Landslides in the main urban areas of the Granada province, Andalucia, Spain

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Abstract: Landslide incidence in urban areas of the city of Granada, and the main towns of the province with more than 20 000 inhabitants, is here analysed following a methodology based on the following steps: collection of information about historical or antecedent events; compilation of a landslide inventory from field and aerial photography surveys; GIS (ArcGIS, ESRI) implementation using a DEM and detailed thematic maps; and analysis of landslide determinant factors. Finally, landslide susceptibility maps were derived for quadrangles around the towns of Granada, Motril, Almuñécar, Loja, Montefrío, Santafé, Ugíjar, Órgiva, Guadix and Baza. The maps were prepared for the main types of landslide types: rockfalls; earth and debris flows; rotational and translational slides; and complex landslides. The landslide susceptibility analysis and modelling followed the GIS matrix method and was spatially validated with new landslides with reliable results. In addition, a methodology is presented for the derivation of landslide hazard and risk in urban areas using the obtained susceptibility zones, and the destructive potential of the landslide types based on the expected magnitude and speed of the future events for the different landslide types. This is useful when local information about the temporal distribution of landslides and critical heavy rainfall are lacking. As the research was undertaken at a scale 1:50.000 the results are not intended for a precise knowledge of hazard at a detailed scale. Nevertheless, it is possible to identify zones in towns with relative higher hazard in order to promote programmes of control and mitigation of the expected landslides and also to reduce the vulnerability of the affected urban areas to the landslides processes.

Résumé: La fréquence des mouvements des versants dans les régions urbaines de la ville de Grenade et principaux villes de la province avec plus de 10.000 habitants, est analysé dans cet étude en suivant une recherche basé sur rassemblement d'information sur les événements historiques, inventaire des mouvements de versants sur terrain et par l'interprétation des photographies aériennes, l'utilisation d'un SIG (ArcGIS, ESRI) pour obtenir le MDE, différents cartes thématiques et analyse des facteurs déterminant de différents processus d'instabilité de terrain. Finalement les cartes de susceptibilité aux mouvements de versants ont été obtenues autour des villes principales de la province de Grenade pour les principaux types des mouvements de versants á savoir les écroulement, écoulements, glissements rotationnel et translationnel et aussi pour les mouvements complexes. L'analyse et la modélisation de la susceptibilité aux mouvements de versants est faite suivant la méthode de la matrice développée dans une SIG et validée spatialement avec des nouveaux mouvements avec des résultats fiables. On présente aussi une méthodologie pour la dérivation des cartes de alea et des risques dans les régions urbaines en utilisant les cartes de susceptibilité et le potentiel destructif des mouvements des versants sur la base de la magnitude et vitesse attendue des futurs événements pour les différents types de ces mouvements. Puisque la recherche a été faite à une échelle 1:50.000 les résultats ne sont pas prévus pour une connaissance précise des dangers à des échelles détaillées. Néanmoins, c'est possible d'identifier avec ces cartes des zones en villes avec plus haut dangers relatif pour encourager des programmes de contrôle et mitigation des glissements de terrain attendus et aussi réduire la vulnérabilité des régions urbaines affectées par ces processus.

Keywords: geological hazards, geographic information systems, engineering geology maps, land use planning, mass movement, risk assessment

INTRODUCTION

The Granada province, with a planimetric area of 12 635 km^2, is in the eastern Andalucía region of southern Spain. It shows a varied landscape including the Sierra Nevada mountain chain, where the Mulhacen mountain attains the highest height (3481 m) on the Spain Peninsula; several mountain chains of middle heights at the Mediterranean border (Contraviesa, Alpujarras, etc), and also to the north of province (Arana, Filabres, Baza, Segura, San Clemente, etc), all delimited by wide fluvial valleys, such as the Granada, Guadix, Baza and Ugíjar Valleys (Figure 1a). The climate shows varying conditions from continental to subtropical, with a low average annual rainfall (<450 mm p.a.), although relatively frequent heavy storms associated with "cold drop" atmospheric conditions which are developed in the eastern Mediterranean border of Spain do occur. The geology of Granada is also complicated, with metamorphic Alpine rocky formations cropping out in the core areas of Sierra Nevada and southern chains, and sedimentary formations of Mesozoic to Quaternary ages affected by a number of tectonic phases derived from the relationships between the Eurasian and African plates along the last Wilson cycle (Figure 1b).

