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Building models for automatic landslide-susceptibility analysis, mapping and validation in ArcGIS

J. D. Jiménez-Perálvarez · C. Irigaray · R. El Hamdouni · J. Chacón

Abstract In this paper, ModelBuilder^{TM} in ArcGIS (ESRI) has been applied to landslide-susceptibility analysis, mapping and validation. The models (scripts), available for direct downloading as an ArcGIS tool, allow landslide susceptibility to be computed in a given region, providing a landslide-susceptibility map, with the GIS matrix method, and ensuring a quality validation. The paper details the steps needed for the model-building process, enabling users to build their own models and to become more familiar with the tool. The susceptibility model leads the user first through a Digital Elevation Model (DEM), depicting the morphological and morphometric features of the study area, and then through a Digital Terrain Model (DTM), useful as a source of landslide-determinant factors, such as slope elevation, slope angle and slope aspect. In addition, another determinant factor is the lithological unit, independent of the DEM. Once the determinant landslide factors are reclassified and in a vectorial format, all the combinations between the classes of these factors are determined using the geoprocessing abilities of ArcGIS. The next step for the development of the landslide-susceptibility model consists of identifying the areas affected by a given surface of rupture (i.e. source area) in every combination of the determinant-factor classes. This step leads to the landslide matrix based on a previously georeferenced landslide database of the region, in which the slopes are distinguished into two simple classes: with or without landslides. In the last stage, to build a landslide-susceptibility model, the user computes the percentages of area affected by landslides in every combination of determinant factors. In the resulting landslide-susceptibility map a progressive zonation of areas or slopes increasingly prone to landslides is performed. A model for the

J. D. Jiménez-Perálvarez · C. Irigaray (✉) · R. El Hamdouni · J. Chacón
Department of Civil Engineering. ETSICCP, University of Granada, Spain, Campus Fuentenueva s/n, Granada 18071, Spain
e-mail: clemente@ugr.es

J. D. Jiménez-Perálvarez
e-mail: jorgejp@ugr.es

R. El Hamdouni
e-mail: rachidej@ugr.es

J. Chacón
e-mail: jchacon@ugr.es

validation of the resulting landslide-susceptibility map is also presented, based on the determination of the degree of fit, which is calculated from the cross tabulation between a set of landslides (not included in the susceptibility analysis) and the corresponding susceptibility map.

1 Introduction

Landslides (slope movements) are natural or man-induced phenomena that generate risks (Varnes 1984; Fell 1994; Glade et al. 2005; Chacón et al. 2006), and therefore it would be necessary to consider such processes in land-use planning. Unfortunately, slope movements are commonly taken into account only in *post mortem* analyses of catastrophic events, or for civil engineering purposes (Varnes 1978; Chacón et al. 2006).

Landslide susceptibility, a measure of how prone land units are to landsliding, was quantitatively approached by Brabb et al. (1972). In mathematical form, it can be expressed as the probability of spatial occurrence of slope failures, given a set of geoenvironmental conditions (Guzzetti et al. 2005). In general, susceptibility can be evaluated by two methods: (1) those based on modelling techniques founded on physical and mechanic laws of the equilibrium of forces, and (2) those based on statistical techniques founded on the principle of actualism, in which the GIS can be of great utility. Geographical Information Systems (GIS) offer a powerful tool for analysing the processes which occur on the Earth's surface (Bonham-Carter 1994). The availability of personal computers and the great number of commercial GIS software packages favoured a widespread use of GIS for the analysis and modelling of georeferenced data, and the development of specific applications for physical processes such as slope instability (Carrara et al. 1995; Irigaray 1995; Ayalew and Yamagishi 2005; Chacón et al. 2006; Davis et al. 2006).

Methods for GIS landslide-susceptibility mapping evolved over time, taking into account different significant contributions (Crozier 1986; Carrara et al. 1991; Chung et al. 1995; Canuti and Casagli 1996; Guzzetti et al. 1996; Soeters and Van Westen 1996; Aleotti and Chowdhury 1999; Iovine et al. 2003a, b) and the increasing worldwide experience on GIS landslide mapping (Chacón et al. 2006). According to Van Westen et al. (1997) and Van Westen (2000) in the analysis of susceptibility in GIS, several methodologies can be differentiated into:

– the empirically based approach, particularly suited for small-scale regional surveys. It relies on the production of landslide-hazard maps investigated and controlled by the earth scientist responsible for the analysis (heuristic qualitative approach) (Carrara and Merenda 1974; Stevenson 1997; Kienholz et al. 1983).
– the statistical quantitative approach for medium-scale surveys or inventory-based method (also empirically based). It allows for a better comprehension of the relationships between landslides and preparatory factors, and guarantees lower subjectivity levels with respect to the heuristic approach (Ermini et al. 2005). In the statistical analysis, the combinations of factors that led to landslides in the past are determined statistically, and quantitative predictions can be made for areas currently free of landslides, in which similar conditions exist. Notable within the statistical methods are basically multivariate and bivariate statistics.

- the data-driven multivariate statistical analysis. All the parameters at unstable sites are analysed by multiple-regression techniques; alternatively, parameter maps are crossed with landslide-distribution maps, and the correlation is established for stable and unstable areas by employing discriminant analyses. One of the pioneer works was that of Carrara et al. (1977), which was continued by other works (Carrara 1988; Carrara et al. 1992, 1995; Chung et al. 1995).

- the experience-driven bivariate statistical analysis, based on indirect mapping. In this method, the causal factors are entered into a GIS and crossed with a landslide-distribution map. There are different varieties of this method, notably the weights of evidence (Bonham-Carter et al. 1988; Agterberg et al. 1989, 1993; Poli and Sterlacchini 2007), the landslide-index method (Van Westen 1993, 1994; Van Westen et al. 1997) and the one used in the present work, the matrix method (DeGraff and Romesburg 1980; Maharaj 1993; Cross 1998; Irigaray 1995; Irigaray et al. 1999, 2007; Clerici et al. 2002).

