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Remote sensing and geographic information systems for geologic hazard mitigation

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A disaster is defined as "a calamitous event bringing great damage, loss or destruction" [3]. These events can be earthquakes, landslides, floods, hurricanes, volcanic eruptions, etc.

The debris flows accompanying a volcanic eruption are not—by themselves—considered a disaster if they occur in an uninhabited area. When debris flows move into inhabited valleys downslope, however, they become hazards. And they may result in a disaster if they hit a city, as did the debris flows triggered by a volcanic eruption of the Nevado del Ruiz, which wiped out the entire city of Armero, Colombia, in November 1985, killing 30,000 people.

Some disasters, such as earthquakes, strike within short periods with devastating outcomes, while others have a slow onset period with equally or even more serious repercussions (such as drought).

Disasters can be classified in several ways. One possible division is:

- natural disasters are events caused by natural phenomena (such as earthquakes, volcanic eruptions, droughts, hurricanes)
- human-caused disasters are events brought on by human activities (such as atmospheric pollution, industrial chemical accidents, major armed conflicts, nuclear accidents, oil spills, desertification).

Another subdivision is into geologic disasters (earthquakes, volcanic eruptions, landslides, floods) and ecologic disasters (drought, desertification, erosion, deforestation).

Almost all disasters are accompanied by a loss of some kind. This can be in the form of property, infrastructure or human life. The losses experienced vary with the type of disaster, its magnitude and the areas effected.

Globally, it appears that the toll of death and damage in natural disasters is increasing, although there is no international databank of sufficient comprehensiveness to verify this supposition. The cost to the global economy now exceeds US $50 billion per year, of which one-third represents the cost of predicting, preventing and mitigating disasters and the other two-thirds represent the direct cost of the damage [1]. Death tolls vary from year to year, around a global mean of about 250,000, of which major disasters account for an average of 140,000 people each year.

There seems to be an inverse relationship between the level of development and loss of human lives in a disaster. About 95 percent of the deaths occur in the Third World, where more than 4.2 billion people live. Economic losses attributable to natural disasters in developing countries may represent as much as 10 percent of gross national product. In industrialized countries, where warning systems and building codes are more sophisticated, it is easier to predict the occurrence of natural phenomena and to warn people in sufficient time; the damages are usually less severe than in developing countries with strictly limited resources [1]. An example of this can be given by comparing the great floods in Bangladesh (1988), which caused the death of 1410 people, with the Mississippi flood in the United States (in 1993), which caused only about 30 fatalities. However, when we compare the economic losses of the two events, the results are reversed: in Bangladesh a total loss of US$ 1.1 billion was estimated, while US$ 15.8 billion was estimated in the United States. Even more striking is a comparison of the hurricane disasters of 1990 in Bangladesh and the 1992 hurricane Andrew in the United States.

These statistics illustrate well the importance of disaster mitigation. The international community has become aware of the necessity to increase their work on disaster management, and the period 1990-2000 has been designated the "international decade for natural disaster reduction" by the General Assembly of the United Nations.

To reduce the impacts of natural disasters, a complete strategy for disaster management is required [4, 5], involving the following aspects:

- Disaster prevention
  Hazard analysis: assessing the probability of occurrence of potentially damaging phenomena
  Vulnerability analysis: assessing the sensitivity of specific "elements at risk", such as the population, infrastructure and economic activities, for a specific type of hazard of a certain magnitude
  Risk assessment: assessing and quantifying the numbers of lives likely to be lost, personal injuries, property damage and costs of disruption of economic activities caused by a particular natural phenomenon
  Land use planning and legislation: implementation of the risk map in the form of building codes and restrictions
- Disaster preparedness
  Forecasts/warnings/predictions of disasters (for example hurricane warnings)
  Monitoring: evaluating the development through time of disasters (for example floods)
- Disaster relief
  Damage assessment shortly after the occurrence of a disaster
  Defining save areas to indicate possible escape areas

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Infrastructural monitoring to ensure an undisturbed supply of aid

TOOLS IN HAZARD MITIGATION

Mitigation of natural disasters can be successful only when detailed knowledge is obtained about the expected frequency, character and magnitude of hazardous events in an area. The zonation of hazards must be the basis for any hazard mitigation project and should supply planners and decision makers with adequate and understandable information. This information is given in the form of risk maps. To be able to prepare a risk map, we should have information on the probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area (*ie*, the "hazard").

