Geographic Information Systems as applied to landslide hazard zonation

by Kees van Westen, Rob Soeters and Niek Rengers

Introduction

LANDSLIDES are one of the normal landscape building processes in mountainous areas. They become a problem when they interfere with human activity (see fig 1). Landslide disasters annually result in considerable damage and loss of life.

Mitigation of landslide disasters can be successful only when detailed knowledge is obtained about the expected frequency, character, and magnitude of landslides in an area. The zonation of landslide hazard, *ie* representing the likelihood for the occurrence of landslides in a map, provides the basis for any disaster mitigation project and should supply planners and decision makers with the information where measures are required.

The analysis of landslide hazard is, as with most other types of hazard, a complex task, due to the large variety of terrain parameters that play a role in the occurrence of the process. The application of GIS, facilitating the combination of different data sets, has been the technological solution to the problem.

In a research project, sponsored by UNESCO and EEC, a methodology was developed for the use of GIS in the analysis of landslide hazard at various degrees of detail, taking into account different options with respect to the availability of input data. Based on this methodology, a user can select the optimal method of analysis which can be applied to his particular case.

Input data

For the analysis of landslide hazard many different types of information have to be collected, which can be summarised as follows:

Figure 1. Example of landslide damage.

- **geomorphological data**
  - geomorphological maps;
  - landslide distribution maps;
- **topographical data**
  - digital terrain models;
  - slope angle, aspect and concavity;
- **engineering geological data**
  - soil and rock material sequences;
  - geological structures;
  - earthquake records;
- **land-use and infrastructual data**
  - land-use maps from different times;
  - infrastructural maps from different times;
- **meteorological and hydrological data**
  - rainfall records;
  - drainage conditions;
  - water-table depths.

Although remote sensing has proved to be an excellent tool for data collection, a problem faced in the practical application of remote sensing is related to the fact that information on the distribution and type of landslides, is only obtainable from large scale aerial photographs. As a consequence, an adapted methodology had to be developed, combining an optimal use of the potentials of remote sensing with an acceptable cost level and a reasonable degree of objectivity. The methodology takes into account the different possibilities for data-collection and analysis at three different scales of analysis:

- **regional scale** (1 : 100,000 scale);
- **medium scale** (1 : 25,000 scale), and
- **large scale** (1 : 10,000 scale)

In the following sections some examples are given of the analysis techniques on each of these scales, illustrated with data from a pilot study area in the Cordillera Central in Colombia, near the Nevado del Ruiz volcano and the city of Manizales.

Regional scale hazard mapping

The objective of this scale of hazard analysis is to outline areas, where slope instability problems can be expected. The information is mainly intended for agencies dealing with regional planning and infrastructural development. The analysis of the landslide in relation to the terrain conditions is the crucial problem in small scale surveys, as the scale does not allow for systematic landslide inventory mapping. The relevant terrain parameters involved in slope instability can successfully be interpreted from small scale aerial photographs and stereo SPOT imagery. Instead of introducing several factor maps, a terrain classification, differentiating terrain mapping units (TMUs; Meijerink, 1988) can be made and lithology, soils, predominant slope classes, land-use and morphometric aspects, can be labelled as attributes to those terrain units. An example of such a

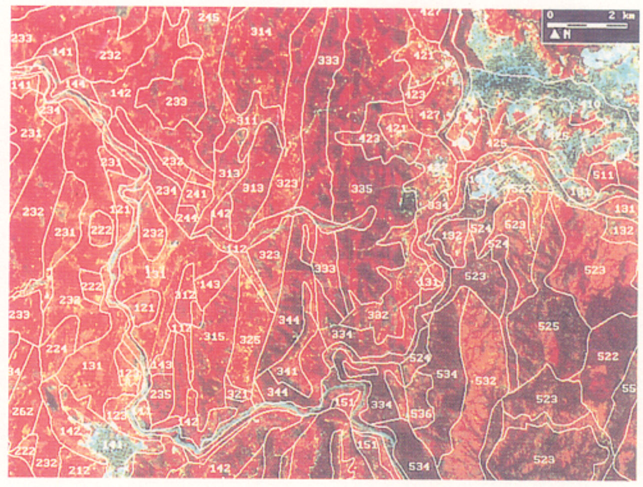

Figure 2. Terrain classification derived from visual interpretation of stereo SPOT images.

terrain classification, overlain on top of a false colour SPOT satellite image is given in figure 2.