– the physically based or process-based approach for detailed studies. These consist of slope-stability analyses generally aimed at evaluating a safety factor (Okimura and Kawatani 1986; Mulder and Van Asch 1988; Hammond et al. 1992; Pack et al. 1998).

As a whole, a high number of GIS landslide-susceptibility (or hazard) methods were developed (Carrara et al. 1995; Guzzetti et al. 1999). Nevertheless, susceptibility maps need to be validated. Through validation (sometimes called evaluation or test), the quality of the proposed susceptibility estimate must be evaluated (Irigaray et al. 1999, 2007; Chung and Fabbri 2003; Guzzeti et al. 2006). The quality of a landslide-susceptibility model can be ascertained using the same landslide data used for the estimate, or by using independent landslide information not employed for the assessment (Guzzetti et al. 2006). Three basic techniques can be used to obtain an independent sample of landslides for validating a landslide-susceptibility map (Remondo et al. 2003): (a) the original inventory can be randomly split into two groups, one for the susceptibility analysis and one for validation; (b) the analysis can be conducted in a part of the study area, and the susceptibility map tested in another part (i.e. affected by different landslides); (c) the analysis can be made using landslides generated in a certain period, and validation performed by considering landslides occurred in different periods. The latter technique, used in the present work, is considered to be the most reliable technique to test the validity of the prediction made (Irigaray et al. 2007).

The currently available commercial GIS packages include programming tools and graphic interfaces which enable the user to rapidly design their own geoprocessing applications. "Model Builder" is a programming tool developed by ESRI (ArcGIS 2004), added to the GIS suite of packages since ArcView 3.0, which includes geoprocessing tools for the generation of recyclable models (McCoy 2004).

The main intention of the paper is the presentation of ArcGIS implemented geoprocessing models (scripts) based on ESRI's "Model Builder" utility for automatic landslide-susceptibility analysis, using a validated methodology: the GIS matrix method (GMM). The latter offers a good opportunity to GIS users to conduct simple, inventory-based landslide-susceptibility analyses within a familiar commercial GIS environment. Different public organisms (ministries, city halls, research centres) have databases on slope movements that are continuously updated. The proposed landslide-susceptibility model, described in this work, can employ such updated databases in order to validate and revise susceptibility maps with the aim of incorporating them in territorial ordination plans. The tool is available for free downloading as an ArcGIS tool (see details in Appendix).

For the application and activation of the models, a study area characterized by a considerable incidence of landslides was selected (El Hamdouni 2001; Fernández 2001; Chacón et al. 2002; Jiménez-Perálvarez et al. 2005; Chacón et al. 2006; Irigaray et al. 2007). The area (Fig. 1) is located on the southern slopes of Sierra Nevada, in the Betic Cordillera (Spain), with an approximate extent of 158 km^2. In the area the units of the Internal Zones of the Betic Cordillera and post-tectonic materials (Neogene and Quaternary) outcrop. In this sector, the Internal Zone is represented by the Alpujarride and Nevado-Filabride Complexes. Dark schist and feldspar-bearing micaschist are widespread in the Nevado-Filabride Complex up to the Alpujarride Complex, which is composed of Triassic calcareous schist, marble, phyllite and quartzite (Gómez-Pugnaire et al. 2004). The Neogene materials are composed of marl and silt covered by conglomerate (Ortega et al. 1985).

2 Foundations of the models and of required data

The landslide-susceptibility model presented in this work (tool: "susceptibility_model") is based on the GMM, which is a GIS-based method developed by improving a previous method (DeGraff and Romesburg 1980), contributed by Irigaray (1995). In the empirical analysis, an assumption is made that future landslides will occur under the same conditions as in the past. The method is based on bivariate statistical analysis, in turn, founded on cross analysis of maps of determinant factors and spatial frequency of slope movements. It permits an evaluation of the instability index in a given zone, although it is not capable of predicting the susceptibility to slope movements in terms of absolute probability. However, it enables to evaluate the potential relative instability in a broad region by using a series of measurable factors.

The GMM is an appropriate methodology for the working scale of this work (Van Westen et al. 1997). The GMM requires an inventory of landslides and a selection of the most significant determinant factors to be included in the analysis. The determinant factors
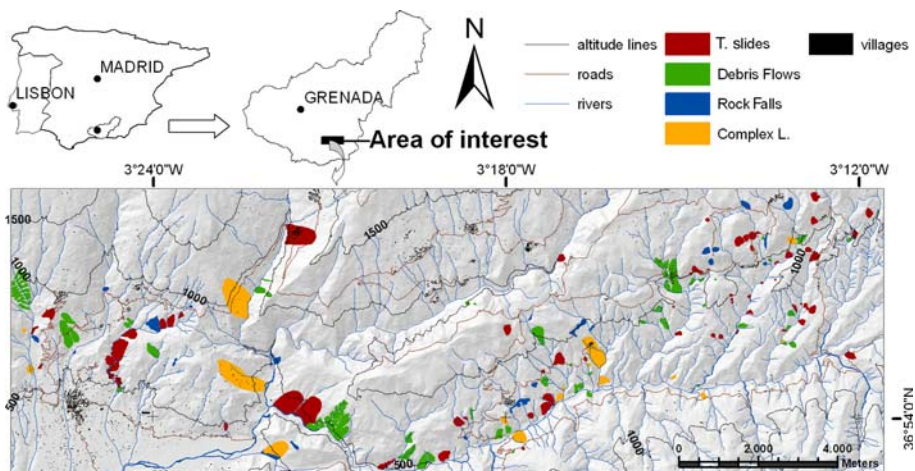
Fig. 1 Location and landslide inventory map. The landslide inventory is composed of 69 translational slides, 52 debris flows, 31 rock falls and 17 complex slides

are not weighted: the weighting factors are in fact intrinsically performed by the matrix method, as described by different authors (Maharaj 1993; Cross 1998; Irigaray et al. 1999, 2007; Clerici et al. 2002; Fernández et al. 2003). It was also validated with excellent results in the same region where the study area is located (Irigaray et al. 1999, 2007; El Hamdouni 2001; Fernández 2001; Fernández et al. 2003). A quantitative comparison between the GIS matrix method and other bivariate statistical-analysis techniques (Landslide Susceptibility Index—Van Westen 1993, 1994; and weight of evidence—Bonham-Carter 1994) is presented in Sect. 3.5.

