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Remote sensing techniques for landslide studies and hazard zonation in Europe

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Remote sensing techniques for landslide studies and hazard zonation in Europe

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Abstract

An inventory is presented of researches concerning the use of remote sensing for landslide studies and hazard zonation as mainly carried out in the countries belonging to the European Community. An overview is given of the applicability of remote sensing in the following phases of landslide studies:

(1) Detection and classification of landslides. Special emphasis is given to the types of imagery required at different scales of analysis.

(2) Monitoring the activity of existing landslides using G.P.S., photogrammetrical techniques and radar interferometry.

(3) Analysis and prediction in space and time of slope failures. The different factors required in a landslide hazard study are evaluated, and the optimum remote sensing imagery for obtaining each of these factors is indicated.

Examples are given of research work carried out in these three phases from EC countries. Finally an evaluation is given of the aspects of uncertainty associated with the use of remote sensing data, and conclusions are given as to the incorporation of remote sensing techniques within the overall framework of techniques.

1. Introduction

Remote sensing is defined as the art and science of obtaining information, without physical contact, from the object under consideration (Lillesand and Kiefer, 1987), e.g. the utilisation at a distance (as from a ground station, aircraft or spacecraft) of any device and its attendant display for gathering information pertinent to the environment. For earth scientists remote sensing can be defined as comprising the measurement and recording of electromagnetic energy reflected from, or emitted by, the earth's surface and the relating of such measurements to the nature and properties of objects on the earth surface. The products which are mostly used in earth sciences are aerial photographs, satellite images and radar images.

Until now the use of remote sensing data in the study of landslides can be considered rather haphazard, due to the limited availability of funds and images, lack of knowledge of the applicability of the different kinds of remote sensing, and limited cooperation between various research groups. Generally one works with what is available. Aerial photographs are the most frequently used type of remote sensing data. Airphoto-interpretation has become a standard ?

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procedure within most landslide projects, although the extent and detail of the interpretation may vary considerably. Satellite images have been used in landslide studies since the mid-seventies; however, only on a scientific level. They have seldom been included within applied projects.

In general, it can be stated that the full capabilities of remote sensing data, regarding spatial, temporal and spectral resolutions, are not fully exploited in landslide studies. The use of images with different spatial resolutions and scales in a hierarchical analysis, e.g. zooming in on problem areas from smaller scale images to larger scale ones, is not very common. Neither is the use of multispectral information to obtain information outside the visible part of the spectrum to analyse soil humidity, or vegetation characteristics on landslides, for example. Also the use of multispectral images in the evaluation of the activity of landslides has been applied only in a limited number of cases.

The use of remote sensing data can be differentiated for the various phases within a landslide study: detection and classification of landslides, monitoring the activity of existing landslides, and analysis and prediction in space and time of slope failures.

This paper will give a general overview of the research done in each of these three phases of landslide studies within the EC countries. Some of the work has been done in the framework of the European Programme on Climatology and Natural Hazard (EPOCH).

We apologise to those researchers whose valuable contributions are not cited in this paper, as we did not have information on their research, for various reasons.

2. Remote sensing in landslide detection

Detection is used here as a general term for mapping landslides within a remote sensing image. It includes two aspects: *recognition* (is it a landslide?) and *classification* (what type of landslide is it?). Recognition of a landslide, used in a general sense, means whether it is possible to map a landslide, with varying forms and spectral characteristics, within a remote sensing image. Important aspects in the recognition of landslides are the size of the features, their contrast (the difference in spectral characteristics between the landslides and the surrounding areas) and the morphological expression.

For the recognition of landslide features a number of remote sensing tools are available. The most widely used are shown in Table 1, together with some of their technical specifications (after Rengers et al., 1992). The table indicates the minimum sizes needed for features to be recognised for various conditions of contrast with respect to their background.

