among the pioneers in this field were Brabb and co-workers in California (Brabb *et al.*, 1978) and Carrara and co-workers in Italy (Carrara *et al.*, 1977). Nowadays, practically all research on landslide susceptibility and hazard mapping makes use of digital tools such as GIS, GPS and Remote Sensing. These tools also have defined, to a large extent, the type of analysis that can be carried out. It can be stated that GIS has determined, to a large degree, the current state of the art in landslide hazard and risk assessment. This is particularly so for landslide studies that cover larger areas. Glade and Crozier (2005) present an interesting discussion on the relation between data availability, model complexity and predictive capacity, based on earlier work by Grayson *et al.* (2002). They conclude that each type of model has an optimum data set (in terms of resolution, accuracy, and complexity) and that an increase in the data availability will not lead to an increase in the predictive capacity, when using models with the same complexity. In general it can be stated that data availability decreases with increasing size of study areas and therefore, the optimum complexity of the models used in hazard and risk analysis also decreases with scale. Advanced 3-D slope stability models can be used at site investigation scales when a detailed understanding of the subsurface conditions is available from boreholes, geophysical studies, and laboratory analysis, along with on-site monitoring of water conditions and landslide movement history. However, these types of data are typically available at too few locations to apply the same 3-D model approaches at mapping scales of 1:5000 or smaller.

Landslide risk assessment intends to estimate the expected losses due to landslides for a particular area and time period. These losses can be direct or indirect, and can be physical, social, economic, or environmental in nature. Most of the published work on landslide risk assessment is limited to the estimation of direct physical losses to buildings and infrastructure, and to evaluations of human casualties/injuries (Alexander, 2005). When dealing with physical losses,

(specific) risk can be quantified as the product of vulnerability, cost or number of elements at risk, and the probability of occurrence of the event (Varnes, 1984; Fell, 1994; Leroi, 1996; Lee and Jones, 2004; Glade *et al.*, 2005). When we look at the total risk, the hazard is multiplied with the expected losses for all different types of elements at risk (= vulnerability x amount), and this is done for all hazard types (see Figure 1).

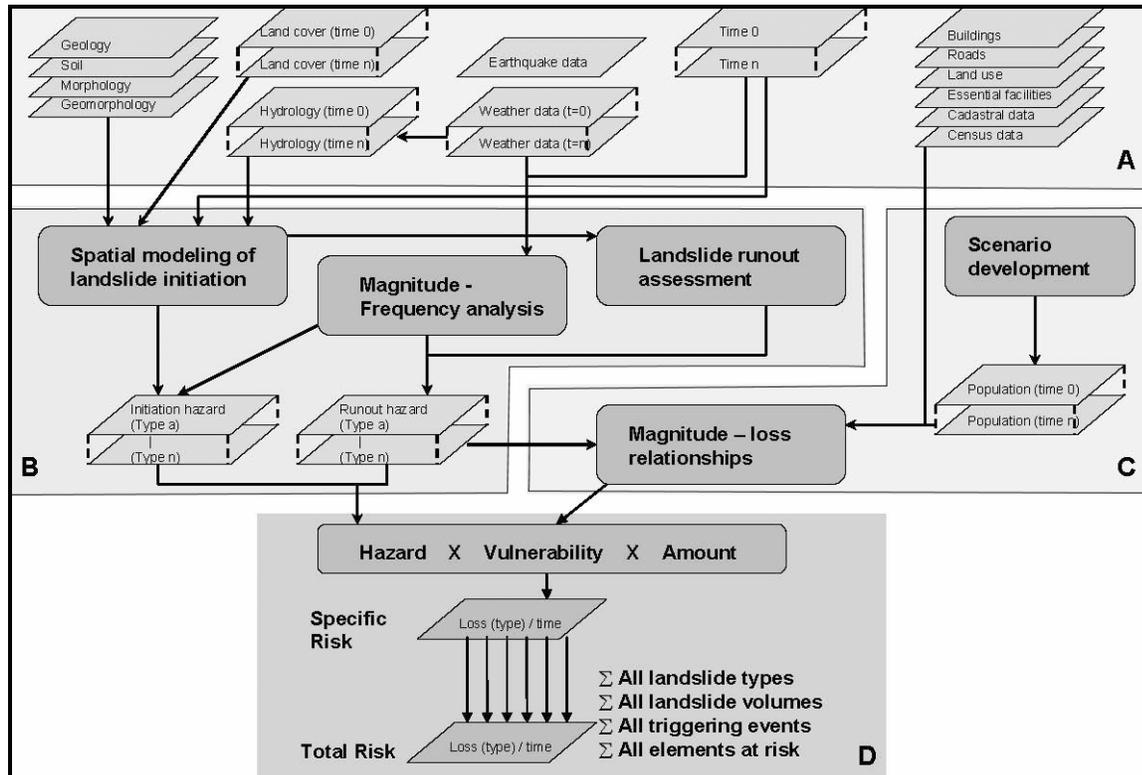


Figure 1: Schematic representation of landslide risk assessment procedures. A: Basic data sets required, both of static, as well as dynamic type; B: Hazard modeling component; C: Vulnerability assessment component; D: Risk assessment component.

GIS-based landslide risk assessment at a large or medium mapping scale (e.g. 1:10,000-100,000) requires four basic data sets: (i) environmental factors, (ii) triggering factors, (iii) historic landslide occurrences, and (iv) elements at risk (Van Westen *et al.*, 2005). Of these, the historic information on landslide occurrences is by far the most important, as it gives insight into the frequency of phenomena, the types involved, and the volumes and the damage that has been caused. Landslide inventory databases, derived from historic archives, field data collection, interviews, and interpretation of satellite images and aerial photographs, are essential. In the following sections, a summary is provided of the developments in digital spatial data collection for landslide inventory mapping.

BASE DATA ACQUISITION

With respect to the collection of the basic data sets for landslide hazard and risk assessment (indicated in the upper row of Figure 1), developments in the acquisition and processing of digital data have been very rapid in the recent past. The basic data can be subdivided into those

that are more or less static, and those that are dynamic and need to be updated regularly. Examples of static data sets are related to geology, soil type, geomorphology and morphography. The time frame for the updating of dynamic data may range from daily information, which is required in the case of meteorological data and consequently in slope hydrology data, to months and years for land use and population data (see Figure 2). Figure 2 also gives an indication of the extent to which remote sensing data can be utilized to generate the various data layers (based on Soeters and van Westen, 1996).

