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Mountain hazard analysis using a PC-based GIS

Analyse des risques naturels en terrain montagneux, un domaine d'application pour SIG sur PC

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ABSTRACT: The use of Geographical Information Systems (GIS) opens new possibilities for mountain hazard analysis, but also confronts us with very specific requirements where the input of data is concerned. A description is given of the structure of input data in a GIS, and the various techniques for small, medium and large-scale analysis, with some examples from the Alps and the Andes.

RESUME: L'utilisation des Systèmes d'Information Géographique (SIG) ouvre des nouvelles perspectives quant à l'analyse des risques naturelles en terrain montagneux. Mais elle nous confronte également aux exigences spécifiques à l'élaboration des bases de données. Sont décrites dans cet article, la structure de ces bases de données pour un SIG, et les différentes techniques d'analyse, que ce soit à petite, moyenne ou grande échelle. Certains cas provenants des Alpes et des Andes sont reprès comme exemples.

INTRODUCTION

Geographical Information Systems are increasingly recognized as a powerful tool in earth sciences. They allow the user to store, retrieve and analyze large quantities of data needed in a relatively short time, and are very helpful for planning. The UNESCO has declared the use of GIS in environmentally sound management of natural resources one of their major goals for this decade, that has been designated as the "International Decade for Natural Disaster Reduction (IDNDR)" by the UN. Recently UNESCO and ITC have started a project that aims at assisting the national earth science organizations in the Andean countries through the development of mountain hazard mapping methodologies and techniques using GIS, and the transfer of this knowledge to the organizations responsible for hazard mapping.

Although the use of computers for modelling and statistical analysis of landslides is very advanced (Bonnard 1988), the use of GIS is still rather scarce in this field. The first coarse raster based GIS systems were used for landslide hazard susceptibility mapping in the late seventies (Newman et al 1978). A much more elaborate method, using field checklists and multivariate analysis was presented by Carrara et al (1978). More recently examples of the use of GIS for mountain hazard mapping can be found in Stakenborg (1986), Wagner et al (1988), Kienholz et al (1988) and Wadge (1988).

1 PC-BASED GIS: ILWIS

The Integrated Land and Watershed Information System (ILWIS) was recently developed at the International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, the Netherlands. It combines conventional GIS procedures with image processing capabilities and a relational database. All operations can be performed on a 80286-based computer (IBM-AT), with a coprocessor, a digitizer, a Matrox graphics card, high-resolution monitor and output devices (colour printer, plotters). The system was developed for a PC, taking into consideration the situation of most developing countries, where mainframes or minicomputers are still very rare (Valenzuela 1988). Modelling can be done in the separate modules, in the relational database and in the GIS software kernel (described by Gorte et al 1988).

2 THE TEST AREA

The test area for the UNESCO-ITC project on mountain hazard analysis using GIS is located in the catchment of the Chinchina river, in the highest part of the Central Cordillera, Colombia (see fig. 1).

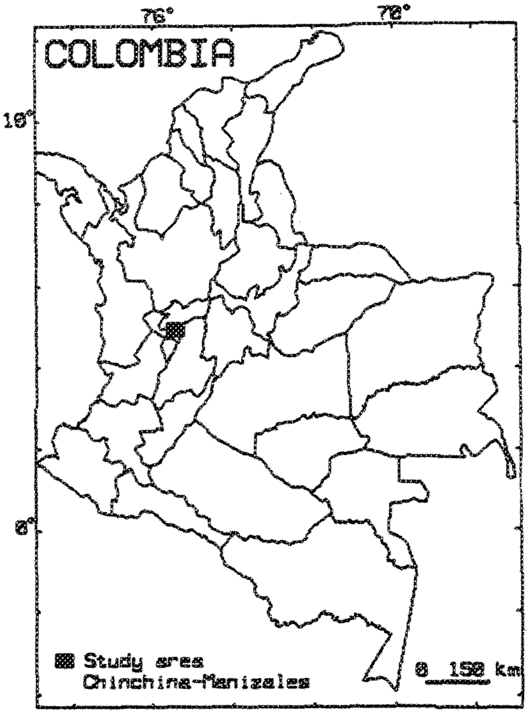


Figure 1. Location of the study area for the UNESCO-ITC project. The sample areas for each scale are indicated.