Hazard is commonly expressed in maps that display the spatial distribution of hazard classes. 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. Vulnerability analysis requires detailed knowledge of the population density, infrastructure and economic activities, in addition to the hazard. This part of the analysis is therefore done mainly by persons from other disciplines, such as urban planning, social geography and economics.

In each of these aspects the use of remote sensing and geographic information systems (GISs) can play an important role. Remote sensing data, such as satellite images and aerial photos, allow us to map the variations of terrain properties, such as vegetation, hydrology and geology, in both space and time [3]. They can provide information on the extent of a disaster within a relatively short period of time. And they are of extreme importance in obtaining the necessary data to make an evaluation of the hazard, vulnerability and risk if combined with the other types of data.

Analysis of hazards is a complex task, as many factors can play a role in the occurrence of the disastrous event (*eg*, an earthquake or a landslide). The analysis requires a large number of input data, and analysis techniques may be very costly and time-consuming. The increasing availability of computers during the last decades has created opportunities for a more detailed and rapid analysis of natural hazards.

Geographic information systems permit us to use different types of data in our analyses. Defined as a "powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes" [2], GISs allow us to combine spatial data, *ie*, data with a geographic component, such as maps, aerial photographs, satellite images and rainfall data, borehole data, etc.

SCALES OF ANALYSIS

Before collecting his data, an earth scientist working on a hazard analysis project will have to answer a number of interrelated questions:

- what is the aim of the study?
- at what scale and with what degree of precision must the result be presented?
- what are the available resources in the form of money and manpower?

Selecting the working scale for a hazard analysis project is determined by the purpose for which it is executed. The following scales of analysis can generally be distinguished:

- national scale (< 1:1,000,000)
- synoptic or regional scale (< 1:100,000)
- medium scale (1:25,000 - 1:50,000)
- large scale (1:5,000 - 1:10,000)

In the following sections two examples of the application of remote sensing and GISs will be demonstrated: one on determining flood hazards in Bangladesh, and the other on determining landslide hazards in the Andes.

FLOODS IN BANGLADESH

Bangladesh is the country which is probably most effected by natural catastrophes, especially floods. Approximately 40 percent of the country is subjected to regular flooding. It contains more than 250 perennial rivers, of which 56 originate outside the country, in Tibet, India, Bhutan and Nepal. Ninety percent of the river discharge from the main rivers—the Ganges, the Brahmaputra and the Meghna—originates in other countries.

The primary cause of flooding in Bangladesh is directly or indirectly related to rainfall in the catchment areas of the three major river systems. The rainfall, together with snow-melt from the Himalayas, generates enormous amounts of runoff to be discharged through Bangladesh into the Bay of Bengal.

Moderately strong semidiurnal tides prevail in the Bay of Bengal. Because of the extremely flat topography of the country (half the country lies below the 8 m contour line), the tidal influence reaches very far into the country. During the monsoon, recession of the floodwater is delayed by the tidal effect. Cyclonic sea flooding occurs when the friction of the wind on the surface of the sea causes a storm surge to move inland.

Between 1960 and 1981, Bangladesh suffered 63 disasters with the loss of 655,000 lives. Of these events, 37 were tropical cyclones which killed 386,200 people. The last major floods were in 1987 and 1988, and a cyclone in 1990 killed about 140,000 inhabitants on the Bay of Bengal coast [1].

The evaluation of the flood hazard is an international effort, as rainfall and river discharge must be monitored in the entire catchment of the major rivers; in addition, sea levels must be monitored and warning systems implemented for tropical cyclones.

For flood stage mapping and river dynamics determination, a GIS was used for digital image processing and analysis of sequential Spot images. The study area covers the confluence of the Meghna and Ganges rivers, southeast of the capital of Dhaka. Four Spot images were used in this analysis (see Figure 1):

- January 1987, during the dry season
- November 1987, just after a moderately severe flood with a recurrence interval of 50 years
- October 1988, just after a severe flood with a recurrence interval of 100 years.
- February 1989 (dry season) showing the resulting changes in the river courses.

