Geo-Information tools for Landslide Risk Assessment. An overview of recent developments

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ABSTRACT: The aim of this contribution is to give an overview of recent developments in the use of Geographical Information Systems and Earth Observation which have been applied for improved landslide inventory mapping, landslide susceptibility and hazard assessment, elements at risk mapping, and finally landslide vulnerability and risk assessment. Geo-Information science and earth observation consists of a combination of tools and methods for the collection - through aerospace survey techniques -, storage and processing of geospatial data, for the dissemination and use of these data and of services based on these data. New relevant advances in this field are discussed, such as the wider availability and higher accuracy of Digital Elevation Models (e.g. from ASTER, SRTM, Lidar) and the improved spatial and spectral resolution of satellite images. Another important development is in the field of digital data collection through digital stereo image interpretation, and the use of mobile GIS for data collection of landslides and elements at risk. Finally an overview is given of the use of GIS in landslide hazard, vulnerability and risk assessment.

1 INTRODUCTION

Landslide risk is defined as the expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular landslide hazard for a given area and reference period (Varnes, 1984). When dealing with physical losses, (specific) risk can be quantified as the product of vulnerability, cost or amount of the elements at risk and the probability of occurrence of the event. When we look at the total risk, the hazard is multiplied with the expected losses for all different types of elements at risk (= vulnerability * amount), and this is done for all hazard types. Schematically, this can be represented by the following formula:

$$\textbf{Risk} = \Sigma\,(H * \Sigma(V * A))$$

Where:
H = Hazard expressed as probability of occurrence within a reference period (e.g., year)
V = Physical vulnerability of a particular type of element at risk (from 0 to 1)
A = Amount or cost of the particular elements at risk (e.g., number of buildings, cost of buildings, number of people, etc.). Theoretically, the formula would result in a so-called *risk curve*, containing the relation between all events with different probabilities, and the corresponding losses.

Out of the factors mentioned in the formula for risk assessment, the hazard component is by far the most difficult to assess, due to the absence of a clear magnitude-frequency relation at a particular location, although such relations can be made over larger areas. Furthermore, the estimation of both magnitude and probability of landsliding requires a large amount of information on the following aspects:

- Surface topography;
- Subsurface stratigraphy;
- Subsurface water levels, and their variation in time;
- Shear strength of materials through which the failure surface may pass,
- Unit weight of the materials overlying potential failure planes;
- The intensity and probability of triggering factors, such as rainfall and earthquakes.

All of these factors, required to calculate the stability of individual slopes, have a large spatial variation, and are only partly known, at best. If all these factors would be known in detail it would be possible to determine which slopes would generate landslides of specific volumes and with specific runout zones for a given period of time.

Risk analysis, assessment and management require a large amount of information. Relatively large volumes of multi-disciplinary and technical information have to be collected, processed, analyzed, and eventually communicated to a broad range of users under quite different conditions, ranging from planning and regulatory activities to emergency management (Fedra, 1998). Modern information technology provides some of the tools to support these activities, leading to the development of risk information systems that can be used for both analyzing risk and evaluating the consequences of decisions that have to be taken to mitigate or reduce risk at both short term (emergency planning) and long term (development planning).

The aim of this paper is to give an overview of recent developments in the use of Geographical Information Systems and Earth Observation which have been applied for improved landslide inventory mapping, landslide susceptibility and hazard assessment, elements at risk mapping, and finally landslide vulnerability and risk assessment. This paper does not intend to give an overview of the various methods for landslide hazard and risk assessment. For overview publications regarding landslide hazard methods the reader is referred to publications such as Varnes (1984), Soeters and Van Westen (1996), Aleotti and Chowdury (1999) and Guzzetti *et al.* (1999; 2000). The fairly recent topic of landslide risk assessment is discussed by Einstein (1988), Chowdhury (1988), Fell (1994), Fell and Hartford (1997), Hungr et al. (1999), Hearn and Griffiths (2001) and Dai *et al.* (2002), collections of publications on risk assessment can be found in Turner and Schuster, (1996), Sennestet, (1996), Cruden and Fell (1997), and McInnes and Jakeways (2002). This paper is partly based on an extensive literature search using a Web-based search engine (Geobase) for scientific journal articles basically from the past 8 years.

2 GEO-INFORMATION SCIENCE AND EARTH OBSERVATION FOR LANDSLIDE HAZARD AND RISK ASSESSMENT

Geo-information science and earth observation consist of a combination of tools and methods for the collection, storage and processing of geo-spatial data and for the dissemination and use of these data and of services based on these data. This implies the development and application of concepts for spatial data modeling, for information extraction from measuring and image data, and for the processing, analysis, dissemination, presentation and use of geo-spatial data. It also implies the development and implementation of concepts for the structuring, organization and management of geo-spatial production processes in an institutional setting.

Due to the diversity and large volumes of data needed, and the complexity in the analysis procedures, quantitative landslide risk assessment has only become feasible in the last decade or so, due to the developments in the field of Geo-Information science. When dealing with GIS-based landslide hazard assessment, elements at risk mapping, and vulnerability/risk analysis, experts from a wide range of disciplines, such as earth sciences, hydrology, information technology, urban planning, architecture, civil engineering, economy and social sciences need to be involved.

Carrara *et al.* (1999), in an interesting overview paper on the use of GIS technology for the prediction and monitoring of landslide hazards, indicated some of the negative aspects of the extensive use of GIS in the process, such as:

- Computer-generated results are considered to be more objective and accurate than products derived by experts in the conventional way through extensive field mapping;
- The use of GIS and the production of less accurate hazard maps by users that are not experts in earth sciences;
- The increased focus on the use of new computational techniques for landslide hazard assessment, and less interest on the collection of reliable data;

For the average earth scientist it is difficult to keep up with the rapid developments in the field of Geo-information Science and Earth Observation. The number of new sensors and platforms, and the amount of acronyms is overwhelming. Also the change of GIS software from one version to the next, in which the methods that had been developed earlier on do no longer function, because of changes in file structure or interface, can be frustrating to many earth scientists. Nevertheless, GIS has become an almost compulsory tool in landslide hazard and risk assessment, and it is the challenge to keep on using it as a tool, and not as an objective in itself. When using GIS, the following components of a landslide risk project can be differentiated: data collection, data entry, data management, and data modeling. An overview of the various aspects related to the use of GIS technology in landslide risk assessment is given in Figure 1. In the following section a number of specific aspects will be treated further.

3 COLLECTING, ENTERING AND ORGANIZATION OF DATA FOR LANDSLIDE RISK ANALYSIS.

In the field of data collection for landslide hazard, vulnerability and risk assessment, the developments in the fields of Geo-Information Science and Earth Observation have shown a major impact in the fields of DEM generation, digital mapping and mobile GIS.