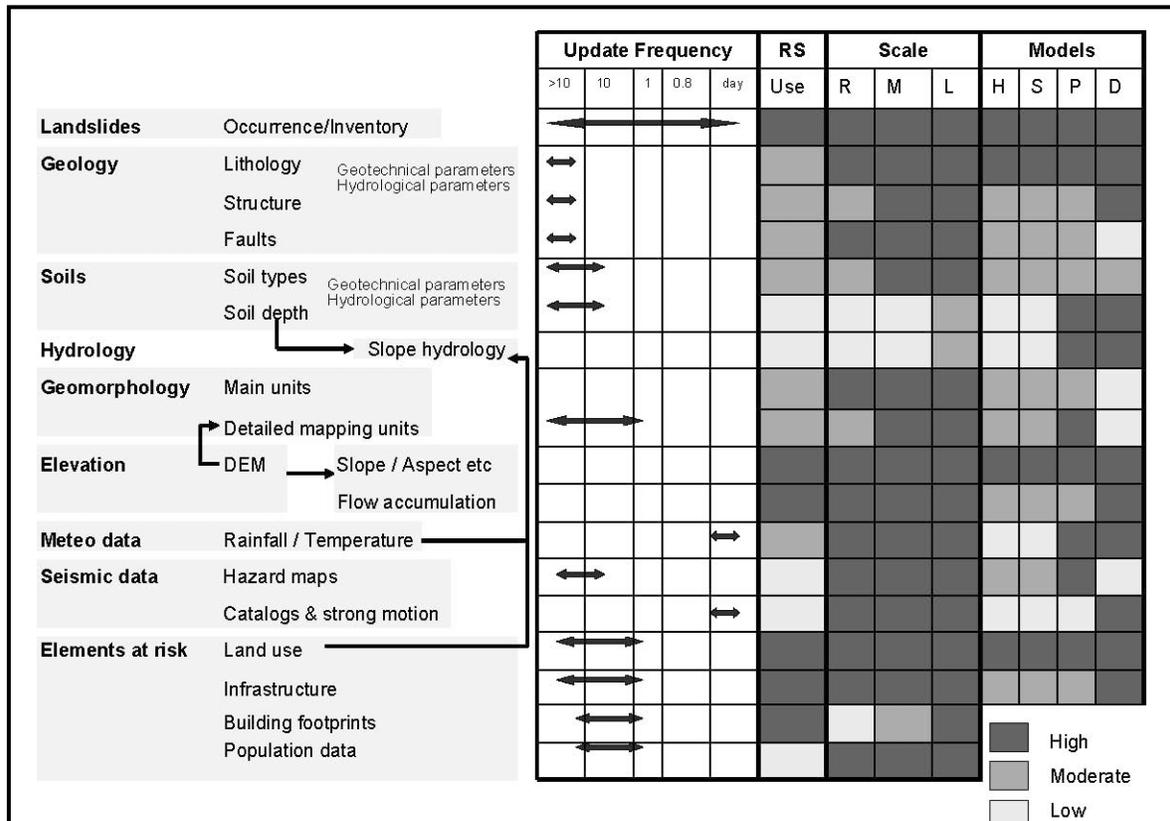


Figure 2: Schematic representation of basic data sets for landslide risk assessment. Left: indication of the main types of data, and how some are derived from others; Middle: Indication of the ideal update frequency of these data; RS: column indicating the usefulness of Remote Sensing for the acquisition of the data; Scale: indication of the feasibility of collection at regional (R), medium (M) and large scale (L); Models: Indication of the importance of the data set for heuristic models (H), statistical models (S), probabilistic models (P) and deterministic models (D).

For a number of data layers the main emphasis in data acquisition is on field mapping, measurement or laboratory analysis; remote sensing imagery is only of secondary importance (Van Westen, 2004). This is the case for the geological, geomorphological, and soil data layers. The soil depth and slope hydrology information, which are very important in physical modeling of slope stability are also the most difficult to obtain, and remote sensing has not proven to be a very important tool for these. On the other hand, there are data layers for which remote sensing data can be the main source of information. This is particularly so for landslide inventories,

Digital Elevation Models, and land-use maps. Land-use maps are made on a routine basis from medium resolution satellite imagery such as LANDSAT, SPOT, ASTER, IRS1-D, etc. Although change detection techniques, such as post-classification comparison, temporal-image differencing, temporal-image ratioing, multifractal analysis, or Bayesian probabilistic methods, have been widely applied in land-use applications, fairly limited work has been done on the inclusion of multi-temporal land-use-change maps in landslide hazard studies (Mantovani et al., 1996).

Landslide inventories and databases

In order to make a reliable map that predicts the landslide hazard and risk in a certain area, it is crucial to know as much as possible of the spatial and temporal frequency of landslides, and therefore each landslide study should start by making a landslide inventory that is as complete as possible in both space and time (Ibsen and Brunsden, 1996). Landslide inventories can be carried out using a variety of techniques, such as the analysis of historical information from archives and newspapers, interviews, and field mapping, and supported by a wide range of dating methods such as pollen analysis, radiocarbon dating, tephra chronology, lichenometry and dendrochronology (Glade, 2001). However, the most applicable techniques for larger study areas make use of remote sensing images to undertake tasks ranging from qualitative image interpretation to change-detection based on spectral or altitude information.

Visual Interpretation of landslides

For visual interpretation of landslides, stereoscopic images with a high to very high resolution are required (Soeters and Van Westen, 1996). Optical images with resolutions larger than 3 meters (e.g. SPOT, LANDSAT, ASTER, IRS-1D, RESOURCESAT LISS IV Mono), as well as SAR images (RADARSAT, ERS, JERS, ENVISAT), have proven to be useful for visual interpretation of landslides in some individual cases (Singhroy, 2005), but not for landslide mapping on the basis of landform analysis over large areas.

Very high resolution imagery (QuickBird, IKONOS, CARTOSAT-1, CARTOSAT-2) has become the best option now for landslide mapping from satellite images (IGOS, 2003), and the number of operational sensors with similar characteristics is growing year by year as more countries are launching earth observation satellites with stereo capabilities and resolution of 3 meters or better. The high costs may still be a limitation for obtaining these very high resolution images for particular study areas, especially for multiple dates after the occurrence of main triggering events such as tropical storms or cyclones.

One of the most interesting recent developments is the launch of Google Earth, in which a steadily growing part of the world is covered by very high resolution imagery from Digital Globe, or even aerial photography, which is less than 3 years old. As an example, Figure 3 shows several screen dumps from Google Earth for areas that have been affected by recent landslides, such as the area near Atitlan Lake in Guatemala, which was affected by Hurricane Stan in October 2005. The 3-D capabilities and zooming functions that are available in Google Earth, together with the possibility of drawing polygons on the image, greatly facilitates interpreting and mapping landslides.