The Spot images were used in this study to assess the spatial distribution of the inundations (flood stage mapping) and the river dynamics (changes in channel geometry and channel pattern). The images show different water levels, corresponding to flood recurrence intervals. The flooded areas can be separated from dry land, using the spectral characteristics of different satellite image bands. In this case water and land were separated using spectral band ratios.

Repetition of this procedure for several flood levels and overlaying the corresponding digital maps resulted in a map showing the areas that are frequently flooded, areas affected by lateral shifting caused by river dynamics and areas that have a low flood probability. The low flood probability areas will obviously be more suitable for major investments, whereas the other areas may need additional protective measures. It can also be concluded that relief centers to mitigate flood disaster impact should be situated in areas of low flood risk, but near high-risk areas.

Regarding the use of satellite images and GISs, the study has shown that the use of Spot images provided good results, although the inundated areas could be somewhat underestimated because of the time lag between the floods and the acquisition dates of the images. This problem could be partly overcome by combining Spot images with NOAA data (with a high frequency of data acquisition but at less detail). Combination with radar satellite data (ERS-1, JERS) could overcome the problem of obtaining cloud-free images during the monsoon.

MASS MOVEMENTS IN THE ANDES

The second example of the use of remote sensing and GIS in natural hazard analysis comes from the Andes, and deals with the evaluation of landslide hazards. The Andes are a mountain chain still being uplifted by the collision of the Earth's mantle plates, leading to hazards such as earthquakes and volcanic eruptions. Many of these hazards are the triggering mechanisms for landslides.

The major problem areas in the Andean region with respect to landslides are the boundaries of the major cities, such as La Paz and Medellin. In Medellin, some 400 people were killed in 1988 when a large landslide covered a part of the squatter areas in the northern margin of the city. Most of these cities are growing very rapidly, and have an urgent need for planning. In the plans for urban extensions, an analysis of natural risks has not usually been taken into account, resulting in slope failures within recently constructed parts of the cities.

In the evaluation of landslide hazards the use of remote sensing data and GIS plays a very important role. Landslides are controlled by a large variety of factors, such as slope angle, soil and rock material types, vegetation, land use, rainfall and earthquakes. Many of these factors can be evaluated from remote sensing data, especially aerial photos. To evaluate the combined effect of these factors, the use of GISs in the modelling of landslide hazards—using many different maps—is indispensable. Many different methods have been developed, related to the scale of analysis, the availability of input data and the required detail of the hazard map [6].

REGIONAL SCALE

Regional-scale mass-movement hazard analysis (<1:100,000 scale) is used to outline problem areas with potential slope instability. The maps are intended mainly for agencies dealing with regional (agricultural, urban or infrastructural) planning. The areas to be investigated are very large, on the order of 1000 km^2 or more, and required level of map detail is low. The maps indicate regions where severe mass movement problems can be expected to threaten rural, urban or infrastructural projects. Terrain units with areas of at least several tens of hectares are outlined on the basis of satellite images (Figure 2). Within these so-called "terrain mapping units", the degree of hazard is assumed to be uniform. General landslide information is obtained from small-scale aerial photographs. Qualitative analytic methods are used to combine the various characteristics within the terrain mapping units and to come to a qualitative rating of the "hazardness".