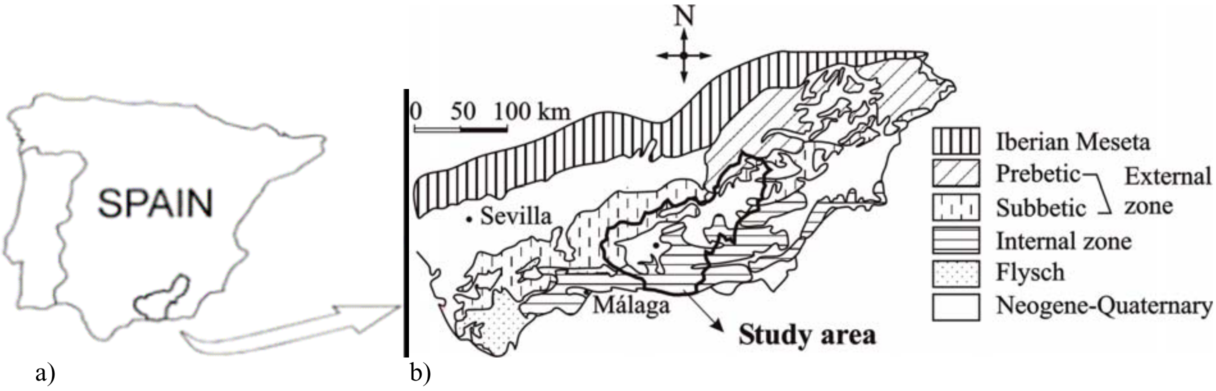

Figure 1. Geographic (a) and geologic (b) setting of the Granada province in South of Spain.

Holocene active tectonics are expressed through different seismic structures and the southern half of the Granada province comprises the most earthquake-prone area in Spain according to the official technical code for building under dynamic actions (NCSE-02). Basic horizontal accelerations from 0.16g to 0.024g are assigned by the code to the building projects for most of Granada province. Nevertheless the level of earthquake activity may be considered to be moderate when the frequency of magnitude above 5.0 is considered, and only two large regional earthquakes (the 1755 Lisbon earthquake and 1884 Andalusian earthquake) of catastrophic consequences have been recorded. More abundant are local shallow earthquakes with epicentres with depths around 10-12 km, causing fairly heavy damage and population loss at a local scale. The influence of the long term earthquake activity is registered in the geomorphology of the southern Sierra Nevada border, where the slopes and river valleys show an active tectonic dependence, as evidenced by a number of geomorphic indexes (Keller et al.; 1996; García et al., 1998 a, b; 1999 a, b; 2003; 2004; Chacón et al, 2000 a; El Hamdouni et al., 2000 a, b)

Table 1. Distribution of elevation units in the Granada province

Height intervals	Area (%)	Accum.A. (%)	Surface (km^2)
1 0 - 500	4.40	4.40	555.7
2 500 - 1000	43.71	48.11	5523.2
3 1000 - 1500	38.76	86.87	4897.5
4 1500 - 2000	8.92	95.79	1127.0
5 2000 - 2500	2.72	98.51	344.1
6 2500 - 3000	1.31	99.82	165.7
7 3000 - 3500	0.18	100.00	22.4
Total	100.00		12635.6

Considering a humid year, in the Table 2 shows the distribution of precipitation by area for Granada province.

Table 2. Distribution of registered amount of rain in millimetres by area of Granada province (Source of data; Hydrogeology of Andalucía, Junta de Andalucía).

Class	interval (mm)	Area (%)	Accum.A. (%)	Surface (km^2)
1	1 200 - 600	24.10	24.10	3045.1
2	2 600 - 1000	49.88	73.98	6304.0
3	3 1000 - 1400	14.87	88.85	1878.4
4	4 1400 – 1800	7.60	96.45	960.1
5	5 1800 - 2100	3.55	100.00	448.0
Total		100.00		12635.6

The is abundant evidence of landslides in the mountain areas of Spain (Cendrero et al., 1997), and therefore in Granada province (table 3), where the main triggering factors are flash rainfall storms (Lamas et al., 1998; Irigaray et al., 2000 a; Chacón et al., 2001) and earthquake activity. There are many cases of transient landslide activity and a limited number of cases of permanent slides with very slow displacements. The normal situation is represented by "dormant" or inactive landslides, or by ephemeral earth & mud flow masses that are quickly erased by erosion or cultivation.

***The Betic Domain or Internal Zone** (figure1)*

The predominance of landslide types associated with the rock massifs are rockfalls and translational slides, and also some debris flows and rotational slides. The tectonic boundaries between lithological units with different mechanical properties, such as marble, phyllite and schist, are frequently affected by instability processes. The Alpujarride tectonic units with thick phyllite and schist formations followed by marble at the southern border of Sierra Nevada, along the inclined slopes of the Guadalfeo river valley, show the highest level of instability, and during periods of heavy rain the roads and villages in these materials are heavily damaged. For example, in the last rainfall crisis between September 1996 and May 1997 (Lamas et al, 1998, Irigaray et al., 2000a), major impacts were observed at Otívar and Almuñécar. Along the Mediterranean coast of Granada several incipient slides affected a large number of villas in the late 1970's and early 1980's, when construction was underway to convert the old narrow coastal road into a modern roadway. These sliding processes were typically limited to the opening of tension cracks and the delimitation of a main head without any further development of the landslide. Nevertheless the damage to villas existing on the tension cracks was very important.

Debris flows are relatively frequent during heavy rain along the slope of the Alpujarra in the south of Granada, affecting roads and urban areas with damage of variable impact. The slopes around Sierra de Lújar and La Contraviesa are also places in which colluvial deposits are mobilized during heavy rain, flowing as debris onto roads with hazardous consequences. Creeping and solifluction processes are widespread distributed in Sierra Nevada above 2100 meters, although usually with only minor impacts.