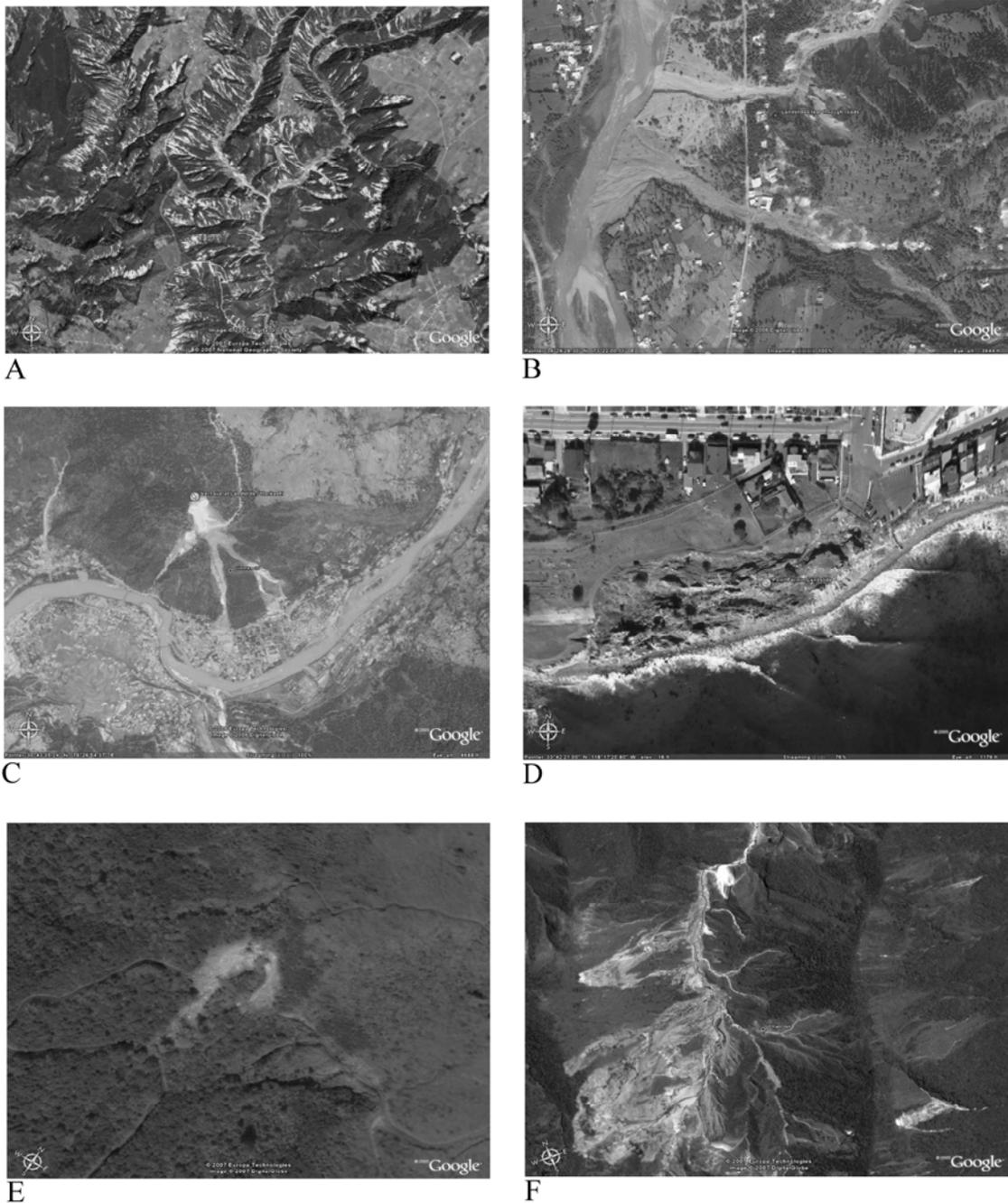


Figure 3: Examples of Google Earth images depicting landslides triggered by recent events. A: Landslides triggered by Hurricane Stan in October 2005, near Lago Atitlan, Guatemala. B: Debris flow triggered by the October 2005 earthquake in the Pakistan-Indian border area. C: Varunavat Parvat landslide, Uttarkashi, India, which initiated in September 2003. D: Point Fermin landslide, Los Angeles, with a long history of movement; E: Landslide on the island of Guadeloupe, triggered by an earthquake in November 2004. F: Large landslides in Taiwan triggered by a series of rainfall and earthquake events.

Another interesting development is the visual interpretation of landslide phenomena from shaded relief images produced from LIDAR DEMs, from which the objects on the earth surface have been removed, producing so called bare earth DEMs or Digital Surface Models (Schulz, 2004). Haugerud *et al.* (2003) discuss the potential of LIDAR for the mapping of geomorphological features, including landslides in a forested area northwest of Seattle. The illumination conditions of the shaded relief image can be manipulated to produce optimal images for landslide recognition. The use of shaded relief images of LIDAR DEMs also allows a much more detailed interpretation of the landslide mechanism when deformation features within a large landslide are visible (Haneberg, 2004). Another major advantage of LIDAR is that landslides can be mapped in areas that are covered by forests.

However, in practice, aerial photo interpretation still remains the most broadly used technique for landslide mapping (Tribe and Leir, 2004; Metternicht *et al.*, 2005). Cardinali *et al.* (2002) present a clear example on the use of multi-temporal airphoto interpretation for the generation of a landslide database that can be used in landslide hazard and risk assessment. An analysis of the Magnitude–Frequency relationship based on landslide interpretations from multi-temporal airphotos has been carried out by Reid and Page (2002).

Conventional landslide inventory mapping from aerial photographs traditionally used hardcopy stereo photos under a mirror stereoscope with the interpretation drawn onto a sheet of tracing paper. The interpretation then had to be digitized, converted from the central projection of the photograph into an orthogonal projection, and glued and matched with the interpretation of neighboring photos. Nowadays, digital interpretation can be accomplished with two scanned stereo images. These images could be any two scanned hardcopy airphotos that form a stereopair. However, with the current GIS and image processing software, it is also possible to generate a stereopair out of one orthorectified image and a DEM. This is especially useful in those cases where the original image data is only available monoscopically. Several techniques can be used to visualize the digital stereo images, such as anaglyph, chromadepth, polarized light, or through the use of a screen stereoscope, which is mounted on the computer screen (Van Westen, 2004).

Automated landslide mapping

During the last decade, several methods for the automatic detection of landslides based on their spectral or altitude characteristics have been developed. The automatic characterization of landslide areas is based on the assessment of a number of features (Soeters and Van Westen, 1996):

- Disrupted or absent vegetation cover, anomalous with the surrounding terrain, has been used as the main diagnostic feature for the recognition of landslides from multi-spectral images.
- Slope characteristics, related to the overall slope changes, and the presence of slope concavities and breaks of slope that might be recognizable from DEMs.
- Surface characteristics, such as internal deformation structures, fissures, tension cracks, flow lobes, step-like morphology, scarps, and semi-circular features are detectable as increased surface roughness, if the detail of the DEM is sufficiently large.
- Surface drainage characteristics, such as disrupted drainage, ponds, seepage zones, and exceptionally wet or dry zones might be detected using radar imagery or using thermal imagery.

Landslide classification using spectral information

When landslides are fresh and unvegetated, image classification of multi-spectral images such as SPOT, LANDSAT, ASTER and IRS-1D LISS3 has proven to be applicable for landslide mapping (Cheng *et al.*, 2004). If the landslides are not recent, such imagery will not be sufficient, as proven by Petley *et al.* (2002) and Marcelino *et al.* (2003). Roessner *et al.* (2005) applied a range of different types of satellite images (LANDSAT-(E)TM, ASTER, and MOMS-2P) during a study of landslide inventory mapping in an area of Kyrgyzstan that is characterized by relatively large landslides, and concluded that these were sufficiently detectable from the images used.

Nichol and Wong (2005) demonstrated the use of change detection methods, including subtraction of single bands, band ratios, and post-classification comparisons using a Neural Network Classifier and Maximum Likelihood Classifier (MLC), for landslide identification in an area of Hong Kong. They reported an accuracy of 70% using SPOT images, while IKONOS data allowed a much larger accuracy. As demonstrated after Hurricane Mitch, image classification of multi-spectral images for landslide studies can be successful for identifying a large number of unvegetated scarps that have been produced during a single triggering event (Restrepo and Alvarez, 2006).