The landslide analysis of the area is obtained by the detailed interpretation of representative areas selected on the TMU map,or by a walk-over survey in the field along carefully chosen lines, which are sampling the different TMUs. During this part of the survey the terrain parameters controlling the slope instability phenomenon are established by a direct evaluation of the slope failure in its environmental setting. Weight factors, based on the professional experience of the specialist, are attributed to the parameter classes (blind weighting) (see fig 3). In GIS, by overlaying the factor-maps and simple addition of the assigned weights, a new map is created with qualitative data regarding the potential instability of the slope. By this operation, the degree of hazard for every TMU is calculated. No new mapping units are created, but the existing TMUs are reclassified according to their susceptibility for slope movements. A resulting qualitative hazard map is presented in figure 4.

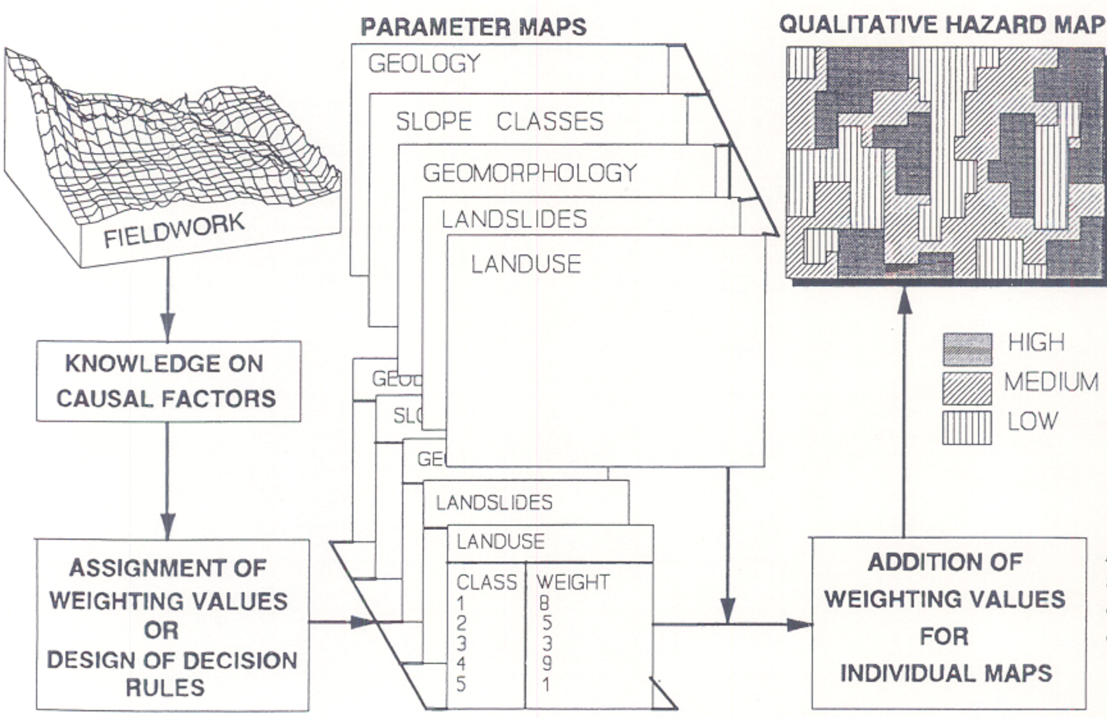

Figure 3. Simplified working method for qualitative hazard analysis.

