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Landslide susceptibility zoning for risk analysis using a geographical information system (GIS) in the Jerte Valley (Spanish Central System)

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Abstract

The Jerte Valley is a linear tectonic depression (NE-SW), generated by several fracture systems associated with the Odemira-Plasencia fault which is one of the most important in the Iberian Peninsula.

One of the most significant processes in the Quaternary evolution of this valley is that of mass movements. An analysis of the natural factors controlling these processes in this area reveals that, in current conditions, major mass movements are unlikely to be generated. However, our working hypothesis considers that a phenomenon with catastrophic consequences is feasible, chiefly due to anthropic activity; in recent years there has been a process of replacement of the natural vegetation with cherry-tree plantations and considerable urban and road infrastructure development. Therefore we have commenced a series of studies on landslide hazards in the Jerte Valley. The first step, the results of which we present here, was to divide the area into zones based on the values of certain causality indices or factors (what some authors call zonal susceptibility or propensity). The cartographic zoning was carried out using a GIS which, based on the most standardised procedures.

1 Introduction

The basic objective of work on natural risks is to prevent or at least reduce to a minimum the "damages" that can be caused by natural phenomena. It is therefore evident that in this area there are three aspects to be taken into consideration: the

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natural dynamics or "physical processes" and their effects on a particular area; the human activity or "anthropic processes" which may be exposed to these effects; and the true magnitude of the interference between the two processes.

Since the 1970's the most commonly used methodology for Risk Evaluations is that proposed by the UNDRO and Unesco; this methodology [1][2] is summarized as follows (1):

$$Rt = E \cdot H \cdot V \qquad (1)$$

where: Rt, total risk; E, elements at risk or exposition; H, natural hazard; and V, vulnerability.

The efficacy of this proposal is borne out by numerous studies. However, as some specialists have pointed out (see, for example Bersani & Vesseron [3]), there are specific situations and aspects which require other supplementary methodological approaches. This is our own view, for various reasons:

- The complexity of certain processes sometimes makes it very difficult to quantify H, in which case it is necessary to use qualitative appraisals.
- The risk issues are linked to "natural catastrophe" issues which, in turn, are associated with the existence in many populations and regions of a "culture" based on experience, signs and narrations of these events. This culture can significantly facilitate the putting into practice of measures to prevent or mitigate catastrophes but, at the same time, it may give rise to certain limitations due to the particular features of these populations "used to living with risk".
- The methodology proposed by UNDRO-Unesco is a quantitative procedure very well adapted to evaluate the economic damage in monetary terms. However, in certain situations these economic aspects are secondary, since the important factor is the conservation of certain resources: landscape, monuments, archeological remains, unusual ecosystems, highly productive soils, etc. For example, in Environmental Management studies natural processes and their hazardousness (established by various different quantitative or qualitative procedures) are considered to be a "limiting factor" which serves to restrict the expansion of human activity.
- In risk analyses there are various different levels or stages and it is not always necessary or possible to perform all of them (risk assessment or total risk) in order to recommend certain measures; in many cases it is enough to have cartography indicating the potentially affected area (susceptibility or propensity maps), in others hazard maps, and in others it is sufficient to establish natural hazards or hazard assessment.

If we apply these considerations to the Jerte Valley, which is the area in which the work we present here is located, the following observations can be made:

- In this Valley large mass movements are not recent phenomena (historical) and, accordingly, there is no "social awareness" regarding these risks. The proposal to introduce restrictive measures based on the "potential hazardousness" of these phenomena is not easily accepted by the population and by the administrative bodies.

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- To a considerable extent, as will be detailed later, the hypotheses we are using consider anthropic activity as a triggering cause of a whole set of processes; the natural risks in question are therefore induced. This is due to the major changes which have occurred in recent years in the Valley, with the replacement of the natural or "seminatural" vegetation with cherry tree (*Prunus avium*) cultivation. Since the ecological effects of this change are significant, an Environmental Management is necessary to assess these effects and regulate this cultivation. In this case, the most important data which can be provided by a risk analysis are those relating to natural hazards or hazard assessment.

According to the UNDRO and Unesco [1], "the natural hazard means the probability of occurrence within a specific period of time and within a given area of a potentially damaging phenomena."

Also, according to Varnes *et al.* [2], "the hazard zonation means the division of the land surface into homogeneous areas or domains and their ranking according to different degrees of hazard."