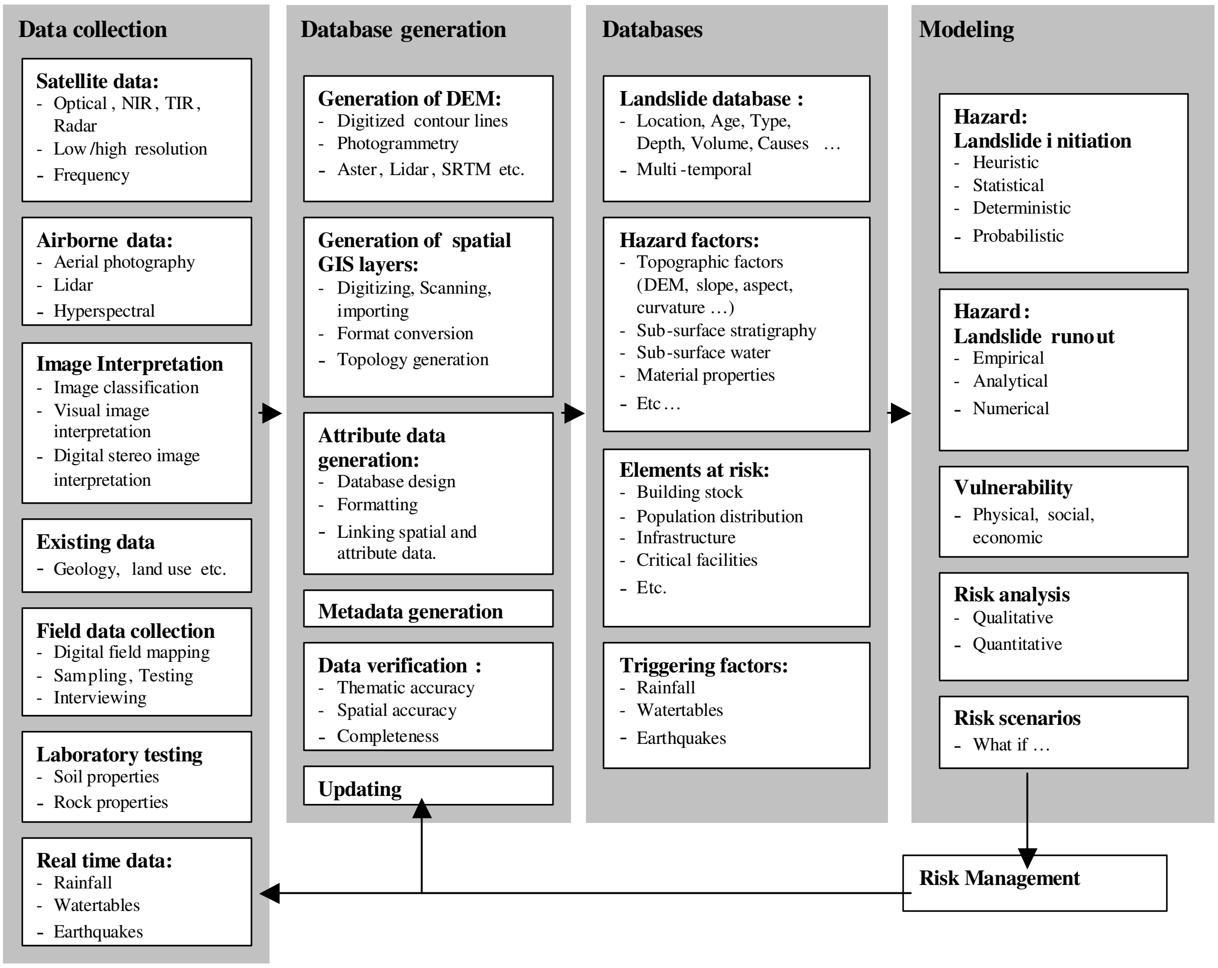


Figure 1: Different components related to the use of Geo-Information tools and methods for risk analysis.

3.1 DEM Generation

As topography is one of the major factors in landslide risk analysis, the generation of a digital representation of the surface elevation, called Digital Elevation Model (DEM), plays a major role. During the last 15 years there have been important changes both in terms of data availability, as well as in terms of software that can be used on normal desktop computers, without extensive skills in photogrammetry**.** Global DEMs are available with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometer), such as GLOBE or GTOPO30 (Hastings and Dunbar, 1998). GTOPO30 was derived from various existing sources of topographic information in both raster and vector format. The GTOPO30 data set was completed in 1996 and was developed by the USGS. It has an overall vertical accuracy of 30 meters. Data can be downloaded from Internet.

3.1.1 SRTM

The NASA Shuttle Radar Topography Mission (SRTM) has gathered topographic data for about 80% of the Earth's land surface, in the area between 60 degrees latitude (Rabus *et al.*, 2003). SRTM used the technique of interferometry, in which two radar images are taken from different points of the same area. Altitude of the surface can be calculated from the phase difference in the two images. The SRTM radar used two types of frequencies: C-band and X-band. The C-Band radar data was used by NASA's Jet Propulsion Lab (JPL) to generate DEM, and the X-Band by the German Space Agency DLR for detailed DEM generation (Rabus *et al.* 2003). These data are being distributed through the United States Geological Survey's EROS Data Center. The released SRTM DEMs for the United States are at 30-meter resolution, and those for the rest of the world at 90 meters. As they are very recent, no publications were encountered on the use of SRTM DEMs in landslide hazard assessment. It is expected that

SRTM DEMs will be used extensively in the near future in regional scale landslide hazard assessment projects in developing countries. Although a resolution of 90 meter is still not very detailed, and not suitable for generating slope maps, it would allow for the characterization of the terrain using morphometrical analysis.

3.1.2 ASTER

Another source of DEMs is ASTER. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is one of 5 instruments on the Terra platform, launched in 1999. One of the added benefits of the ASTER system is that it offers stereoscopic imagery, as the VNIR subsystem is specifically designed with a backward-viewing telescope for high-resolution (15 meter) stereoscopic observation in the along-track direction. Several authors (Toutin and Cheng, 2001; Kaab, 2002) report on the generation of Digital Elevation Models from ASTER images. Through the comparison of a DEM derived from aerial photographs with one derived from ASTER, an accuracy of ± 60 m RMS of the ASTER DEM was found for rough high-mountain topography, and ± 18 m RMS for moderately mountainous terrain (Kaab, 2002). ASTER data is currently one of the least expensive types of satellite data available. Initially ASTER data could be downloaded for free, but now one frame costs around $55. ASTER's 14 multi-spectral bands (in the VNIR, SWIR and Thermal IR) and stereo capability facilitate mapping and assessment of landslide hazard on a regional scale and especially in areas where detailed geological maps and topographic maps are not available (Liu *et al.* 2004). Digital Elevation Models from ASTER can either be generated by the user, with ground control points taking by GPS and software such as Erdas Imagine Orthobase pro, or can be purchased (http://edcdaac.usgs.gov/)

