Landslide hazard assessment using GIS and multicriteria evaluation techniques in the Tirajana basin, Gran Canaria Island

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Abstract
Landslide hazard analysis has been undertaken in the Barranco de Tirajana basin, Gran Canaria Island. The area is mostly covered by deposits derived from gravitational sliding of lava flow and volcanic breccia sequences. Primary large landslide bodies have undergone a number of partial reactivation episodes from the Pleistocene to present times emplacing subsequent landslides. A GIS indexing approach has been developed to assess hazard from further reactivation and new mass movements. Parameters including slope angle, landslide activity, material consolidation and fragmentation, proximity to drainage channels and reservoirs, and land use change have been combined using multicriteria evaluation techniques within a GIS to derive a hazard map. Despite expert knowledge is involved during class evaluation, the approach has revealed adequate for landslide hazard assessment at medium scales in areas where no geotechnical data are available.

Introduction
Landslides may occur as a consequence of a number of determining and triggering factors (Varnes, 1978; Popescu, 1994). In order to assess hazard from landslides it is therefore necessary to identify and analyse the most important determining factors leading to slope failure. Approaches to landslide hazard assessment using GIS have been reported, among other authors, by Brabb (1984), Carrara et al. (1991), Van Westen (1993) and Leroi (1996). The applicability of various GIS methods with respect to the characteristics of the study area, the landslide type and extension, the type of data available and the mapping scale has been discussed by Soeters and Van Westen (1996). Most direct methods include landslide inventories and heuristic analysis, where the hazard assessment is made by the earth scientist using site-specific knowledge obtained through photo-interpretation and fieldwork.

A further elaborated heuristic method includes qualitative parameter combination, where the analyst assigns weighting values to a series of terrain parameters and to
each class within each parameter. The parameter layers are then combined within the GIS to produce hazard values. Heuristic methods use selective criteria, which need expert knowledge to be suitably applied.

Another approach includes bivariate or multivariate statistical analysis. The combination of factors that have led to landslides in the past are determined statistically, and quantitative predictions are made for areas currently free of landslides. In these methods the use of complex statistics require the collection of large amounts of data to produce reliable results.

Deterministic approaches, based on stability models, can be very useful for mapping hazard at large scales, for instance for construction purposes. However, they require the availability of geotechnical and groundwater data, and can suffer from oversimplification.

As part of the EU Environment and Climate Programme’s RUNOUT project, a GIS indexing approach has been applied to map hazard from mass movements at a medium scale (1:25,000) in a high-relief area in central Gran Canaria Island, Spain. Much of the area is covered by large landslide deposits derived from lava flow and volcanic breccia sequences. Most landslides have experienced a number of major reactivation episodes since the Pleistocene to present times. In this approach, weights are assigned to terrain parameters and classes using expert knowledge and multicriteria evaluation techniques. The parameter layers are then combined within the GIS through a weighted linear sum to produce a landslide hazard map.

The study area
Geographical and geomorphological setting
The Barranco de Tirajana basin is located in central Gran Canaria Island, Canary Islands. It has an extension of 50 km², spreading over the municipalities of San Bartolomé de Tirajana and Santa Lucía (Figure 1). The basin is a major erosive feature formed on interbedded volcanic breccia, ignimbrites and lava flows since the Pliocene by large landslides (Lomoschitz and Corominas, 1997a). It makes up a deep oval-shaped amphitheatre, bounded by very steep slopes and cliffs reaching up to 350 m of height, which are remnants of ancient, large landslide scarps (Figure 2). Altitudes range from 1949 m in the northernmost sector to 360 m in the southern end, with differences of up to 900 m on slopes next to the basin boundaries. The area is drained by the Barranco de Tirajana stream and its tributaries, all with intermittent or seasonal flow. Average annual rainfall ranges from 370 mm at the bottom of the basin and 890 mm near the cliff tops, although much of it concentrates within days. It is believed that rainfall is responsible for the major landslide reactivations occurring this century (Lomoschitz and Corominas, 1997b).