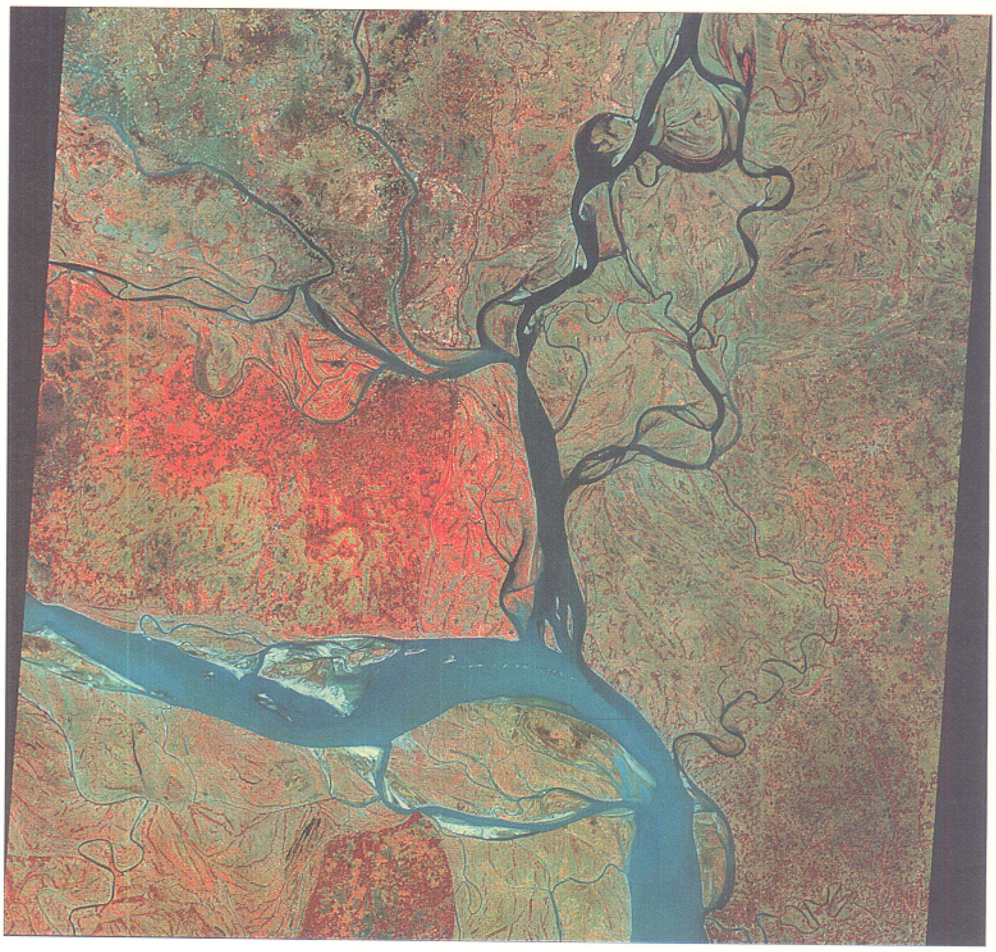
MEDIUM SCALE

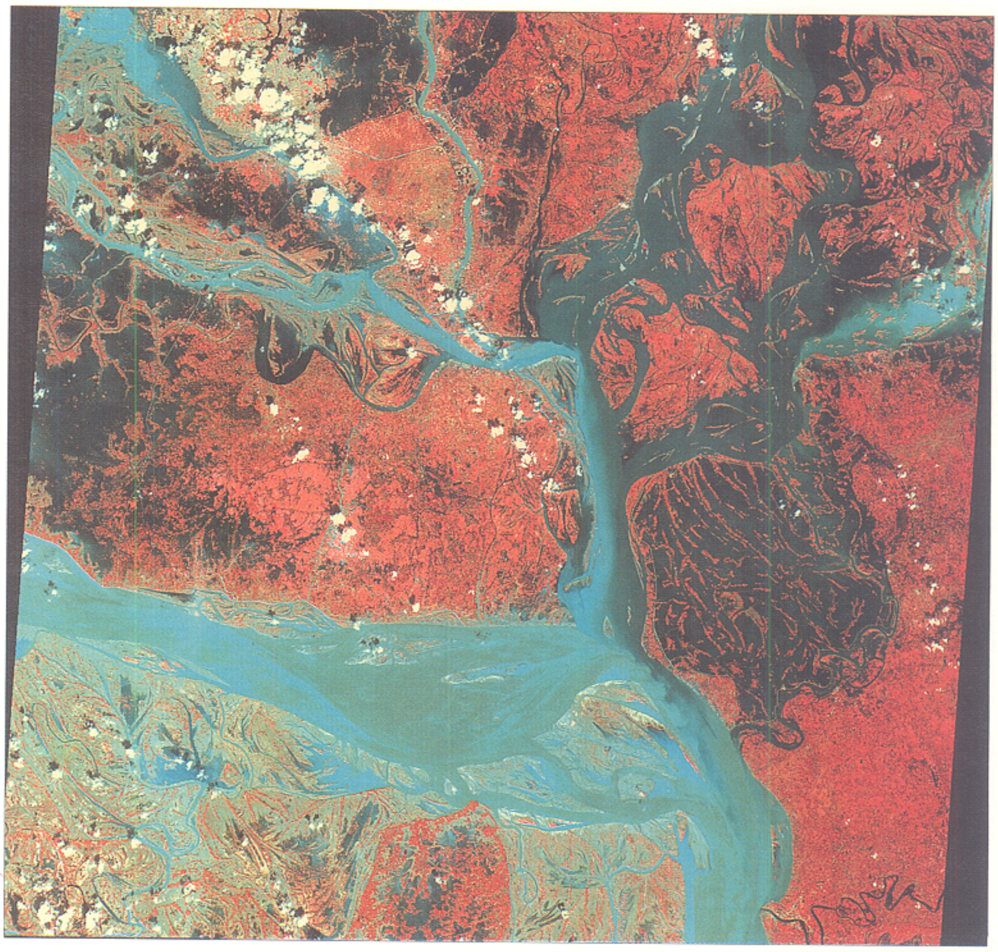
Medium-scale hazard maps (1:25,000 scale) are made mainly for agencies dealing with intermunicipal planning or companies dealing with feasibility studies for large engineering works (such as dams, roads, railroads). The areas to be investigated will comprise several hundred square kilometers. At this scale, considerably more detail is required than at the regional scale. The maps may serve, for example, for the choice of corridors for infrastructure construction or zones for urban development. At this scale it is feasible to map the various factors leading to landslides. Interpretation of aerial photographs is the main source of information for many of the input maps and should be carried out in a well-structured manner, with the use of clear criteria and photo checklists. Emphasis is placed on the use of multitemporal aerial photo interpretation to evaluate changes in mass movement activity and land use patterns. Fieldwork techniques have been developed which include the use of checklists for the description of mass movement phenomena and the collection of soil and rock data, also using simple field tests. The landslide hazard is statistically analyzed by evaluating those conditions that have led to landslide occurrences in the past, and to use those critical combinations in the prediction of landslides in the future (see Figure 3).