3.1.3 InSar

SAR interferometry (InSAR) is gaining increasing importance as a technique for rapid and accurate topographic data collection. Synthetic Aperture Radar (SAR) images contain both the amplitude and phase information of the return signals from the earth surface. SAR interferometry (InSAR) is a technique in which two SAR images of the same portion of the earth taken from slightly different satellite positions are used (Massonnet and Feigl, 1998; Rosen *et al.*, 2000). Combining the two images results in an interferogram, which represents the phase difference between the return signals in the two SAR images, which result from topography and from changes in the line-of-site distance (range) to the radar due to displacement of the surface or change in the propagation path length. The phase differences can be converted into a DEM if very precise satellite data are available. This technique can be applied for measuring displacements at the earth's surface with very high accuracy and for topographic mapping (Massonnet and Feigl, 1998). A number of spaceborne InSAR systems are operational, (ERS, ENVISAT, RADARSAT) or in the planning and implementation stages and therefore it is important to understand the accuracy and limitations of the technique for different applications (Crosetto, 2002). For the generation of Digital Elevation Models a combination of ascending and descending mode data is often used (Pasquali *et al.,* 1994), to cover areas affected by foreshortening and layover in one image (e.g. ascending mode) by data from the other image. The InSAR processing involves coregistration of the tandem data, calculation of the interferometric phase and coherence, phase unwrapping and computation of the height. Since the phase unwrapping is the most crucial part of InSAR processing involving reconstruction of phase to extract height information, any error committed at this stage affects the quality of the DEM (Crosetto, 2002). Although in some areas Digital Elevation Models (DEM) produced from this technique are becoming available the generation of Digital Elevation Models through InSar however is still mainly in the development stage, and due to the complex technical procedure it is not likely that DEM generation from InSar will become a custom operation for the average landslide researcher.

As mentioned earlier the phase difference results from topography as well as due to displacement of the surface. Therefore, by separating the motion-related and the topography related phase contributions, mapping of landslide movements is possible. This can be done by differential interferometry (DInSAR) technique using two interferograms of different time periods

In recent years this technique has been used to monitor and measure landslide movements (Fruneau *et al.*, 1996; Rott *et al.*, 1999; Vietmeier *et al.*, 1999: Kimura and Yamaguchi, 2000; Rizo and Tesauro, 2000; Squarzoni *et al.*, 2003). Singhroy et al (1998) have used both airborne C-band radar data and RADARSAT data combined with LANDSAT TM data for landslide mapping in several areas in Canada. Rott *et al.* (1999) demonstrated the application of radar interferometry to detect slope movements on the order of millimeters to centimeters per year in a high mountain area above the treeline. The applicability of the DInSar method for detecting slope movements in vegetated terrain however is much less, due to phase decorrelation and atmospheric disturbances. Bernardino et al (2003) tried to reduce these disturbances by using new algorithms for phase unwrapping and they compared the results of DinSar measurements for the movement of a large landslide over a period of several years with the results from GPS and Electronic Distance Meter (EDM) measurements. They concluded that the accuracy of displacement values derived from DinSar as compared with those from GPS is higher for those places with higher coherence, and that values measured at low coherence sites should not be used as absolute values. Better results can be obtained by carrying out measurements on a subset of image pixels corresponding to pointwise stable reflectors (Permanent Scatterers, PS) and exploiting long temporal series of interferometric data, as demonstrated by Colesanti et al (2003) with data from California and landslide areas near Ancona in Italy. The permanent scatterer method however, has the drawback that a large number of SAR scenes are required and that measurements can only be made for a limited number of points in the terrain. Radar interferometry has also been applied very successfully on the ground, as ground-based interferometry for the monitoring of landslides in Italy, as demonstrated by Tarchi *et al.* (2003) and Pieraccini *et al.* (2003).

3.1.4 Lidar

One of the most promising new techniques for high accuracy DEMs is Lidar. Lidar is an acronym standing for Light Detection and Ranging. It is in literature also sometimes referred to as Laser altimetry (Ackermann, 1999). Lidar is using a pulse laser to measure the distance between the sensor and the surface of the Earth (Flood and Gutelius, 1997). The position of each measured point is identified using a differential GPS and an Inertial Measurement Unit (Wehr and Lohr, 1999). Normally Lidar point measurements will render so-called Digital Surface Models (DSM), which contains information on all objects of the Earth's surface, including buildings, trees etc. (Ackermann, 1999). Through sophisticated algorithms, and final manual editing, the landscape elements are removed and a Digital Terrain Model is generated. The difference between a DSM and the Digital Terrain Model (DTM) can also provide very useful information, e.g on elements at risk (buildings etc. see later section) or the forest canopy height (Wehr and Lohr, 1999).

More and more areas are now mapped using Lidar, although this can be said mainly for developed countries, as the costs of Lidar surveys are still rather high. In literature, there are still very few publications on the use of Lidar in landslide inventory mapping, hazard assessment and elements at risk mapping. Most applications reported deal with forest mapping, coastal mapping, flood hazard and risk assessment and building mapping. Lidar data have been used by Montgomery *et al.* (2000) and Dietrich *et al.* (2001) in the analysis of landslide susceptibility related to forest management. McKean and Roering (2004) have used Lidar data to measure local topographic roughness in order to detect and map large deep-seated landslide in an area in New Zealand. Crosta and Agliardi (2002) used a very detailed DEM (pixelsize of 1 meter) made by Lidar-ALTM in combination with airphoto interpretation, detailed field surveys and geotechnical data in the analysis of the movement mechanism of a large rockslide. Haugerud *et al.* (2003) discuss the potential of Lidar for the mapping of Geomorphological features, such as landslides, faultscarps, uplifted beaches and periglacial- and glacial landforms in a forested area Northwest of Seatle. Norheim *et al.* (2002) made an extensive comparison of DEMs derived from Lidar and airborne InSar for the same area and concluded that the accuracy of the Lidar DEM was far better, and that is was comparable in accuracy and more ecomical as compared with a DEM derived by photogrammetrical techniques from aerial photographs.

Also terrestrial laser scanning methods have been developed, and successfully used in the characterization of the 3-D structure of landslides or rockslopes (Rowlands *et al.*, 2003)

3.2 Landslide mapping from remotely sensed images

In this section some of the recent developments in the use of remotely sensed images for landslide inventory mapping will be discussed. Overview of earlier work on this topic can be found in McKean *et al.* (1991), Mantovani *et al.* (1996), Soeters and Van Westen (1996) and CEOS (2001).