This scenic area includes two major villages and numerous scattered houses. It contains artificially irrigated orchards within extensive shrubby areas and bare ground (soil and rock outcrops) with some coniferous patches. Tourism is also starting to flourish because of its proximity to a major beach resort.
Mass movements
The Tirajana basin contains at least 28 large landslides, some with surfaces exceeding 400 hectares and volumes over 1 km³. Main landslide types include rock slides, debris slides, earth slides, debris flows and rockfalls (Lomoschitz and Corominas, 1997a). Several generations of movement since the Pleistocene can be recognised, typically consisting of a major primary failure of the bedrock, followed by a succession of smaller, secondary displacements due to sliding of the primary body. Following primary failure and emplacement, the landslide materials suffered from progressive weathering and weakening, so that further generations show a fragmented structure.

Recent slope movements in the basin have been reported, particularly an earth slide seriously affecting the village of Rosiana in 1956 after intense rainfall (Lomoschitz and Corominas, 1997b). Active rockfalls have been observed on cliffs, landslide scarps and denuded gully sides.

Figure 1: Location of the Barranco de Tirajana basin
Over 60% of the Tirajana basin is covered by landslides, which makes difficult the application of GIS statistical methods to assess hazard from mass movements based on samples of landslides and their relationships with the terrain parameters. This constraint, together with the unavailability of geotechnical and groundwater data, necessary for applying deterministic methods, suggests considering an alternative approach.

A GIS indexing approach has been developed (Figure 3). Firstly, a database of the terrain parameters considered the most important determining factors of slope instability in the area has been compiled. Relevant data have been collected by means of aerial photo-interpretation, field surveys, satellite image processing and digitising of base maps.

Next, each parameter map has been classified into a number of significant classes based on their relative influence on mass movements. Weighting values have been subsequently assigned to each class (Figure 4). The relative importance of each terrain parameter as a determining factor of slope instability has been quantitatively determined by pairwise comparison using the so-called analytical hierarchy process (AHP) (Saaty, 1980). The integration of the various factors in a single hazard index has been accomplished by a procedure based on their weighted linear sum (Voogd, 1983) as follows:
\[ H = \sum_{j=1}^{n} w_j x_{ij} \]

where:

- \( H \): landslide hazard
- \( w_j \): weight of parameter \( j \)
- \( x_{ij} \): weight of class \( i \) in parameter \( j \)

The continuous landslide hazard raster map thus generated has been eventually thresholded into five hazard classes (Figure 5).

In multicriteria evaluation techniques the weighted linear sum is considered a compensatory procedure. The derived value of each alternative is primarily a function of the weight assigned to the parameters and, secondarily, of the weight of each parameter class (Barredo, 1996). In this approach, however, subjectivity is involved both in the assignment of weight values to classes and, although quantitatively less significantly, in the pairwise comparison of the parameters relevance. Expert knowledge is therefore required in this phase.

**Figure 3**: GIS and multicriteria evaluation modelling for landslide hazard assessment
Terrain parameters

1) Slope angle
Slope angle has been derived from a digital elevation model (DEM) following digitising of 1:5000 topographic maps. A raster layer of continuous angle values has thus been generated. Weights related to mass movement occurrence have been linearly assigned in the range from zero to 100, corresponding to the minimum and maximum slope angle value respectively. Highest weights have therefore been allocated to cliffs bounding the basin, secondary landslide scarps and gully sides (cf. Figure 4).

2) Proximity to streams
It has been assumed that the intermittent flow regime of the streams and gullies in the basin encompasses remarkable erosive processes, which, in turn, are the cause of intense, superficial mass wasting phenomena in areas adjacent to drainage channels. A 200-m area of influence across most channels has thus been considered. Weights within this buffer have been linearly allocated from zero to 200 m away from the streams. Areas beyond 200 m have not been regarded at risk.

3) Proximity to reservoirs
Instability hazard has also been considered from high pore-water pressures in the very fragmented landslide deposits making up the Tirajana reservoir banks following possible rapid drawdown. Weight values have been linearly assigned, decreasing from the average shoreline of the reservoir up to a distance of 200 m.

4) Landslide activity
Three classes of activity have been distinguished, namely active, dormant and inactive. Each class has been allocated maximum, intermediate and nil weight values respectively. In the absence of displacement records, except for the active Rosiana earth slide, it has also been considered as active the areas including inclined palm
Figure 4: Terrain parameters for landslide hazard assessment. Class weights are indicated in brackets.
trees and the sectors of landslide deposits showing tension cracks, both resulting from recent shallow movements. Active sites are also considered the cliffs, landslide scarps, very steep slopes and gully sides displaying evidence of rockfalls. Dormant landslides include the bodies or part of them not assigned to the class above. The remaining areas in the basin have been classified as inactive.