The Prebetic-Subbetic Domain *(figure 1)*

The widespread abundance of formations with marls and clays within all the Mesozoic deposits, such as the Triassic Keuper; the presence of swelling clays in marl and limestone units from the Middle to Upper Jurassic to the Cretaceous; and the presence of Tertiary flyschoid sequences also with marl and limestone, is expressed in the abundance and extension of earth and mud flows in this domain. These represent 65% of the movements inventoried not only in the Granada province but also in Andalucia. The largest landslides in the domain are mainly earth flows (Olivares, 1986; Diezma, 1997). The rocky formations of the Lower Liassic or Jurassic dolostone and limestone are affected by rockfall and slides, and there are a high number of examples of slide flow in the aforementioned sequences of marl and limestone.

Neogene and Quaternary basins *(figure 1).*

These were developed since Miocene times during the post-tectonic uplift of the Betic Cordillera. These geographical depressions originated as branches of the old Tertiary sea, but then evolved to lacustrine and fluvial environments. Therefore, the sediments show this evolution with thick flyschoid sequences of marls and limestones with some evaporite layers, followed by increasingly coarse clastic deposits with silts, sands and conglomerate. The present borders of these basins are tectonically delimited from the Alpujarride units, and these boundaries are heavily affected by slope instability and geotechnical problems. Rockfalls and debris flows are frequent on the slopes of the northern border of the Ugíjar, Guadix and Granada basin, as also are earthflows and slide flows in the Miocene marl and limestone sequence (Chacón et al., 2001). The previously mentioned large earthflow of Olivares (1986) and Diezma (1997), although in the Subbetic Domain, are located very close to the boundary with the Granada basin.

Table 3. Area distribution of landslide masses in the Granada province

Landslide Type	Area (%)	Accum.A. (%)	Surface (km^2)
1 Rockfalls	0.39	0.39	48.891
2 Slides	2.21	2.26	279.816
3 Earth & Mud flows	0.74	3.34	93.476
4 Debris flows	0.39	3.73	49.838
5 Shallow very slow m.	2.32	6.05	293.677
Total	6.05		765.698

METHODOLOGY: LANDSLIDE INVENTORY, SUSCEPTIBILITY, HAZARD AND RISK

Landslide inventory

This research has focussed upon small scale (1:200 000) mapping as a part of the construction of the Atlas of Geological Hazards of the Granada Province, made in cooperation with the Spanish Geological Survey (IGME), although it was developed using a 1:20 000 digital elevation model (DEM). A landslide classification system based on Varnes (1978) was applied, whereby five basic movement types were distinguished: rockfalls; slides; earth & mud flows; debris flows; and shallow, very slow creeping and solifluction movements. Movements were considered to be complex if they resulted from a combination of two or more of the main types. The first stage in compiling the inventory consisted of interpreting the 1:18 000-scale stereoscopic aerial photographs. Once the movements had been mapped, a field campaign was carried out in order to verify the typology of each movement and collect further data (e.g. on activity, make a photographic record, take samples, etc.). The final inventory (fig. 2) based on the aerial photographs, and the field survey was then converted to digital ARCGIS (ESRI) format, introducing the appropriate number of control points in order to optimize the adjustment.