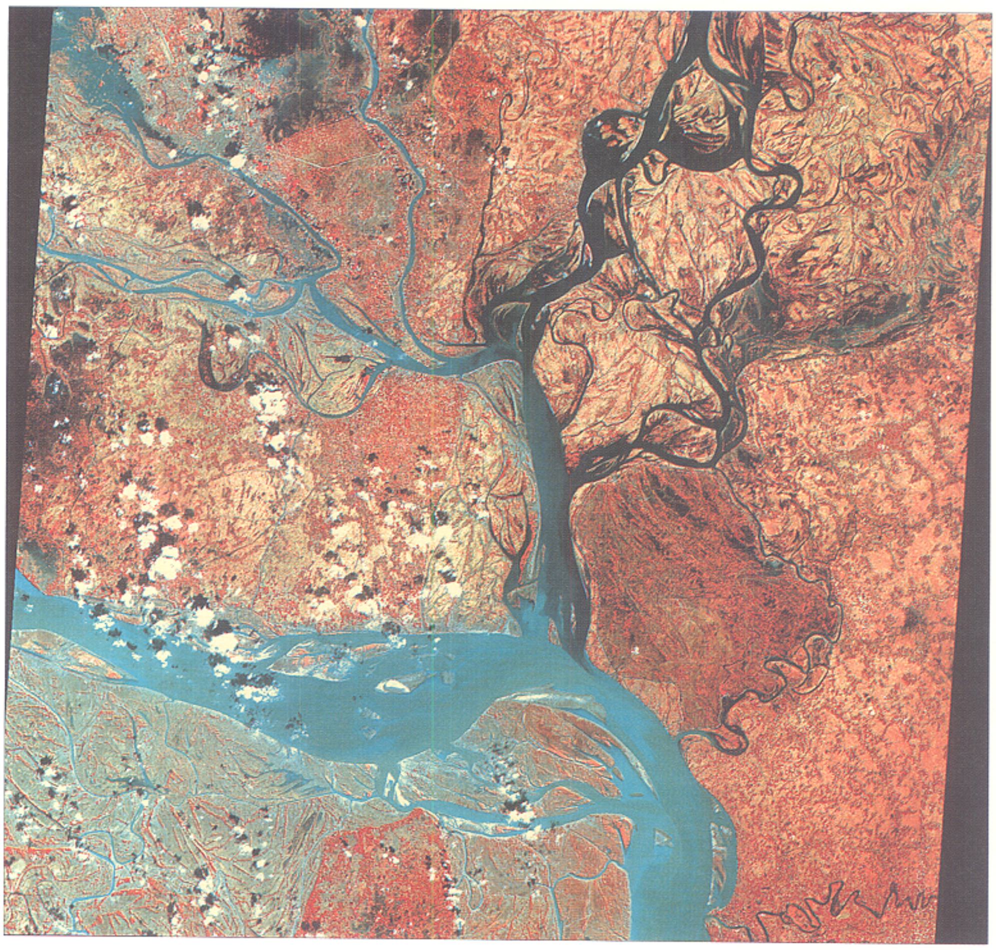
LARGE SCALE

Large-scale hazard maps (1:10,000) are produced mainly for authorities dealing with detailed planning of infrastructural, housing or industrial projects, or with evaluation of risk within a city. The size of an area under study would be on the order to several tens of square kilometers. The hazard classes on such maps should be absolute, indicating, for example, the probability of failure for each individual unit, with areas down to less than a hectare. Detailed material mapping, in combination with geotechnical testing and groundwater level measurements, should provide sufficient information for the application of deterministic slope stability models.

FIGURE 1 Spot images used in the analysis of flood hazard in the Dhaka region of Bangladesh:
(A) January 1987, during the dry season,
(B) November 1987, just after a moderately severe flood,
(C) October 1988, just after a severe flood,
(D) February 1989, in the dry season following the 1988 flood
—note the changes in river channels (the city of Dhaka is in the northwest corner of the images)


(A) January 1987


(C) October 1988



(B) November 1987

(D) February 1989

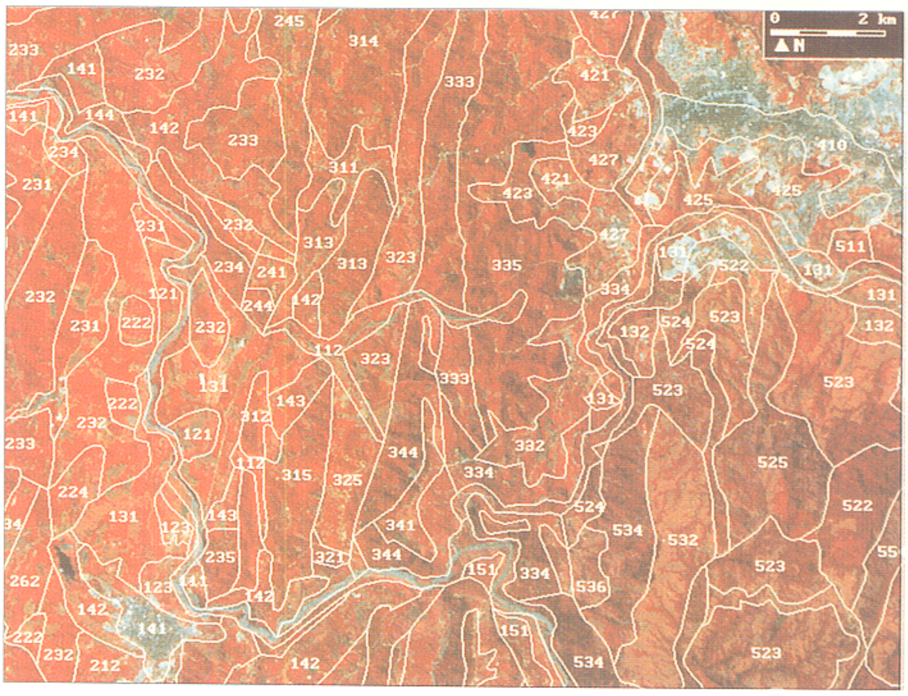


FIGURE 2 Delineation of terrain mapping units obtained by interpreting stereo Spot images of the Manizales region, Colombia