Finally, according to Carrara *et al.* [4] "the hazard maps should both display the location of actual and potential slope-failure, and provide information on the time or probability of their future occurrence (return period). In other words, these maps establish or should establish *where* and *when* the phenomenon occurs; if not, "the work is limited to preparing *susceptibility or propensity maps* and must avoid using the term *hazard,* since this implies a "quantitative prediction" [4]. Based on these considerations, the work we present here should be seen in this context of analyses of susceptibility or propensity to the occurrence of potentially hazardous phenomena, such as mass movements, in a particular area: the Jerte Valley.

2 Physical setting of Jerte Valley

The Jerte Valley is an intramountainous depression of 437.85 km^2 of area, located at the western end of the Gredos mountain range. This mountain range forms part of the Spanish Central System, which is a "block mountain" type intraplate orographic belt which arose during the Cenozoic era (basically in the Miocene and Pliocene periods) due to the reactivation of old tardyhercynian fractures.

All these areas belong to the geological region of the Iberian Peninsula known as the "Hesperico Massif" (figure 1) which is an old massif of Paleozoic origin (it formed part of what some authors have called "the great European Hercynian Mountain Range") but with some inherited pre-Paleozoic features.

The origin and course (NE-SW) of the Jerte Valley are controlled by the "Plasencia fault" or "Odemira-Plasencia fault", which is one of the major strick-slip faults which originated at the end of the Hercynian Orogeny [5]. Due to its length and evolutionary history, it is also one of the most important tectonic structures in the Iberian Peninsula. During the Mesozoic era it initiated a "rifting" process which was subsequently interrupted; when the Central System was formed (between the Paleogene and the end of the Pliocene periods) during the Alpine Orogeny, this fault acted with a strike-slip movement which

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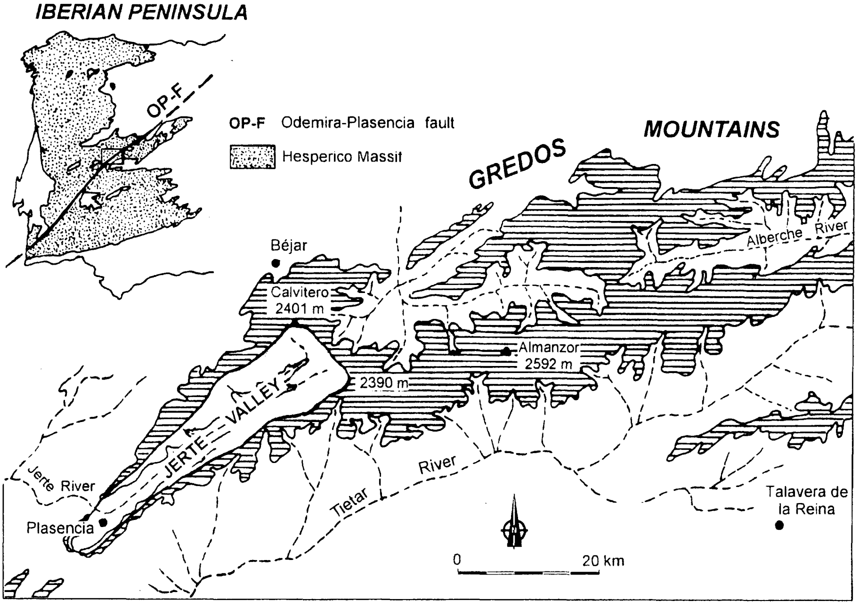

Figure 1: Situation of the Jerte Valley in the "Hesperico Massif".

generated "pull-apart type" compensatory basins [6][7][8]. At the end of the Pliocene or the beginning of the Pleistocene period the tectonic system in these areas became distensive, giving rise to significant sinkings which form the main intramountainous depressions in the Central System, one of which is the Jerte Valley [9][10]. Lastly, in the Upper Pleistocene and the Holocene the distensive tectonic system continued, but with scant activity and in certain locations only, as is evidenced by the low seismicity recorded in the Valley.

According to data of the Spanish National Geographical Institute [11], only one earthquake has been recorded in the Jerte Valley, on October 11, 1997, at 10:54:07 (universal time). The epicenter was in the extreme SW of the Valley in the town of Plasencia, at a depth of 2 km, with Mb of 2.9 on the Ritcher scale. The maximum intensity experienced in this area is V on the European Macroseismic Scale (EMS).