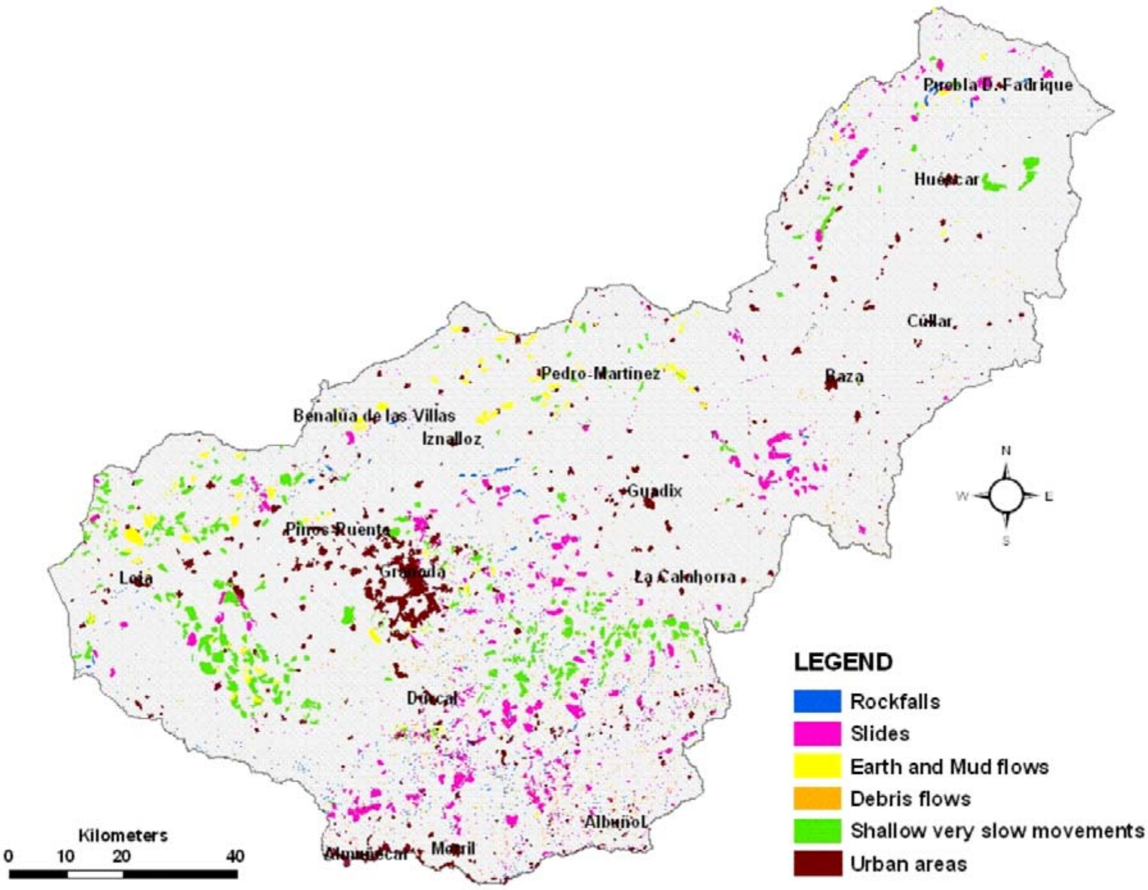

Figure 2. Landslide inventory of the Granada province (South Spain)

Landslide susceptibility

The concept of landslide "susceptibility" was originally design in the USGS to indicate "how prone to generate a landslide is a geological unit" (Brabb et al., 1972); this can be measured from the correlation between determining factors together with the spatial distribution of the movements (Brabb, 1984). The susceptibility level of a given terrain may be assessed using GIS analysis of the factors contributing to the susceptibility level or class in every particular slope unit (Chacón et al., 1993; Irigaray et al., 1994; 1996 a,b,c; Fernández et al., 1994; 1996 a,b; El Hamdouni et al., 1996). The determining factors used in this project for the GIS analysis were altitude, slope angle, slope aspect, slope curvature, lithology, tectonic units, aquifer units, permeability and geomorphic units.

The matrix method of susceptibility analysis (DeGraff and Romesburg, 1980, with GIS development by Irigaray, 1995) is a quantitative method for establishing an instability index for a given area. Although it cannot predict the landslide susceptibility in terms of absolute probability, it does enable relative potential instability to be calculated for a widespread area using a series of measurable factors. Once a set of factors has been identified that can condition a slope for landsliding, a matrix is constructed with each cell representing one possible combination of the classes of factors considered. From the landslide inventory, the area affected by movements can then be calculated for each combination of factors. The result is a landslide matrix. A similar procedure is used to construct the management unit matrix, representing the total area for each combination of factors. The landslide-susceptibility matrix has the same number of combinations as the management unit matrix. The value of each cell in this new matrix is obtained by dividing the values from the landslide matrix by those from the management unit matrix. Combinations that are not associated with landslides are assigned a value of `0' on the landslide-susceptibility matrix; the remainder will have values of >0, up to a maximum of 1 (or 100 per cent, if expressed as a percentage). The susceptibility matrix values represent the proportion of landslides as a function of the total area, and represent the relative susceptibility of each combination of factors. Since any given point in the study area is characterized by a certain combination of factors, the relative susceptibility at that point will be the one corresponding to that combination within the susceptibility matrix. The resulting landslide susceptibility map of the Granada province was expressed using five classes with the surface distribution shown in table 4, where the landslide incidence is referred as the percentage of surface of the combination of factors covered by landslides: <1%, 1-5%, 5-10%, 5-25% and >25%. It is observed that from a total surface area of 12635.6 km^2, 58% shows only minor incidence of landslides (< 5%), and only 1.13% is heavily affected (>25%), with 31% of the land affected having high susceptibility. After the analysis the degree of difference between the susceptibility classes in the map and the landslide inventory gives an assessment of the quality of the map.

Table 4. Distribution of landslide susceptibility classes in Granada province.

Class	Susceptibility	Area (%)	Accum.A.(%)	Surface(km^2)
1	Very low (<1%)	18.16	18.16	2294.8
2	Low (1-5%)	39.82	57.98	5031.4
3	Moderate (5-10%)	22.89	80.87	2891.9
4	High (5-25%)	18.00	98.87	2274.4
5	Very high (>25%)	1.13	100.00	143.1
	Total	100.00		12635.6

Landslide hazard and risk.