2.1 Landslide inventory

When adopting a statistical probabilistic approach, the landslide inventory is the first step in any landslide-mapping project intended to provide a susceptibility, hazard or risk assessment. It is perhaps the most important set of data in the entire assessment process and greatly influences the quality of the final results.

   In this study, a database containing 169 landslides, described with internationally accepted terms and classifications (Varnes 1978; Cruden and Varnes 1996), was first implemented by collecting data gathered through a phase of interpretation of aerial photographs (at scale 1:20,000) followed by field surveying. The definitive inventory of slope movements was made at a scale of 1:10,000. This landslide inventory is based on movements generated before 1996. The inventory includes a total of 69 slides (translational slides, mainly in phyllite and marble), 52 flows (debris flows, mainly in phyllite), 31 falls (rock falls, mainly in marble) and 17 complexes (complex slides, mainly in quartzite), all identified and mapped (Tables 1, 2 and Fig. 1). The landslides, considered from the source areas to the deposits, were found to affect 3.79% of the total study area. Phyllite units resulted to be the most unstable materials, comprising 38% of the inventoried landslides, followed by marble units at 25%.

2.2 Determinant factors

The determinant factors account for the overall slope-stability condition: the strength of the geological units can in fact be related to the type of soil or rock, to discontinuities or to slope morphology in terms of slope angle, aspect, elevation, size, amplitude (surface covered by a homogeneous slope unit with slope aspect approximately uniform), roughness (describes different combinations of slope angle and aspect in a given region), curvature (describes the slope profile and differences between concave and convex profiles), etc.

Table 1 Landslide inventory, typologies and dimensions

Affected area (m^2)						
Typology	n	Maximum	Minimum	Mean	Total	% Relate to total area
Slide (translational slide)	69	686,172	232	37,484	2,661,346	1.68
Flow (debris flow)	52	355,198	287	40,088	2,084,598	1.32
Fall (rock fall)	31	64,244	453	12,792	396,557	0.25
Complex	17	462,465	3,547	57,849	867,741	0.55
Total	169	686,172	232	35,564	6,010,241	3.79

Table 2 Landslide inventory, percentages in each lithology

% of landslides inventoried in each LITHOLOGY relate to total lithologies of each typology

Typology	Cs.	Cgm.	Qtze.	Scht.	Marb.	Mscht.	Pht.
Slide (translational slide)	9.86	9.86	18.31	0.00	22.54	0.00	39.44
Flow (debris flow)	0.00	1.92	21.15	5.77	0.00	9.62	61.54
Fall (rock fall)	6.45	0.00	3.23	16.13	74.19	0.00	0.00
Complex	0.00	0.00	40.00	0.00	26.67	6.67	26.67
Total	4.14	4.73	18.93	5.33	24.85	4.14	37.87

Cs Calcareous schist; *Cgm* Conglomerate; *Qtze* Quartzite; *Scht* Schist; *Marb* Marble; *Mscht* Micaschist; *Pht* Phyllite

The model presented in this paper uses four determinant factors: three DEM derivatives (slope angle, slope elevation and slope aspect), and one derivative from a thematic GIS layer (lithology). Among these factors, those ones most frequently considered in the international literature are slope angle and lithology (Rodríguez-Ortiz et al. 1978; Hansen 1984; Crozier 1986; Guzzetti et al. 1996, 1999; Irigaray et al. 1996, 1999, 2007; Fernández et al. 2003; Ayalew and Yamagishi 2005).

In the study zone, an exhaustive analysis of the most relevant determinant factors was recently published (Irigaray et al. 2007). Even so, with the aim of selecting the set of significant determinant factors, an analysis was performed by crossed tabulation (contingency tables) between the source areas of the landslides and determinant factors. Different correlation coefficients were calculated and significance tests were used to identify the most influencing factors: Chi-square, Coefficient of linear correlation of the contingency coefficient, Tschuprow's T and Cramer's V coefficients (Table 3). Those determinant

Table 3 Correlation between the source areas of the landslides and the determinant factors

| Factor	χ^2	R	T	V
AL	6.27	0.40	0.07	0.12
IL	3.51	0.35	0.06	0.09
LC	1.20	0.27	0.05	0.05
VC	1.12	0.26	0.03	0.05
FT	0.25	0.18	0.02	0.02
SA	6.80	0.41	0.09	0.12
PP	2.06	0.31	0.05	0.07
LT	12.95	0.48	0.10	0.17
W	0.32	0.19	0.03	0.03
LU	0.46	0.21	0.02	0.03
SL	6.75	0.41	0.09	0.12

Lithology, slope angle, slope aspect and altitude are the determinant factors which show the highest degree of association

AL Altitude; *IL* Illumination; *LC* Lithological contacts; *VC* Vertical curvature; *FT* Faults; *SA* Slope aspect; *PP* Precipitation (annual mean); *LT* Lithology; *W* Distance to watercourses; *LU* Land use; *SL* Slope angle; χ^2 Chi-Square; *R* Lineal and contingency correlation coefficient C $R = \sqrt{(C/C_{max})}$; T Tschuprow's *T*; V Cramer's *V*

factors showing the highest degree of association with the landslide inventory were then taken into consideration: lithology, slope angle, slope aspect and altitude (or elevation).

