FIRST DRAFT COMMUNICATIONS DEPT - COMPOSER DTP service

JAG • Volume 2 - Issue 1 - 2000

Comparing heuristic landslide hazard assessment techniques using GIS in the Tirajana basin, Gran Canaria Island, Spain

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KEYWORDS: landslide hazard, GIS, Tirajana Basin

ABSTRACT

As part of the EU Environment and Climate Programme's RUNOUT project dealing with the modelling of large-volume landslides, a GIS database was compiled and used to generate mass movement hazard maps at a medium scale (1:25,000) in a high-relief area in central Gran Canaria Island, Spain. The Barranco de Tirajana study area is a 49 km2 large depression that is semi-oval in plan, 11 km long and 6.5 km wide. Its base presents a very irregular topography and it is almost completely enclosed by large rock scarps, up to 350 m high, with total altitude differences reaching 1600 m from the lowest part of the Barranco de Tirajana river to the upper scarps. The Barranco de Tirajana depression is composed of a series of large landslide masses, derived from gravitational sliding of lava flow and volcanic breccia sequences. The landslides are believed to have originated during intensive erosive periods during the Quaternary, as a consequence of the rapid deepening of the central ravine. These primary large landslide bodies have undergone a number of reactivation episodes, from the Middle Pleistocene to the present, as well as retrogressive enlargement of the depression. Currently the most active processes are rockfalls, and reactivation of the landslide toe areas, due to further undercutting by the streams. In order to evaluate the present mass movement hazard, a GIS-based study was carried out using two different types of knowledge-driven approaches: a direct method and an indirect method. In the direct method very detailed geomorphological mapping was carried out, using uniquely coded polygons, which were evaluated one-by-one by an expert to assess the type and degree of hazard. The indirect method followed an indexing approach. Parameters including slope angle, landslide activity, landslide phases, material, proximity to drainage channels and reservoirs, and land use change were combined using multi-criteria evaluation techniques.

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 by, among others, 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 & Van Westen [1996]. Most direct methods include landslide inventories and heuristic analysis, in which the hazard assessment is made by the earth scientist using site-specific knowledge obtained through photo-interpretation and fieldwork.

In the literature three main types of landslide hazard assessment techniques are used: deterministic, statistical and heuristic approaches. Deterministic approaches, based on stability models, can be very useful for mapping hazard at large scales, for instance for construction purposes. Deterministic landslide hazard maps normally provide the most detailed results, expressing the hazard in absolute values in the form of safety factors, or the probability of failure given a set of boundary conditions for groundwater levels and seismic acceleration. However, deterministic models require the availability of detailed geotechnical and groundwater data, and they may lead to oversimplification if such data are only partially available.

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 requires the collection of large amounts of data to produce reliable results. These methods are most suitable to predict future landslides at medium scales (1:25,000 to 1:50,000). Each landslide type should be analysed separately, since it is related to a different combination of input factors. The method is less suitable in the Barranco de Tirajana area, where the hazard is not so much related to the occurrence of new landslides, but to the reactivation of existing ones, as well as to rockfalls. Furthermore, since each reactivation may be controlled by a unique set of conditions, the use of statistical methods is less desirable, since they will normally lead to generalisation.

The approach selected as most suitable for the Barranco de Tirajana area was the heuristic, or expert-driven approach, in which a geomorphological expert decides on the type and degree of hazard for each area, using either a direct mapping or indirect mapping approach. In a direct mapping approach the degree of hazard is mapped directly in the field, or is determined after the fieldwork on the basis of a detailed geomorphological map. The advantage of this method is that each individual polygon outlined on the map can be evaluated separately, based on its unique set of conditions. It is, however, a more time-consuming method that depends also to a large degree on the expertise of the geomorphologist. The indirect heuristic approach utilises data integration techniques, including qualitative parameter combination, in which 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.

As part of the EU Environment and Climate Programme's RUNOUT project, it was decided to test and compare a number of GIS-based landslide hazard assessment approaches at a medium scale (1:25,000) in the Barranco de Tirajana basin, a high-relief area in central Gran Canaria Island, Spain. The landslides in this area have been studied in detail by the University of Las Palmas de Gran Canaria (ULPGC) [Lomoschitz & Corominas, 1997a,b].

STUDY AREA

The Barranco de Tirajana basin is located in central Gran Canaria Island, Canary Islands. It has an extension of 49 km^2, 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 & Corominas, 1997a]. It makes up a deep oval-shaped amphitheatre, bounded by very steep slopes and cliffs reaching up to 350 m in height, which are remnants of ancient, large landslide scarps (Figure 2). Altitudes range from 1949 m in the northernmost sector to 300 m in the southern end, with differences of up to 900 m on slopes next to the basin boundaries. Two rivers drain the area. The main drainage network is formed by the Barranco de Tirajana stream and its tributaries, all of which have intermittent or seasonal flow. The SW part is drained by the Barranco de Fataga stream. Average annual rainfall ranges from 370 mm at the bottom of the basin to 890 mm near the cliff tops, although much of it is concentrated within a short period of days. It is believed that rainfall is responsible for the major landslide reactivations that have occurred in the last century [Lomoschitz & Corominas, 1997b].

The depression is filled with a number of large landslide complexes, all of which have different stages of reactivation. Figure 2 provides an overview of the SE part of the depression, with large landslide complexes around the village of Santa Lucía. This view was produced using a Digital Elevation Model of the area, combined with an orthophoto and the landslide map using GIS. 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 the area's proximity to a major beach resort.

CREATION OF A GIS DATABASE

In order to utilise the heuristic landslide hazard approaches in the Barranco de Tirajana area, an extensive GIS database was generated containing topographical, geological and geomorphological data.

TOPOGRAPHICAL DATA

The digital contour data available were derived from a series of 1:5000 scale contour maps, in AutoCad DXF format, with a contour interval of 5 metres. After joining the data from the various sheets into a single file, a Digital Elevation Model with a pixel size of 5 metres was generated, as well as a series of derivative maps, such as a hillshading map, a slope angle map and a slope direction map. A set of 1:18,000-scale colour aerial photos was scanned and converted into orthophotos, for display purposes (see Figure 2) and in order to facilitate the con-

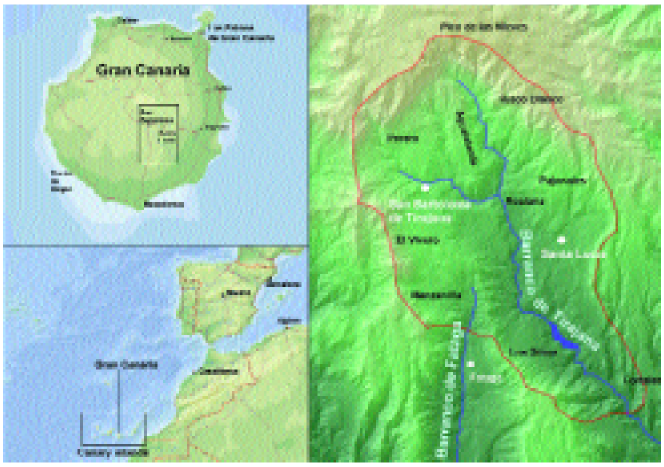

FIGURE 1 Location of the Barranco de Tirajana basin.

version of the photo-interpretations into the topographical map.

GEOMORPHOLOGICAL MAPPING

The geomorphological mapping of the area of Barranco de Tirajana (BdT) was based on the interpretation of the set of colour aerial photos. Homogeneous geomorphological terrain units, representing slope facets, or individual landforms were delineated and mapped as individual polygons. Every polygon received a unique identifier. In total 720 individual polygons were outlined in the study area. During the photo-interpretation and subsequent fieldwork, every uniquely identified unit was described according to 7 different parameters:

- Geomorphology
- Material
- Landslide Complexes
- Reactivation Phase of Landslide Complexes
- Landslide Activity
- Steepness
- Hazard

These descriptions were made using a set of standard legends and a checklist, both during the photo-interpretation as well as during the fieldwork. After extensive field checking, the polygon map was digitised, and the checklist data was stored in a related attribute table. The unique identifier map can be reclassified according to any of the parameters in the related attribute table, and 7 attribute maps were generated.