ASTER, which has an advanced optical sensor with 14 bands, with visible light, near infrared (VNIR), short wave infrared (SWIR), and thermal infrared (TIR), has particularly proven to be a useful tool in landslide inventory mapping, also because of its low costs, stereo capabilities, and reasonable spatial resolution. However, practice has shown that the use of optical satellite imagery for multi-temporal landslide detection after major triggering events, especially in tropical areas, is often hampered by the persistent cloud cover in the affected area, which makes it difficult to obtain cloud-free images for a long period of time.

Hervas *et al.* (2003) successfully used digital airphotos and automatic image classification to identify landslides. Geometrically registered and radiometrically normalized sequential images were used in a thresholding procedure to derive landslide-related change pixels, and filtering techniques were applied to remove land-use-related changes.

Whitworth *et al.* (2005) have demonstrated the use of the high-resolution Airborne Thermal Mapper (ATM) sensor with image processing for both color composites and thermal imaging. They show that such data can provide information on the ground surface that is not visible in conventional aerial photography, and which can be used for semi-automated landslide identification. Airborne hyperspectral imagery from sensors like MIVIS, AVIRIS, HyMap and AHI have been used alongside field work to identify surface mineralogy, soils, lithologies, drainage networks, and land use. However, no results can be found in the literature concerning these applications for landslide classification.

Image classification methods used for landslide mapping can be differentiated into pixel-based and non-pixel-based approaches. Barlow *et al.* (2003) used a non-pixel-based approach for evaluating post-event images. Martin and Franklin (2005) also used a non-pixel-based approach, the application of object-oriented image segmentation. Shape criteria were used to identify objects, followed by a hierarchical classification of the segmented image by the inclusion of landslide-related information, such as geomorphometric data and NDVI..

Landslide classification using altitude information

Digital Elevation Models (DEMs) can be derived through a large variety of techniques, such as digitizing contours from existing topographic maps, topographic leveling, EDM (Electronic Distance Measurement), GPS measurements, (digital) photogrammetry, image correlation, radargrammetry, InSAR, and LIDAR. Digital photogrammetry can be used on a variety of images, ranging from metric air photographs taken on official surveys from National Mapping Agencies, to small format photography taken from helicopters, light aircraft, and drones (Henry *et al.*, 2002).

Many methods for landslide mapping make use of Digital Elevation Models of the same area from two different periods. The subtraction of the DEMs allows visualization of where displacement due to landslides has taken place, and the quantification of displacement volumes (Oka, 1998; van Westen and Getahun, 2003; Dewitte and Demoulin, 2005).

As far as satellite derived DEMs are concerned, the SRTM DEMs do not have sufficient accuracy to be useful for landslide inventory mapping. ASTER DEMs have a root-mean-square error (RMSE) of 7 to 15 m in areas with limited relief and with good quality data. In high relief areas these errors are substantially higher (Hirano *et al.*, 2003). The magnitude of these errors makes ASTER and SRTM less useful for landslide change detection.

The recently launched Japanese ALOS satellite has a panchromatic radiometer (PRISM), as does the Indian CARTOSAT-1. Both satellites provide 2.5 m resolution, and two panchromatic cameras that allow for near simultaneous imaging of the same area from two different angles (along track stereo). These are designed to produce highly accurate Digital Elevation Models that might be useful in automatic detection of large and moderately large landslides.

Airborne Light Detection and Ranging (LIDAR), also called laser scanning, can provide high-resolution topographic information (<1 m horizontal and a few centimeters vertical accuracy), depending on the flying height, point spacing and type of terrain. The vertical accuracy may be as low as 100 cm in difficult terrain (Haneberg, 2004). McKean and Roering (2004) and Glenn *et al.* (2006) report results of a new approach that exploits measurements of local topographic roughness to detect and map deep-seated landslides. Hsiao *et al.* (2004) have used a combination of Airborne Laser Scanner (ALS) and Terrestrial Laser Scanner (TLS) for the quantification of landslide volumes. They applied a combination of airborne and multiple ground-based laser scans in a landslide area triggered by the 1999 Chi-Chi earthquake in Taiwan. Control points are systematically distributed on the 1000 m by 2000 m landslide surface. Surveys are made by a combination of total stations, GPS and airborne LIDAR, as well as ground-based LIDAR data.

Rowlands *et al.* (2003) and Jones (2006) have successfully applied terrestrial LIDAR measurements for the monitoring of individual landslides by. Similar systems have been developed that can be mounted on a helicopter (Vallet and Skaloud, 2004). Chang and Liu (2004) use an Artificial Neural Network for the classification of landslide areas that formed after the Chi-Chi earthquake by combining Normalized Difference Vegetation Index (NDVI) values derived from IKONOS data with slope angles and locations derived from airborne LIDAR DEMs. They report an accuracy of 85 % correctly classified landslides.

Interferometric Synthetic Aperture Radar (InSAR) has been used extensively for measuring surfaces and many studies have also attempted to use the method either for the mapping of new landslides or for the monitoring of existing features. Unfortunately, in most environments InSAR applications are limited by problems related to geometric noise due to the different look angles of the two satellite passes and temporal de-correlation of the signal due to scattering

characteristics of vegetation, as well as by atmospheric variability in space and time (Catani *et al.*, 2005). To overcome these problems, the technique of Persistent Scatterer Interferometry (PSI), or “Permanent Scatterers” has been introduced (Ferretti *et al.*, 2001). This technique uses a large number of radar images and works as a time-series analysis for a number of fixed points in the terrain with stable phase behavior over time, such as rocks or buildings. The availability of ERS-1, ERS-2, and RADARSAT, together with the recent ENVISAT and ALOS PALSAR, now offer many more opportunities for obtaining a large time series spanning 4 to 10 years (with 30-100 images). These techniques are only possible if the landslide displacement is not too large (on the order of centimeters), and therefore cannot be applied for mapping new landslides with large displacements. Ground-based interferometry, using a ground-based radar system forming the synthetic aperture by the sliding of the antennas on a linear rail, has also been successfully applied to detect landslide movements (Tarchi *et al.*, 2003), but this is more applicable for landslide monitoring than for landslide inventory mapping.

GENERATION OF LANDSLIDE DATABASES

Besides the application of remote sensing products, many additional data sources are required to develop a detailed landslide database. Landslide occurrence information can often be derived from the archives of organizations dealing with the maintenance of roads or railway lines. However, such databases should be treated with care, as the exact reporting date might not be the date that the landslide occurred, but rather the date on which the maintenance took place. Newspaper archives and logbooks of fire brigades or police stations may be another source of information. However, generally, the only landslides that are reported are those that have caused major damage. Interviews with the local population and farmers using community-based approaches have also been applied for obtaining landslide information. Although these methods may provide a good insight in the location of past landslides, they generally do not result in reliable temporal information, especially for landslides that have happened many years ago.