The orographic alignments which bound the Valley are arranged in a series of levels which descend steeply from 2,200-2,300 m in the north-east to 600-650 m in the south-west. The morphology of its versants or sides is determined by a succession of small plains (shelves or shoulders) and articulated scarps (with developments at times over 600 m and gradients over 30%), which define a series of steps joining the summits to the valley bottom.

The lithology is basically granitoid (there are numerous biotitic granites with two micas), with some outcrops of metamorphic rocks distributed mainly in the

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south-west area of the valley. Generally speaking, all these rocks are fairly weathered, but above all the granite rocks in areas (or bands) controlled by the network of fractures which are transformed into highly fragmented and decomposed materials (grus).

The climate is the mountain variant of the continental Mediterranean climate, although the strong altitudinal contrasts give rise to significant thermometric and pluviometric variations; ranging from annual averages of 16° C and 600 mm in the SW to 6° C and 1800 mm in the NE.

Biogeographically the Jerte Valley belongs to the Mediterranean Region and the climax vegetation formations are structured in accordance with the bioclimatic seam layers typical of this region [12].

The natural vegetation of the Jerte Valley has been modified by anthropic action over the centuries. The first changes commenced with Roman and Moorish colonization (approximately between the 3rd-4th C B.C. and the 11th C A.D.) when part of the forests of oak (*Quercus pyrenaica*), holm oak (*Quercus ilex*) and cork oak (*Quercus suber*) were replaced by terraced cultivation of chestnut (*Castanea sativa*), grapevine (*Vitis vinifera*), olive (*Olea europea*), cherry (*Prunus avium*) and other fruit trees. Between the 12th and 16th C the process of deforestation intensified throughout the Valley as the cultivated areas (unirrigated and irrigated land) and pastureland (livestock) were extended; in the 18th C the "Tinta" (a disease caused by the *Phytophthora cambivora*) led to the disappearance of most of the chestnut trees and the extension of other types of tree, particularly cherry. In the 19th and 20th C deforestation continued due to the demand for wood and the increasing of cherry tree cultivation; lastly, since 1950 —and above all since 1970—, cherry tree cultivation has spread spectacularly and is today the main production activity in the Valley.

3 Background

Mass movements are one of the most significant processes in the development of the slopes in the Jerte Valley. In all, 830 cases have been mapped [9][10][13] which occupy 23% of the total surface area of the Valley, of which 8.15% corresponds to rockfalls, 7.72% to avalanches, 5.51% to landslides, and 62% to flows.

In detailed studies carried out recently, three mass movement sequences or "generations" have been defined. The first of these, possibly from the Lower to Upper Pleistocene, relates to *debris avalanches* and *landslides* with deep ruptures, of significant size (the surface area of the tongues ranges from an average of $0,3x10^6$ m^2 to, in exceptional cases, $3x10^6$ m^2), uniform distribution in space and associated with fault scarps. The second, which is more recent and possibly from the Upper Pleistocene-Holocene period, are surface *debris avalanches* of smaller size (from an average of $0.02x10^6$ m^2, occasionally reaching $0.1x10^6$ m^2), unevenly distributed, but located on fluvial versants. Lastly, the third generation are the current phenomena (including events in historical times), which fall into two types: new mass movements (*rock falls*, *debris flows* and *debris avalanches* associated with *debris floods* have been

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observed), similar to those of the second sequence but of much smaller size (around $6x10^3$ m^2), and instability or "reactivation" in the materials of the tongues originated by the mass movements of the first and second sequences; this instability is usually a very slow flow or creep movement.

The lithology (grus), the morphology and morphotectonics (gorge scarps, fluvial channel trenches, fault and fault line scarps, seismicity), the climate (temperature and precipitations), the hydrogeology (differential permeability between unweathered rock and grus), the hydrology (pluvial, fluvial, fluvioglacial and pluvionival runoff), and human activity (deforestation due to agriculture, grazing and forestry, public works, etc.), are factors which have regulated the evolution of the versants in the Jerte Valley throughout the Quaternary period and, therefore, the mass movement processes. The importance of each of these factors has varied over the years, allowing us to establish the following dominant genetic associations: mass movements of the first generation and seismicity, mass movements of the second generation and fluvial entrenching, and mass movements of the third generation and human activity.

With regard to risk analysis, on the basis of field direct observations, it can be deduced that the maximum activity and hazardousness is posed by the debris avalanches and the balance ruptures (or "reactivation") in the old tongues.