The area is subjected to a variety of hazards:

- seismic hazard, due to the presence of an active fault system;
- volcanic hazards, caused by the active Ruiz volcano; and
- erosion and mass movement hazards, caused by the combination of deep weathering, strong uplift and incision, high rainfall intensities and active human interference.

3 INPUT DATA

The use of a GIS such as ILWIS requires a different methodology of data capture and display than the conventional mapping methods as used in geomorphology (see Demek & Embleton 1978). Unlike the conventional maps, that are mostly symbol maps with all information in one layer, the ideal maps in a GIS are areal type maps, with different information stored in different layers. The four basic types of maps within a GIS are point maps (for which the table is more important than the map), line maps, polygon maps (units) or pixel maps (different values per pixel).

In table 1 a list is given of the way the input maps for mountain hazard analysis were stored in ILWIS. The list is an extensive one, and all types of information will only be available in an ideal case. However, as can be seen from the right column of the table, the information levels available determine the type of hazard analysis that could be used, going from a qualitative one where little information is available to complex statistical models. In table 1 also the type of map is given, the way it is obtained, for which scale it can be made (regional, medium or large) and the type of attribute table linked to the map. The last columns of table 1 display which maps are used for which type of analysis.

For the information layers 4, 13, 14, 15, 16, 17, 18, 25 and 31 a series of parameters will have to be sampled in the field in a number of observation points using checklists or field computers.

Table 2 gives the list of parameters to be sampled. For levels 13, 14 and 31 laboratory testing is needed. The information layers 19, 25, 26, 27, 28, 29, 30 and 31 require a series of continuous mea-

Table 1. The structuring of input data for mountain hazard analysis in ILWIS.