The techniques described above are intended to support the generation of landslide databases. Such databases may have a very large degree of uncertainty, which can be related to the incompleteness of historical information (with respect to the exact location, time of occurrence, and type of movement), or to the experience and dedication of the persons carrying out the image interpretation and field mapping (Soeters and Van Westen, 1996). The difficulties involved in obtaining a complete landslide database, and its implications for landslide hazard assessment are illustrated in Figure 4. The graph indicates a hypothetical landslide frequency in the period 1960-2006, and the main triggering events (either earthquakes or rainfall events) with the return period indicated. Five different sets of imagery are available for this study (indicated by arrows A to E below the graph in Figure 4). In order to be able to capture those landslides related with a particular triggering event, it is important to be able to map these as soon as possible after the event occurred. For example, the imagery collected at times C and E can be used to map the landslides triggered by rainfall events with different return periods. The imagery collected at times B and D however, are either taken some time after the triggering event has occurred, so that landslide scarps will be covered by vegetation and so be difficult to interpret, or they occur after a sequence of different triggering mechanism, which would make it difficult to separate the landslide distributions.

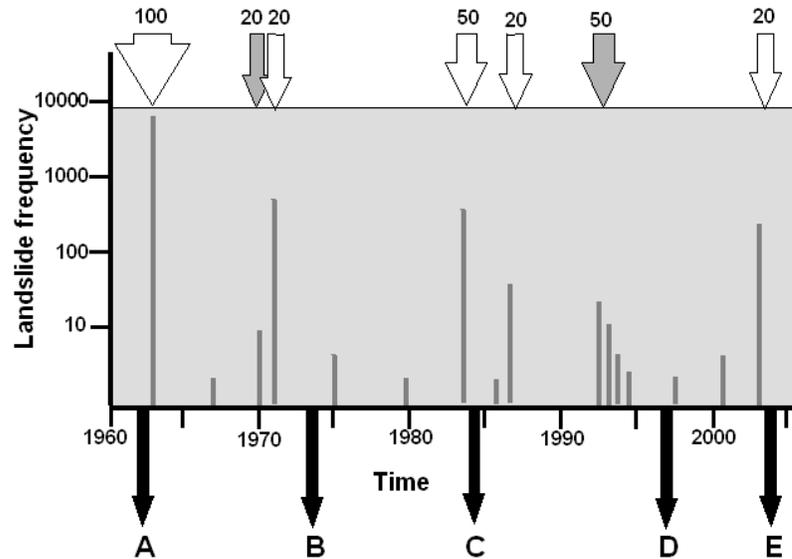


Figure 4: Schematic presentation of landslide frequency in relation to triggering events and dates of imagery. On top of the graph, arrows define the rainfall events (white arrows) and earthquakes (gray arrows) along with an indication of their return periods in years. The black arrows below the graph (labeled A to E) refer to dates of available remote sensing imagery for landslide inventory mapping.

A landslide database should contain information on the following topics:

- Location and area coverage of the landslide, indicated as a polygon with differentiation between the scarp area and the accumulation area. This is required because in many types of hazard assessment the conditions should be analyzed for the part of the slope where the landslide initiated, directly upslope of the scarp area.
- Typology, according to International Standards, such as Cruden and Varnes (1996). However, the classification should not be too complex, as this will result in too many unknown attributes in the database. Related to this should be information on the size and movement velocity.
- Date of occurrence, or dates of activity, for reactivated landslides; or a relative indication if detailed information is not available. The date and timing of the occurrence is one of the most important aspects in order to be able to link landslides to triggering events and to analyze magnitude–frequency relations.
- Information on the damage caused by the landslide event is important in order to be able to generate vulnerability curves for the types of landslides and elements at risk that are present in the study area. This is required for the risk assessment.
- Information on causal factors is extremely important in order to be able to make a good selection of the factors that will be taken into account in the landslide hazard assessment, in terms of both the environmental factors and the triggering factors.
- The source of information and description of the level of certainty of mapping should be included so that the “certain” landslides are used in generating the landslide hazard models.

Web-based landslide databases

Much progress has been made in developing landslide inventories at regional or national levels. The AVI project in Italy is one of the first comprehensive projects for landslide and flood inventory mapping. Collection of information was done through interviews, systematic review of newspapers, and analysis of technical reports, scientific papers, monographs, and books. An archive of 39,953 newspaper articles, 18,894 source-forms, 9,973 event-forms, and 707 analytical forms was collected for the period 1918-90 and stored in a database (Guzzetti *et al.*, 1994).

Many countries are developing landslide databases through map servers on the Internet, including, for example: Hong Kong (CEDD, 2007), Canada (Grignon *et al.*, 2004), Australia (Geoscience Australia, 2006), Japan (NIED, 2006), Norway (Norges geologiske undersøkelse (NGU), 2006), Italy (CNR-IRPI 2006), and New Zealand (Glade and Crozier, 1996). Many other countries are less advanced and are still developing a national mapping system for landslides in analog form. In Sri Lanka for example, the mapping of landslides was initiated after a major landslide-triggering event in 1994 (Raviskanthan and Perera, 1994) and the work intensified after a similar event in 2003. Landslides are mapped in the field without the use of recent imagery, which makes the process very time consuming. Many other countries have barely started a national inventory project, or are only in the planning phase. For instance, Cuba only recently established a reporting system for landslides that is conducted by the various levels of the Civil Defense (Castellanos and Van Westen, 2005).

Figure 5 shows two examples of WebGIS applications for landslide inventories. One of them is from Nicaragua (INETER, 2006), where all available maps and reports related to Hurricane Mitch and earlier events were used to extract the landslide information, which is stored in a GIS database with a limited number of information attributes. Another example, from Japan, contains a very comprehensive landslide database, consisting of 150 digitized quadrangle landslide maps, with a scale of 1:50,000 (NIED, 2006). Landslide scarps and accumulation areas have been identified and landslides are classified according to type (Slide, Creep, Flow, Fall, Slow movement with rotation), movement direction, internal structure, and state of activity. Age information of the landslides is lacking. Expert geomorphologists mapped the landslides using 1:14,000 scale aerial photographs. The “Natural Terrain Landslide Inventory” of Hong Kong contains information about 27,000 natural terrain landslides interpreted from 1945-1997 aerial photographs (CEDD, 2007).

CONCLUSIONS

There are good examples in the literature of the use of landslide inventories for hazard assessment (Guzzetti *et al.*, 1994; Guzzetti, 2000; Chau *et al.*, 2004; Guzzetti and Tonelli, 2004). However, existing landslide databases often contain several drawbacks related to the completeness of the information sources in space, and even more so in time, and because they are biased to landslides that have affected infrastructures such as roads (Guzzetti, 2000; Ardizzone *et al.*, 2002; Guzzetti and Tonelli, 2004).