The *debris avalanches* must be taken into account since they take place as a rule on gorge sides due to fluvial trenching. They are extremely rapid, difficult to predict, and can subsequently give rise to *debris floods* with considerable destructive effects in the channel and its banks which in many cases are cultivated. This is what happened, for example, in the early morning of January 24, 1996, in the Jubaguerra stream, and the effects caused it to flow into the Jerte river 2.5 km downstream. The morphology of the channel and its banks (between 25 and 100 m wide) was substantially transformed and all the cherry tree cultivation and the related infrastructures were lost. Although this process may now be exacerbated by the deforestation on the slopes, it is a natural phenomenon (as shown by historical and geological data) triggered by the exceptional spates in certain streams [9]. We should point out that the case described above is not an isolated phenomenon. There are other noteworthy instances such as that which occurred in the early morning of January 29 in the Balaflor gorge, and several along the Bonal and Cubo gorges. Based on personal references we have received, they took place around 1939.

The "reactivated tongues" must be taken into account since they are located in areas of intense anthropic activity. Their effects can be perceived in numerous infrastructures created for cherry tree cultivation (ruptures in terraces, invasion of tracks and roads, etc.). Minor destabilizations (rock and soilfall, slump, debris slides and avalanches, etc.) also occur when acted on to generate artificial taluses for means of communication and building construction. Together with these phenomena, other less perceptible and more worrying features can be detected. A series of morphological changes are taking place over the whole of the tongue, especially on the toe and on its ridges, cracks and scars, which suggest widespread and increasing destabilization. This is a working hypothesis, which considers that the human activity is likely to be the triggering factor of mass

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movements ocurrence of some magnitude and, in any event, highly hazardous and involving a high risk, since they would affect some population centers.

If progress is to be made in this connection, we consider that some of these areas should be monitored. This year we have prepared, in collaboration with other European colleagues, a project (LEMON, 2000) under which, if funding is obtained from the European Union, a highly efficient system would be installed to monitor and control these phenomena. It is based in a central recording system which would provide us with the data obtained through inclinometric tubes and vire extensiometers with Global Positioning Systems (GPS); it also includes piezometrical measures and cartographic control of the morphology of the tongue. The efficiency of these controls might be very limited unless we use as a starting point fundamental information, i.e. knowledge of the critical areas or those in which the phenomena identified as problematic are most likely to occur. The work we present here addresses this issue and was prepared using a Geographical Information System (GIS).

4 Procedure for preparing susceptibility maps

As has been described in detail in various different treatises on GIS [14][15][16], these techniques are the most appropriate for addressing phenomena which are distributed in space over the earth's surface and approached from a multivariable standpoint. This, inter alia, is the case of natural risks, and specifically those caused by mass movement processes [17][18].

The main problem to be resolved in most of these procedures is the definition and evaluation (quantitative or qualitative) of the instability factors (variables or parameters) involved in the phenomenon, in order thereby to determine its influence (weight) on the end result of the process being researched. As regards landslide hazards and the zonation thereof, the factors involved have by now been practically standardized (see, for example Varnes [2] and Carrara *et al.* [4]). This is not the case with the estimation of its influence (weight), which, furthermore, can vary depending on the regional context. In this respect, the procedures more widely used are those that follow deterministic or geotechnical models (based on the studies by Fellinius, Terzaghi, Taylor, etc.; see [19]) and probabilistic or statistic models (for instance those by Campbel, Carrara and collaborators, Kojan, etc.; see [19]).

The parameters considered in the Jerte Valley are the result of applying the general knowledge to a specific situation. With respect to the influence of each parameter in the process, when the data population available is consistent, they have been determined statistically (as is the case of reactivations), but where this is not possible due to the scarcity of events (as is the case with the present avalanches), a qualitative estimation has been made based on field observation and comparative analysis.

The IDRISI 32 software, which was also employed for the statistical treatment and implementation of the results thereof, was used for the integration and management of this spatial information.

As pointed out earlier when describing the problems relating to the Jerte Valley, there are two groups of active processes to be considered: the "possible

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reactivations" of the tongues of old landslides and avalanches, and the "possible occurrence" of new avalanches in torrential gorges.

4.1 Possible reactivations of the tongues of old landslides and avalanches

According to the surveys made of the area, certain first- and second-generation mass movements have stabilized (i.e., are "inactive", to use the terminology of the Unesco Working Party on World Landslide Inventory [20]). However, other movements show a slow creep-type flow conditioned by gradient and orientation ("suspended or dormant" [20]). In some cases there are signs of a marked acceleration in the movement, which could indicate a reactivation ("reactivated" [20]) of some magnitude and hazardousness. We associate this second phenomenon with the destabilization introduced by anthropic activity. The development of the cartographic model is represented in figure 2.