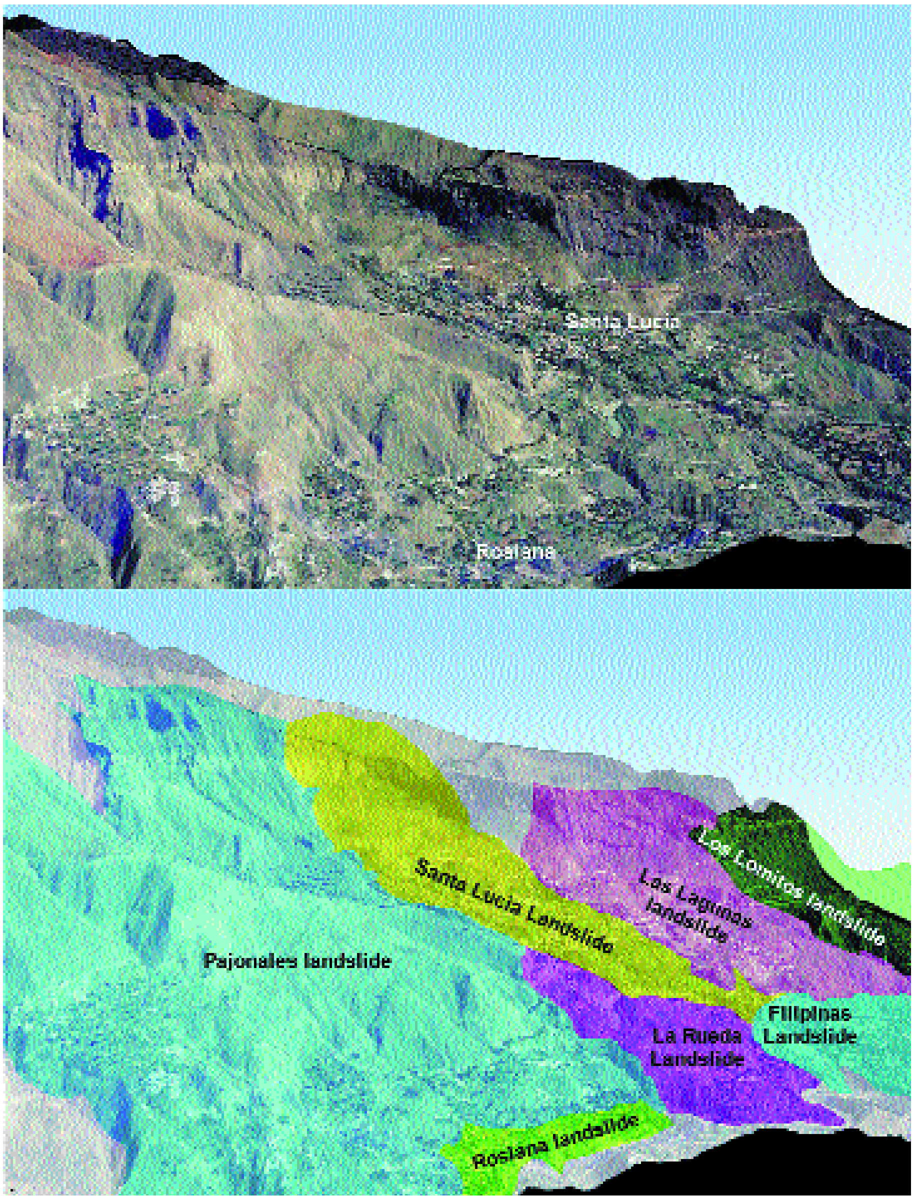

FIGURE 2 Above: Three-dimensional view of the Rosiana-Santa Lucía area, generated using an orthophoto and a Digital Elevation Model. Below: Same three-dimensional view in which landslide complexes are indicated.

GEOMORPHOLOGICAL UNITS

The geomorphological map and legend are shown in Figure 3. Four main types of geomorphological units were distinguished: alluvial landforms, denudational landforms (hilltops, slopes, valleys, niches), scree slopes and rockfall areas, and landslide areas.

The landslides, scree slopes and rockfall deposits were not included as part of the denudational landforms because of their large extent and importance in the morphology of the area. The landslides are the cause of the formation of the Barranco de Tirajana depression and the huge scree slopes are the result of the further erosion of the landslide scarps. Therefore, polygons mapped as denudational units were only those that were not generated by landslides directly but by other processes such as stream incision, or those that cannot be classified as a single component of a landslide, such as the main scarp of the depression. As can be seen from Figure 3, the Barranco de Tirajana actually consists of two separate depressions, with two separate outlets that are connected in the upstream area.

MATERIAL TYPES

A large part of the bedrock formations of Gran Canaria can be found within the Barranco de Tirajana area, outcropping basically in the steep cliffs and the deepest valley incisions. In the Geological Map of Spain (Mapa Geológico de España, 1992), the magmatic periods have been grouped in three large cycles: Cycle I, Cycle II (Roque Nublo) and Cycle III (Post Roque Nublo). Cycle I is