The determinant factors of instability can vary according to the study zone. In each area, those factors which show the highest degree of association with the landslide inventory should be selected. The model can be easily edited in order to add any other determinant or triggering factor. In this case, previous results (El Hamdouni 2001; Fernández 2001) concerning the reclassification of the determinant factors were adopted, and an entire numerical value was assigned to each class of determinant factors, although further developments of the model could be improved by using other classification methods (natural-breaks, standard deviation, equal intervals, etc.) (Irigaray et al. 2007).

Slope elevation is not the most common determinant factor in the literature, except for studies of mountain areas (like the study area) with pronounced differences in elevation (Fernández et al. 2008). Usually, elevation is considered as an indirect factor, related to/or conditioning other factors such as rainfall, temperature, freeze/thaw cycles, soil development, vegetation, etc., which may be more difficult to quantify. In the zone, the elevation varies between 300 and 1800 m, representing an interval wide enough to introduce significant changes in such climatic conditions such as rainfall and temperature, and also a variable set of vegetation units. The slope angle is one of the most commonly used determinant factors in GIS applications concerning slope-stability (Fernández et al. 2008). The slope aspect (or exposition) has only an indirect influence on landsliding. It is related to other variables, such as soil moisture and development, weathering, etc., which are commonly more intense on north-oriented slopes, because of the lower insolation. Lithology is the most common determinant factor in most stability studies. The model (tool) presented here requires the lithology map as an input datum in order to evaluate the landslide susceptibility. It represents the strength of the materials in terms of slope behaviour during landslides or instability processes. From the Mining and Geology Information System of Andalusia (Spain) (SIGMA 2002), the 1:50,000 geological map of the region was drawn. With the recommendations on map use in geological engineering projects of UNESCO (1976), a number of lithological complexes were reclassified in the units shown on the source map (Fig. 2).
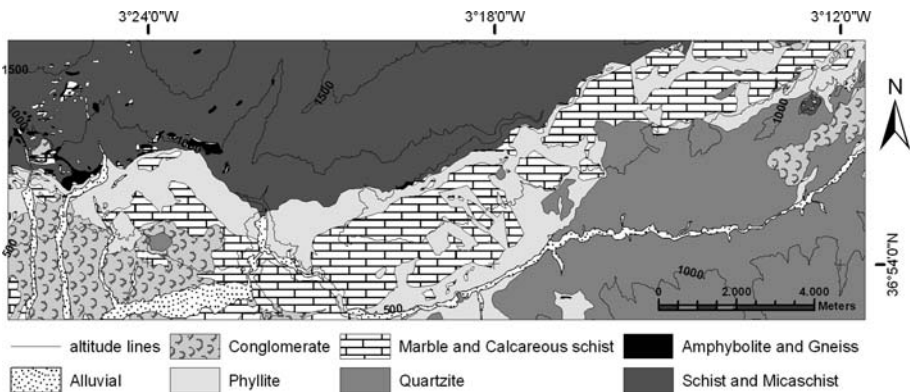
Fig. 2 Lithological complex map

2.3 Method of analysis: the GIS matrix method

Once the relevant determinant factors are identified, the landslide susceptibility can be evaluated by delimiting terrain units differently prone to landslides. The GMM was successfully applied to different geological settings and countries (Irigaray 1995; Cross 1998; Irigaray et al. 1999, 2007; Fernández 2001; El Hamdouni 2001). It is based on the computation of three matrices: landslide matrix (LM), total surface of the study area matrix (TSM), and susceptibility matrix (SM). First, a LM is established by calculating areas or extensions affected by the source areas of the landslides in each combination of classes of the selected determinant factors. The TSM matrix is calculated by making all the possible combinations among the classes of determinant factors selected, and then calculating the area occupied by each combination. Finally, in the SM, each cell shows a value calculated by dividing the value of the cell in the LM by the value of the cell in the TSM. The cell values in the SM represent an assessment of relative susceptibility corresponding to each combination of determinant factors in the cell. Each SM value shows the percentage of source areas in each combination of determinant factors with regard to the total area occupied by the respective combination of determinant factors. The susceptibility maps are based on 5 levels of classification, automatically assigned to each zone by using the natural-breaks method (Irigaray et al. 2007; ArcGIS 2004). In this method, class breaks are determined statistically by finding adjacent feature pairs which show relatively large differences in data value (ArcGIS 2004).

2.4 Validation of susceptibility maps

The landslide-susceptibility validation model presented in this work (tool: "validation_model") uses the *degree of fit* to assess the association between the inventory and the landslide-susceptibility map. The quality of the maps was assessed by techniques of spatial autocorrelation and measuring the *degree of fit* between a given set of data and the maps (Goodchild 1986). The final aim was to assess the quality of the susceptibility map as a predictive tool to explain the landslide inventory of the study area. Only when a given level of quality was attained, a given landslide susceptibility or hazard map may be considered acceptable as a predictive tool for future landslides. There are different approaches (Irigaray et al. 1999; Remondo et al. 2003; Guzzetti et al. 2006), and excellent results were achieved in landslide areas of the Betic Cordillera (Irigaray et al. 1999, 2007; El Hamdouni 2001; Fernández 2001; Fernández et al. 2003). In this paper a different inventory (i.e. not the one employed for computing the susceptibility map) was used for validation. However, a validation with the inventory map used to derive the landslide-susceptibility map was also made (Sect. 4.3). The *degree of fit* (DF), as applied to landslide maps, is defined as follows:

$$\mathrm{DF}_i = \frac{m_i/t_i}{\sum m_i/t_i}$$

where m_i is the area occupied by the source areas of the landslides at each susceptibility level i, and t_i is the total area covered by that susceptibility level. The *degree of fit* for each susceptibility level represents the percentage of mobilized area located in each susceptibility class. The lower the *degree of fit* (less than 7%) in the low and very low susceptibility classes (relative error), and the higher the *degree of fit* in the high or very high susceptibility classes (relative accuracy), the higher the quality of the susceptibility map will be (Fernández et al. 2003; Irigaray et al. 2007).