The use of stereoscopic imagery in slope stability studies is very important in view of the clear and diagnostic morphology, created by mass movements. Features such as scarps, disrupted vegetation cover, and deviations in soil moisture or drainage conditions are generally used in conjunction with morphological features. Considering the size of most landslides, which is in the order of several tens to a few hundreds of metres, the most useful photographic scale is around 1:15,000. At this scale the phenomenon cannot only be identified as a slope instability feature, but a preliminary analysis of the feature is also possible, as the elements of the landslide

Table 1
Minimum sizes of objects to be recognised for various conditions of contrast with their background in various types of imagery. Values should be used only as an indication of the order of magnitude. All units are in metres

	Landsat MSS	Landsat TM	Spot XS	Spot PAN	Aerial photos 1:50,000	Aerial photos 1:25,000	Aerial photos 1:10,000
Ground resolution cell size	80	30	20	10	0.5	0.25	0.1
High contrast: features–background	800	300	200	100	5	2.5	1
Low contrast: features–background	3200	1200	800	400	20	10	4

can be recognised and analysed. Using smaller scale imagery, a slope failure may be recognised as such, if size and contrast are sufficiently large. However, the amount of analytical information, enabling the interpreter to make conclusions on type and causes of the landslide, will be very limited at scales smaller than 1:25,000. It can be concluded from Table 1, that the satellite imagery available today is not suitable for identifying mass movement phenomena, unless they are very large. Nevertheless, several authors have used LANDSAT or SPOT images for identification of mass movements (Gagon, 1975; McDonald and Grubbs, 1975; Sauchyn and Trench, 1978; Stephens, 1988; Huang and Chen, 1991; Vargas, 1992; Scanvic and Girault, 1989; Scanvic et al., 1990). In these cases individual landslides are not mapped from the images, but terrain conditions associated with landslides, as lithology, differences in vegetation and soil humidity (Mantovani et al., 1982).

Black and white aerial photographs are used extensively in landslide inventories, where the classification of the slope movements is required (Flageollet and Helluin, 1984; Marcolongo et al., 1986). Many different systems have been proposed for the classification of slope movements. For an overview, the reader should refer to M.J. Hansen (1984a), Varnes (1978) or Hutchinson (1988). However, practically all these systems include factors which cannot be identified on the basis of image interpretation alone. Therefore, a more simplified classification should be used during the image interpretation, based on diagnostic features directly visible on the photographs or derived from the interpretation of the terrain conditions. Such a simplified classification is obtained by local knowledge and stereoscopic interpretation of the morphological features, vegetation and drainage conditions. Statements can be made on type of movement, degree of activity and depth of the movement (see Table 2; Van Westen, 1993).

Table 2
Example checklist used in photo-interpretation of mass movements

Type	Subtype	Activity	Depth	Vegetation	Scarp–body
Slide	Rotational	Stable	Shallow	Bare	Scarp
Flowslide	Translational	Dormant	Deep	Low vegetation	Body
Flow	Complex	Active	–	High vegetation	–
Derrumbe	–	–	–	–	–
Creep	–	–	–	–	–

For landslide classification the relation between the size of the objects and the spatial resolution of the imagery should be better than for detection. Every individual element of a landslide (scarp, body, rotated blocks, etc.) should be recognisable. Therefore, large scale stereoscopic imagery has to be used.

3. Remote sensing in landslide monitoring

Monitoring means the comparison of landslide conditions, such as areal extent, speed of movement, surface topography, soil humidity etc., from different periods in order to assess the activity of a landslide.

For the monitoring of landslides a wide range of techniques, providing very detailed measurements of the surface topography can be used (Agostoni et al., 1991). The Global Position System (G.P.S.) is a technique which uses a whole series of satellites to determine the X, Y, Z location in the terrain. It has been recently applied in Italy in studies of monitoring of the Tessina landslide in the region of Veneto by the local Geological Department. The principle advantages of this system are the flexibility and relative ease of operation, still allowing an accuracy in the order of centimetres. Scanvic et al. (1993) report the first results of the use of radar-interferometry in the detection of landslide movements. This relatively new method, which is considered to give results within a centimetre accuracy, will most probably be used frequently with the availability of radar data from ERS-1.