Nr	Map data-base	Type	Scale			Made from	Tables	Analysis									
			R	M	L*			QL	HD	HI	SS	SP	SC	RF	SS	CS	DM
Geomorphological																	
1.	Main Geomorphological units	Units	+	+	-	API+fieldcheck	DC	+	-	-	-	-	+	-	-	+	-
2.	Geomorphological subunits	Units	+	+	+	API+fieldcheck	DC	+	-	-	-	-	+	+	-	+	-
3.	Morphography/morphometry	Line	-	+	+	API+fieldcheck	D	-	-	-	-	-	-	-	+	+	-
4.	Denudational features (1986)	Point	-	+	+	API+fieldwork	FD	-	+	+	+	+	+	-	+	+	+
5.	Denudational features (1969)	Point	-	+	+	API	D	-	+	+	-	+	+	-	-	+	+
6.	Denudational features (1945)	Point	-	+	+	API	D	-	+	+	-	+	+	-	-	+	+
Topographical																	
7.	Digital Elevation Model	Pixel	+	+	+	Contour interpol.	-	-	-	-	-	-	+	+	+	+	+
8.	Slope map (degrees or %)	Pixel	-	+	+	From 7	-	-	-	-	+	+	+	-	-	+	+
9.	Slope direction map	Pixel	-	+	+	From 7	-	-	-	-	-	-	+	-	-	+	+
10.	Hillshading map	Pixel	+	+	+	From 7	-	for display only									
11.	Anaglyph map	Pixel	+	+	+	From 7	-	for display only									
12.	Block diagrams	Pixel	+	+	+	From 7 + SPOT	-	for display only									
Geotechnical																	
13.	Engineering soil type map	Unit	-	+	+	API+fieldwork	RFD+RLD	-	-	-	+	+	+	+	+	+	+
14.	Engineering rock type map	Unit	+	+	+	Geology+fieldwork	RFD+RLD	+	-	-	+	+	+	+	+	+	+
15.	Isopach map of pyroclastics	Pixel	-	+	+	Field data+model	RFD	-	-	-	-	-	+	-	+	+	+
16.	Isopach map of weathering	Pixel	-	+	+	Field data+model	RFD	-	-	-	-	-	+	-	+	+	+
Structural geology																	
17.	Faults and lineaments	Line	+	+	<	API+SPOT+fieldwork	FD	+	-	-	+	+	+	-	-	+	+
18.	Structural zones	Unit	-	+	+	API+fieldwork	RFD	-	-	-	-	-	+	-	-	+	+
19.	Seismic events	Points	+	+	<	Existing data	RSD	-	-	-	-	-	+	-	+	+	+
Landuse/vegetation/infrastructure																	
20.	Present land use	Unit	+	+	+	API	D	+	-	-	+	+	+	+	-	+	+
21.	Landuse 20 years ago	Unit	-	+	+	API	D	-	-	-	-	-	+	-	-	+	+
22.	Landuse 40 years ago	Unit	-	+	+	API	D	-	-	-	-	-	+	-	-	+	+
Hydrological																	
23.	Drainage (different orders)	Line	+	+	+	API+topomap	D	+	-	-	-	-	+	-	-	+	+
24.	Catchment (different orders)	Unit	+	+	+	API+topomap	D	+	-	-	-	-	+	-	-	+	+
25.	Watertable	Pixel	-	+	+	Model	RFD	-	-	-	-	-	+	-	+	+	+
26.	Isohyets	Pixel	+	<	<	Model	RSD	-	-	-	-	-	+	-	-	+	+
27.	Isotherms	Pixel	+	<	<	Model	RSD	-	-	-	-	-	-	-	-	+	+
28.	Evapotranspiration	Pixel	+	+	<	Model	-	-	-	-	-	-	-	-	-	+	+
29.	Specific discharge	Pixel	+	+	+	Model	-	-	-	-	-	-	-	-	-	+	+
30.	Climatic zones	Pixel	+	-	-	Model	RSD	+	-	-	-	-	+	-	-	+	+
Volcanological																	
31.	Sampling points	Point	-	+	+	Existing data	SD+FD+LD	-	-	-	-	-	+	-	-	+	+

Explanation:
* Scale of analysis
R= Regional (1:100.000)   M= Medium scale (1:25.000)
L= Large scale (1:5.000)
+= Made on this scale, -= Not needed on this scale,
<= Data from the smaller scale is used.
** Table types:
D= Descriptive   FPD= Field point-data
LPD= Laboratory point-data   SPD= Station point-data
RFD= Reworked field data   RLD= Reworked laboratory data
RSD= Reworked station date   DC= Data from map crossing

*** Type of analysis
QL= Qualitative analysis
HI= Hazard isopleth
SP= Probability
RF= Rockfall calculation
CS= Complex statistics
HD= Hazard distribution
SS= Simple hazard susceptibility
SC= Complex susceptibility
SS= Slope stability models
DM= Complex deterministic models.

surements over a long period, using more or less expensive equipment. The gathering of these types of data will be the most expensive and time consuming in a hazard analysis project.

4 QUALITATIVE ANALYSIS

Basically this type of analysis is intended as a desk study on a regional scale when only the general geomorphological information (nos. 1, 2) and a general rock type map (no. 14), without any point observation data, or a general geological map are available. In most cases a topographical map at a 1: 100.000 scale will be available too so that a coarse DEM can be made, however, without the necessary accuracy to create a slope map (8). From the topographical map, together with airphoto or SPOT interpretation layers 17, 20, 23 and 24 can also be made.

The method is such that for each Terrain Mapping Unit of level 1 a series of attributes from the other available maps are sampled in a semi-automatic way with GIS, such as lithological types, land use, altitude range, internal relief, drainage density, slope steepness distribution, slope length, slope and crest forms and occurrence of various mass movement and erosion processes (described in Meijerink 1988).

5 QUANTITATIVE ANALYSIS

When the analysis is done on a medium or large scale, more data can be gathered in the field, and other type of hazard analysis techniques with GIS come within reach (see table 1).