The selected set of source areas of the landslides for this validation is composed of 12 slides (translational slides, mainly in phyllite and marble), 6 flows (debris flows, mainly in phyllite), 1 fall (rock fall in marble) and 3 complexes (complex slides, mainly in quartzite). The landslides are homogeneously distributed in the study zone (Fig. 3) and reach 17.9% of the total surface covered by the set of source areas of the landslides considered for the LM calculation.

The landslide inventory used for the validation of the susceptibility map, is based on movements generated in the 1996–1997 winter season, as a consequence of heavy rains in the study area in late 1996 and early 1997 (212 mm in November 1996, 386 mm in December and 222 mm in January 1997, i.e. the mean annual rainfall for the area reached in only three months). The heavy rains damaged mainly the road network of the study zone (Irigaray et al. 2000).
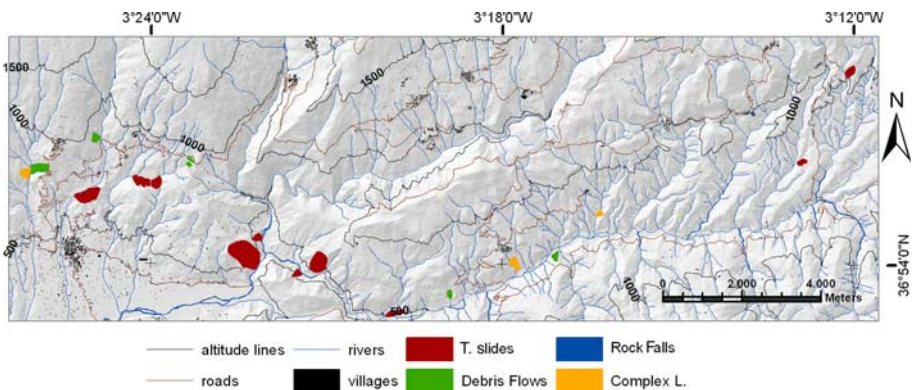
3 The model for landslide-susceptibility mapping (susceptibility_model): input data, methodology and results

A model based on the assessment of landslide susceptibility was developed following the GMM. The model is inside the tool "susceptibility.tbx" and its name is "susceptibility_model".

3.1 Input data

Three input data are required for mapping the landslide susceptibility automatically: the DEM, the lithological map of the study area and the landslide inventory.

The DEM has to be a continuous raster surface or map. There are different techniques to determine DEMs from vectorial data, (IDW, Kriging, etc.), although there are high-quality DEMs supplied by public or commercial sources. The DEM of the present study is made by regular matrices with a pixel resolution of 10×10 m, achieved by transforming a TIN (Triangulated Irregular Network) to GRID. The TIN was generated from interpolation of digital contour lines and elevation points taken from a map at scale 1:10,000 (Andalusia Institute of Cartography; ICA 1999).

Fig. 3 Landslide inventory used for the validation of the landslide-susceptibility map. The inventory is composed of 12 translational slides, 6 debris flows, 1 rock fall and 3 complex slides

The lithological map has to be a vectorial layer showing a classification of lithological units. Each lithological complex has to be associated with an integer number.

The landslide inventory has to be a vectorial layer reclassified in two classes: presence of source areas of the landslides ("value_2"), or their absence ("value_1"). The sum of these two classes gives the total surface of the study area.

3.2 Modelling the matrix of the total surface of the study area (TSM)

From the DEM, three terrain digital models were derived as by-products showing three determinant factors: elevation, slope angle, and slope aspect (by means of the ArcGIS geoprocessing tools "Reclassify", "Slope" and "Aspect", resp.). The determinant factors expressed in raster format were reclassified and transformed into a vectorial format, and were generalized by classes, in order to attain a simpler attribute table for the map. These ArcGIS tools work in a raster format, which is necessary for the spatial analysis. Nevertheless, to improve the presentation of the data and reduce the size of the files, the three layers or maps (elevation, slope angle and slope aspect) were transformed from raster into vectorial format (".shp"). The maps were transformed into a vectorial format in order to work with different attribute layers. In the ArcGIS 9.0 version, it is not possible to edit attribute tables from raster maps. Each pixel in a raster map has that value in the vectorial map: afterwards it is homogenized to have in the attribute table a number of files equal to the number of map classes. The transformation of the format did not result in any loss of information. The fourth determinant factor, lithology, was introduced as parameter or input data, and each lithological complex was associated with an integer number. The TSM was computed by making all the possible combinations among all the classes of determinant factors selected by means of the ArcGIS geoprocessing tool "Intersect". Afterwards, a new column was added ("value") to the TSM generated layer. The value of this column is a simple identifier which was necessary to compute the TSM as a table, making further unions with other tables possible.

3.3 Modelling the landslide matrix (LM)

The LM was calculated by crossing the reclassified landslide inventory with the TSM by means of the ArcGIS geoprocessing tool "Tabulate Area". The results are shown in table "crossed.dbf", with three columns: "value", previously added from the TSM and corresponding to the identifier of each combination of classes of the determinant factors selected, "value_2" with the area affected by the source areas of the landslides in each combination, and "value_1" with the area not affected in each combination. The column "value_2" with the layer "intersect.shp" is, properly speaking, the LM (Sect. 2.3).

## 3.4 Modelling the susceptibility matrix (SM)

With the purpose of calculating the percentage of area affected by the source areas of the landslides in each of the classes of determinant factors, two new columns were generated in the LM table ("crossed.dbf"). The first column is the total area occupied by each of the combinations of classes of determinant factors selected. The second column is, in percentages, the area affected by the source areas of the landslides in each of the combinations of classes of determinant factors cited above. The column "value" of the table "crossed.dbf" shows the identifier of each combination, and coincides with the identifier "FID"

in the layer "intersect.shp", where each combination of factors may be seen in the different columns "GRIDCODE". By means of the ArcGIS geoprocessing tools "Make Feature Layer", "Add Join" and "Copy Features", the model links SM with the map or layer obtained by combining all the factors ("intersect.shp", which has the SM as an attribute table) in order to achieve a spatial representation of the area affected by the source areas of the landslides. This is the spatial presentation of the SM ("suscep_matrix.shp") with an attribute, a table composed of a series of columns. In column "crossed_po" the percentage of area affected by the source areas of the landslides in that factor combination is preserved, this being the corresponding susceptibility value.