More traditional methods of aerial photogrammetry for the monitoring of landslides have been widely applied in Spain (Rispoll and Corominas, 1992) and in the studies of the landslide in Ancona, Italy (Cunietti et al., 1986). In the latter paper also the uncertainties of photogrammetric measurement of slope movements are discussed. Techniques of terrestrial photogrammetry have been used by Chandler (1989) and Kalaugher and Grainer (1990) in Great Britain, by Rispoll and Tarrida (1988) in Spain and by Marcolongo and Spagna (1974) in Italy. Bison et al. (1989, Bison et al. (1990) report the use of

Thermal Infra Red data obtained from a ground platform in monitoring soil moisture conditions in relation to landslide movements.

4. Remote sensing in landslide hazard analysis

The term *hazard* is defined by Varnes (1984) as: *the probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area. Landslide* hazard is commonly shown on maps, which display the spatial distribution of hazard classes (landslide hazard zonation). *Zonation* refers to "the division of the land in homogeneous areas or domains and their ranking according to degrees of actual/potential hazard caused by mass movement" (Varnes, 1984). Landslide hazard zonation requires a detailed knowledge of the processes that are or have been active in an area, and of the factors leading to the occurrence of the potentially damaging phenomenon. This is considered the task of earth scientists.

The potential and the specific requirements for input data for a landslide hazard analysis is scale dependent. Generally three scales of analysis are distinguished: a regional scale (< 1:100,000), a medium scale (1:50,000 to 1:25,000) and a large scale (> 1:10,000). Table 3 provides a summary of the input data required at each of these three scales, together with a description of the data collection techniques and an indication of the feasibility of obtaining the information (Van Westen, 1993).

An ideal map of slope instability hazard should provide information on the spatial probability, temporal probability, type, magnitude, velocity, runout distance, and retrogression limit of the mass movements predicted in a certain area (Hartlèn and Viberg, 1988). Hazard analysis is seldom executed in accordance with the definition given above, particularly when based on image interpretation, as the probability of occurrence of a potential damaging phenomenon is extremely difficult to obtain for larger areas. The determination of actual temporal probabilities requires an analysis of triggering factors, such as earthquakes and rainfall, in relation to landslides and the application of complex models. In most of the cases, however, there is no clear relationship between these triggering factors and landslides. Therefore, the legend classes used in most hazard maps give merely information on the susceptibility of the terrain for slope movements in terms of high, medium or low hazards and are thus limited to a differentiation of the spatial probability of occurrence landslides.

A large amount of research on hazard zonation has been done over the last 30 years as the consequence of an urgent demand for slope instability hazard mapping. Overviews of the various slope instability hazard zonation techniques can be found in Cotecchia (1978), Brabb (1984), A. Hansen (1984b), Varnes (1984), and Hartlèn and Viberg (1988). Initially the investigations were oriented mainly towards problem solving at the scale of site investigation and development of deterministic models. A wide variety of deterministic slope stability methods is now available to the engineer. Good reviews of these can be found in work by Lambe and Whitman (1969), Chowdury (1978, Chowdury (1984), Hoek and Bray (1981), Graham (1984), Bromhead (1986) and Anderson and Richards (1987).

The large regional variability of geotechnical variables such as cohesion, angle of internal friction, thickness of layers, or depth to groundwater, is inconsistent with the homogeneity of data required in deterministic models. The site investigation approach provides an unacceptable cost/benefit ratio for engineering projects over larger areas during the planning and decision-making phases due to the high cost and time requirements of data collection. Several types of landslide hazard zonation techniques have been developed to tackle such problems encountered in the application of deterministic modelling. A summary of the various trends in the development of techniques is given in Table 4.