Landslide inventory databases are very important for generating reliable prediction maps of the spatial and temporal probability for landslides. Multi-temporal landslide information is essential to new approaches for the generation of quantitative landslide probability maps (e.g., Chung and Fabbri, 2005 and Guzzetti *et al.*, 2005). Many developments have facilitated the collection of landslide information, especially the wider availability of high-resolution satellite

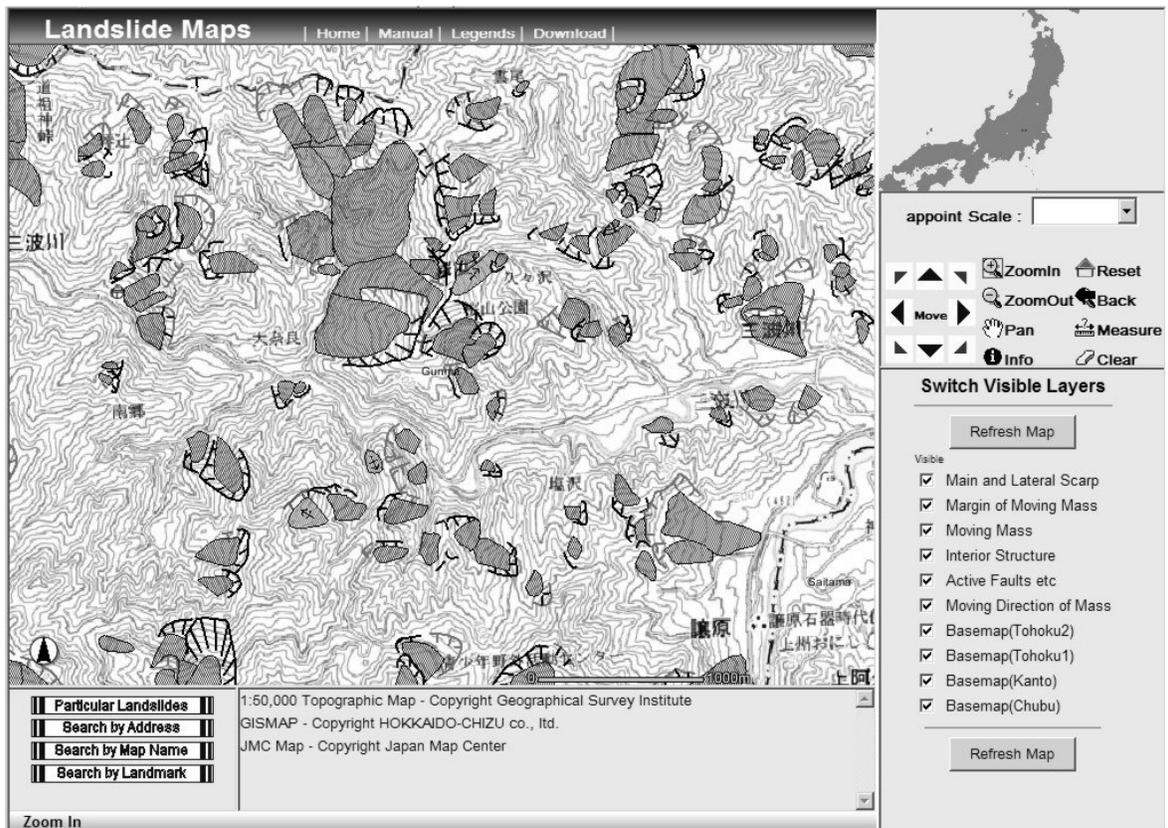


Figure 5: Examples of a web-based landslide databases. Above: General database from Nicaragua (INETER, 2006). Below: Detailed landslide database from Japan (NIED, 2006)

imagery with stereo capabilities that are finally a good substitute for aerial photographs. Emphasis should be given to the generation of event-based landslide inventory maps that are related to particular triggering events. In order to be able to quantify landslide risk, the following aspects of quantitative hazard information should be obtained: temporal probability, spatial probability, magnitude-frequency relationships, and run-out potential.

A landslide magnitude – frequency relationship is needed in order to be able to estimate the probability of occurrence of a potentially damaging landslide with a particular size and volume, within a given period of time. There is still no standard classification system for landslide magnitude, and in practice the surface area of landslides is often used as an indication of magnitude or volume if depth information is also available. A Magnitude–Frequency distribution is normally established by analyzing the number and size of landslides over an area (a watershed for example) using only those features that have occurred within a particular time period. Hence, mapping event-based landslides is very important.

A relationship between triggering events (rainfall or earthquakes) and landslide occurrences is needed in order to be able to assess the temporal probability. Temporal probability assessment of landslides is established by using rainfall threshold estimations, through the use of multi-temporal data sets in statistical modeling, or through dynamic modeling (van Beek and Van Asch, 2004). Rainfall threshold estimation is mostly done using antecedent rainfall analysis, for which the availability of a sufficient number of landslide occurrence dates is essential. If distribution maps of landslides that have been generated during the same triggering event are available, a useful approach is to derive susceptibility maps using statistical or heuristic methods, and link the resulting classes to the temporal probability of the triggering events. The most optimal method for estimating both temporal and spatial probability is dynamic modeling, where changes in hydrological conditions are modeled using daily (or larger) time steps based on rainfall data. The methods for hazard analysis should be carried out for different landslide types and volumes, as these are required for the estimation of damage potential. Landslide hazard is related to both landslide initiation and to landslide deposition. Therefore landslide run-out analysis should also be included on a routine basis.

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REFERENCES

- ALEXANDER, D. 2005. Vulnerability to landslides. *In*: T. Glade, M. Anderson and M.J. Crozier (eds). *Landslide Hazard and Risk*. Wiley. 175 -198
- ARDIZZONE, F., CARDINALI, M., CARRARA, A., GUZZETTI, F. & REICHENBACH, P. 2002. Impact of mapping errors on the reliability of landslide hazard maps. *Natural Hazards and Earth System Sciences*, Vol.2, pp.3-14.
- BARLOW, J., MARTIN, Y. & FRANKLIN, S.E. 2003: Detecting translational landslide scars using segmentation of Landsat ETM+ and DEM data in the northern Cascade Mountains, British Columbia. *Canadian Journal of Remote Sensing*, Vol.29, pp.510-517.
- BRABB, E.E., PAMPEYAN, E.H., & BONILLA, M.G., 1978. *Landslide susceptibility in San Mateo County, California*. US Geological Survey Misc. Field Studies Map, MF-360, map at 1: 62,500 scale.