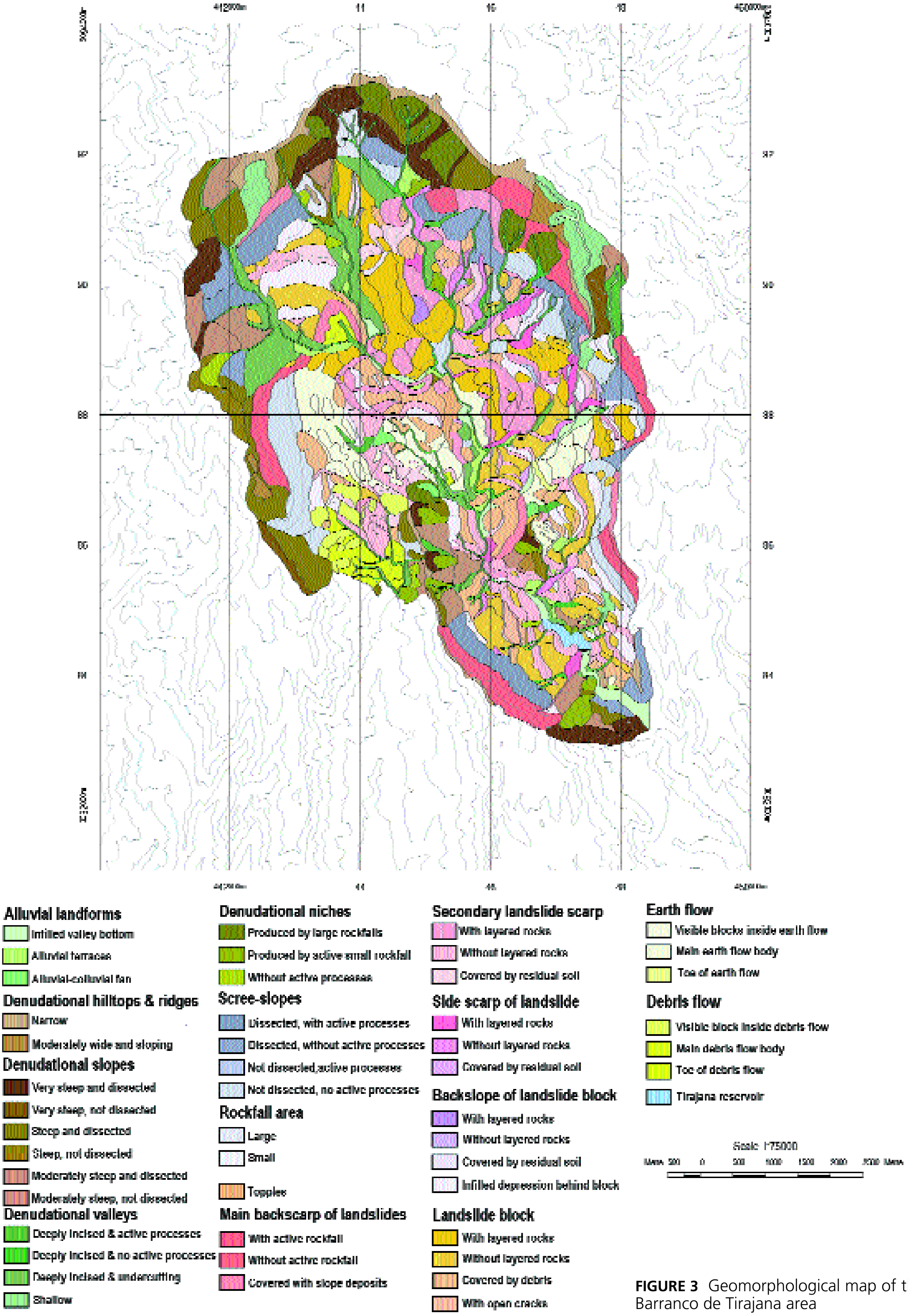

FIGURE 3 Geomorphological map of the Barranco de Tirajana area

mostly characterised by lavas and ignimbrites with trachytic and phonolitic composition. Rocks of Cycle II are found extensively in the area. The succession of basaltic, basanitics and tephritic lava flows of this cycle are visible in the main scarp of the depression as well as in the Roque Nublo breccia, which are easily recognisable due to their bright colour. Phonolitic domes, developed during the last stage of this cycle, are also present in the area. Risco Blanco, located in the main scarp of Barranco de Tirajana, is a characteristic example of this feature with a remarkable whitish colour. Cycle III is more alkaline than the others, but volumetrically smaller. Nepheline, basanitic and tephritic lavas covered the already existing strong relief.

On the basis of the geological and geomorphological mapping, the materials present in the study areas have been classified in four categories (see Figure 4):

- Bedrock
- Landslide deposits
- Slope deposits
- Alluvial - colluvial deposits.

The western scarp of the depression is completely covered by rocks from Cycle I, mainly phonolitic lavas. The older ignimbrites of this cycle are present along the bottom of the ravines, as a result of river erosion. Rocks from Cycle II Roque Nublo are present in the eastern scarp, and basaltic lavas and breccias are visible throughout the scarp. In the southern part the basanites of Cycle III appear, extending inside the valley till Las Fortalezas. The landslide deposits are related to the bedrock material from which they are derived. Some landslides consist mainly of rocks that were not highly deformed during the movement and still have the original features, such as the typical layering of the volcanic rocks. But in most of the landslides the original rocks were destroyed during the mass movement, and have since been reduced to debris of different sizes. Slope deposits are widely present in the area. Scree slopes and rockfall areas are very common below the main scarps of the depression as well as below major reactivation scarps and in steep river incisions.

LANDSLIDE COMPLEXES

Lomoschitz & Corominas [1997a] have distinguished at least 28 landslides in the Barranco de Tirajana, which can be grouped into 20 different landslide complexes (see Figure 5), some with surfaces exceeding 400 hectares and with volumes of over 1 km^3. Main landslide types include rockslides, debris slides, earthslides, debris flows and rockfalls. Several generations of movement since the

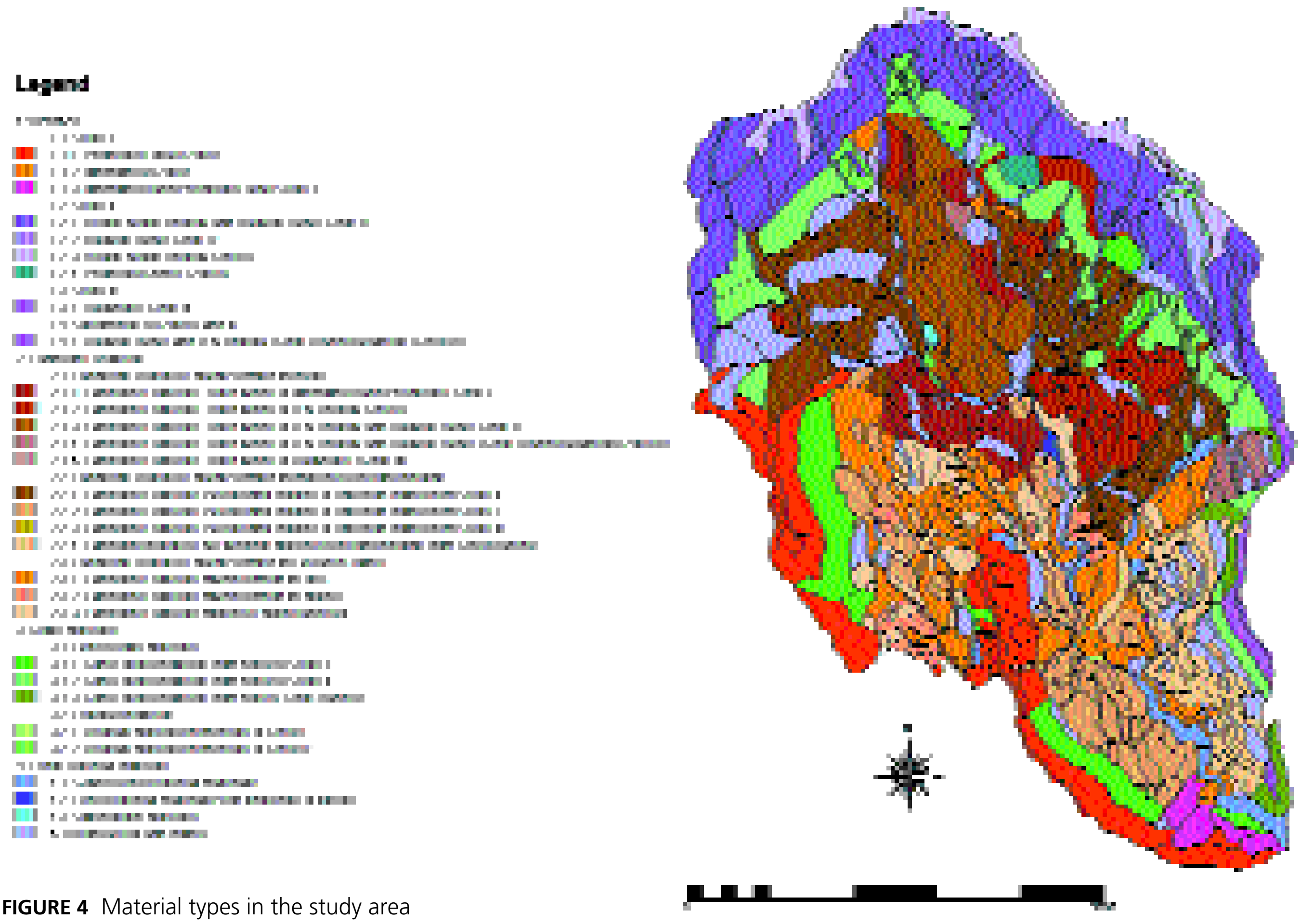

FIGURE 4 Material types in the study area

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 have 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 earthslide that seriously affected the village of Rosiana in 1956 after intense rainfall [Lomoschitz & Corominas, 1997b]. Active rockfalls have been observed on cliffs, landslide scarps and denuded gully sides.