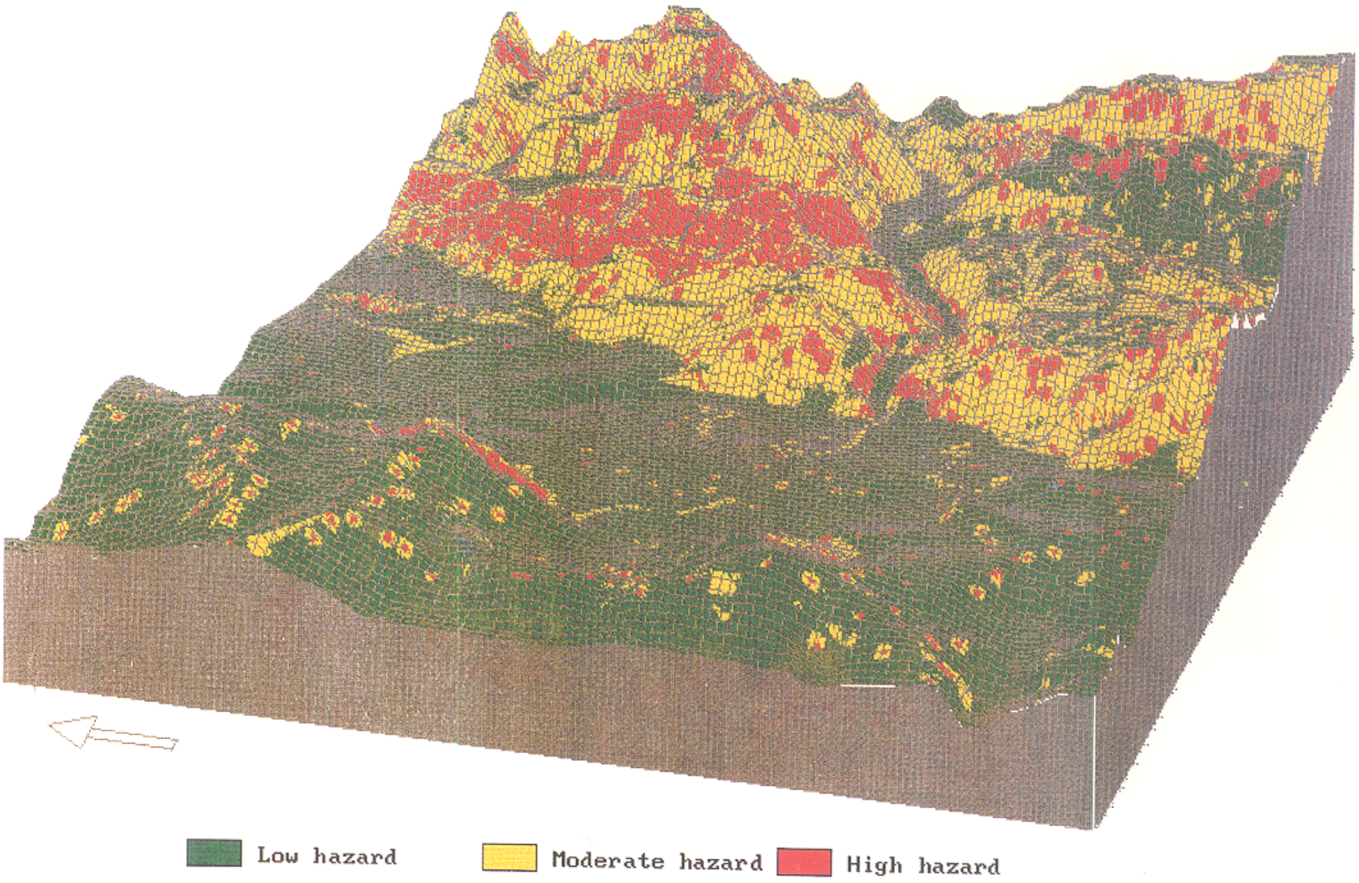


FIGURE 3 Statistically derived hazard map of the Chinchina area, Colombia

CONCLUSION

Remote sensing and GIS are considered to be useful tools in the assessment of natural hazards. These tools, however, apart from their potential for data manipulation, updating and analysis, confront the user with the importance of detailed, accurate and reliable input maps and ample field experience.

The results from the mass-movement study, which was financed by the EC and the Dutch Ministry of Education and Science, are published in the form of a training package [6]. With this training package, earth scientists from developing countries can learn the various aspects of working with GIS in landslide hazard zonation. ITC is also working on the development of training packages in the assessment of other geologic hazards, such as volcanic, seismic and flood hazards. Based on these training packages, a number of workshops have been held to disseminate the knowledge of these powerful tools to experts from developing countries.

The establishment of a Unesco center for the integration of environmental and development aspects in disaster reduction could also play an important role in the further development of new techniques for natural hazard assessment and to disseminate this knowledge to scientists from developing countries.

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