5) Material consolidation and fragmentation
Basic distinctions regarding the consolidation degree between bedrock (volcanic sequences), scree, talus deposits and alluvial and obstruction deposits have been made with respect to hazard. Additional classes have been considered based on the degree of fragmentation of the landslide deposits as a function of their reactivation stage. Weights have thus been assigned to eight classes of material, the highest corresponding to the scree partly covering some major ancient landslide and erosion scarps, while the lowest to the undisturbed volcanic deposits. No significant differences with respect to mass movement occurrence within the bedrock material have been observed.

6) Land use change
Land use change maps were derived from classification of multitemporal (1984-1995) Landsat TM data (Hervás et al., 1999). Highest weighting values were given to areas covered by irrigated crops on artificial terraces, recently abandoned agricultural land and the reservoir. Lower weights were assigned progressively to permanent soil cover, new and permanent soil cover with mixed vegetation, and new and permanent built-up areas and shrubby vegetation cover. Areas reforested with *pinus canariensis* were given a nil weight.

**Parameter weight assignment**
Although there exists a variety of procedures for establishing parameter weights, the AHP permits to evaluate the consistency of the parameter pairwise comparison. In this procedure a value comprised between 9 ("extremely more important than"), 1 ("equally important as") and 1/9 ("extremely less important than"), is assigned to each pair of parameters in a square reciprocal matrix by rating rows relative to columns. Weights of parameters are derived by taking the principal eigenvector of the parameter matrix. The procedure requires the principal eigenvector of the matrix to be computed to produce a best-fit set of weights. The procedure offers an advantage over other weighting methods, since it produces a consistency ratio (CR) which reveals the degree of consistency that has been used when developing the ratings. The CR indicates the probability that the matrix rating were randomly generated. Saaty (1980) suggests that matrices with CR greater than 0.10 should be re-evaluated. Table 1 shows the application of the AHP to the parameters selected.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Weight</th>
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<tr>
<td>Slope angle</td>
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<tr>
<td>Proximity to reservoirs</td>
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<td>Landslide activity</td>
<td>0.33</td>
</tr>
</tbody>
</table>

**Table 1:** Parameter weight assignment based on the analytical hierarchy process (CR = 0.02)

**Figure 5:** Landslide hazard map of the Barranco de Tirajana basin
Discussion of results

As a result of the analytical hierarchy process, terrain parameters such as landslide activity and slope angle largely outweigh others like proximity to streams and land use change. As a consequence, the highest landslide hazard, as derived from the GIS-based analysis, corresponds to rockfall occurrence on cliffs and on scree and some talus deposits partly covering primary landslide headwalls. A number of sectors on gully sides in the most recent generation of landslides also show high hazard of instability, most likely in the form of shallow movements and small falls of the uncovered rock fragment deposits during heavy rainfall periods. Most of the ancient large landslide bodies do not appear to be subject to a major reactivation though. Some human activities, especially crop irrigation on terraced hillsides, also suggest a moderate susceptibility to small shallow displacements. No hazard from large, deep-seated landslides could be inferred, mainly because of the lack of subsurface information in most of the basin. However, such hazard is believed to be very low.

Conclusions

GIS assisted by multicriteria evaluation techniques for terrain parameter indexing has revealed as a relatively simple and cost-effective approach for assessing landslide hazard at medium scales when costly geotechnical and groundwater data are not available. Such approach has also proved a valid alternative to direct hazard mapping methods and, especially, to statistical methods in an area like the Barranco de Tirajana Basin, where the dominant landslide occurrence prevents the use of robust sampling strategies.

The main drawback of this approach however lies in the subjectivity involved mainly when assigning weights to the parameter classes. Nevertheless, the allocation of parameter weighting values can be helped by the analytical hierarchy process, which permits a quantitative evaluation of each parameter based on the analyst expertise.

Acknowledgements

This work is part of the RUNOUT project, funded by the European Commission under contract no. ENV4-CT97-0527 with DG XII, within FP4 Environment and Climate Programme. The authors would also like to thank A. Quintana, F. Santana and F.J. Martín, of the University of Las Palmas, for their contribution to map digitising.
References