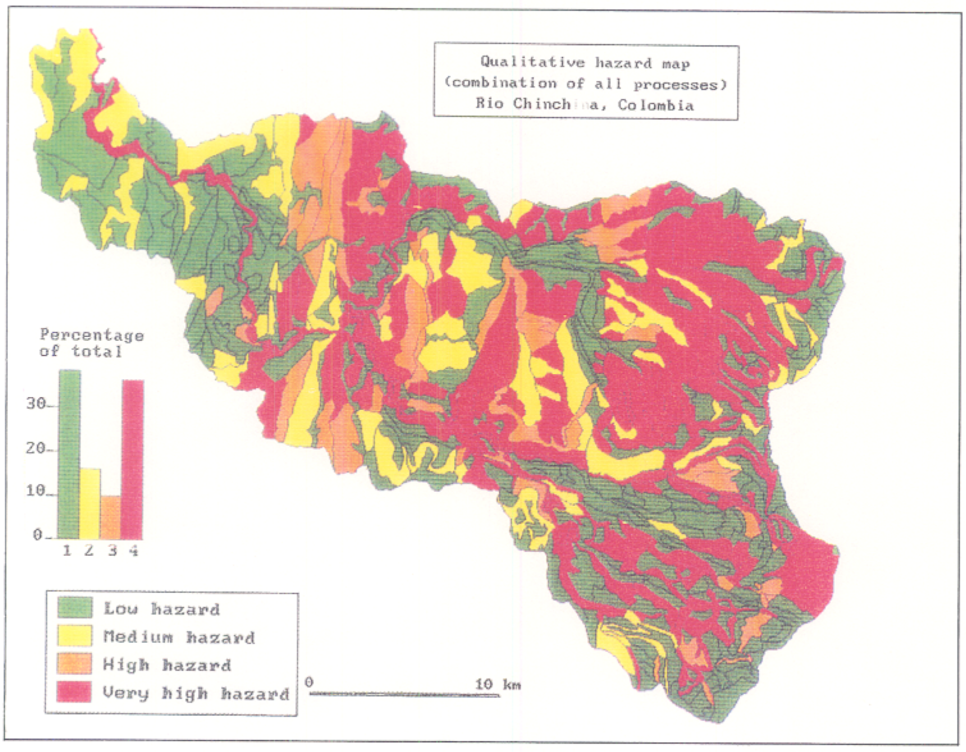

Figure 4. Qualitative hazard map.

Medium scale hazard mapping

The medium scale hazard maps specify the areas where slope instability problems are likely to occur and give information on the type of difficulties which can be expected. This information is mainly intended for agencies involved in local planning and for offices dealing with feasibility studies for large engineering works and infrastructural planning.

The areas to be investigated are in the order of several hundreds of square kilometres and the detail required for these studies justifies a detailed landslide inventory of the whole area. Sequential photo-interpretation is used to evaluate the differences in landslide activity through time (fig 5). The basic function of a landslide inventory map is to relate the spatial distribution of slope instability phenomena with the spatial variability of the terrain parameters which can be involved in slope movements.

The analysis techniques which are most suitable for this working scale are of a statistical nature. The importance of each parameter in respect to the occurrence of landslides is evaluated by calculating the landslide density within the parameter area. Two basic approaches were used. The first is based on multivariate analysis carried out on homogeneous terrain units, defined by photo-interpretation or by automatic extraction from DTMs (Carrar *et al*, 1991). GIS is used to create the matrix expressing the presence/absence or the density of each parameter in the homogeneous units (see fig 6), and statistical analysis is performed with software packages outside of the GIS.

A disadvantage of this method is related to the sampling of these terrain units. This is particularly serious if slope movements in a unit do not coincide with a parameter assigned to this unit. Moreover the multivariate approach is perceived as something of a black box solution – one that gives little flexibility for the final hazard classification.

Therefore, an alternative methodology has been developed using univariate statistical techniques (Westen, 1993). The landslide inventory map is used to determine the correlation of the process with the parameters by calculating the landslide density in a parameter class and comparing this with the overall landslide density in the entire area (see fig 7).

This frequency analysis of the landslide occurrence is undertaken for single parameters as well as for selected combinations of parameters. The statistical analysis is experience or hypothesis-driven, which means that the professional is choosing parameters on the basis of his professional evaluation of the variables involved in the slope instability. Based on a selected number of parameters, a scenario for instability conditions is established in GIS by summing up the weights assigned to the variables, which is executed in raster domain. The results are compared to the known unstable areas and if the model has to be rejected, parameters are easily adjusted, or new variables can be added.