3.2.1 Higher spatial resolution

In the last decades the use of satellite data has become a normal input into landslide hazard assessment projects. Until recently the technology for this use of satellite remote sensing data for identification and mapping of small-scale slope failures was not yet available. However, now there is a potential value for the application of multispectral and panchromatic data with up to 1-meter spatial resolution (Singhroy *et al.*, 2000). LANDSAT data has remained quite popular for the mapping of landslide areas, especially in those situations where unvegetated landslide area can be differentiated spectrally from the rest of the areas (Honda *et al.*, 2002). Also higher resolution imagery, such as SPOT (Yamaguschi *et al.*, 2003) and IRS-1C (Nagarajan *et al.*, 1998) has been used for change detection and landslide mapping. There are not so many authors reporting on the use of very high-resolution imagery, such as IKONOS or Quickbird in landslide inventory and hazard assessment. De la Ville *et al.* (2002) have used IKONOS panchromatic images for the mapping of landslides and debris flows in six mountain catchments in Venezuela after a major rainstorm event. Petley *et al.* (2002) have used IKONOS data for landslide inventory mapping and compared the results with LANDSAT ETM+ data. Hervas *et al.* (2003) discussed a method for automatic change detection based on high-resolution imagery, which are suitably pre-processed (geometrically registered and radiometrically normalized) for the Tessina landslide in Northern Italy, near Belluno. Airborne Thematic Mapper (ATM) imagery has also been used in the mapping of landslides (Whitworth *et al.*, 2001)

3.2.2 *Higher spectral resolution*

In another rapidly developing field of earth observation, that of hyperspectral remote sensing, limited work has been done sofar to explore the possibilities of the available sensors for landslide inventory mapping. Hyperspectral remote sensing, or imaging spectroscopy, consists of acquiring images in many (>100) narrow, contiguous spectral bands, from which a continuous spectrum is obtained for each pixel, instead of only broad information in a few wide spectral bands. Hyperspectral images enable detailed spectral identification of minerals, rocks, soils and vegetation types (Curran, 2001) at the surface. Spectra from airborne systems such as the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and Hyperspectral Mapper (HyMap) have been used to successfully map soiltypes and swelling clays (Chabrillat *et al,* 2002). Airborne hyperspectral data are available for limited parts of the world. Spaceborne imaging spectrometers are available, such as the ASTER and MODIS on board the EOS-AM1, and the MERIS on ENVISAT. The spatial resolution of these is still too general in order to be useful for landslide detection, with the exception of ASTER, although it can be used for soiltype mapping (van der Meer *et al.*, 1999). ASTER has three spectral bands in the visible near-infrared (VNIR), six bands in the short-wave infrared (SWIR), and five bands in the thermal infrared (TIR) regions, with 15, 30, and 90 meters ground resolution respectively. This combination of wide spectral coverage and high spatial resolution allows ASTER to discriminate amongst a large variety of surface materials, ideal for geological studies.

3.2.3 *Digital techniques for landslide change detection*

Despite the theoretical availability of high-resolution satellite images, aerial photographs are used more extensively for landslide studies because they have been in existence for a long time and have a suitable spatial resolution. Techniques for change detection using digital aerial photos are often based on the generation of high accurate orthophotos, using high precision GPS control points, for images from different periods. A detailed procedure is given in Casson *et al.* (2003) with a multi-temporal example from the La Clapiere landslide in France. Hervas *et al.* (2003), and Van Westen and Lulie (2003) have made similar attempts for the Tessina landslide in Italy. Powers *et al.* (1996) developed a digital method for visual comparison between two sets of multi-temporal aerial photographs, of the active portion of the Slumgullion earthflow in Colorado, to determine horizontal displacement vectors from the movements of visually identifiable objects, such as trees and large rocks. Baum *et al.* (1998) report on the result of displacement gradients obtained through photogrammetrical work of multi-temporal aerial photos in Honolulu, Hawaii. Maas and Kersten (1997) present two practical studies on the helicopter-based use of a high-resolution digital still-video camera for digital aerotriangulation and the automatic generation of digital elevation models and orthophotos. Test regions were an alpine village and a landslide area in Switzerland.

3.2.4 *Digital stereo image interpretation*

Conventional landslide inventory mapping from aerial photographs has always been done using hardcopy stereo photos under a mirror stereoscope, through the drawing of the interpretation on 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 the interpretation of stereo images can be done digitally, using two scanned stereo images. These images could be the two scanned hardcopy airphoto's which form a stereopair. However, with the current GIS and image processing software such as ERDAS StereoAnalyst or ILWIS, 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, such as in the case of LANDSAT data. 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 (see figure 2).

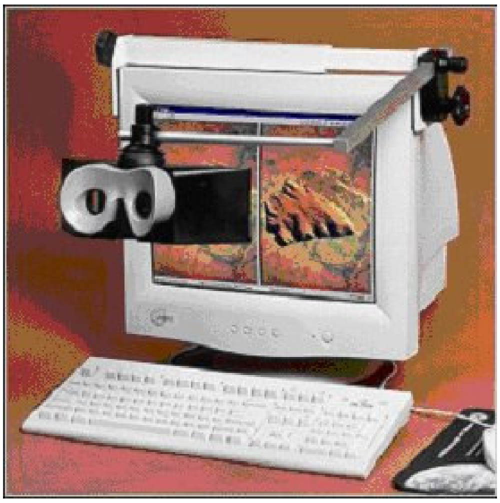


Figure 2: screen stereoscope for digital stereo interpretation (source: http://www.stereoaids.com.au)

The advantage of anaglyphs is that viewing glasses are cheap and widely available. The disadvantage is that for color images the colors are different from the original ones. Anaglyph images can be generated by merging two scanned stereo airphotos in red and green colors using a photo editing software. They can also be generated using special software from a single image combined with a Digital Elevation Model.

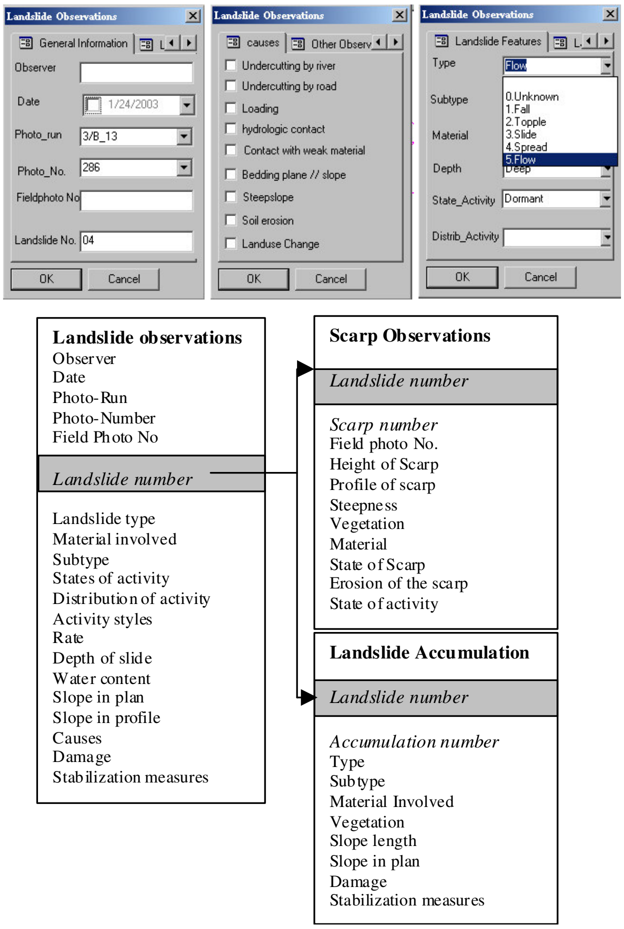
3.3 Digital landslide data collection in the field