4.1.1 Compilation of the initial information (data adquisition)

A digital map is used showing all the tongues of landslides and avalanches of the prior mass movements (landslide inventory): all the cases obtained from the Geomorphological and Active Processes Map [9][10] are considered.

Based on this map and on field work, another more detailed map is drawn up showing only those tongues with evident signs of present movement, in order to subsequently deduce, using IDRISI 32 spatial analysis modules, the influence of the factors involved in the reactivation of those deposits.

Using the scale 1:25,000 National Topographical Map, a Digital Elevation Model (DEM) is obtained which is used as a basis for drawing up its derivatives maps of slope and aspect.

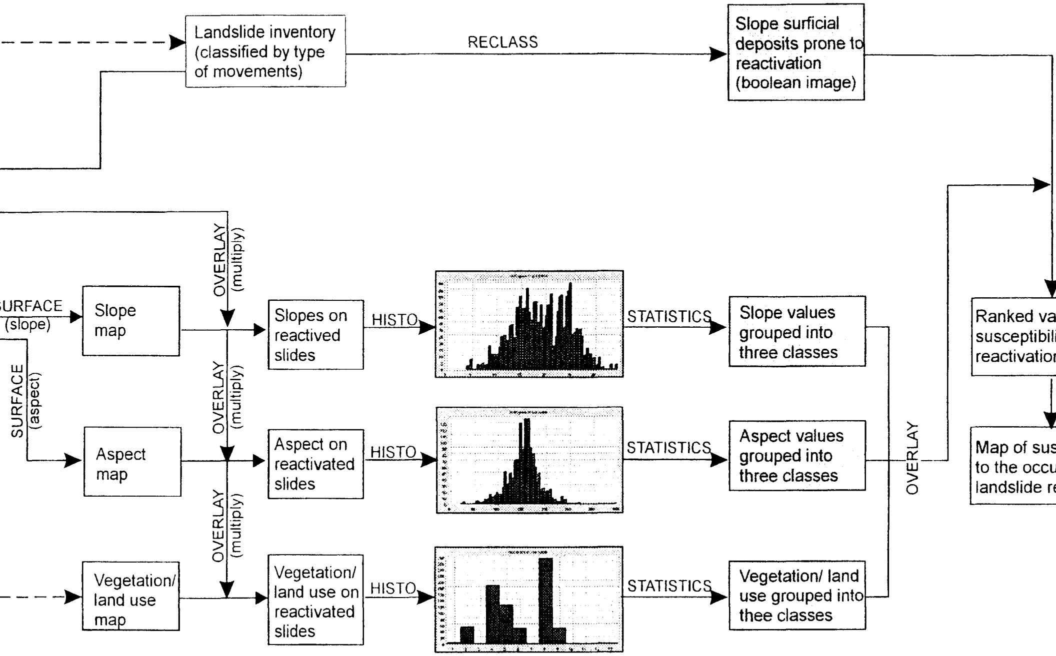
Lastly, a detailed map of vegetation and land use (types of cultivation) is prepared, which is also stored digitally.

4.1.2 Influence of the factors involved in the process

The instability factors and their analysis are as follows.

Slope. Due to the terraced morphostructure of the Valley, the tongues of certain prior mass movements have not attained their stable gradient. To determine the critical slope at which reactivations occur, the statistical modules of images contained in IDRISI 32 were used and the values of slopes representing pixels of reactivated masses were analyzed. The results obtained, while the reactivations occur in the form of landslide, flow or creep, are interpreted as follows: the reactivation of new masses requires greater humidity in the subsoil, which occurs in northern orientations, so that critical slopes are lower in NW facing slope.

Orientation. The orientation values critical for reactivation into each slope, i.e. those which would condition movements today, are obtained in a similar way to the slope analysis: only the pixel orientation values relating to masses in movement are shown, and a frequency histogram is obtained.



graphic model of the procedures and operations carried out outside and inside the IDRISI 32 GIS
sceptibility to mass movement reactivations. Dotted rectangles and lines represent data adquisitio
ersion to digital form; raster images are represented by rectangles. Particular operations using I
les are written in upper case. Sometimes, specific module names are also written (e.g. multiply). E
ifferent behaviour of each slope in the Jerte Valley, the model shown here has been applied to
nt (NW and SE slopes), and has finally been joined.