- CARDINALI, M., REICHENBACH, P., GUZZETTI, F., ARDIZZONE, F., ANTONINI, G., GALLI, CACCIANO, M., CASTELLANI, M. & SALVATI, P. 2002. A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy. *Natural Hazards and Earth System Sciences*, Vol.2, pp.57–72
- CARRARA A, CARRATELLI EP & MERENDA L 1977. Computer-based data bank and statistical analysis of slope instability phenomena. *Zeitschrift für Geomorphologie*, Vol.21, pp.187-222.
- CASTELLANOS, E. & VAN WESTEN, C.J., 2005. Development of a system for landslide risk assessment for Cuba. In: E. Eberhardt, O. Hungr, R. Fell and R. Couture (Eds), *Proceedings, International Conference on Landslide Risk Management, May 31-Jun 3, 2005, Vancouver, Canada*.
- CATANI, F. FARINA, P. MORETTI, S. NICO, G. & STROZZI, T. 2005. On the application of SAR interferometry to geomorphological studies: estimation of landform attributes and mass movements, *Geomorphology*, Vol.66, (1-4), pp.119-131.
- CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT (CEDD) 2007. *The Natural Terrain Landslide Inventory*. Civil Engineering and Development Department, Hong Kong. URL: <http://hkss.cedd.gov.hk/hkss/eng/whatsnew/index.htm>
- CHANG, K.T., LIU, J.K., 2004. Landslide features interpreted by neural network method using a high-resolution satellite image and digital topographic data. *Geo-Imagery Bridging Continents, XXth International Society for Photogrammetry and Remote Sensing (ISPRS) Congress, 12-23 July 2004 Istanbul, Turkey*, <http://www.isprs.org/istanbul2004/comm7/papers/114.pdf>
- CHAU, K.T., SZE, Y.L., FUNG, M.K., WONG, W.Y., FONG, E.L., & CHAN, L.C.P. 2004. Landslide hazard analysis for Hong Kong using landslide inventory and GIS. *Computers & Geosciences*, Vol.30, (4), pp.429-443.
- CHENG, K. S., WEI, C. & CHANG, S.C. 2004. Locating landslides using multi-temporal satellite images. *Advances in Space Research*, Vol.33 (3), pp.296-301
- CHUNG, C.J. & FABBRI, A. 2005. Systematic procedures of landslide hazard mapping for risk assessment using spatial prediction models. In: T.Glade, M. Anderson and M.J. Crozier (eds). *Landslide hazard and risk*. Wiley, pp.139-174
- CNR-IRPI (2006) *Sistema Informativo sulle Catastrofi Idrogeologiche (SICI)*, Gruppo Nazionale per la Difesa dalla Catastrofi Idrogeologiche (GNDCI), del Consiglio Nazionale delle ricerche (CNR)
URL: <http://sicimaps.irpi.cnr.it/website/sici/viewer.htm>
- CRUDEN, D. M. & VARNES, D.J., 1996. Landslide types and processes. In: Turner, A.K. and Schuster, R. L. (eds.), *Landslides, Investigation and Mitigation*. Transportation Research Board, Special Report 247, Washington, pp.36–75.
- DEWITTE, O. & DEMOULIN, A. 2005. Morphometry and kinematics of landslides inferred from precise DTMs in West Belgium, *Natural Hazards and Earth System Sciences*, Vol.5(2), pp.259-265.
- FELL, R. 1994. Landslide risk assessment and acceptable risk. *Canadian Geotechnical Journal*, Vol.31, pp.261-272.
- FERRETTI, A., PRATI, C., & ROCCA, F., 2001. Permanent Scatterers in SAR interferometry. *IEEE Trans. Geosci. Remote Sensing*, Vol.39 (1), pp.8-20.
- GEOSCIENCE AUSTRALIA, 2006. *Australian Landslides Database*. Australian Government, Geoscience Australia. http://www.ga.gov.au/oracle/landslid/landsl_online.jsp

- GLADE, T. 2001. Landslide hazard assessment and historical landslide data – an inseparable couple? *In: Glade, T., Albini, P. and Frances, F. (eds) The Use of Historical Data in Natural Hazards Assessment. Advances in Natural and Technological Hazard Research*, Kluwer, pp.153-168.
- GLADE, T., ANDERSON, M. & CROZIER, M.J. 2005. *Landslide Hazard and Risk*. John Wiley & Sons, Ltd., Chichester, England, 802p.
- GLADE, T. & CROZIER, M.J. 1996. Towards a National Landslide Information Base for New Zealand. *New Zealand Geographer*, Vol.52 (1), pp.29-40
- GLADE, T. & CROZIER, M.J. 2005. A review of scale dependency in landslide hazard and risk analysis. *In: T.Glade, M. Anderson and M.J. Crozier (eds). Landslide Hazard and Risk*. Wiley, pp.75-138
- GLENN, N.F., STREUTKER, D.R., CHADWICK, D.J., THACKRAY, G.D. & DORSCH, S.J. 2006. Analysis of LiDAR-derived topographic information for characterizing and differentiating landslide morphology and activity. *Geomorphology*, Vol.73, pp.131-148
- GRAYSON, R.B., BLOSCHL, G. WESTERN, A.W. & MCMAHON, T.A. 2002. Advances in the use of observed spatial pattern of catchment hydrological response. *Advances in Water Resources*, Vol.25, pp.1313-1334.
- GRIGNON, A., BOBROWSKY, P., & COULTISH, T. 2004. Landslide database management philosophy in the Geological Survey of Canada. *Geo-Engineering for the Society and its Environment*. 57th Canadian Geotechnical Conference and the 15th joint CGS-IAAH Conference, Québec, Canada, October 24-27, 2004
- GUZZETTI, F., CARDINALI, M. & REICHENBACH, P. 1994. The AVI project: a bibliographical and archive inventory of landslides and floods in Italy. *Environmental Management*, Vol.18(4), pp.623-633.
- GUZZETTI, F. 2000. Landslide fatalities and the evaluation of landslide risk in Italy. *Engineering Geology*, Vol.58(2), pp.89-107.
- GUZZETTI, F. & TONELLI, G. 2004. Information system on hydrological and geomorphological catastrophes in Italy (SICI): a tool for managing landslide and flood hazards. *Natural Hazards and Earth System Sciences*, Vol.4, pp.213-232.
- GUZZETTI, F., REICHENBACH, P., CARDINALI, M., GALLI, M. & ARDIZZONE, F. 2005. Probabilistic landslide hazard assessment at the basin scale. *Geomorphology*, Vol.72, pp.272-299
- HANEBERG, W.C. 2004. The ins and outs of airborne LIDAR: An introduction for practicing engineering geologists. *AEG News*, Vol.48(1), pp.16-19
- HAUGERUD, R.A., HARDING, D.J., JOHNSON, S.Y., HARLESS J.L., WEAVER, C.S., SHERROD, B.L. 2003. High-resolution LIDAR topography of the Puget Lowland, Washington – A bonanza for earth science, *GSA Today*, Vol.13, pp.4-10
- HENRY, J.B., MALET, J.P., MAQUAIRE, O. & GRUSSENMEYER, P. 2002. The use of small-format and low-altitude aerial photos for the realization of high-resolution DEMs in mountainous areas: application to the Super-Sauze earthflow (Alpes-de-Haute-Provence, France). *Earth Surf. Process. Landforms*, Vol.27, pp.1339–1350
- HERVAS, J., BARREDO, J.I., ROSIN, P.L., PASUTO, A., MANTOVANI, F. & SILVANO, S. 2003. Monitoring landslides from optical remotely sensed imagery: the case history of Tessina landslide, Italy. *Geomorphology*, Vol.54, pp.63-75.