A landslide hazard assessment was generated using data regarding susceptibility level and the observed and expected landslides in every urban area with regards to size and speed. At the scale 1:200,000 chosen for the provincial landslide map, data about landslide vulnerability of the different elements at risks (roads, buildings, water supply, social services, etc.) in every urban area could not be included. Therefore an approach was adopted as a way to generate a preliminary assessment of hazard and risk based on a table of destructive potential of each type of landslide (table 5). In this way, using susceptibility maps obtained separately for rockfalls, slides and flows, and taking into account local assessments of the size and speed of each type of previously observed landslide event, and also considering local slope geomorphology, susceptibility and geotechnical properties, it was possible to give an approximate indication of the destructive potential based on the following definitions:

Very low: Accumulated damage is observed over time periods of more than 20 years that need repair, and long term maintenance of infrastructure and social service, particularly water and electricity supply, is required. No casualties are reported.

Low: Damages are observed over a time period of less than 10 years, and therefore there is an increasing cost of maintenance services. Generally no casualties are reported excepting eventual accidents derived from unexpected impacts of stone or small rocks. A general maintenance and surveying programme is required

Moderate: the damage observed over a period of 10 years is abundant, although without does not cause interruption of main services as water and electricity to the whole population. Some casualties may be recorded from a direct exposure to landslides. Specific maintenance of services is necessary, and studies of landslide risk in the urban context at a scale 1:5,000 are required.

High: The damage is abundant and significant. The interruption of services for days or weeks are observed repeatedly during time periods of less than 10 years. The number of casualties depends on the damaged structures and the urban areas affected by landslide processes attaining rapid to very rapid evolution and high levels of destructive energy. Specific maintenance of the services is necessary and also studies of landslide risk in the urban context at a scale of 1:5,000 are required. A survey and control programme for the evolution of the unstable slopes is required and works of mitigation and stabilization of the affected urban areas should be programmed in the mid to short term, and followed in order to reduce the vulnerability of the affected urban areas. Eventually, studies of alternative settlements of the more hazardous urban areas should be considered.

Very high: The damages are considered catastrophic, with total loss of the affected local social organization and services or infrastructures. The number of casualties may be high depending of the population in the affected slope and may attain an important percentage of the total population in the urban area. A specific maintenance programme for the services is necessary, and studies of landslide risk in the urban context at a scale 1:2,000 to 1:5,000 are required. Also a programme of surveying of the unstable slope is required with instrumentation of the control and warning system to anticipate the evolution of the landsliding process. Civil works for the stabilization of the instable slope should be programmed in the short term. An alternative settlement of the affected slopes in the urban area should be considered in case of very high costs of an effective mitigation program.

The assessment of landslide hazard in the urban areas was supported by the combination of the landslide susceptibility classes and the potential destructive capacity of the observed landslide types. Table 6 shows the expected consequences of these combinations. Because of the general lack of local data about previous landslides or detailed studies on the existence of unstable slopes in the urban areas the methodology proposed by Varnes (1984) was only partially followed. Instead of using the definition of natural hazard as the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon (Varnes, 1984), and a landslide risk map which shows the expected annual cost of landslide damage throughout the affected area and combines the probability information from a landslide hazard map with an analysis of all possible consequences (property damage, casualties and loss of service) (Spieker and Gore, 2000), a new method adapted to the current information was adopted. Following Einstein (1988) it was considered that a susceptibility class for a given landslide represents in a qualitative approach an expression of the corresponding landslide hazard as an increase in the susceptibility class for an increase in the probability of a new landslide on the corresponding slopes, as it is shown in table 8. Here, relationships between the susceptibility classes and the destructive potential of the landslide (DPL) defines the different landslide hazard classes.

Table 5. Destructive potential of the different type of landslides

m^3	SIZE	*Shallow very slow slope mov.*	*Earth & Mud flow*	*Debris flow*	*Rock fall*	*Slide*
1–50	*SMALL*	VERY LOW	LOW	MODERATE	MODERATE / HIGH	MODERATE / HIGH
50–500	*MIDDLE*	MODERATE	HIGH	HIGH	HIGH / VERY HIGH	HIGH
500–5000	*LARGE*	LOW	HIGH	HIGH / VERY HIGH	VERY HIGH	VERY HIGH
5000–50000	*VERY LARGE*	LOW	HIGH	VERY HIGH	VERY HIGH	VERY HIGH
>50000	*EXT. LARGE*	MODERATE	HIGH	VERY HIGH	VERY HIGH	VERY HIGH

As data on the vulnerability of the urban elements at risk are lacking the use of table 5, combined with data obtained from the landslide susceptibility map of the Granada province at 1:200 000 scale, is oriented toward a preliminary assessment of the landslide risk exposures of the urban areas.

Table 6. Landslide hazard classes by combination of landslide susceptibility and destructive potential

DPL	SUSCEPTIBILITY *LOW*	SUSCEPTIBILITY *MODERATE*	SUSCEPTIBILITY *HIGH*
Very low	LOW	LOW / MODERATE	MODERATE
Low	LOW	MODERATE	MODERATE
Moderate	MODERATE	MODERATE	HIGH
High	MODERATE	HIGH	HIGH
Very high	HIGH	HIGH	VERY HIGH

If all the urban areas in Granada province are considered as being a homogeneous continuum with similar vulnerability (what is far from realistic) a combination of tables 5 and 6 with data corresponding to a given locality is a preliminary tool for a local landslide hazard assessment. Also, it may be useful for the establishment of priorities for a mitigation and control program of landslide risks.