The most straightforward approach to landslide hazard mapping is a *landslide inventory map*, based on aerial photo interpretation, ground survey, and/or a database of historical occurrence of landslides in an area. The final product gives the spatial distribution of mass movements, represented either at scale or as points (Wieczorek, 1984). Mass movement inventory maps are the basis for most of the other landslide hazard zonation techniques. They can, however, also be used as an elementary form of hazard map, because they display where in an area a particular type of slope movement has occurred.

They provide information only for the period shortly preceding the date the aerial photos were taken or the fieldwork was conducted. They provide no insight into the temporal changes in mass movement distribution.

Many landslides that occurred some time before

Table 3
Overview of input data needed for landslide hazard analysis

Data types	Summary of data collection techniques	Feasibility of data collection		
		Regional scale	Medium scale	Large scale
Geomorphology				
Terrain Mapping Units (TMU)	Satellite stereo image interpretation + walk over study area + radar (limited)	high	moderate	low ?
Geomorphological units	Aerial photointerpretation + field check	moderate	high	high
Landslide (recent)	Aerial photointerpretation + field description + thermal IR	low	high	high
Landslide (older period)	Aerial photointerpretation + collection of landslides records from newspaper, fire brigades, or church archives	low	high	high
Topography				
Digital Terrain Model (DTM)	Collection of existing contour maps + photogrammetrical techniques with airphotos or SPOT	moderate	high	high
Slope map (deg or %)	Made from a DTM	moderate	high	high
Slope direction map	Made from a DTM, no extra data collection is required	moderate	high	high
Breaks of slope	Aerial photointerpretation	low	moderate	high
Concavities/convexities	Made from a DTM, or detailed photointerpretation	low	low	high
Engineering Geology				
Lithologies	Checking of existing geological maps, or by mapping if no data are available using airphotos, satellite images and/or radar + fieldwork	moderate	high	high
Material sequences	Made by a combination of other maps (geomorphological, geological, slope and DTM)	low	moderate	high
Sampling points	Field descriptions of soil and rock outcrops, and laboratory analysis of selected samples to characterize material types	moderate	high	high
Faults and lineaments	Satellite image, aerial photo, radar interpretation, and fieldwork	high	high	high
Seismic events	Collection of existing seismic records	high	high	high
Isolines of seismic intensity	Questionnaires on the observed damage from earthquakes	low	moderate	high
Land use				
Infrastructure (recent)	Aerial photo and satellite image interpretation + topographic map. Thermal IR limited extent	moderate	high	high
Infrastructure (older)	Aerial photointerpretation + topographic map	high	high	high
Land use map (recent)	Aerial photointerpretation + classification of satellite images + field check + field description	moderate	high	high
Land use map (older)	Aerial photointerpretation	moderate	high	high
Hydrology				
Drainage	Aerial photointerpretation + topographic map	high	high	high
Catchment areas	Aerial photointerpretation + topographic map or modelling from a DTM	moderate	high	high
Meterological stations	Collection of existing meterological data	high	high	high
Water table	Field measurements + modelling	low	low	moderate

the photographs were taken may have became undetectable. Therefore a refinement is the construction of *landslide activity maps*, based on multitemporal aerial photo interpretation (Canuti et al., 1979; Canuti and Focardi, 1986).