Table 2. List of parameters gathered in the field and laboratory for different input maps

Map	Parameters
4	Recent denudational features. Type, area affected, age, development, activity, dimensions, source, transport or accumulation, material, slope angle, slope angle before slope direction, slope form, contact, damage, possible causes, risk, vegetation, land use, drainage, water table
13	Engineering soil type map Code, thickness, % in profile, texture, sorting, layering, cementation, moisture content, permeability, consistency, vane shear strength, weight%of boulders, cobbles, gravels, sand andfines, dry strength, toughness, dilatancy, Atterberg limits, density For a limited number of samples: cohesion, angle of internal friction, clay types, pF, permeability
14	Engineering rock type map Code, thickness in profile, % of profile, weathering class, weathering susceptibility, layer thickness, spacing, characteristic block size, material strength, Schmidt hammer rebound value, tilting angle, point load strength
15/16	Isopach map of pyroclastic deposits and weathering soils Depth, slope angle, signs of erosion
17	Faults and lineaments Width, orientation, displacement
18	Structural zones Strike and dip, bedding, foliation, discontinuity
24	Depth of freatic water level Date, depth

5.1 Hazard susceptibility maps

Most of the map based quantitative analysis techniques are based on map crossings. In this way the relations between the various types of mass movements and a whole series of other parameters can be displayed, either as a relation between two, three or more variables. Therefore it is of crucial importance that the mass movement phenomena are mapped accurately. In figure 2 the relation between mass movements and slope angle for an earlier test area in Austria is displayed as an example.

For the hazard susceptibility analysis a varying number of maps can be used, depending on those that have a clear relation with mass movements. Therefore it is advised to evaluate their importance first by crossing them individually with the maps displaying denudational features.

In a simple hazard susceptibility analysis only five maps are taken into account: 8, 13, 14, 20 and 4. The procedure is shown in figure 3. The four input maps (rock type, soil type, slope class and vegetation/land use) are crossed with each other resulting in a combination map and a cross-table. This combination map is then crossed with the maps for the various denudational features, and for each of these the percentage for the combination of the other four maps is stored (%1, %2, etc.). For each type of process the combination map is then renumbered with the respective values of these columns, resulting in a susceptibility map with a scale of 1 to 100. This is reclassified to fewer classes and the actual occurrences of mass movements are displayed in this map with the highest susceptibility class.

If more maps are to be used, then this method will not be suitable due to the large number of possible combinations. In that case it is advised to design decision rules with IF statements, using the frequency distributions of the map crossings by pair.

The method can de improved by taking the time factor into account. By overlaying the maps 4, 5

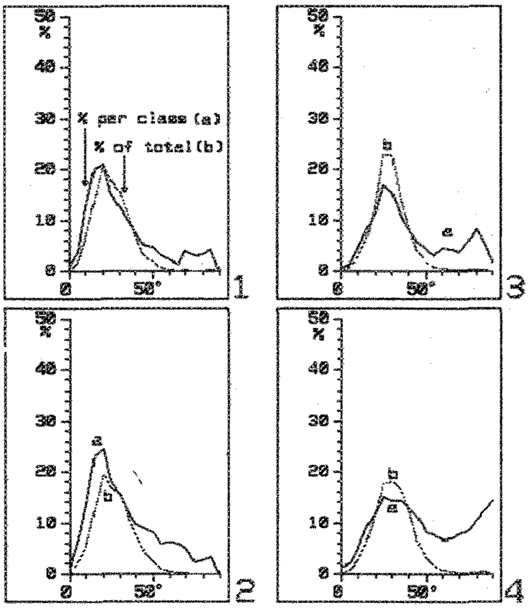


Figure 2. Relation between mass movement types and slope angle
A: % per class B: % of total
1= surficial sliding
2= flow type mass movement
3= deep-seated sliding
4= rockfall accumulation

and 6, maps of active phenomena within a 20 years' period can be obtained.

5.2 Deterministic models

When sufficient field data is available on geotechnical properties, deterministic models can be used in connection with the information levels stored in the GIS (see table 1). Here, two examples are given.