For image interpretation and field mapping of landslides the use of checklists for standardized data collection is an important, but also time-consuming component (Van Westen, 1993). Hard copy checklists and photointerpretation maps were used before, and had to be manually digitized later. With the use of mobile GIS this process can be speeded up considerably. Several methods for digital field data collection have been developed. A number of software packages have been specifically developed for digital geological field data collection, such as the FieldLog software, developed by the Canadian Geological Survey (Brodaric, 1997; 2000), the PenMap system (Kramer, 2000) developed by the University of California, and the GSMCAD system (Williams, 1997) which is a Microsoft Windows based program developed by the US Geological Survey. Other, more generic systems for mobile GIS are MapLT, PocketGIS, and the ArcPad software from ESRI, which is the most convenient one when working with ArcGIS. The input application can be made on a desktop PC and loaded into a palmtop. The software works with vector data (shape files) and raster data (JPEG, MrSID). The software runs on laptops, tablet pen computers, palm top computers which operate in a Windows CE environment and personal data assistants (PDA) operating in Palm OS. The system is integrated with a GPS system. A simple structure for a mobile GIS interface and the landslide attributes that are collected is given in figure 3.

3.4 Elements at risk mapping.

In order to be able to make an adequate landslide risk assessment information should be collected on the elements at risk. Elements at risk refer to the population, buildings, civil engineering works, economic activities, public services, utilities and infrastructure, etc., that are at risk in a given area (AGSO, 2001). Each of these elements at risk has its own characteristics, which can be spatial (related to the location in relation to the hazard), temporal (such as the population, which will differ in time at a certain location) and thematic characteristics (such as the material type of buildings, or the age distribution of the population).

Elements at risk inventories can be carried out at various levels of detail, depending on the requirement of the study. In urban and rural areas the detail of inventory will also differ. Normally such an inventory is time consuming and expensive. Furthermore, such an inventory is not only made for landslide risk analysis, but can be used in more development planning processes and can also be related to cadastral information systems (Montoya, 2000).



Landslide Observations

General Information

Observer:

Date: 1/24/2003

Photo_run: 3/B_13

Photo_No.: 286

Fieldphoto No:

Landslide No.: 04

Landslide Observations

causes

☐ Undercutting by river
☐ Undercutting by road
☐ Loading
☐ hydrologic contact
☐ Contact with weak material
☐ Bedding plane // slope
☐ Steepslope
☐ Soil erosion
☐ Landuse Change

Landslide Observations

Landslide Features

Type: Flow

0.Unknown
1.Fall
2.Topple
3.Slide
4.Spread
5.Flow

Depth: Deep

State_Activity: Dormant

Distrib_Activity:

Landslide observations
Observer
Date
Photo-Run
Photo-Number
Field Photo No
Landslide number
Landslide type
Material involved
Subtype
States of activity
Distribution of activity
Activity styles
Rate
Depth of slide
Water content
Slope in plan
Slope in profile
Causes
Damage
Stabilization measures

Scarp Observations
Landslide number
Scarp number
Field photo No.
Height of Scarp
Profile of scarp
Steepness
Vegetation
Material
State of Scarp
Erosion of the scarp
State of activity

Landslide Accumulation
Landslide number
Accumulation number
Type
Subtype
Material Involved
Vegetation
Slope length
Slope in plan
Damage
Stabilization measures

Figure 3: Top: three input screens of the ArcPad application for digital landslide data collection. Below: structure of the tables and names of fields used in the database. Most of the fields are linked to lookup tables.

The procedures for the collection and classification of elements at risk for landslide risk analysis is much less advanced than for other types of hazard, such as earthquakes or flooding. These might range from simple classifications (RADIUS, 1999) to very complex ones. One of the best examples of a GIS-based methodology for elements at risk mapping and loss estimation for earthquakes, flooding and windstorms is HAZUS (FEMA, 2004). It has been produced in the United States by the Federal Emergency Management Agency (FEMA) under a cooperative agreement with the National Institute of Building Science. It contains a detailed description of the classification methods for all major types of elements at risk and how they should be classified and stored in the database, which is only for the US. For landslide risk assessment, normally a much more simpler classification of elements at risk is used (Kong, 2002) the following groups of elements at risk are considered essential:

- *General building stock:* with information regarding the construction type (e.g. masonry, wood, reinforced concrete), occupancy type (e.g. commercial, residential, industrial etc.) and number of floors;
- *Transportation Infrastructure:* with information regarding the type (e.g. highway, main road, unpaved road, railroad), width, and traffic volume (for different times of the day);
- *Population distribution:* The spatial distribution of the population as well as the distribution according to age classes. In the absence of census information this might also be obtained from occupancy classes of buildings;
- *Essential facilities:* Essential facilities, including medical care facilities, emergency response facilities and schools, are those vital to emergency response and recovery following a disaster.

There are rarely reliable and complete databases available that provide the necessary information on the elements at risk and their characteristics (Montoya, 2002). In an increasing number of cases, however, some form of basic digital topographic information will be available. Very often such topographic information will also contain a building footprint map, which can be considered as one of the main inputs for a proper landslide risk assessment. In other the basic units for risk analysis could be used from existing cadastral databases. Population data may be derived from existing census data, although this will very often not be made available at the individual building level.

In any case, even if digital information is available, a considerable amount of work needs to be done in developing a GIS database for elements at risk mapping, which will include the characterization of the building types, mapping of building occupancies, and collection of population information through field inquiries. Also here the use of mobile GIS is essential (Montoya, 2003). If no digital data exist, the elements at risk mapping can be based on detailed orthorectified imagery, which could be on aerial photographs or high-resolution satellite imagery. From such imagery it is possible to delineate the built-up area on the basis of textures, patterns, tones, size and shadows. On the orthophoto image all buildings can be digitized, as well as the land parcels, and the roads and other infrastructures. Each polygon should be described in the field making use of checklists for the collection of data on hazard and vulnerability. In case data collection at individual building level is too time consuming, a building survey can also be done at a more aggregated level in the form of homogeneous units, which are groups of buildings, characterized by a relative homogeneity of building type, construction materials, number of floors and land use distribution. For each homogeneous unit information should be collected during a field survey, on building characteristics, land use distribution, socio-economic data on population, age distribution and employment. Also intends have been made on the automatic classification of buildings from InSar (Stilla *et al.*, 2003), Lidar (Priestnall *et al.*, 2000; Dash *et al.* 2004) and IKONOS (Fraser *et al.*, 2002).