In *geomorphological methods*, mapping of mass movements and their geomorphological setting is the main input factor for hazard determination. The basis for this approach was outlined by Kienholz (1977), who developed a method to produce a combined hazard map based on the mapping of "silent witnesses (Stumme Zeugen)". In this method the degree of hazard is evaluated at each site in the terrain. The decision rules are therefore difficult to formulate, as they vary from place to place. Because the hazard analysis is in fact accomplished "in the mind of the geomorphologist", geomorphological methods are considered subjective. In this study the terms *objective* and *subjective* are used to indicate whether the various steps taken in the determination of the degree of hazard are verified and reproducible by other researchers, or whether they depend upon the personal judgement of the researcher. The term subjective is not intended as a disqualification: subjective analysis may result in a very reliable map when it is executed by an experienced geomorphologist and objective analysis may result in an unreliable map when it is based on an oversimplification of the real situation. Some examples of geomorphological hazard maps can be found in work by Carrara and Merenda (1974), Brunsden et al. (1975), Malgot and Mahr (1979), Kienholz (1977, Kienholz (1978, Kienholz (1980, Kienholz (1984), Kienholz et al. (1983, Kienholz et al. (1988), Grunder (1980), Ives and Messerli (1981), Rupke et al. (1987, Rupke et al. (1988), Perrot (1988), Hermelin (1990, Hermelin (1992), Hearn (1992) and Seijmonsbergen (1992).

To overcome the problem of the "hidden rules" in geomorphological mapping, other qualitative methods have been developed based on *qualitative map combination*. On the basis of his expert knowledge on the casual factors of slope instability, the geomorphologist assigns weighting values to different classes in a number of parameter maps. This

Table 4
Summary of the feasibility and usefulness of applying techniques for landslide hazard zonation in three working scales

Type of landslide hazard analysis	Main characteristic	Regional scale	Medium scale	Large scale
Distribution analysis	Direct mapping of mass movement features resulting in a map which gives information only for those sites where landslides have occurred in the past	2-3	3-3	3-3
Qualitative analysis	Direct or semi-direct methods in which the geomorphological map is renumbered to a hazard map or in which several maps are combined into one using subjective decision rules based on the experience of the earth scientist	3-3	3-2	3-1
Statistical analysis	Indirect methods in which statistical analysis are used to obtain predictions of the mass-movement from a number of parameter maps	1-1	3-3	3-2
Deterministic analysis	Indirect methods in which parameter are combined in slope stability calculation	1-1	1-2	2-3
Landslide frequency analysis	Indirect methods in which earthquakes and/or rainfall records or hydrological models are used for correlation with known landslide dates to obtain thereshold values with a certain frequency	2-2	3-3	3-2

The first number indicates the feasibility of obtaining the information using remote sensing techniques (1 = low: it would take too much time and money to gather sufficient information in relation to the expected output; 2 = moderate: a considerable investment would be needed, which only moderately justifies the output; 3 = good: the necessary input data can be gathered with a reasonable investment related to the expected output). The second number indicates the usefulness (1 = of no use: the method does not result in very useful maps at the particular scale; 2 = of limited use: other techniques would be better, 3 = useful).

method of qualitative map combination has become very popular in slope instability zonation. The problem with this method is that the exact weighting of the various parameter maps is often based on insufficient field knowledge of the important factors, which will lead to unacceptable generalisations. The term "blind weighting" for this was suggested by Gee (1992).

Aiming at a higher degree of objectivity and better reproducibility of the hazard zonation, which is important for legal reasons, statistical techniques have been developed for the assessment of landslide hazard. These quantitative methods have benefited strongly from the availability of computers. Brabb et al. (1972) presented a method for quantitative *landslide susceptibility analysis* at a regional scale, which is based on landslide occurrence, substrate material type, and slope angle. Geological units are grouped according to their landslide density and relative susceptibility values are assigned. Combining these values with a slope map produces final susceptibility classes. The method is easy to use, although it is usually not sufficient to use only the factors of rock type and slope angle.

Carrara et al. (1977, Carrara et al. (1978) introduced a method for *multivariate statistical analysis* of mass movement data. Two main approaches of multivariate analysis exist:

1. Statistical analysis of point data obtained from checklists of causal factors associated with individual landslide occurrences (Neuland, 1976; Carrara et al., 1977; Lessing et al., 1993; Corominas et al., 1992; Othman et al., 1992).
2. Statistical analysis performed on terrain units covering the whole study area. For each of the units data on a number of geological, geomorphological, hydrological, and morphometrical factors is collected and analysed using multiple regression or discriminant analysis (Carrara et al., 1978, Carrara et al., 1990, Carrara et al., 1991; Carrara, 1983, Carrara, 1988a, Carrara, 1988b, Carrara, 1992).