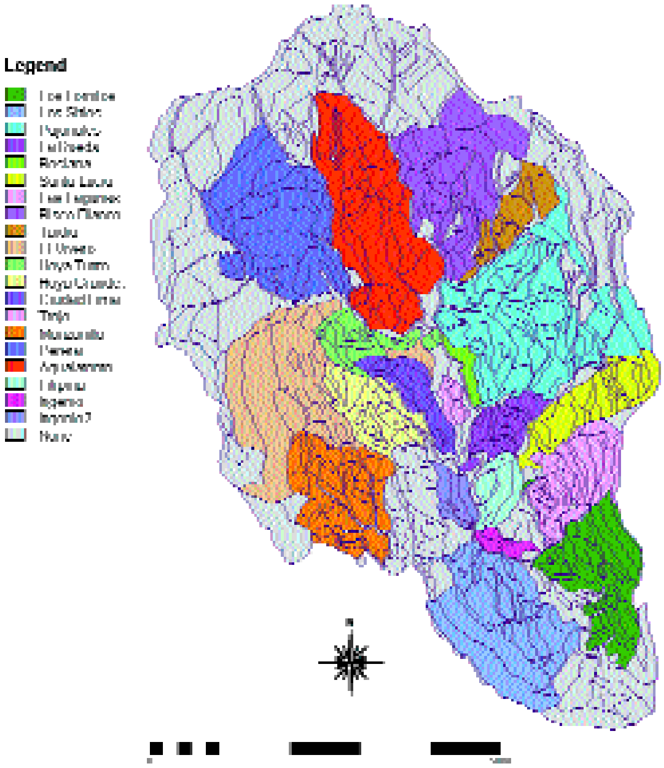

FIGURE 5 Landslide complexes within the Barranco de Tirajana area

LANDSLIDE PHASES

The landslides were also classified according to the various reactivation phases. As can be seen from Figure 6, some landslides may have up to 10 different reactivation phases. Before the occurrence of the landslides, the area was divided into two lithologically and morphologically different zones. The western sector was occupied by the rocks from Cycle I, and its relatively high altitude formed a topographic barrier for the further emissions during Cycles II and III. The second area in the north and east was formed by rocks from Cycle II and later on by the basanitic lavas of Cycle III, which occurred simultaneously with the first stages of the depression, as evidenced by lavas reaching into the Barranco de Tirajana valley, downstream of the landslide area. Initially the area was divided into two catchments, the Barranco de Tirajana in the east, and the Barranco de Fataga to the west. When the erosion of the former stream reached the level of tuffs and ignimbrites of Cycle I, the first landslides took place. In the following section an overview is presented of the chronological sequence of landslide events.

LOS LOMITOS LANDSLIDE

Among the oldest landslides in the area is the rotational *Los Lomitos* landslide (see Figure 6), which covered an extensive area, including the part that is now covered by *Las Lagunas* landslide, where a remnant ridge of landslide material belonging to *Los Lomitos* can still be found. Severe erosion has taken place since the occurrence of the landslide. The failure plane is now exposed rather high in the ravine of the Barranco de Tirajana. Although most landslide blocks are very eroded, some landslide features such as scarps, blocks and depressions are still visible. Some reactivation phases have also taken place.

LOS SITIOS LANDSLIDE

Los Sitios landslide could have occurred simultaneously with *Los Lomitos* landslide, on the other side of the river incision. The failure plane in ignimbrites of Cycle I can be found quite high above the present day level of erosion of the Barranco de Tirajana. Large blocks of different reactivation phases are visible, formed by disintegrated material of Cycle I, mainly phonolitic lavas. *Los Sitios* is classified as a rotational landslide. Although it has been classified as being very old, the presence of cracks in the frontal part of some blocks indicates that reactivation of this landslide is taking place.

PAJONALES LANDSLIDE

When the erosion of the Barranco de Tirajana reached further upstream, one of the largest landslides in the study area took place: the *Pajonales* landslide (see Figures 2 and 6), located in the central part of the area. During the initial phases of the landslide, huge blocks formed by rocks from Cycle II were moved as rotational blocks. Some of these blocks show clear back-tilted layers of basaltic lavas and Roque Nublo breccia. The frontal parts of the landslide were reactivated several times, resulting in a step-like morphology. The secondary scarps of different reactivation phases present active rockfall.

LAS LAGUNAS LANDSLIDE

Las Lagunas landslide took place as a result of the strong undercutting by the Tirajana river, which was located at that time more to the east of its present location. Apart

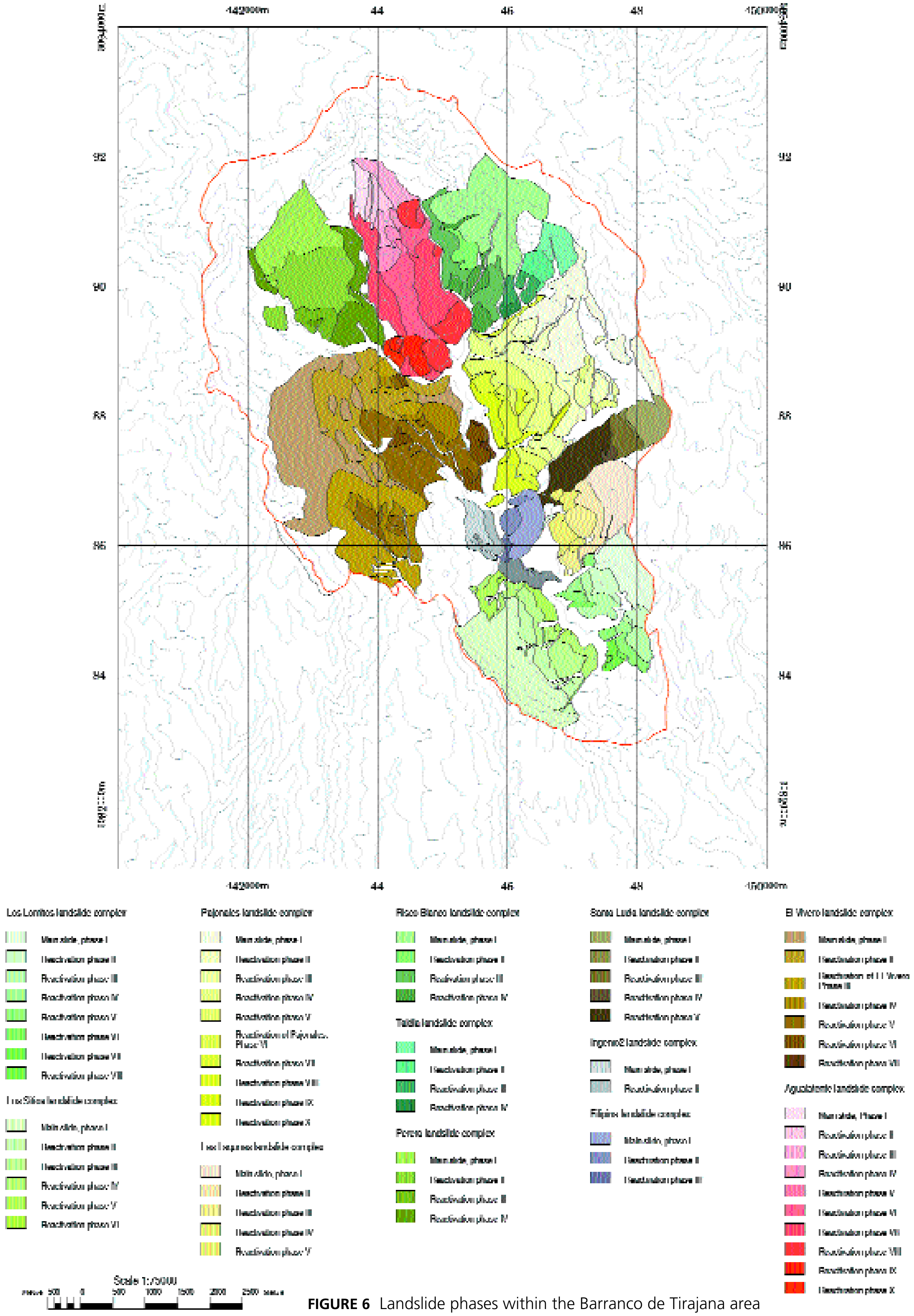

FIGURE 6 Landslide phases within the Barranco de Tirajana area

from rocks from Cycles II and III, the landslide also involved old material of the *Los Lomitos* landslide. The failure plane is in the ignimbrites of Cycle I. The *Las Lagunas* landslide has had some reactivation phases and the landslide features, such as the blocks, scarps and depressions, are still clearly visible. The frontal part of *Las Lagunas* has been reactivated and an earth flow is recognisable with some massive blocks in it.