LANDSLIDE INCIDENCE IN URBAN AREAS OF THE GRANADA PROVINCE

Landslide susceptibility

In order to assess the incidence of landslides in the 168 urban areas in the province, a GIS analysis was undertaken taking as a reference the surface covered by these urban areas in the official Map of Andalucía at a scale 1:200,000. All the polygons corresponding to these 168 towns were selected and projected onto the landslide susceptibility map, indicating landslide incidence in urban areas. The GIS susceptibility analysis of urban areas was plotted into a three class ("traffic light") map comprising low (<5%), moderate (5-25%) and high susceptibility (>25%), where the percentages refer to the area of landslides relative to the total surface of the combination of factors in every class.

Table 7 shows the results obtained, which indicate an increasing projection of observed landslides with the increase of the relative susceptibility of the classes on the map in all the urban areas. The "degree of adjustment" between the surface extension of the different types of landslides and the combination of factors which define the three susceptibility classes are shown. The existence of 1.2% to 3.6% of landslides in the low class is mainly derived from the incidence of construction work on flat and low susceptibility units, which lead to changes in the slope morphology with induced instability processes.

Table 7. Percentage of surface area for five types of landslides in Granada province, and their correlation with the landslide susceptibility map.

Landslide type	Susceptibility classes		
	Low	Moderate	High
Rock fall	88.43 / 1.2	10.99 / 5.17	0.58 / 83.1
Slides	49.39 / 3.6	34.03 / 21.1	16.59 / 75.3
Earth & Mud flow	71.23 / 2.6	20.71 / 24.2	8.06 / 73.2
Debris flow	81.80 / 1.6	18.11 / 17.2	0.09 / 81.2
Shallow very slow m.	65.49 / 2.6	21.34 / 19.7	13.17 / 77.7

In order to show the incidence of landslide susceptibility in all 168 villages of Granada province a triangular plot of the villages is shown in figure 3 and the incidence in urban areas with more than 10 000 inhabitants is presented in table 8.

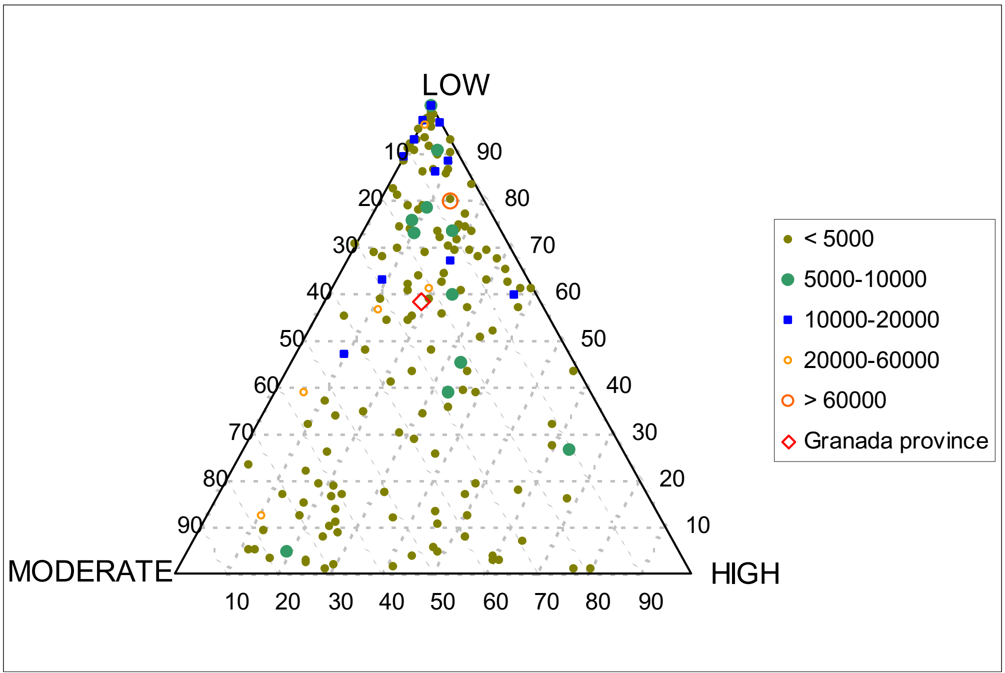

Figure 3. Landslide susceptibility diagram showing 168 urban areas in a triangular plot of surface extension of the susceptibility classes (low, moderate, high) as a percentage of urban area surface. The legend shows the number of inhabitants represented by the symbols (The capital of the province is Granada with 238,292 inhabitants). The average landslide susceptibility of the Granada province is also plotted.

An example of hazard assessment of a given urban area.

In figure 4 the susceptibility maps of the village of Benalúa de las Villas (1 377 inhabitants) are shown for the five type of landslides. The average incidence of the susceptibility classes on the 1:200 000 map of Granada province is distributed with 25.6% in the low class, 37.5% in the moderate class and a 36.9% in the high class. It is observed in figures 4 and 5 that there is a low incidence of rockfalls and debris flows; a predominantly low incidence of slides, with some in the middle susceptibility class; and predominantly middle to high incidence of earth and mud flows and shallow, very slow movements. Using tables 6 and 7 it is possible for the users of the map to establish several preliminary features of the landslide hazard and risk that may be expected in this town.