These methods are rather time-consuming, for both data collection and data processing. Several other statistical methods have been applied in landslide hazard analysis, such as the *information value method* (Yin and Yan, 1988; Kobashi and Suzuki, 1991), the *logical message model* (Runqiu and Yuanguo, 1992) and *probabilistic modelling* (Gonzales, 1992; Sabto, 1991).

Despite problems related to collection of sufficient and reliable input data, deterministic models are increasingly used in hazard analysis over larger areas. They are applicable only when the geomorphological and geological conditions are fairly homogeneous over the entire study area and the landslide types are simple. The advantage of these "white box models" is that they have a physical basis. The main problem with these methods is the high degree of oversimplification. This method is usually applied for translational landslides using the infinite slope model (Ward et al., 1982; Brass et al., 1989; Murphy and Vita Finzi, 1991). The methods generally require the use of groundwater simulation models (Okimura and Kawatani, 1986). Stochastic methods are sometimes used for selection of input parameters (Mulder and Van Asch, 1988; Mulder, 1991; Hammond et al., 1992).

Most of the methods mentioned so far do not result in real hazard maps as defined by Varnes (1984). Assessing the probability of occurrence at a certain location within a certain time period, is possible only when a relationship can be found between the occurrence of landslides and the frequency of triggering factors, such as rainfall or earthquakes. Especially for rainfall-related landslides, various techniques have been developed which determine threshold values of "antecedent rainfall" (Crozier, 1986; Capecchi and Focardi, 1988; Mantovani et al., 1976).

A new field in landslide prediction which still has to be explored is the use of METEOSAT/NOAA images, which allow rainfall estimations every half hour (METEOSAT) to every half day (NOAA) (see Hielkema, 1989). These data could be used in combination with a statistical analysis of rainfall threshold values, or with a dynamic slope stability model. At present, however, the only applications in Europe concern provisional models for evaluation of river floods (Lanza and Siccardi, 1992; Lanza et al., 1992).

5. Uncertainty

One of the important aspects which should be taken into account with respect to the use of remote sensing techniques in landslide study is an assessment of the error and uncertainty. Errors and uncertainty related to the use of existing data, to data collection, data analysis and production of final hazard maps, can be distinguished. An extensive treatment of the various error sources in landslide hazard analysis is given by Carrara et al. (1992).

The occurrence of landslides is governed by complex interrelationships between factors, some of which cannot be determined in detail and others only with a large degree of uncertainty. It is important at this point to distinguish *error* and *uncertainty*. The error in a map can be assessed only if another map, or field information is available which is error-free, and with which it can be verified. Slope angles, for example, can be measured at several points on the terrain, and these point values can be compared with a slope map to assess the degree of error. This evaluation is different for maps which are not based on factual, measured data, but on interpretation, such as the genetic elements for a geomorphological map. Such a map can also be checked in the field, but it is still possible that different geomorphologists will not agree on the specific origin of a certain landform. In other words, there is no absolute way to verify the map. Only the uncertainty of the map can be assessed, by comparison of different maps by different observers. If the area identically mapped in several maps is small, the map is considered to contain a high degree of uncertainty. This method will only render reliable results if the field experience of the observers, and the mapping method is identical. Usually this is not the case, and it may be that one of the observers has made a lot of errors in mapping, and that the other observer has mapped more reliably. For this reason, although it is possible to express the difference between the various maps in a quantitative way, the actual uncertainty of such maps is difficult to determine in a absolute manner.