LA RUEDA LANDSLIDE

La Rueda landslide is a reactivation of the *Pajonales* landslide. The main scarp shows the composition of the blocks of *Pajonales*, which consist of a typical mixture of unsorted debris from Cycle II. At the beginning of its development, *La Rueda* was a rotational landslide, as evidenced by slump blocks with depressions behind them. The *La Rueda* landslide might actually have been connected with the *Las Lagunas* landslide, as the main headscarps of both are exactly in line. In the centre the connection is lost due to the later occurrence of the *Santa Lucía* landslide. The frontal part of the *La Rueda* landslide developed into a debris flow, and the remnants of this can now be found at the other side of the Tirajana ravine, indicating the posterior erosion.

RISCO BLANCO AND TAIDIA LANDSLIDES

The *Risco Blanco* and *Taidía* landslides took place just after the *Pajonales* landslide along the eastern scarp of the depression. These two landslides are rather difficult to outline due to the extensive coverage of scree deposits. However, back-tilted layers are exposed on the slopes of these landslides. Both landslides happened in rocks from Cycle II, and the underlying rocks from Cycle I are now exposed in the river valley.

SANTA LUCÍA LANDSLIDE

The *Santa Lucía* landslide is younger than the *La Rueda* and *Las Lagunas* landslides, since it remobilised the central part of the old landslide, which was formed by the combination of the other two. The *Santa Lucía* landslide is quite complex, showing typical features of a rotational landslide in the upper part, but turning into a large earth flow in the downslope part. Parts of the *Santa Lucía* landslide are still believed to be active, as evidenced by cracks in some of the buildings in the village of Santa Lucía.

INGENIO AND FILIPINA LANDSLIDES

These landslides were generated on the sides of the Tirajana valley, after it had made its main gorge more towards the west with respect to the formation of the *Las Lagunas* landslide. These landslides occurred in ignimbrites from Cycle I. The *Ingenio* landslide is still active in the form of rockfalls coming from the scarp. *La Filipina* is a relatively small landslide formed in the northwestern slope of the hill covered by old landslide deposits from *Las Lagunas*. It occurred in two main phases. Debris from the rocks from Cycle I and the old landslide deposits probably form the body of this landslide. Both landslides are covered by residual soil and have plenty of vegetation.

PERERA LANDSLIDE

All of the landslides discussed so far occurred in the Tirajana river valley. At the time there was still an elongated watershed divide between the Barranco de Fataga and the Barranco de Tirajana. Although the latter had more severe erosion, landslides also occurred in the valley of the Barranco de Fataga. The first of these is believed to have been the *Perera* landslide. This landslide too shows typical features of a rotational landslide. The backscarp is very clear as well as the blocks and the infilled depressions behind the blocks. It appears that the movement was violent, disintegrating the rock to blocks without creating clear layering features.

EL VIVERO

El Vivero landslide is the largest landslide complex in the study area, having a massive scarp and typical scree slopes with material of Cycle I. This landslide occurred on the western slope of the old Fataga catchment (which extended much further to the north at that time) and drastically changed the entire morphological situation in the study area.

The original *El Vivero* landslide must have been a very violent movement, which ran downslope, overriding the old Fataga river valley and crashing into the narrow ridge that formed the watershed divide between the Fataga and Tirajana rivers. At the central point of collision, this ridge was broken up and the frontal part of the landslide pushed part of this ridge several hundred metres further, where it now forms the opposite slope of the *Rosiana* landslide. Along the southern margin the landslide reached as high as the watershed divide, as can be clearly seen from the outcrops near the top. The main body of this landslide was translational, turning into flow-like forms at the downslope margins. *El Vivero* has suffered many further reactivations, which are in themselves other landslide complexes: *Hoya Grande*, *Hoya Tunte*, *Ciudad Lima*, *Manzanilla* and *Trejo*.

AGUALATENTE

One of the effects of the occurrence of the *El Vivero* landslide was the blocking of the upper catchment area of the Fataga stream. This led to the creation of a temporary lake, as evidenced by lake deposits found on the southern part of the *Perera* landslide. However, this situation did not exist for very long, and soon there was an opening along the northern margin of the *El Vivero* landslide, where it had destroyed the narrow watershed divide. In this way a large part of the upper Fataga catchment was captured by the Tirajana river. The rapid erosion of this valley triggered the destruction of the remaining watershed divide to the north, forming the *Agualatente* landslide.

The *Agualatente* landslide was a combination of a rotational and a translational landslide. It presents a series of blocks, still in the form of a ridge, with movement both along the axis of the ridge as well as to the sides. The movement was very slow and gradual, preserving the original structure of the rocks. *Agualatente* contains rocks from Cycles II and III, whereas ignimbrites of Cycle I are present along the base of the landslide. Most of the landslide blocks appear stable, except for the frontal parts, which have active rockfall areas.

LATEST REACTIVATIONS

The latest reactivations in the area can be found in the landslide complexes of *Pajonales*, *Las Lagunas* and *El Vivero*. For example, the *Manzanilla* debris flow is a reactivation phase of the *El Vivero* landslide, which had caused a temporary damming of the Fataga river. Another important series of reactivations of the *El Vivero* landslide is the *Hoya Tunte* landslide complex, consisting of some reactivation levels at different elevations. The main scarp is located in a huge displaced block, which still maintains the original features of the phonolitic lavas from Cycle I. After the first movement of *Hoya Tunte*, a number of other reactivations took place, some of which are still dangerous due to rockfalls.

The most recent activity in the study area took place in February 1956, when the frontal part of the *Pajonales* landslide, also known as the *Rosiana* landslide moved forward and destroyed several houses and a bridge. This event coincided with a period of heavy rainfall (272mm in 24 hours), which is exceptional in the normal atmospheric regime of the region.

LANDSLIDE ACTIVITY

One of the main characteristics used to determine the hazard degree of a certain unit was the activity of denudational processes (see Figure 7). Three categories were included, and the classification of units within categories was based on direct observation of each unit in the field.

- Active
- Partially Active
- Inactive.

The classification *Inactive* was given to units in which no active mass movement processes are recognisable. These units are often covered by residual soil and vegetation and are commonly stable landslide blocks or old scree slopes. Most of the units within the category *Active* show clearly recognisable evidence of active mass movement. This category includes not only the active reactivation parts of the landslides units, but also all of the units in which some kind of hazardous process is currently taking place, such as rockfall, erosion, etc. Units were classified as Partially Active if vague evidence of active mass movements was found in only a part of the included area.