1. Rocksfall and debris flows: these are landslide types that are not expected to happen in the village because of the surrounding gentle slope morphology. A local field survey should enough to make clear this view and confirm the expected low hazard (fig. 4 A and D).

2. Shallow very slow slope movements of creeping and solifluction: following the susceptibility map in this village (fig 4E) more than a third of the urban area occupies a moderate class and another third is in the high susceptibility class. These imply that the existence of soils with marls and silty clays, combined with elevation and slope morphology, promote such very slow movements. The urbanization of the village with buildings, pavements, asphalted roads and ways, reduce considerably the availability of exposed soils affected by water infiltration and creeping processes. Nevertheless the presence of damage in fences or walls should be examined in order to implement a mitigation program, and control and maintenance of the water supply, sewer system and water irrigation of the abundant kitchen gardens that are present in many of the houses of the village is needed. The available evidence about this landslide type leads to the verdict that this hazard is low.

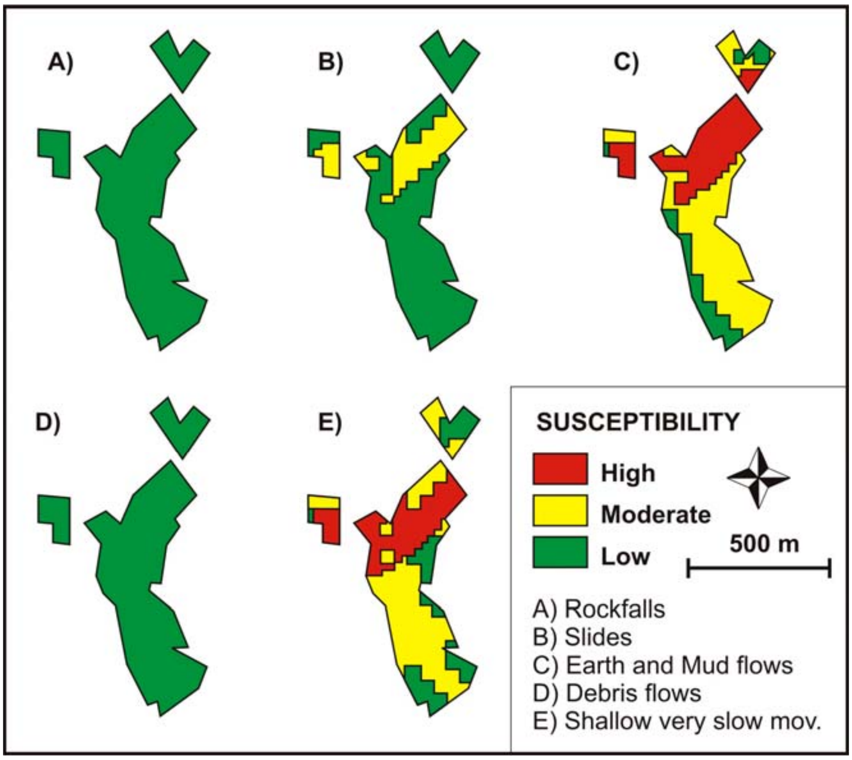

Figure 4. Landslide susceptibility maps in the village of Benalúa de las Villas (Granada, Spain).

Table 8. Distribution of the percentage of the land surface in each susceptibility classes in urban areas with a population of greater than 10 000 inhabitants in Granada province. (Population data from the last official census of 2004).

	SUSCEPTIBILITY (%)		
LOCALITY (population)	Low	Moderate	High
ALBOLOTE (14 862)	95.8	4.2	0.0
ALMUÑECAR (23 073)	27.5	63.1	9.5
ARMILLA (16 938)	100.0	0.0	0.0
ATARFE (12 355)	99.0	1.0	0.0
BAZA (21 600)	82.8	1.8	15.4
GABIA GRANDE (10 400)	89.5	6.3	4.2
GRANADA (238 292)	89.8	9.1	1.1
GUADIX (20 035)	97.0	3.0	0.0
HUETOR-VEGA (10 362)	91.3	8.7	0.0
ILLORA (10 072)	72.2	15.8	12.0
LOJA (20 707)	70.0	26.6	3.5
MARACENA (17 232)	99.8	0.2	0.0
MOTRIL (55 078)	90.1	9.9	0.0
OGIJARES (11 324)	95.0	5.0	0.0
PINOS-PUENTE (13 303)	92.1	7.7	0.1
SALOBREÑA (11 420)	49.5	49.4	1.1
SANTA FE (13 803)	100.0	0.0	0.0
ZUBIA (LA) (15 312)	66.7	33.2	0.1

3. Earth and mud flows (fig 4C) in this area are usually shallow and are associated with similar factors as the previous landslide types. The expected masses correspond in this case to small, middle and large sizes with decreasing annual probabilities as the associated return periods are 10 years, 30 years and above 100 years. The amount of rain, including both accumulated and daily rainfall, controls these processes. Therefore the hazard assessment in this case may be assessed as low, moderate or high in the low, middle and high susceptibility zones of figure 5 with risk consequences which may also attain high values depending of the size and speed of the expected flow. It is recommended the preparation of a landslide risk maps of the village and surrounding areas at a scale 1:5.000 based on geotechnical studies in order to obtain a detailed assessment of the landslide hazard.