The level of uncertainty is strongly related to the degree of subjectivity of a map. The terms *objective* and *subjective* are used mostly to indicate whether the various steps taken in the determination of the degree of hazard are verifiable and reproducible by other researchers, or whether they depend upon the personal judgement of the researcher. The larger the subjectivity is, the larger also the uncertainty, as the possibility increases that different individuals will come to different conclusions.

Many of the input maps used in landslide hazard analysis are based on aerial photo-interpretation and will therefore contain a large degree of uncertainty. Table 5 gives a list of factors that are considered to be important in controlling slope instability and a qualitative description of uncertainty (partly after Carrara et al., 1992).

The degree of uncertainty is related to many factors, such as the scale of the analysis, the time and the money allocated for data collection, the size of the study area, the experience of the researchers, and the availability and reliability of existing maps. From this list it can be seen that many factors contain an intermediate or high degree of uncertainty, either because they are based on a limited amount of factual data (such as soil characteristics) or they are made by subjective interpretation. The landslide occurrence map is by far the most important map in a landslide hazard survey, since it gives the locations where landslides have occurred in the

Table 5
Main factors in landslide hazard zonation and their estimated degree of uncertainty

Factors	Uncertainty	Factors	Uncertainty
Slope angle	Low	Rainfall distribution	Intermediate
Slope direction	Low	Morphological setting	Low
Slope convexity	Low	Detailed geomorphological situation	Intermediate/high
General lithological zonation	Low	Present mass movement distribution	Intermediate
Detailed lithological composition	High	Present mass movement typology	Intermediate
General tectonic framework	Low	Present mass movement activity	Intermediate/high
Detailed rock structure	High	Past mass movement distribution	High
Soil type distribution	Low/intermediate	Land use	Low
Soil characteristics	Intermediate/high	Past climatological conditions	High
Soil thickness	High	Earthquake acceleration	High
Groundwater conditions	High		

recent past. Furthermore, the resulting hazard maps are compared with the actual distribution of landslides in order to check their accuracy. Therefore a landslide occurrence map should be as accurate as possible.

Photo-interpretation plays a very important role in the creation of a mass movement inventory map, although it should always be followed by an extensive field check. It has been recognized in the literature that creation of mass movement occurrence maps contains a large subjective element. Various authors (Fookes et al., 1991; Carrara, 1992; Carrara et al., 1992; Van Westen, 1993) discuss the results of a comparison of different photo-interpretation maps of landslide areas in Papua, New Guinea, Italy and Colombia. The area which is equally interpreted by different authors may be as small as 7% of all landslide area.

From these examples it is obvious that identification of landslides can contain a very high degree of uncertainty. Several factors play a role in this degree of uncertainty, such as the researcher's experience in photo-interpretation and field knowledge, the aim of the study, the characteristics of the study area, the age and type of mass movements, the scale, quality, and type of photo used and the conversion of the information from the aerial photos to the base map. When working with GIS, digitizing errors will aggravate the situation.

Another input map for landslide hazard analysis which is considered to be very subjective is the geomorphological map. Maps made by different geomorphologists will contain large differences, especially if the maps are made by photo-interpretation, with limited field checks. The differences will be greatest when the geomorphologists design their own legend.

To assess the variability in outlining geomorphological units, a test can be made by comparing photo-interpretations done by several persons. A useful method of comparing various geomorphological photo-interpretations is given by Middelkoop (1990). In a test conducted by Van Westen (1993) only 10% of the area was assigned the same legend unit by all (4) interpreters. About 17% was mapped identically by three and 53% by two interpreters. The remaining 20% of the area was mapped differently by each person. When a simplified legend was used better results were obtained: 36% identically mapped by all four, 32% mapped by three, and 31% by two.

From this example it can be concluded that a geomorphological map has a high degree of subjectivity, and depends strongly on the experience of the person that is making the map, as well as on the amount of time spent in the field for checking the interpretation.