Large scale hazard mapping

The large scale hazard mapping is basically intended for pre-design phases in larger engineering projects; to establish areas where costly site investigation techniques are indispensable. Furthermore, it is used to generate different scenarios under varying environmental conditions. The creation of a detailed digital terrain model is needed in order to obtain the required information for the analysis. Figure 8 shows the difference in terrain elevation, caused by the removal or addition of soil material, as calculated from the comparison of two detailed DTMs from different periods. Furthermore, the large scale hazard mapping looks for the incorporation of deterministic models concerning the stability of the slopes, which implies also that an approximation should be made for the geotechnical properties of the slope

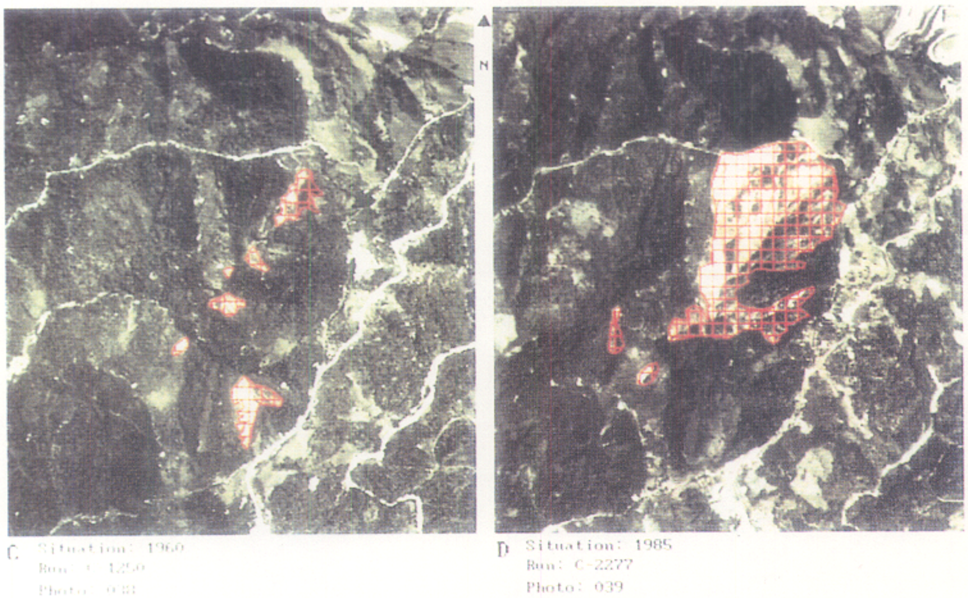

Figure 5. Example of the evaluation of landslide activity through time.