4 GIS DATA ANALYSIS AND MODELING FOR LANSLIDE RISK ASSESSMENT

The number of recent publications on various methods for GIS based landslide hazard assessment is overwhelming, especially when compared with those that also deal with landslide vulnerability and risk assessment, which are still very few. Overviews and classification of GIS based landslide hazard assessment methods can be found in Soeters and Van Westen (1996), Leroi (1996), Carrara *et al.* (1995, 1999), Guzzetti *et al.* (1999) Aleotti and Chowdury, (1999) and Van Westen (2000). In terms of software used, GIS systems such as ArcInfo, ArcView, ArcGIS, SPANS, IDRISI, GRASS and ILWIS are mostly used and statistical packages such as Statgraph or SPSS. Most GIS systems are good in data entry, conversion, management, overlaying and visualization, but not very suitable for implementing complex dynamic simulation models. Some GIS systems are specifically designed for implementing such dynamic models (PCRaster, 2000)

4.1 Landslide hazard assessment

Still most of the published literature on landslide hazard mapping mainly deals with landslide susceptibility mapping, or at best spatial probability assessment. It is mostly very difficult to include the temporal probability in the analysis of larger areas, due to the heterogeneity of the subsurface conditions, which are required for physical modeling, or the absence of a complete historic record of both landslide occurrences as well as rainfall and earthquake records (Terlien, 1996).

4.1.1 Heuristic methods

The increasing popularity of Geographic Information Systems over the last decades has lead to a majority of studies, mainly using indirect susceptibility mapping approaches (Aleotti and Chowdury, 1999). As a repeat consequence there are less publications in which GIS is used in combination with a heuristic approach, either geomorphological mapping, or index overlay mapping (e.g. Barredo *et al.*, 2000;Van

Westen *et al.*, 2000; Perotto-Baldiviezo *et al.*, 2004, Van Westen *et al.*, 2003). An example from the US is the SMORPH model (Shaw and Johnson 1995), which classifies hillslopes as either high, moderate, or low landslide hazard, based on their local topographic slope and curvature.

4.1.2 Statistical methods

GIS is very suitable for indirect landslide susceptibility mapping, in which all possible landslide contributing terrain factors are combined with a landslide inventory map, using data-integration techniques (Van Westen, 1993; Bonham-Carter, 1996; Chung and Fabbri, 1999). Chung and Fabbri (1993, 1999) developed statistical procedures under the name of predictive modeling, applying favourability functions on individual parameters. Using these statistical methods, terrain units or grid cells are transformed to new values representing the degree of probability, certainty, belief or plausibility that the respective terrain units or grid cells may contain or can be expected to be subject to a particular landslide in the future.

One of the aspects that received quite some attention in literature is the basic mapping unit used in statistical landslide susceptibility assessment. Automatic classification of terrain units from DEMs is one of the challenging topics (Rowbotham and Dudycha, 1998; Iwahashi *et al.*, 2001; McMillan *et al.* 2004). Chung *et al.* (1995) defined the concept of unique condition polygons, which are made by overlaying the input layers, as the basic units for statistical analysis. Möller et al (2001) define and describe so-called Soil Mechanical Response Units (SMRU) which are generated from a DEM using GIS, and which are used as input parameters in a combined heuristic and soil mechanical approach to landslide hazard assessment for an area in Rheinhessen, Germany.

Several publications dealt with a combination of fuzzy membership values in GIS based landslide hazard mapping. Some examples are given by Juang *et al.* (1992), Davis and Keller (1997), Binaghi *et al.* (1998) and Gorsevski *et al.* (2003). Ercanoglu and Gokceoglu (2001) assessed the landslide susceptibility in a landslide prone area located in NW Turkey, using several factors such slope angle, land use, topographical elevation, slope aspect, water conditions, and weathering depth. Factor analysis was used to determine the important weight of each conditioning factor, and fuzzy sets and if-then rules were used to produce the GIS index maps. Bivariate statistical analysis, using weights of evidence modeling is reported by Lee *et al.* (2002), Suzen and Doyuran (2003) and Van Westen *et al.* (2003).

Among the most popular statistical landslide hazard methods reported in the recent literature are logic regression and artificial neural network (ANN) classifiers. Logistic regression relates predictor variables (topographic factors, landuse, soiltypes etc.) to the presence or absence of landslides within geographic cells and uses the relationship to produce a map showing the probability of future landslides (Chung et al, 1995; Atkinson and Massari 1998; Rowbotham and Dudycha, 1998; Dai *et al.,* 2001; Ohlmacher and Davis, 2003; Dai and Lee, 2003; Santacana *et al.,* 2003). An artificial neural network offers a computational mechanism that is able to acquire, represent, and compute a mapping from one multivariate space of information to another, given a set of data representing the relationships (Lu and Rosenbaum, 2003). An artificial neural network is trained by the use of a set of associated input and output values. The method is not available within existing GIS systems, and has been programmed in systems like MATLAB (Lee *et al.*, 2003). The use of statistical methods has a number of drawbacks. One of these is the tendency to simplify the factors that condition landslides, by taking only those that can be relatively easily mapped in an area, or derived from a DEM. Another problem is related to generalization, assuming that landslides happen under the same combination of factors throughout the study area. The third problem is related to the fact that each landslide type will have its own set of causal factors, and should be analyzed individually. The statistical models generally ignore the temporal aspects of landslides, and are not able to predict the impact of changes in landslide controlling conditions (e.g. water table fluctuations, or landuse changes).

4.1.3 Deterministic and probabilistic analysis

In deterministic analysis, the landslide hazard is determined using slope stability models, resulting in the calculation of factors of safety. Deterministic models provide the best quantitative information on landslide hazard that can be used directly in the design of engineering works, or in the quantification of risk. However, they require a large amount of detailed input data, derived from laboratory tests and field measurements, and can therefore only be applied over small areas at large scales.

When dealing with deterministic slope stability analysis related to shallow rainfall induced landslides, several authors have developed GIS models coupling a dynamic hydrological model that simulates the pore pressure over time with a slope stability model that quantifies the susceptibility as the critical pore pressure threshold (Terlien *et al.*, 1995; Gritzner *et al.*, 2001; Chen and Lee, 2003). Van Beek and Van Asch (2003) developed a model that couples a distributed hydrological model with a probabilistic assessment of slope stability. They used a raster GIS, PCRaster (PCRaster, 2000), with an embedded meta-language for dynamic modeling. The language is simple to learn and programs need a short development time (Wesseling *et al.*, 1996). The model was used to predict the impact of landuse changes on the changes in slope stability (Van Beek and Van Asch, 2003; Van

Asch *et al.,* 1999). Dietrich *et al.* (1992) developed a physically-based model based on a combination of the infinite slope equation and a hydrological component based on steady-state shallow subsurface flow. This model, called SHALSTAB, has been used extensively by researchers in the forestry field in the western US (Montgomery *et al.,* 1998) and in Italy (Borga *et al,* 1998). Other slope stability models developed by the US Forest Service are the Level I Stability Analysis (LISA) and Stability Index Mapping (SINMAP) which are both based on the infinite slope equation. SINMAP is an ArcView extension and the LISA program enables the user to compute the probability of slope failure using up to 1,000 iterations of a Monte Carlo simulation by varying input values to the infinite slope equation (Hammond *et al.*, 1992). Other interesting applications showing Monte Carlo simulation combined with uncertainty mapping using fuzzy methods are presented by Davis and Keller (1997) and Zhou *et al.* (2003).