3.5 Results

The output datum of the "susceptibility_model" is a vectorial layer: "suscep_matrix.shp". This layer is the result of the analysis, i.e. the landslide-susceptibility map. The susceptibility values varied between 0 and 100 in each combination of classes of determinant factors (one hundred in rows). The values obtained were visualized by means of 5 susceptibility levels (very low, low, moderate, high and very high) (Fig. 4, Table 4) found in surrounding areas (Irigaray 1995; Irigaray et al. 2007; El Hamdouni 2001; Fernández et al. 2003, 2008) using the natural-breaks method. In this example, a reclassification of natural-breaks was made (rounded off to the closest whole number). In this way, the classes distinguished were:

– Very low susceptibility: the affected area in a given combination of determinant factors extends between 0 and 1%.
– Low susceptibility: the affected area in a given combination of determinant factors extends between 1 and 5%.
– Moderate susceptibility: the affected area in a given combination of determinant factors extends between 5 and 15%.
– High susceptibility: the affected area in a given combination of determinant factors extends between 15 and 25%.
– Very high susceptibility: the affected area in a given combination of determinant factors extends above 25%.
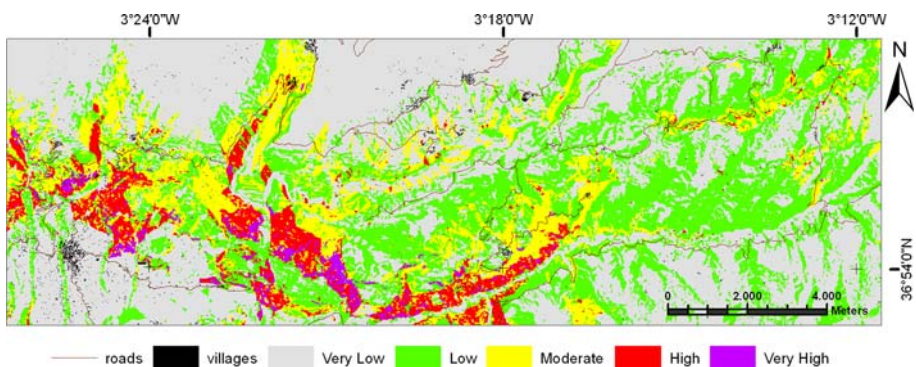
Fig. 4 Landslide-susceptibility map. The values are visualized showing 5 susceptibility levels found in surrounding areas using the natural-breaks method (Irigaray et al. 2007)

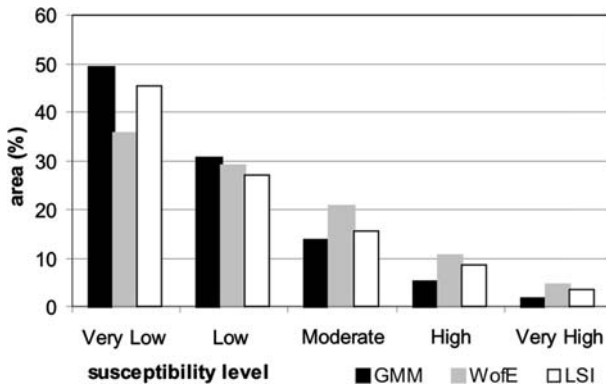| Table 4 Landslide susceptibility by different methodologies	Susceptibility	%	% Accumulate	km²
	Area (GIS matrix method)			
	Very low	49.19	49.19	77.89
	Low	30.51	79.7	48.31
	Moderate	13.5	93.2	21.38
	High	5.18	98.38	8.2
	Very high	1.62	100	2.57
	Area (weight of evidence method)			
	Very low	35.71	35.71	56.56
	Low	28.76	64.47	45.55
	Moderate	20.64	85.11	32.7
	High	10.45	95.56	16.56
	Very high	4.43	100	7.02
	Area (landslides-susceptibility Index method)			
	Very low	45.32	45.32	71.78
	Low	27.02	72.34	42.8
The values show the surface area and percentages of each susceptibility level in relation to the whole area of study	Moderate	15.42	87.75	24.42
	High	8.7	96.45	13.78
	Very high	3.54	100	5.61

The susceptibility values refer to slope instability or landslides without specifying the type of landslide. This may be adequate only for an initial susceptibility zonation, while detailed studies on the subject should consider susceptibility values found for each type of landslide (Chacón et al. 1996, 2006). The low and very low susceptibility levels represent more than 75% of the surface area studied. If moderate susceptibility is also added, this percentage rises to more than 90%. These values indicate that the maps obtained are not conservative, but rather they limit the zones of maximum susceptibility just to the relatively reduced area where the associated combination of factors exists.

Various bivariate-statistical techniques were applied on various mapping units. When comparing these results with those found by applying other susceptibility-analysis methods based on bivariate statistical techniques—Landslide Susceptibility Index (Van Westen 1993, 1994; Van Westen et al. 1997) and weight of evidence (Bonham-Carter 1994)—we found that the matrix method (GMM) is the least conservative of the methods considered (Fig. 5, Table 4). The zone considered by the GMM as exposed to high and very high susceptibility occupies a less area than the corresponding zones found by the other two methods. However, the validation of the susceptibility map by GMM is of the same nature as that made by the other methods (Fig. 6).