DIRECT HAZARD MAPPING

Two different approaches were used in the generation of hazard maps for the Barranco de Tirajana basin: direct hazard mapping and indirect hazard mapping using an expert-based weighting method. In order to carry out the direct hazard assessment of the area, all the geomorphological units represented as unique polygons were evaluated one-by-one in the field, and a hazard class was assigned to each polygon in the attribute table. The actual hazard map was made by classifying the unique identifier polygons with the *hazard* attribute. The most important characteristics taken into account to determine the degree of hazard in a certain unit were:

- Evidence of recent activity, such as bare scarps, cracks, fresh rockfall deposits, etc. (see Figure 7) ;
- Geomorphological setting of the unit (see Figure 3);
- Type and condition of materials (see Figure 4);

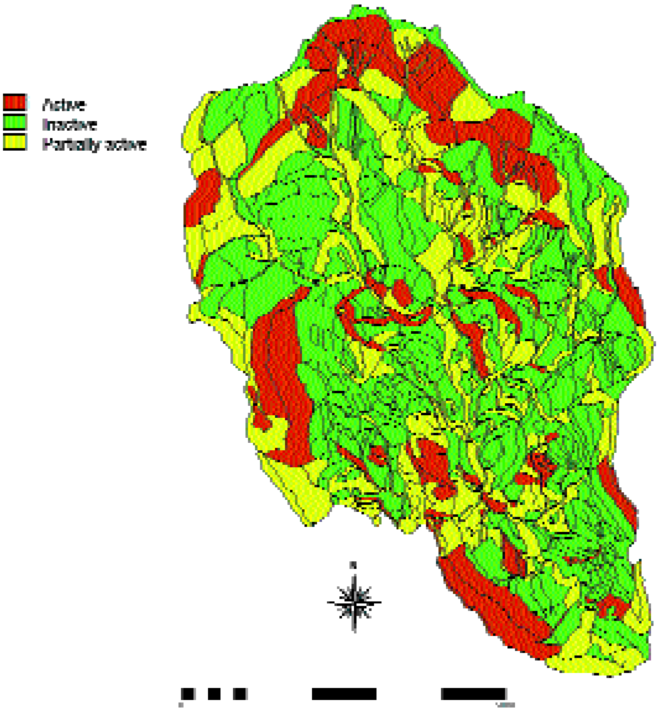

FIGURE 7 Mass movement activity within the Barranco de Tirajana area

- Slope steepness;
- Adjacency of other units that might generate active processes reaching into the neighbouring unit.

Other criteria were also taken into account, such as the remarks made by inhabitants of the area, historical records, the presence of damaged infrastructure, the presence of stabilisation works, and information from the literature. On the basis of these criteria each polygon was evaluated and a hazard class was assigned according to the following four classes:

- *Very low hazard.* In these areas no destructive phenomena (landslides, rockfall, inundation,etc.) are expected to occur within the coming years.
- *Low hazard*. In these areas no destructive phenomena (landslides, rockfall, inundation,etc.) are expected to occur within the coming years, assuming that the land use situation remains the same. Inadequate construction of infrastructure or buildings may lead to problems, however.
- *Moderate hazard*. In these areas there is a moderate probability that destructive phenomena that could damage infrastructure or buildings will occur within the coming years. However, the damage is expected to be localised and can be prevented by relatively simple and inexpensive stabilisation measures.
- *High hazard*. In these areas there is a high probability that destructive phenomena will occur within the coming years. These events are expected to damage infrastructure or buildings considerably. Construction of new infrastructure or buildings is not advised in these areas, at least not until a detailed study has been done.

The hazard map is shown in Figure 8. The percentage of the total area that is classified as very low and low hazard is fairly large (35 percent and 31 percent, respectively), whereas the moderate and high hazard areas (14 percent and 20 percent of the area) occupy mostly the steep slopes throughout the area.

The probability of new landslides occurring with similar dimensions as those that formed the Barranco de Tirajana depression is considered to be very low. Most of the old landslide complexes do not show any signs of current reactivation. However, real hazards are presented in the area by the rockfalls related to the steep scarps, the occurrence of small and rapid translational landslides on steep slopes, the occurrence of earth flows as well as the reactivation of the frontal part of some landslide blocks.

Rainfall is the most important factor that influences the occurrence of landslides. According to the people living in the area, the roads of the region can be quite dangerous during the rainy season and sometimes they have been closed because of imminent danger. Although such events occur seldom in the region, it is worthwhile to point out that rockfalls in the steep scarp areas can take place throughout the year.

The areas subjected to rockfall hazard are mainly located along the main scarp of the depression, both in the western scarp with rocks from Cycle I and in the eastern one, with rocks from Cycles II and III. This kind of rockfall has been very active in the past, which is evidenced by the large rockfall deposits, located especially in the north-eastern part. However, some of the landslide scarps also pose a serious rockfall hazard, such as the ones from *Pajonales* and *Hoya Tunte*.

Another type of hazard is associated with the occurrence of rapid, translational landslides, which occur mostly in loose deposits in the secondary and side scarps of the landslides and in the sides of steep valleys. Some examples of these are the scarp of *La Rueda*, or the frontal part of the *Agualatente* landslide.

The areas with high hazard due to earth flows are all located in the landslide complexes of *Rosiana*, *Hoya Grande, Santa Lucía* and in the frontal part of *Las Lagunas*. Certain areas in the *Hoya Grande* landslide were also classified as having a high or moderate hazard of earth flows, as well as some parts of the *Santa Lucía* earth flow. This earth flow is densely populated and covered by vegetation. However, some features have been recognised that show the possible instability of these materials, such as cracks found in the church and some houses which are located on an old scarp in the village of Santa Lucía.

Reactivation of old landslides has been observed in a few cases. One of these is in the *Los Sitios* landslide, where a series of open cracks have been found. The frontal part of *Las Lagunas* landslide is considered to be reactivated as well. A thick mixture of soil and debris that shows some cracks, small folds and elongated blocks is gently sloping towards the ravine. This area might be active during rainy periods, when the infiltration of water takes place.

INDIRECT HAZARD MAPPING

Over 60 percent of the Tirajana basin is covered by landslides. This makes it difficult to apply statistical methods to assess landslide hazard, since no new landslides with sizes similar to existing ones are expected to occur in currently landslide-free areas. This constraint, together with the unavailability of geotechnical and groundwater data necessary for applying deterministic methods, made it necessary to consider an alternative indirect hazard mapping approach.

A GIS indexing approach was therefore developed. First, the database explained before was used to generate a number of terrain parameter maps, considering the most important determining factors of slope instability in the area. Next, each parameter map was classified into a number of significant classes based on their relative influence on mass movements. Weighting values were subsequently assigned to each class. The relative importance of each terrain parameter as a determining factor of slope instability was 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 was 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 was eventually divided into four hazard classes (see Figure 9).

In multi-criteria evaluation techniques, the weighted linear sum is considered to be a compensatory procedure.