Together with the University of Amsterdam a neighbourhood analysis program was developed for ILWIS that can be used for rockfall hazard mapping. Based on a DEM, the program calculates the rockfall velocity for each pixel, in relation to the velocity of the neighbouring pixel with the greatest height difference. The calculation starts from pixels indicated as rockfall source areas, obtained from the geomorphological map (2) and/or a slope map. Figure 4 shows a result of the calculation, also based in this case on the decelerating effect of forest. With some modifica-

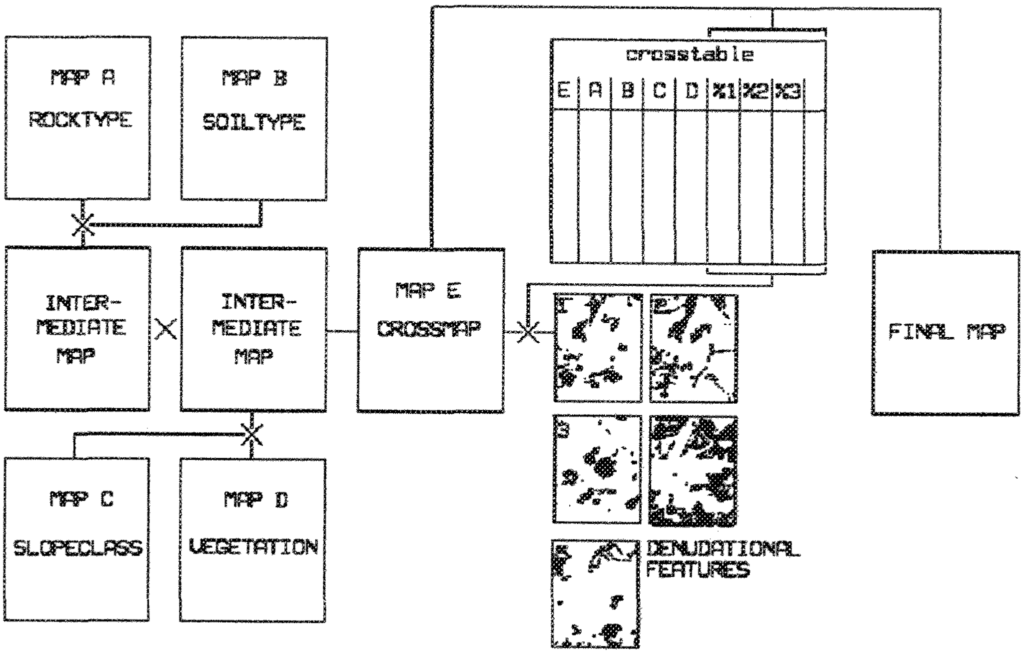


Figure 3. Procedure for hazard susceptibility analysis using 5 input maps

tions the neighbourhood program can also be used for other hazard analyses, such as avalanche run-out distance, or areas affected by a lahar flow of given volume.