4 The model for landslide-susceptibility validation (validation_model): input data, methodology and validation

A model based on the assessment of the *degree of fit* between the source areas of the landslides and susceptibility zonation was developed following previous concepts and results (Goodchild 1986; El Hamdouni 2001; Fernández 2001; Fernández et al. 2003;

Fig. 5 Landslide-susceptibility by different methodologies. GMM, GIS matrix method; WofE, weight of evidence; LSI, landslide-susceptibility index. The values show the percentage of each susceptibility level in relation to the whole area of study
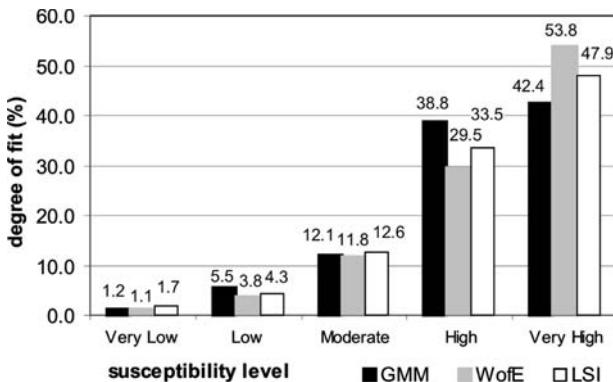
Fig. 6 Landslide-susceptibility map validation. Degree of fit between the source areas of the landslides and each landslide-susceptibility level. GMM. GIS, matrix method; WofE, weight of evidence; LSI, landslide-susceptibility index

Irigaray et al. 1999, 2007). The model is inside the tool "susceptibility.tbx" and its name is "validation_model".

4.1 Input data

Two separate sets of input data are necessary for the landslide-susceptibility validation: the landslide susceptibility map and a landslide inventory of the study area containing sources not employed for the susceptibility analysis.

The landslide-susceptibility map has to be the vectorial layer previously calculated by means of the "susceptibility_model": "suscep_matrix.shp".

The landslide inventory has to be a vectorial layer reclassified in two classes: presence of source areas of the landslides ("value_2"), or their absence ("value_1").

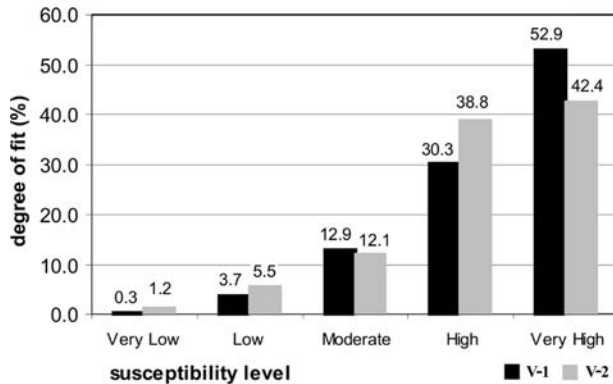4.2 Modelling the validation of the landslide-susceptibility map

The validation model uses ArcGIS geoprocessing tools previously applied to the cal-
culation of the *degree of fit* (*mi*, *ti*, etc.). The area affected by the source areas of the
landslides in each susceptibility model (*mi*) (very low, low moderate, high and very high)
is calculated by crossing the SM with the landslide inventory (binary map) used for the
validation. As mentioned above, this inventory map must be different from the one
employed for computing the SM. In addition, an additional validation phase was per-
formed by considering the inventory map used for deriving the landslide-susceptibility
map. As the SM includes a high number of rows, the SM was transformed into raster
format and reclassified in the set of susceptibility classes previously selected: very low,
low, moderate, high and very high. This reclassified map was crossed with the landslide
inventory. Once the cross tabulation was established, new fields were added and cal-
culated with values of *mi*, *ti*, *mi/ti*, etc. The operation ($\Sigma(mi/ti)$) was calculated by means
of the ArcGIS geoprocessing tool "Summary Statistics", which may later be added
("Add Join") to the required calculations.

4.3 Landslide-susceptibility validation

The output datum of the "validation_model" is the table "adjust.dbf", i.e. the result of
the landslide-susceptibility validation (Fig. 7). The obtained results clearly show a better
degree of fit for the validation which was made with the inventory used to analyse the
landslide-susceptibility map. However, it also shows a good degree of fit for the "true"
validation inventory. The degree of fit for the very low and low susceptibility classes is
6.7%, which is similar to values reported in other works previously made in the same
study zone (Irigaray et al. 1999, 2007; El Hamdouni 2001; Fernández 2001; Fernández
et al. 2003). This error is due to the accumulated error in the technique (Irigaray et al.
2007), mainly due to the determining factors. This would be explained by the limitation
of the method in terms of the DEM capability to express high slopes where the rock falls
really occur. The scale of the geological map is generally less than the digitalization
scale of the slope movements, and therefore a contact can assign an erroneous lithology
to a movement.

5 Discussion and conclusions

The landslide-susceptibility maps are preventive tools intended to minimize risks in the
threatened areas. Because of the social and economic implications in risk prevention, a key
question is the quality of the maps, which derives from an appropriate procedure and can
be tested through a proper validation. The tool presented here offers an automatic process
of landslide-susceptibility mapping and validation; therefore, it allows to reduce the time-
consuming process of development of GIS applications to landslide-susceptibility mapping
and validation. The obtained results pointed out the quality of the maps drawn by means of
the GMM in comparison with those made by other bivariate-statistical techniques. In
general, the GMM effectively explains the spatial distribution of slope movements that
took place after the drawing of the maps. Once the landslide susceptibility map is drawn
and validated, it is possible to make a simple and quick selection of the most appropriate
terrains for the setting of civil engineering or of building projects, or of areas where more
detailed studies would be necessary. Nevertheless, it is vital to emphasize the crucial

Fig. 7 Landslide-susceptibility map validation. Degree of fit between the source areas of the landslides and each landslide-susceptibility level. A comparison by using the inventory used to analyse the landslide-susceptibility map (V-1) and the new landslide inventory (V-2)

influence of an adequate engineering-geology approach, as well as of field and remote sensing surveys, in order to compile the basic data for landslide prevention: the inventory of landslides, the thematic layers related to the determinant factors and also all the available information on landslide-triggering factors.