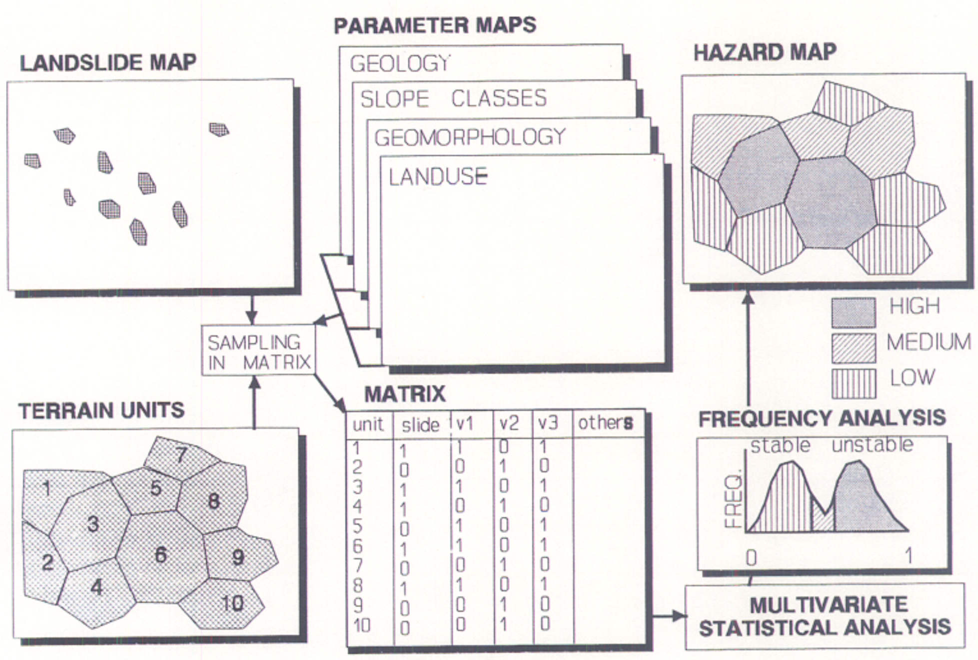

Figure 6. Simplified working method for multivariate analysis.

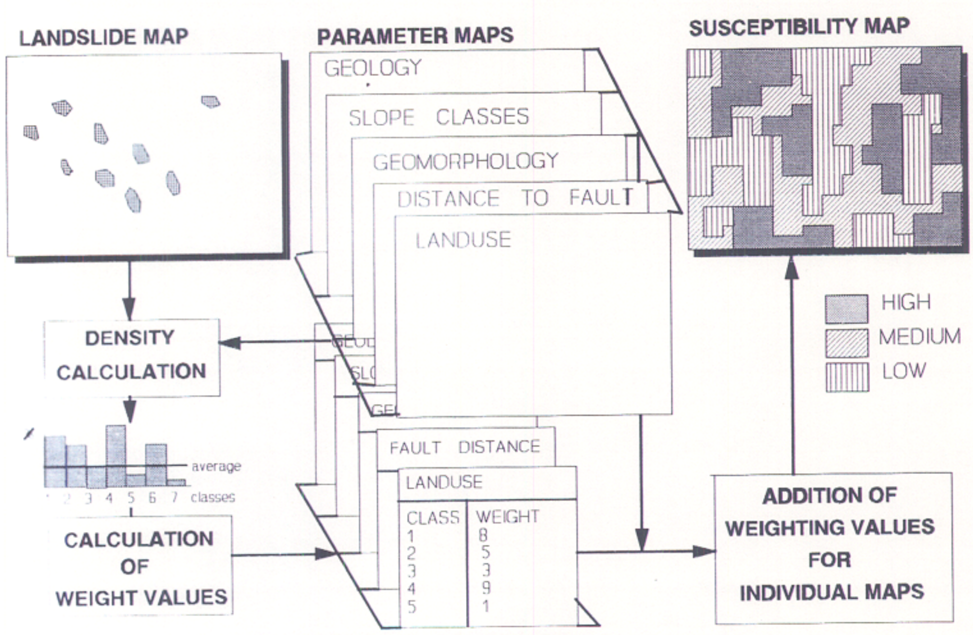

Figure 7. Simplified working method for univariate analysis.