The deterministic approaches for earthquake-induced landslide hazard analysis are based on the simplified Newmark slope stability model, applied on a pixel-by-pixel basis, which can be carried out completely within the current GIS computational environments (Miles and Ho, 1999; Luzi *et al.*, 2000; Randall *et al.*, 2000; Jibson *et al.*, 2000). Refice and Capolongo (2002) have implemented a Monte Carlo simulation in combination with the Newmark slope stability model.

Moon and Blackstock (2003) used an entirely different approach in their study on deterministic landslide hazard assessment for the city of Hamilton in New Zealand. They selected representative slope profiles from a DEM within the various geomorphological units. For the slope stability analysis both circular (using the Bishop Simplified method) and non-circular (using the Spencer- Wright method of analysis) failure surfaces were used, taking into account variations in watertable and seismic accelerations. Miller and Sias (1998) worked with a two-dimensional finite-element model (MODFE) to simulate unconfined groundwater flux and to calculate water table elevations and factors of safety for large landslides using Bishop's simplified method of slices along individual slope transects.

In the field of landslide runout modeling also GIS has been used extensively (Hungr, 1995). Dymond *et al.* (1999) developed a GIS-based computer simulation model of shallow landslides and associated sediment delivery to the stream network, for different rainstorm events and landuse scenarios.. A high-resolution DEM is one of the major components in the model. Cellular automata have also been used extensively in modelling the flow velocity and extend of landslides (Aviolo *et al.,* 2000).

The use of physical distributed models for landslide hazard zonation with GIS also has a number of drawbacks. As the input data normally have a high degree of uncertainty, the values that result from the calculations should not be taken as absolute values of landslide occurrence, and therefore cannot directly serve for quantitative landslide risk assessment. Furthermore, a considerable parameterization is needed, and from sensitivity analysis the estimated soil depth appears to be a crucial factor, which is also most difficult to measure. The models are also not suitable in predicting the development of complex landslides with a complex hydrological system (Van Asch *et al.,* 1999).

4.1.4 Comparison and verification of results.

As Carrara *et al.* (1999) indicated, the popular misconception is that a GIS-based landslide susceptibility map is more accurate and objective than a product where the qualitative hazard classes are derived mainly through expert knowledge. This has also been the objective of several studies, which compared different types of landslide hazard assessment (Irigaray *et al.,* 1996; Van Westen *et al.*, 1999; Guzzetti *et al.,* 1999; 2000). Binaghi *et al.* (1997) made a comparison between two methodologies for landslide susceptibility mapping: a probabilistic approach using certainty factors, and one based on Fuzzy Logic integrated with the Dempster–Shafer theory. These methodologies are applied to an area in Italy. Suzen and Doyuran (2003) made a comparison of bivariate and multivariate methods in the same area. They used the so-called “seed cell” approach to create a buffer around the crown of the landslide for which the input values were sampled from the various factor maps. They concluded that although 80% of the area was classified similarly in general the bivariate susceptibility map was overestimating the susceptibility classes relative to the multivariate map. Chung and Fabbri (2003) give an overview of methods that can be used for the classification of hazard scores into meaningful susceptibility classes, the use of success rates and prediction rates and the validation of landslide susceptibility maps made through statistical methods, using time-, space- and random partition methods. An example of time partition methods is given by Irigaray *et al.*, (1999) who verified a landslide susceptibility map which was made using a statistical method with new landslides that were generated during an extreme rainfall event, and concluded that about 85 % of the new landslides occurred in areas, that were classified as “High” or “Very high” in the susceptibility map.

4.2 Landslide vulnerability and risk analysis

Although there have been quite a number of publications that focus on the proposed methods for landslide risk analysis, relatively few examples have been published with examples of the use of GIS in this process. Initial reviews on the use of GIS in hazard and risk assessment were made by Wadge *et al.* (1993) and Coppock (1995). Concepts of landslide vulnerability assessment are treated by Leone et al. (1996), Leroi (1996), Fell and Hartford (1997), Wong *et al.* (1997) and Dai *et al.* (2002). One of the most important inputs to come to quantitative landslide vulnerability and risk analysis, is the collection of historic landslide information, and the maintenance of this information in GIS-based databases, including information on the damage resulted from the landslides. In Europe, several countries are developing their own national landslide database (Dikau *et al.*, 1996). For example, in Italy the AVI database, contains over 18,000 landslides, of which 1442 had information on human consequences (Guzzetti, 2000).

4.2.1 Vulnerability assessment

Vulnerability is defined as the degree of loss to a particular element or set of elements at risk caused by a potential damaging phenomena with a given intensity (IUGS, 1997). There are four different types of vulnerability: physical, economic, environmental and social vulnerabilities. The vulnerability of elements at risk is normally expressed in the form of a stage-damage curve, which relates the intensity of the hazardous event with the degree of expected damage to the particular type of elements at risk. These curves are derived either by statistical analysis of historic damage data, or in the absence of those by expert rules. Relatively little work has been done on the definition of vulnerability curves for landslides, although some authors have discussed the issue (Wong et al. 1997) Due to the uncertainty of the expected landslide magnitude or volume, and the unclear relationship between landslide magnitude and frequency, often simply a vulnerability of 1 (total collapse) is used for building vulnerability, whereas population vulnerability depends very much on the expected speed of the landslide, and hence on the landslide type. In GIS analysis, the hazard map is then directly overlaid with a building footprint map, and all buildings that fall within the high hazard zone are considered to be in high risk. A bit more detailed is the assignment of vulnerability classes. Alexander (1989) published several landslide damage scales for buildings in landslide initiation zones, runout zones and for a range of lifelines. AGSO (2001) defined a simple classification of vulnerability for three classes of elements at risk (people, buildings and roads) and for different landslide types (See table 1)

	Vulnerability		
	Persons	Buildings	Roads
Debris slides, flows and rock fall, > 25° slope	0.9	1	1
Rotational slides and slumps, < 25° slope	0.05	0.25	0.3
Small debris slides, flows, slumps and rock falls	0.05	0.25	0.3

Table 1: Vulnerability for three classes of elements at risk (people, buildings and roads) and for different landslide types (AGSO, 2001).