The landslide susceptibility and the determinant factors involved in instability differ for each landslide type. In the example presented in this paper, all the landslide types were considered as a whole, and therefore the resulting landslide-susceptibility map was not derived from any particular type of landslide but rather from the overall inventory. This may be adequate only for an initial susceptibility zonation, while a more detailed susceptibility map should be prepared by processing separately the landslides by typologies, and using as input and validation inventories only those in each group or typology. In this paper, the basic data in the inventory are the source areas related to each landslide, this being appropriate for detailed scale maps (1:10,000 to 1:25,000). Nevertheless, at smaller scales, or regional mapping (1:25,000 to 1:400,000), it is possible to use the whole landslide areas as the basic input data in the landslide inventory: in fact, the purpose of low-detail maps is a more approximate indication of unstable zones than a precise location of areas potentially affected by new source areas.

Appendix: Execution of the models and files generated

Downloading the models

The models are available for free downloading as an ArcGIS tool (susceptibility.tbx) on the follow link: "http://www.ugr.es/local/ren03366/susc_model.rar". For availability on this link, the tool has been compressed by mean of standard compression software: WinRAR, version 3.62.00. It is strongly recommended that this software be used to decompress the tool.

The tool box "susceptibility.tbx", contains two models: the "susceptibility_model" to assess susceptibility, and the "validation_model" to validate the landslide-susceptibility

map. The models are also available in Python, Jscript and VBscript programming languages. The tool susceptibility.tbx has been tested with ArcGIS 9.0, 9.1 and 9.2, running on a WindowsXP operating system. The other tips for using the tool are on the read-me_help.pdf file.

Executing (running) the models

The user begins to execute the models by double-clicking on the icons, after introducing the input data and establishing the general parameters (see also the "help" section in the model by right clicking and then clicking on help). The landslide-susceptibility model (susceptibility_model) generates one output datum: the landslide-susceptibility map (suscep_matrix.shp), from three input data: DEM, lithological complexes and landslide inventory. The validation model (validation_model) generates one output datum (the table "adjust.dbf"), from two input data: the landslide-susceptibility map previously obtained (suscep_matrix.shp), and a landslide inventory, which may also be different from the one used in the susceptibility analysis. The model is easily edited (right click and edit the model) and adaptable to the user's needs (i.e. adding more determinant factors). In this case, the way of executing the model is, therefore, to edit the model and execute from the "edit" window, in order to appreciate the steps in which the model shows the user's modifications. The most common changes introduced in the model refer to determinant factors such as vegetation maps, rainfall information, land-use maps, etc., which may be added by the "intersect" tool. Also, different reclassifications may be necessary for particular treatments of some determinant factors; for that purpose simply double click the tool "reclassify" and select some of the available methods (natural breaks, standard deviation, equal intervals or a user-defined method). The most common reclassification is the drawing of the altitude map, since altitude can vary markedly from one area to another, and therefore this possibility is facilitated from the input interface. For the rest of the reclassifications, it is necessary to edit the model.

Determinant factors derived from the DEM

The elevation map ("altitude_7sd.shp") shows a simple reclassification into 7 classes of DEM data, which is a continuous raster surface, converted into a discreet surface ("altitude_7") and finally into a vectorial format ("altitude_7s.shp"). The DEM reclassification is an input datum. This is generalized by classes ("altitude_7sd.shp") in order to simplify the map attributes. The slope-angle layer ("slope_5sd.shp") shows the distribution of slope angles calculated directly by ArcGIS from the DEM. It uses an algorithm of a partial derivate of X (difference of elevation and distance in direction E–W) and the partial derivate of Y (difference of elevation and distance in direction N–S) in a network of 3×3 m around each DEM cell ("slope (2)"). Once calculated, the derivates are combined to determine the slope angles which are reclassified ("slope_5"), transformed into a vectorial format ("slope_5s.shp") and generalized. ("slope_5sd.shp"). The slope aspect layer ("aspect_5sd.shp"), accounting for the distribution of this factor, is calculated as the slope angle, from the X and Y partial derivates in a 3×3 m network around each of the DEM cells ("aspect (2)"). This continuous map of aspect is reclassified ("aspect_5"), transformed into vectorial ("aspect_5s.shp") and generalized ("aspect_5sd.shp").

Landslide-susceptibility map

Using ArcGIS 9.0 and 9.1, in the landslide-susceptibility map (suscep_matrix.shp) the "crossed_1" column corresponds to the area not affected by the source areas of the landslides for a given combination of factors. The "crossed_2" column shows the area affected by the source areas of the landslides for this combination of classes of determinant factors, and the "crossed_3" column represents the total area of the combination of factors considered. Finally, in the "crossed_po" column the percentage of area affected by the source areas of the landslides in that factor combination is preserved, this being the corresponding susceptibility value.

Using ArcGIS 9.2, in the landslide-susceptibility map (suscep_matrix.shp) the "crossed_VA" column is the area not affected by the source areas of the landslides, the "crossed_1" column shows the area affected by the source areas of the landslides, the "crossed_2" column represents the total area of the combination of factors considered and the "crossed_po" column is the percentage of area affected by the source areas of the landslides.

Validation of the susceptibility map

Using ArcGIS 9.2, in the landslide-susceptibility validation (adjust.dbf) the "adjust" column corresponds to the degree of fit at each susceptibility level. This column (adjust) corresponds to the column "validati_6" if the user is working with either ArcGIS 9.0 or 9.1.

The susceptibility levels are shown in ascending order, so that "OID = 0" in table "adjust.dbf" corresponds to the lowest susceptibility level, in this case very low susceptibility. In ArcGIS 9.0, the model must be executed from the edition window. For the completion of the model, the last tool "calculate field (5)" must be executed individually after previously executing the model, since the last tool does not recognize the new columns that are added until these are generated. This step need not be taken with ArcGIS 9.2, where the model is executed directly.

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