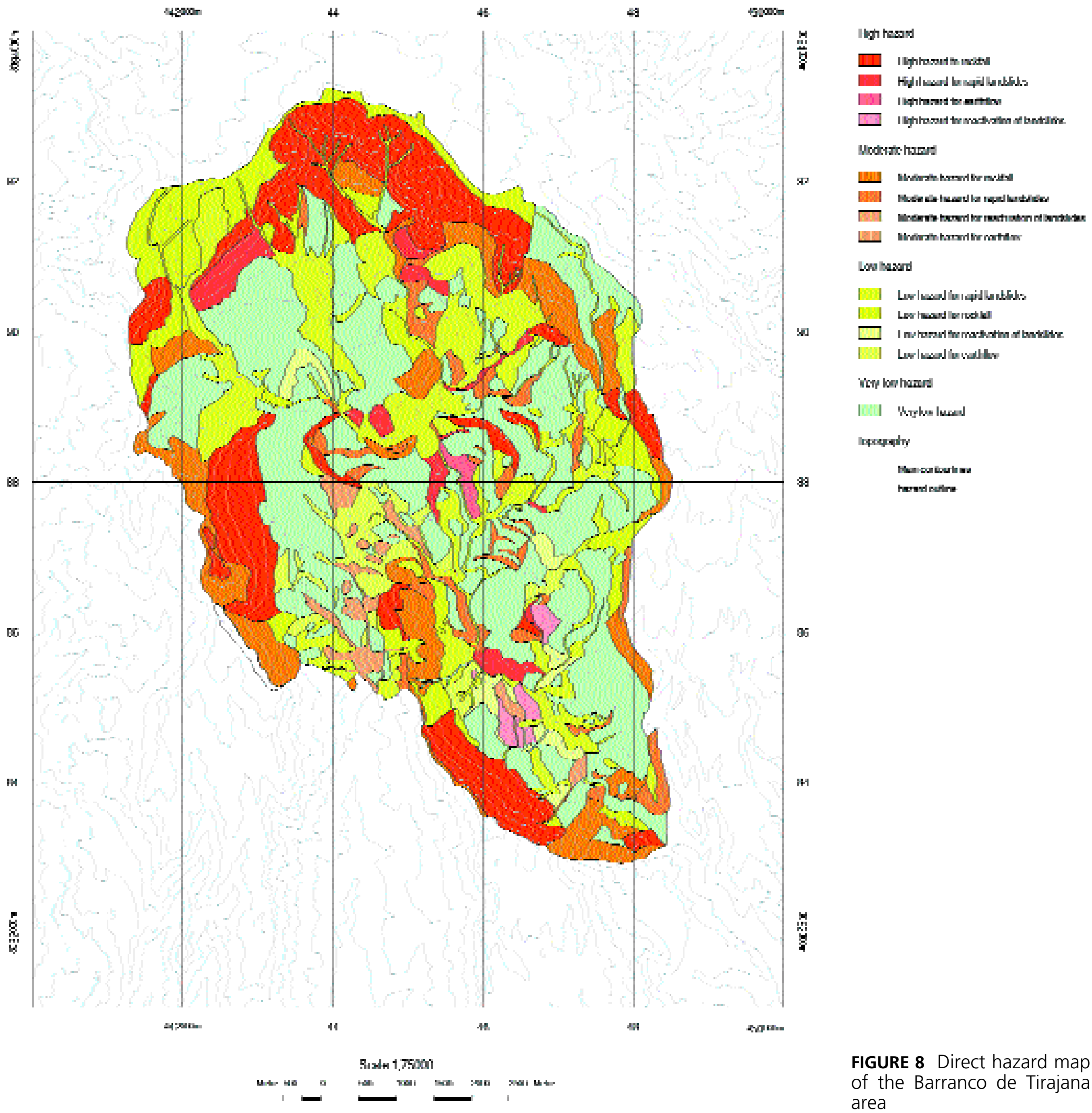

FIGURE 8 Direct hazard map of the Barranco de Tirajana area

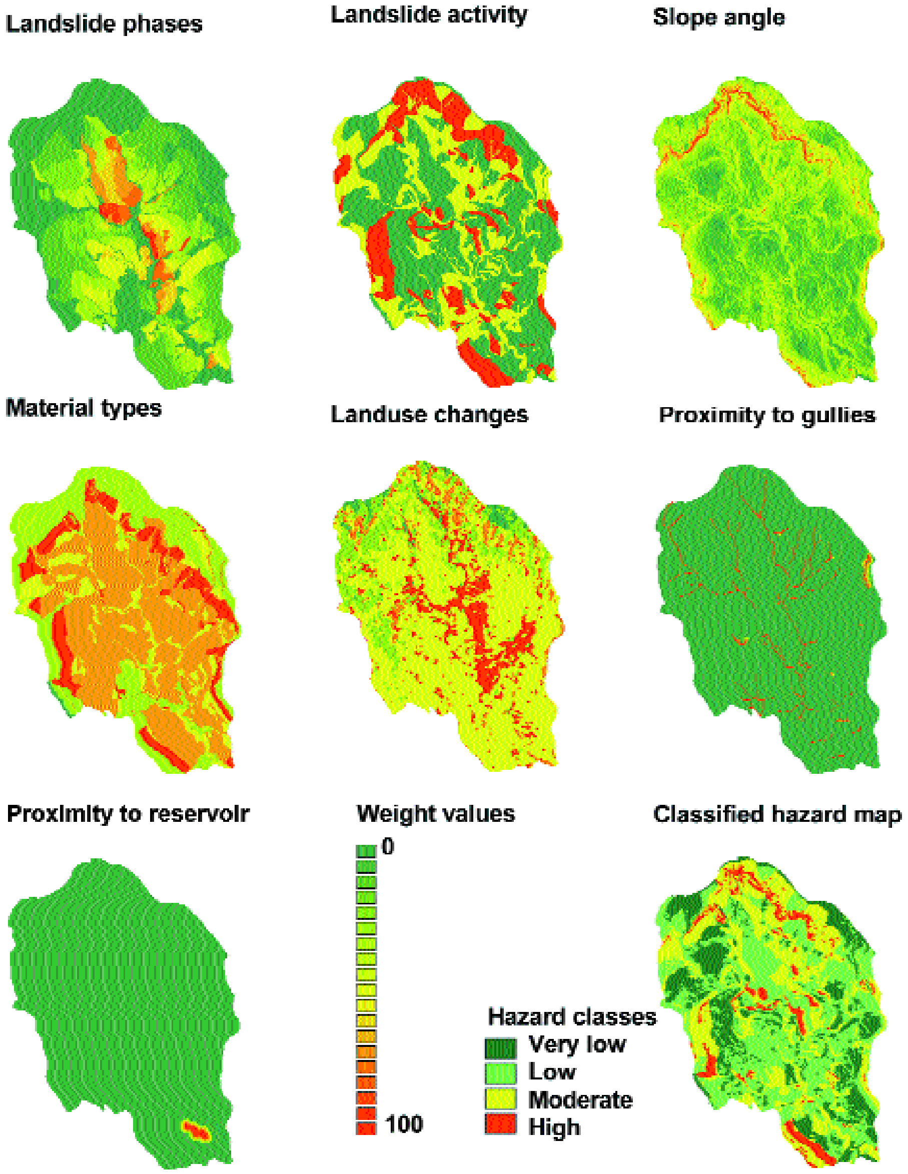

FIGURE 9 Factor maps used in the GIS analysis. The resulting classified hazard map is shown on the bottom-right

Landslide activity
Three classes of activity were distinguished, namely active, partially active and inactive (see Figure 7). Each class was allocated maximum (100), intermediate (50) and zero weight values respectively. In the absence of displacement records, except for the active *Rosiana* earthslide, areas including inclined palm trees and the sectors of landslide deposits showing tension cracks (both resulting from recent shallow movements) were considered as active. Active sites also include the cliffs, landslide scarps, very steep slopes and gully sides displaying evidence of rockfalls. Partially active landslides include the bodies or parts not assigned to the active class. The remaining areas in the basin were classified as inactive.

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

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 significant, in the pairwise comparison of the parameters' relevance. Expert knowledge is therefore required in this phase.

TERRAIN PARAMETERS

Landslide phases
The 10 landslide phases as indicated in Figure 6 were weighted from 10 to 100. To this end, and because of its spatial and temporal relationship with the surrounding landslide complexes, phases I, II and III of *La Filipina* could also be reinterpreted as VI, VII and VIII of *Santa Lucía* and *Las Lagunas* landslides, and therefore assigned weights of 60, 70 and 80 respectively.

Material types
The material map as indicated in Figure 4 was reclassified into 4 units: bedrock (with a weight of 30), alluvial-colluvial deposits, residual soils (weighted as 50), landslide deposits (with a weight of 70) and scree/rockfall material (with a weight of 100).

Land use changes
Land use change maps were derived from classification of multi-temporal (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 zero weight.

Proximity to gullies

It was 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. The gullies were taken from the geomorphological map (Figure 3). Weights were calculated linearly from the gully bottoms (as taken from the stream vector map) to the side slopes within their mapped area of influence.

Proximity to reservoir

Another factor to consider was the instability hazard from high pore-water pressures in the very fragmented landslide deposits making up the Tirajana reservoir banks following possible rapid drawdown. Weight values were linearly assigned, decreasing from the average shoreline of the reservoir up to a distance of 200 m.

PARAMETER WEIGHT ASSIGNMENT

Although a variety of procedures exists for establishing parameter weights, the AHP makes it possible to evaluate the consistency of the parameter pairwise comparison. In this procedure a value between 9 ("much more important than"), 1 ("equally important as") and 1/9 ("much 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 used when developing the ratings. The CR indicates the probability that the matrix rating was 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.

The hazard map was produced by multiplying the weights of the classes with the weights of the parameter maps, and summing up all weights for each pixel, as explained earlier. The resulting scores were classified into four classes: *very low*, *low*, *moderate* and *high*. The result is shown in Figure 9.