Fruit tree cultivation. This can trigger the reactivation of the tongues of old mass movements. The reasons for this are as follows: cherry-tree and olive-tree cultivation, among others, involves road infrastructures and terracing, which introduce significant morphological and hydrogeological changes in the tongues and, in some cases, can modify the previous steady state; the root structure of the cherry tree *(Prunus avium)* is much closer to the surface than that of the chestnut *(Castanea sativa)* or oak *(Quercus pyrenaica)* and, accordingly, it contributes less to stabilizing the slopes; under the cherry-tree plantations the tongues of the old mass movements are not as well drained as under the oak and chestnut woods, since the evapotranspiration in the cherry-tree woods is less due to ecophysiological and woodland density differences. In this case, using once again the frequency histogram of vegetation and land use onto masses in movement, three categories are obtained according to whether or not they can trigger the process.

4.1.3 Overlay and results

Concerning mass movement behaviour, because of the differences between each versant of the Jerte Valley (verified through Mann-Whitney test), the model has been implemented for each of them (see table 1 for results). The spatial concurrence of critical slope and orientation values with areas subject to significant modification of their vegetation cover gives rise to locations in which all the determining factors leading to reactivation are present. By overlaying these determining factors to the map of landslides and avalanches of the prior mass movements, we can define the most probable or critical areas for reactivation to occur (figure 3).

4.2 Possible generation of new avalanches in torrential courses

The data obtained from the study and genetic interpretation of second-generation mass movements and from the control and measurement of certain present-day avalanches (in particular that of the Jubaguerra stream; see section 3) allow us to establish exceptional floods in certain gorges as a factor triggering these phenomena. Determining factors are: the existence of movable material; slope; and human activity (since it modifies the water balance in the soil due to the change in the vegetation cover). The cartographic model and the sequence followed is represented in figure 4.

4.2.1 Compilation of the initial information (data adquisition)

Although the model is different, much of the basic information is common to that of the model developed previously. This is the case with the DEM (and the slope and orientation maps derived from it), the vegetation and cultivation (land use) map, and the digital cartography showing all the slope surficial deposits. In addition, the following maps and data had to be obtained and subsequently stored in digital format: maps of fractures (in order to obtain weathered areas), of the hydrographical network (in order to obtain areas potentially subject to

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exceptional floods) and climatic parameters (rain/snow precipitation amount and regime).

Table 1: Classification of the values of slope, aspect and vegetation/land use factors in categories taking into account their influence to the reactivation of mass movements. The results come from statistical analysis of the image histograms (see figure 2). 0, no influence; +, slight influence; + +, significant influence. For aspect: +, mean ± standard deviation; + +, mean ± 2 standard deviation. For slope: +, mean - standard deviation; + +, mean - 2 standard deviation. For vegetation/land use: 0, no area; +, 0 - 5 % of the total area included in active mass movements; + +, > 5 % of the total area included in mass movements. VLC, Vegetation/Land use categories; AR, area rate. Note the influence of categories 8 (cherry tree cultivation) and 10 (mixed fruit tree cultivation) in active movements in the SE slope, and 9 (olive tree cultivation) in the NW slope. The study of the influence of vegetation/land use factor was carried out as an independent factor of slope and aspect.

ASPECT			
SE Slope		**NW Slope**	
221-91°	0	48-221°	0
91-123°	+	221-268°	+
123-188°	++	268-1.7°	++
188-221°	+	1.7-48°	+

SLOPE			
SE Slope		**NW Slope**	
0-8.6°	0	1-1.6°	0
8.6-14.1°	+	1.6-6.9°	+
>14.1°	++	>6.9°	++

VEGETATION / LAND USE				
	SE Slope		**NW Slope**	
VCL	AR		AR	
1	1.8%	+	0.4%	+
2	4.1%	+	2.2%	+
3	-	0	-	0
4	4.8%	+	2.1%	+
5	5.1%	++	2.1%	+
6	-	0	4.9%	+
7	-	0	-	0
8	6.5%	++	4%	+
9	0.6%	0	8.5%	++
10	7.4%	++	-	0
11	-	0	-	0
12	-	0	1.6%	+
13	-	0	0.3%	+

4.2.2 Influence of the factors involved in the process

The factors triggering the process are grouped together by the cartographic superposition of the critical slope areas and the valley bottoms potentially subject to torrential floods.