- HIRANO, A., WELCH, R. & LANG, H. 2003. Mapping from ASTER stereo image data: DEM validation and accuracy assessment. International Society for Photogrammetry and Remote Sensing (ISPRS). *Journal of Photogrammetry & Remote Sensing*, Vol.57, pp.356-370
- HSIAO, K.H., LIU, J.K., YU, M.F., & TSENG, Y.H., 2004. Change detection of landslide terrains using ground-based LIDAR data. *XXth ISPRS Congress, Istanbul, Turkey, Commission VII, WG VII/5*. 5p.
- IBSEN, M. & BRUNSDEN, D. 1996. The nature, use and problems of historical archives for the temporal occurrence of landslides, with specific reference to the south coast of Britain, Ventnor, Isle of Wight. *Geomorphology*, Vol.15, pp.241-258.
- IGOS 2003. Marsh, S., Paganini, M., Missotten, R. (Eds) *Geohazards Team Report*. <http://igosg.brgm.fr/>
- INSTITUTO NICARAGÜENSE DE ESTUDIOS TERRITORIALES (INETER). 2006. *Inventario nacional de deslizamientos en Nicaragua*.
Hyperlink: <http://mapserver.ineter.gob.ni/website/Mapas/desli/viewer.htm>
- JONES, L.D. 2006. Monitoring landslides in hazardous terrain using terrestrial LiDAR: an example from Montserrat. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol.39 (4), pp.371-373.
- LEE, E.M. & JONES, D.K.C. 2004. *Landslide Risk Assessment*. Thomas Telford, London, 454p.
- LEROI, E. 1996. Landslide hazard - Risk maps at different scales: Objectives, tools and development. In: K. Senneset (Editor), *Landslides - Glissements de Terrain, 7th. International Symposium on Landslides, Trondheim, Norway*. Balkema, pp.35-51.
- MANTOVANI, F., SOETERS, R. & VAN WESTEN, C. J. 1996. Remote sensing techniques for landslide studies and hazard zonation in Europe, *Geomorphology*, Vol.15(3-4), pp.213-225.
- MARCELINO, E.V., FONSECA, L.M.G., VENTURA, F. and SANTA ROSA, A.N.C., 2003, Evaluation of the IHS and wavelet transform fusion techniques for the identification of landslide scars using satellite data. *Proceedings of the Anais XI Simpósio Brasileiro de Sensoriamento Remoto (SBSR), Belo Horizonte, Brazil, 5-10 April 2003* Brazil: National Institute of Space Research, pp.487-494.
- MARTIN, Y.E. AND FRANKLIN, S.E. 2005. Classification of soil- and bedrock-dominated landslides in British Columbia using segmentation of satellite imagery and DEM data. *International Journal of Remote Sensing*, Vol.26, pp.1505-1509.
- MCKEAN, J., ROERING, J., 2004. Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry. *Geomorphology*, Vol.57, pp.331-351.
- METTERNICHT, G. HURNI, L. & GOGU, R. 2005. Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments, *Remote Sensing of Environment*, Vol.98(23), pp.284-303.
- NATIONAL RESEARCH INSTITUTE FOR EARTH SCIENCE AND DISASTER PREVENTION (NIED). 2006. *Landslide Map Database*. National Research Institute for Earth Science and Disaster Prevention, and Japan Science and Technology Agency (JST). URL: http://lswel1.ess.bosai.go.jp/jisuberi/jisuberi_mini_Eng/main.asp
- NICHOL, J. & WONG, M. S. 2005. Satellite remote sensing for detailed landslide inventories using change detection and image fusion. *International Journal of Remote Sensing*, Vol.26(9), pp.1913-1926

- NORGES GEOLOGISKE UNDERSØKELSE (NGU). 2006. *National landslide database*. Norwegian Geological Survey, Trondheim, Norway, <http://www.skrednett.no/>
- OKA, N. 1998. Application of photogrammetry to the field observation of failed slopes, *Engineering Geology*, Vol.50(1-2), pp.85-100.
- PETLEY, D.N., CRICK, W.D.O. & HART, A.B., 2002, The use of satellite imagery in landslide studies in high mountain areas. *Proceedings of the 23rd Asian Conference on Remote Sensing (ACRS 2002)*, Kathmandu, November 2002.
- RAVISKANTHAN, A, & PERERA A.H. 1994. A Database on Landslides in Sri Lanka. *Proceedings of the National Symposium on Landslides in Sri Lanka*, Vol.1, pp.365-370.
- REID, L.M., & PAGE, M.J. 2002. Magnitude and frequency of landsliding in a large New Zealand catchment. *Geomorphology*, Vol.49, pp.71-88
- RESTREPO, C. & ALVAREZ, N. 2006. Landslides and their contribution to land-cover change in the mountains of Mexico and Central America. *BIOTROPICA*, Vol.38(4), pp.446-457
- ROESSNER, S., WETZEL, H.U., KAUFMANN, H. & SARNAGOEV, A. 2005: Potential of satellite remote sensing and GIS for landslide hazard assessment in southern Kyrgyzstan (Central Asia). *Natural Hazards*, Vol.35, pp.395-416.
- ROWLANDS, K., JONES, L. & WHITWORTH, M., 2003. Landslide laser scanning: a new look at an old problem. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol.36, pp.155-157.
- SCHULZ, W.H. 2004. *Landslides mapped using LIDAR imagery, Seattle, Washington*. U.S. Geological Survey Open-File Report 2004-1396
- SOETERS, R. & VAN WESTEN C.J. 1996. Slope instability recognition, analysis and zonation. *In: Turner, A.K. and Schuster, R.L. (eds). Landslides, Investigation and Mitigation*. Transportation Research Board, National Research Council, Special Report 247, National Academy Press, Washington D.C., U.S.A., pp.129-177.
- SINGHROY, V. 2005. Remote sensing of landslides. *In: T. Glade, M. Anderson and M.J. Crozier (eds). Landslide Hazard and Risk*. Wiley. pp.469-492.
- TARCHI, D., CASAGLI, N., MORETTI, S. LEVA, D. & SIEBER, A.J. 2003. Monitoring landslide displacements by using ground-based synthetic aperture radar interferometry: Application to the Ruinon landslide in the Italian Alps. *J. Geophysical Research*, Vol.108(B8), pp.2387
- TRIBE, S. & LEIR, M. 2004. The role of aerial photograph interpretation in natural hazard and risk assessment. *Proceedings of IPC 2004, International Pipeline Conference*, October 4-8, Calgary, Canada. 6p.
- VALLET, J. & SKALLOUD, J. 2004. Development and Experiences with A Fully-Digital Handheld Mapping System Operated From A Helicopter, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Istanbul*, Vol.XXXV, Part B, Commission 5.
- VAN BEEK, L.P.H. & VAN ASCH, T.W.J. 2004. Regional assessment of the effects of land-use change and landslide hazard by means of physically based modeling. *Natural Hazards*, Vol.30(3), pp.289-304.
- VAN WESTEN, C.J., & F.L. GETAHUN 2003. Analyzing the evolution of the Tessina landslide using aerial photographs and digital elevation models, *Geomorphology*, Vol.54(1-2), pp.77-89.
- VAN WESTEN, C.J. 2004 Geo-Information tools for Landslide Risk Assessment. An overview of recent developments. *In: Willy Lacerda, Mauricio Ehrlich, Sergio Fontoura and*

- Alberto Sayao (eds.) *Landslides, Evaluation & Stabilization*. Proceedings 9th International Symposium on Landslides, Rio de Janeiro, June 28-July 2nd 2004, pp.39-56.
- VAN WESTEN, C.J., VAN ASCH, T.W.J. & SOETERS, R. (2005) Landslide Hazard and Risk Zonation; are we trying the impossible? *Bulletin of Engineering Geology and the Environment*, Vol.65(2), pp.167-184
- VARNES, D.J. 1984. *Landslide Hazard Zonation: A Review of Principles and Practice*. Paris: United Nations International.
- WHITWORTH, M.C.Z., GILES, D.P. & MURPHY, W. 2005. Airborne remote sensing for landslide hazard assessment: a case study on the Jurassic escarpment slopes of Worcestershire, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol.38(3), pp.285-300.