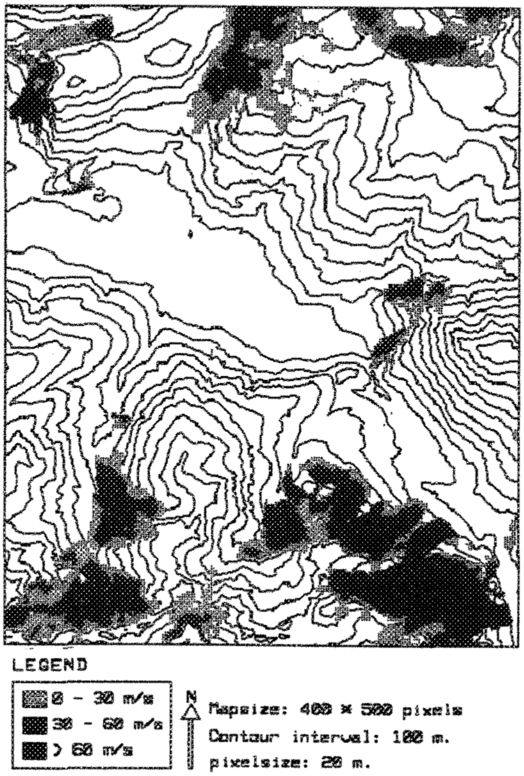
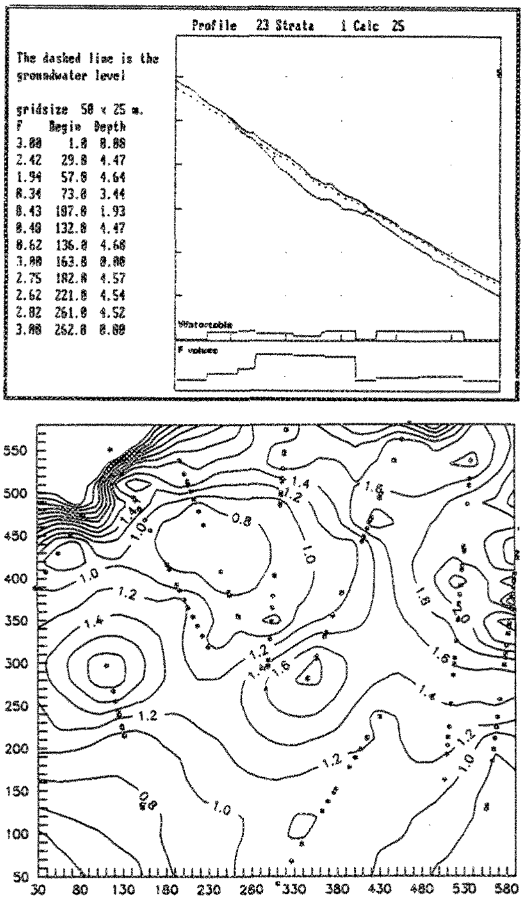


Figure 4. Rockfall hazard map displaying the velocity of a rolling block. Derived from the geomorphological map, with the effect of vegetation included.

A second example of a deterministic model in connection with GIS input data is a slope stability analysis program, developed in cooperation with the University of Utrecht. The program calculates the Factors of Safety along user-defined profile lines with the methods of Bishop or Fellenius. The profiles are selected with the cursor keys on a DEM. The necessary input data are then read simultaneously along those profiles from a number of attribute maps, such as soil depth (15 and 16 in table 2), depth of freatic water level (25). Cohesion, angle of internal friction and bulk density maps are made by renumbering the engineering soil and rock type maps with the attribute values from the corresponding columns. The program calculates the minimum Factor of Safety for slip circles along a user-defined grid. Each grid point is the centre of a number of circles, of which the user can specify the depths. The Factors of Safety values along the profiles can be used in an interpolation program to produce isolines of Factors of Safety, or they can be used in connection with geomorphological data for further analysis. Figure 5 displays a profile and an isoline map of Safety Factors.



```
The dashed line is the
groundwater level

gridsize  50 x 25 m.
F     Begin  Depth
3.00    1.0  0.00
2.42   29.0  4.47
1.94   57.0  4.64
0.34   73.0  3.44
0.43  107.0  1.93
0.40  132.0  4.47
0.62  136.0  4.60
3.00  163.0  0.00
2.75  182.0  4.57
2.62  221.0  4.54
2.82  261.0  4.52
3.00  262.0  0.00
```

Figure 5. A profile as it is read from the input maps in ILWIS (a), and an isoline map of Factors of Safety (b).

CONCLUSIONS

The use of GIS can be an important tool in disaster management. However, the gathering of data and the way the various input maps are stored are different from most of the conventional techniques. The structure of the databases (maps and tables) can be made in such a way that a variety of hazard analysis techniques can be applied in a relatively short time.

As the UNESCO-ITC project still is in the phase of data gathering, not all of the analysis methods could be tested yet. In the near future emphasis will be put on hazard index maps, multivariate analysis and probability maps based on models, including the effects of seismic events and extreme rainfall.

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