4. Slides (fig 4B) observed in the surrounding areas are also associated with the geotechnical properties of the marly formations and the morphology of the slope. Combinations of planar slides and earthflows are possible and the

thickness of the mobilized material may attain metres or even tens of metres. Also, combinations of circular and planar failures are possible in more homogeneous units of marly, silty clays. In the urban area these features observed in the surrounding areas are recommended to be taken in account during the geotechnical studies for new foundations and civil works. In the lower part of the surrounding slopes at the limits of the urban area the appearance of minor cracks or deformation in walls, buildings and pavements are recommended to be surveyed and considered in connection to the stability conditions of the affected area. Depending of the destructive potential of the expected slide, which may range from low to very high, and speeds that range from very low to moderate, the resulting hazard may be variable between moderate and high. It is recommended to develop a reconnaissance of the geotechnical and slope stability conditions of the village and the preparation of a map of exposure to risk at a scale 1:5 000. Finally, the control of water filtration from the water supply or sewer systems, and from the irrigation of the frequent kitchen gardens in the village, is desirable.

DISCUSSION AND CONCLUSIONS

This paper gives a general picture of the landslide incidence in the Granada province (South Spain). A landslide susceptibility map at a scale 1:200 000 developed in a GIS was useful because of the higher base resolution of the application, with DEM inventories and thematic maps at scales 1:18 000, 1:25 000 and 1:50 000. It was possible to obtain particular details for every of the 168 towns and villages composing Granada province. The landslide susceptibility GIS mapping method applied in this research has been successfully employed in different areas (Irigaray, 1995; Fernández et al., 2003; see references below), and validated both internally and externally, in this case by checking the fit of new landslides in previously obtained susceptibility maps (Irigaray et al., 1998 a, b; 1999; 2000 b). The methodology to derive large landslide hazard and risk maps and assessment in the Betic Cordillera (Chacón and Irigaray, 1999; Chacón and Corominas, 2003; Chacon et al., 1993, 1994, 1996 a,b; 2000 b, 2006) is not useful for this case because of the large surface of the Granada province (12636 km^2), and therefore some simplifications were assumed in order to obtain a broad picture of the landslide incidence useful as a preliminary tool. The concepts of landslide size and destructive capacity used here are similar to the terms “magnitude” (Fell, 1994; Bell and Glade, 2004) and “intensity” (Cardinali et al, 2000; Corominas et al., 2003., Castelli et al 2002, 2004; Bonnard et al.,2004, Hollenstein, 2005) although no precise data about landslide velocity are included. Therefore, it is only possible to have a preliminary assessment of the hazard and risk considering that the increase of susceptibility of terrain to generate a give type of landslides increases the level of hazard and also that the at a given size of the landslide its hazardous consequences increase with the type and its usual speed. In this sense the type: shallow very slow slope movements comprise creeping and “solifluction” processes is associated to long-term low hazard and risk. The types rockfalls and debris falls include mass movements with higher velocities than earth & mud flows or slides, and therefore the associated hazard and risk are also higher for a given mass. Detailed mapping and surveying prior to any decision at local level are required.

The usefulness of the research may be pointed out and the following conclusions derived:

1. A general picture of the incidence of landslide in the urban areas of the Granada province is obtained from the landslide susceptibility map at scale 1:200.000 of the Granada province (South Spain).

2. A preliminary view about the susceptibility of the terrains surrounding the 168 localities of the Granada province is available and it is shown that at least 14 villages and cities are exposed to high level of landslide susceptibility (Figure 3).

3. The basic resolution of the 1:200.000 is 25x25 meters making possible to obtain local susceptibility maps for the different type of landslide. An example is given in figure 4.

3. A landslide hazard assessment (table 6) is based on relationships between local susceptibility level and destructive potential of the different type of landslide (table 5) from which a preliminary tool for the provincial program of landslide control and mitigation may be obtained.

4. The criteria for the use of these tables and method of hazard assessment and risk evaluation are given and in all the cases of combinations of susceptibility and landslide type from which moderate to high landslide hazard are assessed. detailed mapping and surveying are required for any further decision on the risk control and mitigation, which may be supported also on detailed studies of the vulnerability of the affected structures and services.

Acknowledgements: The work presented in this paper was carried out with funding from “University of Granada Environmental Research Group: Geologic Hazards and Terrain Engineering, code RNM121 of the Andalusian Research Plan” and the project REN2002-03366 “Landslide and active tectonic in Guadalfeo basin: Vulnerability, and associated risks”. A contract with Spanish Geological Survey (IGME) and the Provincial Council of Granada throught the Foundation Entreprise-Universit of gRanada is also acknowledged.

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