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 indirect assessment method, 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. However, most of the ancient large landslide bodies do not appear to be subject to a major reactivation. Some areas affected by 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 a hazard is believed to be very low.

TABLE 1 Parameter weight assignment based on the analytical hierarchy process (Consistency ratio = 0.03)

	Slope angle	Proximity to gullies	Proximity to reservoirs	Land use change	Material	Landslide activity	Landslide phase	**Weight**
Slope angle	1							**0.22**
Proximity to gullies	1/4	1						**0.06**
Proximity to reservoirs	1/2	2	1					**0.13**
Land use change	1/3	2	1/2	1				**0.07**
Material	1/2	2	1	3	1			**0.14**
Landslide activity	2	4	3	3	2	1		**0.29**
Landslide phase	1/3	2	1/2	2	1/2	1/3	1	**0.09**

DISCUSSION OF RESULTS

The hazard maps generated with the direct method (Figure 8) and the indirect method (Figure 9) were combined in GIS and the overlap of the classes was calculated (see Table 2). As can be seen from this table, there is a striking difference in the percentages of the four hazard classes between the two maps. The direct map indicates more areas as high hazard as well as more areas as very low hazard, compared to the indirect map. The high hazard class appears much less in the indirect map (6.5 percent) than in the direct map (20.1 percent). The indirect map has much more area classified in the intermediate classes low and moderate. This difference might be related to the classification thresholds of the scores used for the indirect map.

The differences between the two maps can be caused by the following factors:

- The indirect method did not differentiate between the various types of mass movements.
- A considerable degree of generalisation is inherent in the use of the indirect mapping approach. With the direct hazard mapping method it is possible to evaluate each polygon separately, based on the unique set of factors that are present in the polygon, whereas the indirect method has to use the same weight values for all locations with the same factors.
- The addition of weight values tends to “flatten out” the result. The combination of multi-factor maps with moderate weights makes the effect of a high or a low weight less pronounced.
- The classification thresholds of the scores used for the indirect map have to be selected arbitrarily, and they might have excluded too much area from the low hazard or high hazard class.

CONCLUSIONS

The application of GIS-assisted direct and indirect heuristic multi-criteria evaluation techniques has been shown to be a relatively simple and cost-effective approach for assessing landslide hazard at medium scales when costly geotechnical and groundwater data are not available. Although direct hazards mapping techniques are quite time-consuming, they may give detailed results, making it possible to evaluate every area individually, based on its own set of unique criteria. However, these methods depend highly on the skill, commitment and expertise of the analyst. The indirect heuristic approach has also proved to be 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, both in the direct mapping as well as in the assignment of weights to the parameter classes. Nevertheless, the allocation of parameter weighting values can be assisted by the analytical hierarchy process, which permits a quantitative evaluation of each parameter based on 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 the FP4 Environment and Climate Programme. The authors would also like to thank A. Quintana, A. Lomoschitz, F. Santana and F.J. Martín, of the University of Las Palmas, for their valuable contributions.

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TABLE 2 Comparison between the hazard maps made using the indirect and direct method. The number of pixels of each overlap is given, as well as the percentage of the entire map (in brackets).

		Direct mapping method				
		High	Moderate	Low	Very low	Total
Indirect hazard Mapping	High	2790	565	62	0	3417 (6.5%)
	Moderate	6833	3852	5001	102	15788 (30.2%)
	Low	920	2926	8605	9810	22298 (42.6%)
	Very Low	2	126	2427	8179	10865 (20.8%)
	Total	10545 (20.1%)	7469 (14.3%)	16095 (30.7%)	18091 (34.6%)	52368 (100%)

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RÉSUMÉ

Dans le cadre du projet RUNOUT du programme de l'Union Européenne sur l'environnement et le climat, traitant de la modélisation de glissements de terrain de grands volumes, une base de données SIG a été créée et utilisée pour générer des cartes de risques de mouvements de masse à échelle moyenne (1:25.000) dans une région accidentée dans les îles de Grande Canarie en Espagne. La zone d'étude de Barranco de Tirajana est une large dépression de 49 km^2 qui est semi-ovale en plan, longue de 11 km et large de 6.5 km. Sa base présente une topographie très irrégulière et se trouve presque complètement entourée par de larges escarpements rocheux, jusqu'à 350 de hauteur, avec des différences d'altitude atteignant 1600m entre la partie inférieure de la rivière Barranco de Tirajana jusqu'aux escarpements supérieurs. La dépression de Barranco Tirajana est composée de séries de grandes masses de glissement de terrain, dérivées de glissements gravitationnels de séquences de coulées de lave et de brèche volcanique. On pense que les glissements de terrain sont le résultat de périodes d'érosion intensive durant le quaternaire, comme conséquence d'un approfondissement rapide du ravin central. Ces grands corps de glissement de terrain primaire ont été soumis à de nombreux épisodes de réactivation, du pléistocène moyen à nos jours, ainsi qu'à un agrandissement régressif de la dépression. Actuellement les procédés les plus actifs sont des chutes de pierres et une réactivation des zones d'éperon de glissements de terrain, dû au creusement ultérieur des cours d'eau. Afin d'évaluer le risque du mouvement de masse actuel, une étude à l'aide d'un SIG a été exécutée en utilisant deux différents types d'approches : une méthode directe et une méthode indirecte. Dans la méthode directe une cartographie géomorphologique très détaillée a été exécutée, en utilisant des polygones codés de manière unique, qui ont été évalués un à un par un expert pour estimer le type et le degré du risque. La méthode indirecte a suivi une approche par indexes. Des paramètres comprenant angle de pente, activité de glissement de terrain, phases de glissement de terrain, matériel, proximité par rapport à des canaux de drainage et réservoirs, et changement d'utilisation des terres ont été combinés en utilisant des techniques d'évaluation multi-critères.

RESUMEN

Como parte del proyecto RUNOUT, del Programa de la Unión Europea sobre clima y medio ambiente, que trata de la modelización de corrimientos de tierras de gran volumen, se ha recopilado una base de datos de GIS y se ha utilizado para generar mapas de riesgo de desplazamiento de masas a escala media (1:25.000) en un área de alto relieve en el centro de la isla de Gran Canaria, España. El área del estudio del Barranco de Tirajana es una gran depresión de 49 km^2 con un plano semioval, de 11 km de longitud y 6,5 km de anchura. Su base presenta una topografía muy irregular y está casi totalmente cercada por laderas de grandes rocas, de hasta 350 m de altura, con diferencias de altitud totales que alcanzan los 1.600 m desde la parte más baja del río del Barranco de Tirajana hasta las laderas más altas. La depresión del Barranco de Tirajana está compuesta de una serie de grandes masas de corrimiento de tierra, procedentes del deslizamiento gravitacional de sucesiones de torrentes de lava y de aglomerados de rocas volcánicas. Se cree que los corrimientos de tierras se originaron durante períodos de intensa erosión en el Cuaternario, como consecuencia del rápido hundimiento del barranco central. Estas grandes masas de corrimientos de tierra primarios han experimentado varios episodios de reactivación, desde el Pleistoceno medio hasta la actualidad, así como un ensanche retrógrado de la depresión. Actualmente los procesos más activos son la caída de rocas y la reactivación de las áreas delanteras de los corrimientos de tierras, debido además al socavado que realizan las corrientes. Para evaluar el riesgo actual de desplazamiento de masas, se llevó a cabo un estudio utilizando GIS y dos tipos diferentes de métodos impulsados por el conocimiento: un método directo y un método indirecto. En el método directo se desarrolló una cartografía geomorfológica muy detallada, utilizando polígonos especialmente codificados, que fueron evaluados uno a uno por un experto para valorar el tipo y el grado de riesgo. El método indirecto siguió una técnica de indiciación. Parámetros tales como el ángulo de la pendiente, actividad del corrimiento, fases del corrimiento, material implicado, proximidad con canales de drenaje y embalses y cambios en la utilización de la tierra, se combinaron empleando técnicas de evaluación multi-criteria.