The prone slope map, is obtained by reclassifying the slope map; the critical gradient for the occurrence of these phenomena is over 21°, according to Carrasco [10].

The gorge bottom map, is obtained by applying to the hydrographic network map a 50-meter buffer, which shows the area potentially affected by fluvial and torrential action in flood periods.

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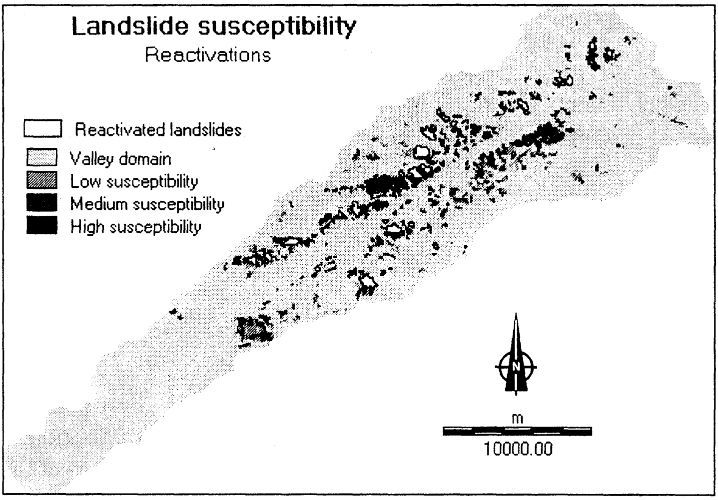

Figure 3: Output map from the model displayed in figure 2. Susceptibility to the occurrence of landslides reactivations in the Jerte Valley.

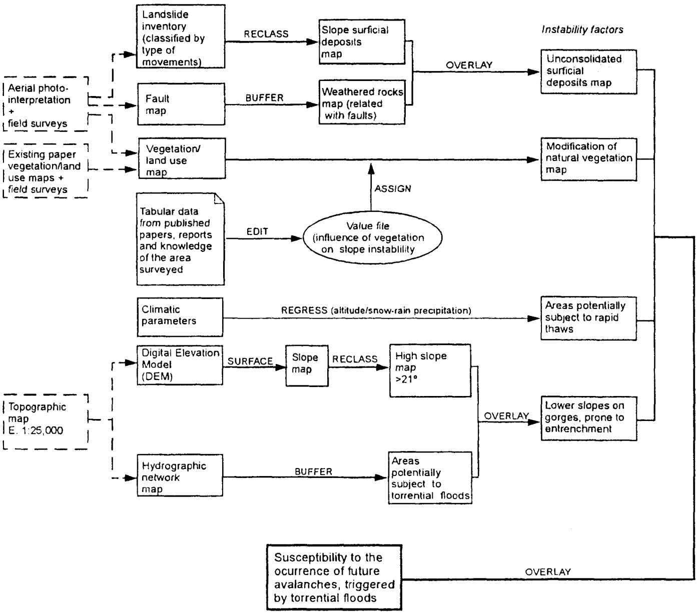

Figure 4: Cartographic model of the procedures and operations carried out outside and inside the IDRISI 32 GIS for the susceptibility zoning to the occurrence of avalanches. Dotted rectangles represent data adquisition and their conversion to digital form; raster images are represented by rectangles, values files by ovals and tabular data by a page with the corner turned down. Particular operations using IDRISI 32 modules are written in upper case. Sometimes, specific module names are also written (e.g., multiply).

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To identify the determining factors, the following were used:

Map of unconsolidated surface deposits. The material susceptible to being moved as an avalanche is a mixture of debris consisting of slope surficial deposits or a regolith generated by weathering favoring fractures (grus); the cartographic superposition of the two parameters determines the working map. The weathered areas (or bands) were obtained by creating a 100-meter buffer on the fracture map showing the average width of the weathering bands according to the fractures, determined by surface measurements taken in the field.

Modification of natural vegetation map. Human influence on the vegetation can be summarized as the removal of the original woodland covering and its replacement with pasture land, brushwood and cultivation. This transformation has led to lower resistance of the soil to movement, since it has been denuded. In this case, two categories of modification (significant and no significant) have been established.