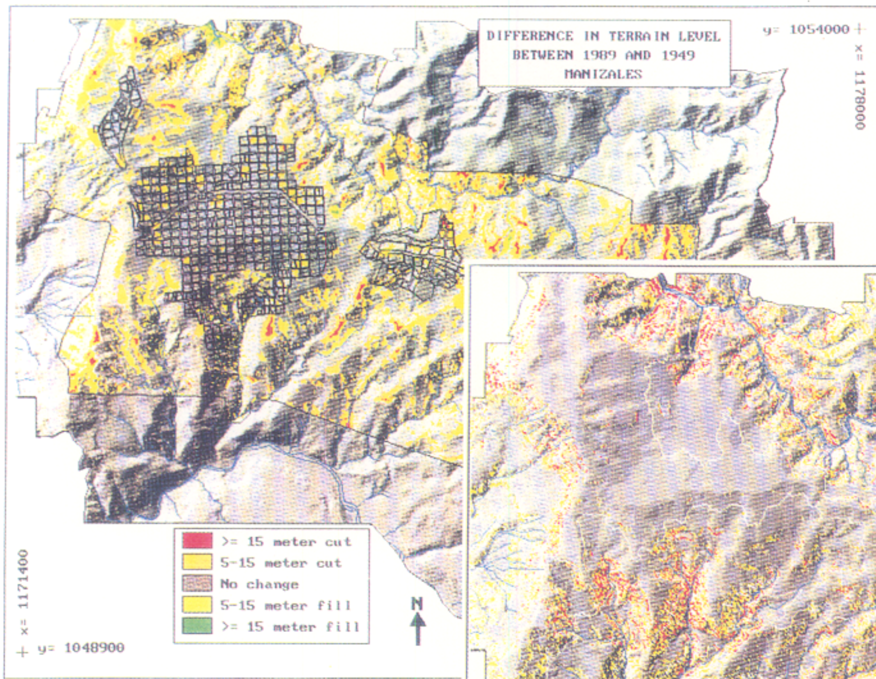

Figure 8. Calculation of cut-and-fill volumes by comparison of DTMs from different periods.

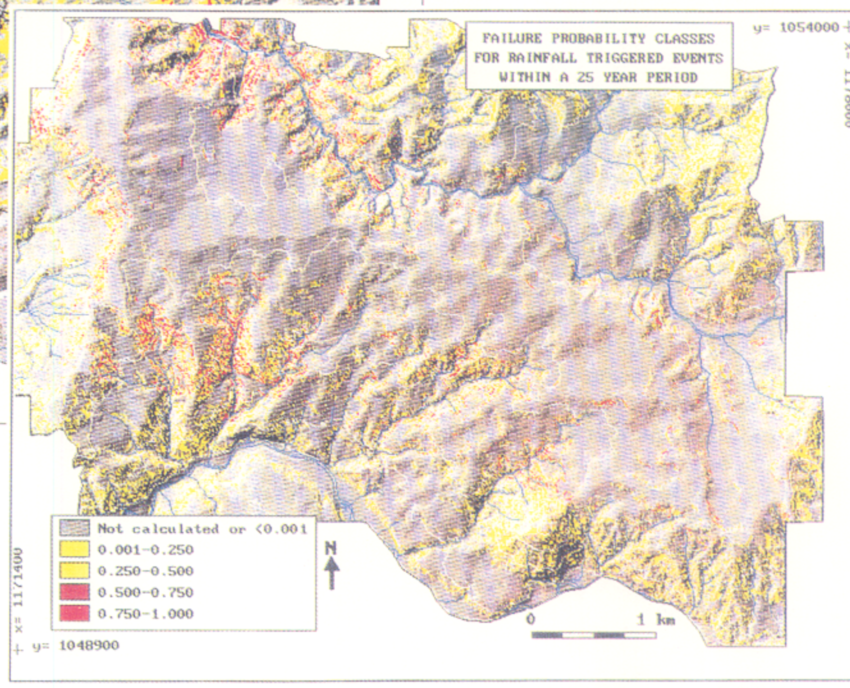

Figure 9. Example of a landslide probability map.

materials. The porewater pressure is approximated by hydrologic slope models. The method is based on the calculation of so-called 'safety-factors', expressing the ratio between the forces which will make the slope fail, and those which prevent the slope from failing. The method results in a map displaying the probability for slope failure in relation to the magnitudes of triggering events, such as rainfall or seismic acceleration. Figure 9 gives an example of a failure probability map for an earthquake with a return period of 25 years.

Summary and conclusions

This project demonstrated that GIS is an important tool in the management of complex data-sets for landslide hazard zonation. GIS is useful in the entire process, not just for data-collection. The main limiting factor, however, is the large amount of time needed to digitise the maps. The use of quantitative techniques in GIS allows the user to define hazardous areas with a higher degree of objectivity. Nevertheless, the field experience of the earth scientists executing the analysis is of crucial importance. GIS also helps the user to quantify the degree of uncertainty of the resulting hazard map, especially that related to the uncertainty of input factors derived from photo-interpretation. The methodology which was developed allows earth-scientists to select the relevant analysis techniques, depending on the specific requirements of the hazard zonation project in which they are working. To facilitate the dissemination of the experience gained with this research project, a training package for the use of Geographical Information Systems in Slope Instability Zonation (GISSIZ) has been prepared. This consists of a textbook, an exercise manual, a tutorial version of a GIS system and ten floppies with training data.

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