For evaluating the consequences of landslides with respect to casualties, it is common practice to plot frequency against consequences in F–N diagrams. In the case of landslides, F–N plots are graphical representations of the cumulative probability per year that landslides will cause N or more fatalities, versus the number of fatalities resulting from landslides, on a log–log scale (Fell and Hartford, 1997). Examples of the use of GIS for landslide vulnerability assessment can be found for example in Mejía-Navarro (1994). Smyth and Royle (2000) evaluated the vulnerability to landslides in Niteroi city, in the state of Rio de Janeiro using satellite images, census data, and field mapping to characterize the vulnerability of the various favelas. Liu and Lei (2003) present a method for the regional analysis of physical, economic and environmental vulnerabilities to debris flows for different counties in Yunnan province (China).

4.2.2 Landslide risk analysis

Risk is the result of the product of probability (of occurrence of a landslide with a given magnitude), costs (of the elements at risk) and vulnerability (the degree of damage of the elements at risk due to the occurrence of a landslide with a given magnitude). A complete risk assessment involves the quantification of a number of different types of losses (FEMA, 2004), such as:

- *Losses associated with general building stock*: structural and nonstructural cost of repair or replacement, loss of contents;
- *Social losses:* number of displaced households; number of people requiring temporary shelter; casualties in four categories of severity (based on different times of day)
- *Transportation and utility lifelines*: for components of the lifeline systems: damage probabilities, cost of repair or replacement and expected functionality for various times following the disaster;
- *Essential facilities*: damage probabilities, probability of functionality, loss of beds in hospitals;
- *Indirect economic impact*: business inventory loss, relocation costs, business income loss, employee wage loss, loss of rental income, long-term economic effects on the region

In many areas hazard and risk assessment procedures have been implemented, for example in California

(Blake *et al.*, 2002), Hong Kong (Hardingham *et al.*, 1998), New Zealand (Glassey *et al.*, 2003), Australia (AGSO, 2001; Michael-Leiba *et al.*, 2003), France (Flageollet, 1989) or Switzerland (Lateltin, 1997). In Australia, the National Geohazards Vulnerability of Urban Communities Project (or Cities project) was a program of applied research and technique development designed to analyze and assess the risks posed by a range of geohazards to urban communities (AGSO, 2001). The Cities Project initiated a series of case studies in Australian cities, e.g. Southeast Queensland, Cairns, and Mackay.

The quantification of landslide risk is often a difficult task, as both the landslide intensity and frequency will be difficult to calculate for an entire area, even with sophisticated methods in GIS. In practice, often simplified qualitative procedures are used, such as the one developed in Switzerland (Lateltin, 1997) (See figure 4).

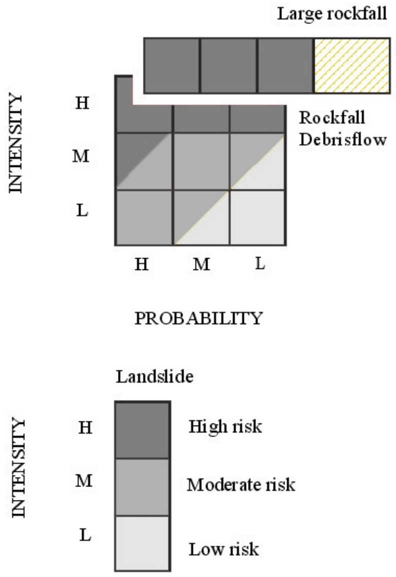


Figure 4: Landslide risk classification scheme proposed by the Swiss Office for Water and Geology (Lateltin, 1997).

4.2.3 Risk information systems

For other types of hazards, risk information systems have been developed and implemented, for example for loss estimation of earthquakes, floods and windstorms (FEMA, 2004), and technological risks (Fedra, 1998). A Risk Information System is the integration of databases, simulation models, expert systems and decision support tools, often linked to real-time datasources, and with a distributed architecture with important data sharing components via the Internet. For example, a risk information system should be connected to a series of mobile GIS units, with which landslide and elements at risk information can be collected real-time in the field. Some examples of risk information systems are given by Fedra (1998). Glassey et al (2003) describe the structure of a GIS-based Hazard Information System developed for the city of Dunedin in New Zealand. The system fundamentally comprises two subsystems; a hazard register, containing known existing hazard data and a hazard zonation system containing modeled hazard zones. In addition, subsurface data (e.g. drillholes) and references to the original data sources are included. The system has a user-friendly interface and property information, linked to a hazard report can be queried interactively. Zerger (2002) examined the user perceptions of risk information systems, and how risk managers perceive the information provided through a GIS-based risk information system. According to Zerger (2002): “If user considerations are assessed early in the risk modeling process, GIS practitioners can minimize data capture, avoid unnecessary levels of complexity in the spatial modeling and generally improve the utility of the risk modeling for decision-making”.

5 CONCLUSIONS

The literature on landslide risk assessment indicates that a lot of developments have taken place in the last decade, and that quantitative risk assessment for individual locations is feasible (Wu *et al.,* 1996; Morgenstern, 1997; Einstein, 1997; Fell and Hartford, 1997; Wong *et al.,* 1997). However, the generation of quantitative risk zonation maps, expressing the expected monetary losses as the product of probability (of occurrence of a landslide with a given magnitude), costs (of the elements at risk) and vulnerability (the degree of damage of the elements at risk due to the occurrence of a landslide with a given magnitude) seems still a step to far. In the meantime, risk maps are produced for many municipalities, following a pragmatic and qualitative approach (Michael-Leiba *et al.*, 2003). Such risk maps form the basis for development and regulatory planning. Geo-Information tools have become essential for landslide hazard, vulnerability and risk assessment. For obtaining landslide probability information the following approaches are possible:

- At large scales deterministic models are used for determining factors of safety, and dynamic models are used to model trajectories of landslides. When combined with probabilistic methods, related to the variability of input data and return periods of triggering events, also failure probability can be obtained.
- At medium scales landslide data is combined with factor maps (e.g. slope angle, lithology etc) using heuristic or statistical methods, resulting in landslide susceptibility maps. When combined with landslide frequency analysis, during which landslide information from temporal databases is combined with rainfall and earthquake records, it is

also possible to obtain landslide probabilities. Earth Observation data should be used more on a routine basis in the regular mapping of new landslide phenomena, and the generation of landslide databases.

The mapping of elements at risk for a landslide risk assessment project is not fundamentally different from other types of hazards, although more research should be carried out, which characteristics of elements at risk are essential for landslide vulnerability study. In the original equation of risk the cost of elements at risk plays an important role, although the cost aspect is hardly ever really taken into account in landslide risk studies. More work also needs to be done on the definition of the vulnerability of elements at risk for landslides, and the generation of damage functions. The difficulty in defining landslide vulnerability values is the uncertainty of the expected landslide magnitude or volume.

Finally, the various components of landslide risk assessment should be integrated in risk information /management systems which should be developed as spatial decision support systems for local authorities dealing with risk management.

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