Climatic factor map. This is undoubtedly the most difficult to evaluate, since it has not been possible to determine critical maximum intensities. Generally speaking, as can be deduced from recent events, the occurrence of these phenomena is associated with climatic situations involving rapid thaws due to the almost instantaneous succession of two storms, one north Atlantic (subpolar cold front) and the other south Atlantic (subtropical warm front), the first bringing snow and the second rain, favoring thawing and increased flow in river courses. Due to its orientation (NE-SW), these situations are frequent in the Jerte Valley and arise mainly in winter (above all in December and January). They also occur in spring, although in this second case their effects on instantaneous increases of flows in river courses are less significant, since the height at which snow falls is much greater (from an average of 1900-2000 m) and the surface covered much smaller. During this winter phenomenon of a change in the climatic situation, the middle band of the Valley suffers most from its effects; in lower areas (under 800 m) precipitations are in the form of rain practically all year, while in higher areas (over 1800 m) winter precipitations are rarely in the form of rain even with this change in the climatic situation. Based on these data (summarized from those contained in the National Meteorological Institute yearbooks), it is possible to establish a zonation of maximum probability with respect to these factors which encompasses the band of the Valley comprised between 800 m and 1800 m.

4.2.3 Overlay and results

As in the case of reactivations, cartographic superposition through the GIS of triggering and determining factors shows the areas with greatest susceptibility to the occurrence of avalanches (figure 5), such as the one which took place in the Jubaguerra stream. In this one two categories were obtained (high and low) based, above all, on the heterogeneity of the anthropic factor and the extent of the changes to the vegetation cover.

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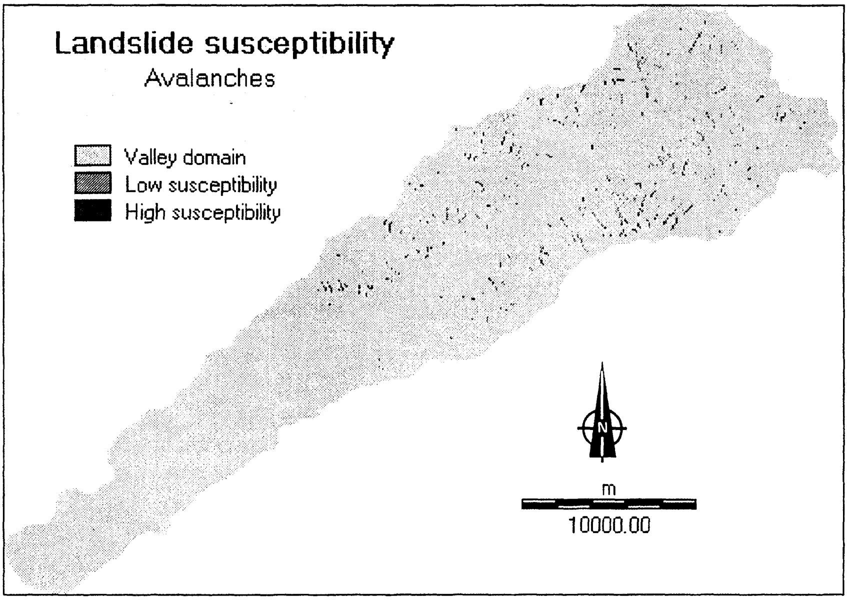

Figure 5: Output map from the model displayed in Figure 4. Susceptibility to the occurrence of future debris avalanches in the Jerte Valley.

5. Conclusions

The procedures applied in this work come fairly close to establishing a series of critical areas which will have to be duly monitored in order to control their dynamics. Should it be possible to carry out this second stage, we will accumulate a sufficient data population to enable us to quantify more exactly the intervention and contribution of each variable in the model representing each phenomenon; we would then be able to undertake a *hazard zonation.* This ould allow us to conduct a subsequent risk analysis on a detailed scale in the areas initially considered to be the most critical. This would be the case with certain villages in the Valley, such as Rebollar, El Torno and Cabrero, among others, situated on and under tongues of mass movements susceptible to reactivation.

In any case, the data obtained to date can be used to draw up a proposal to restrict cultivation and infrastructure planning. In fact, certain data contained in this work have already been used to prepare the Regional Inventory of Natural Risks currently being drawn up by the Government of Extremadura, the region of Spain to which the Jerte Valley belongs. This inventory includes several phases: the prospective (predictive) phase, including a map indicating possible risk areas in the whole of Extremadura; the verification phase, with the selection of "critical points" which will be studied and mapped in detail on a scale of 1:25,000 or 1:10,000; and the execution phase, with specific studies of each risk

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and in each specific area in order to prepare the related Risk Assessment regulations.

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