6. Discussion and conclusions

Any hazard evaluation involves a large degree of uncertainty. Prediction of natural hazards such as landslides, which are caused by interaction of factors which are not always fully understood and are sometimes unknown, confronts earth scientists with especially large problems. For large areas and at small, not detailed, scales it is very possible to make general predictions: the number of landslides that have occurred in the past within a land unit is a good indication of what can be expected to occur in the near future. It is, however, much more difficult when predictions need to be made in more detail for areas presently free of landslides. In this situation, the earth scientist must rely on models based on the assumption that landslides are more likely to occur in places where a combination of conditions exists which has led to landslides in the past. Most of the methods presented in the literature and evaluated in this study are based on this principle. This implies knowledge of causal factors, and the ability to represent these on a map, as well as detailed knowledge about past mass movements. Since hazard maps are used to make predictions over relatively large areas collection of data for and preparation of these factor maps is a time-consuming operation, and cannot be based solely on factual, measured, field data. During the preparation of these factor maps, the subjective evaluation of field conditions by the earth scientist will play an important role. Since all earth scientists are not equally experienced, these maps will normally contain a considerable degree of uncertainty. It is clear that hazard maps prepared by very experienced geomorphologists will have the highest reliability, with or without the use of GIS. However, solutions must be found to upgrade the reliability of hazard maps in studies where less experienced earth scientists are responsible for the collection of basic data and subsequent analysis. For those cases it is important to give recommendations as to how the reliability of the end product can be increased, by reducing the uncertainty of the input factors as much as possible. This should be achieved by clear definition of criteria for the interpretation of landslides and their controlling factors, as well as by thorough fieldwork. Instead of "making a map by photo-interpretation followed by a field check", input map for a hazard zonation should be prepared after "fieldwork preceded by photo-interpretation". During the last decade the rapid development of Geographical Information System (GIS), computerised tools for the collection, storage, display and analysis of spatially related data, has increased the possibilities for merging remote sensing data with other types of data (Digital Terrain Models, geological maps, landuse maps, etc.) enormously. Examples of the use of GIS in landslide hazard analysis con be found in Carrara et al. (1990, Carrara et al. (1991, Carrara et al. (1992), the GARS project (Scanvic et al., 1992) and the UNESCO-ITC project (Van Westen, 1993).

It can be concluded that aerial photos are the most important remote sensing tools in landslide studies. The application of presently available satellite remote sensing is limited as far it refers to the direct mapping of slope instability features. The spatial resolution does not allow the identification of landslide features smaller than 100 m, in conditions of favourable strong contrast between the landslide and the background. If contrast conditions are less favourable then identification is even limited to features up to 400 m. The need for stereo imagery, necessary for the interpretation of the characteristic and diagnostic morphological features of slope failures, is another limiting point in the applicability of an important part of the presently available remote sensing imagery. It is expected however, that within the next decade there will be satellite imagery available with spatial resolution below 10 m, and with stereo capabilities (ADEOS, JAPAN/US system planned for 1995).

Currently the available satellite imagery (SPOT, LANSAT TM, JERS-1) are mostly useful in indirect mapping methods, when the spatial distribution of landslide controlling variables, such as a particular geomorphological condition, a specific lithology or a kind of landuse are identified and outlined on the satellite images. In practice it implies a combined use of satellite imagery and large scale photography. For inventory mapping and the analytical part of slope instability assessment, large scale aerial photography is used in representative sample areas, while the extrapolation of the findings is executed on smaller scale imagery.

The potential of the use of radar imagery for landslide hazard mapping still needs further investigations. Within the coming decade a large increase in the availability of radar satellite imagery is foreseen (ERS-1, ERS-2, JERS-1, Almaz, Radarsat). Although the results on terrain roughness classification, and radar interferometry seem very promising, the geometric distortion due to foreshortening and the speckling will generally give rather poor quality images in mountainous regions.

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