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Susceptibility assessment of rainfall-triggered flows and slides in the central-eastern Pyrenees

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ABSTRACT: Rainfall-induced flows and slides are hazardous processes in mountainous regions and susceptibility assessments with resulting maps are helpful tools for land-use planners. In the present study, all the available information on recent events has been gathered and incorporated in an inventory. The governing factors of the 2262 entries were analyzed and preliminary susceptibility matrices were established. Two different terrain units were applied and compared: grid cells and first-order catchments. The results showed that slope angle between 30 and 35° and land cover classes like debris screes or grassland are the most significant factors. In addition, the Melton Ratio higher than ~0.7 in the first-order catchments seems to be another critical parameter. Finally, two types of susceptibility maps were created, although the ones working with first-order catchments look more appropriate for the application at regional scale and the use for land-use planning.

1 INTRODUCTION

Rainfall-induced shallow landslides, earth flows and debris flows represent a considerable hazard in the Pyrenees, although they are not as frequent as in other mountain ranges. Nevertheless, recent events have shown that important damages can be produced by such mass movements (e.g. White et al., 1997; Portilla et al., 2010). That's why susceptibility, hazard and risk zonation is an essential tool for land-use planner, in the Pyrenees, as in many other mountainous areas. Recently, the administration of Catalonia, which is a Spanish province, has started the elaboration of the Geological Hazard Prevention Map of Catalonia 1:25000scale (Oller et al., 2011).

The triggering conditions of shallow slides and debris flows can be investigated by the analysis of rainfall records and the application of physically-based or empirical/statistical methods using threshold lines (e.g. Crosta & Frattini, 2003; Guzzetti et al., 2008). In contrast, herein we focus on the susceptibility assessment of these rainfall-triggered landslides, which is mostly based on an inventory and a subsequent susceptibility analysis using statistical, deterministic or knowledge-driven techniques (e.g. Corominas et al., 2014; Fell et al., 2008). The merging and harmonizing of different inventories into one single uniform database is a complex task, since divers precisions, terminologies and input data formats must be unified (e.g. Guzzetti et al., 1994).

The visualization of the inventory and also the susceptibility assessment is nowadays typically performed in a Geographical Information System (GIS). It has been taken into account that landslide assessment in a GIS can contain different mapping units including grid cells, terrain units among others (Guzzetti et al., 1999). The selection of the most adequate type of mapping units is of special interest, when the resulting susceptibility maps should be applied by stakeholders in land-use planning. This problematic is of special importance when dealing with debris flows, since there are several publications that propose the drainage basin as mapping units and attribute difficulties to the use of grid cells for a susceptibility analysis at regional scale (Bertrand et al., 2013; Welsh & Davies, 2011; Wilford et al., 2004). A detailed comparison between the different methods and the problematic between grid-cell based or slope-unit based assessments is presented in the work of Carrara et al. (2008).

In the Central-Eastern Pyrenees, some specific landslide inventories have been elaborated and some studies on the landslide susceptibility have been carried out (e.g. Chevalier et al., 2013; Santacana et al., 2003), but no unified inventory has been done and no global interpretation of all the data has been realized.

Therefore, the goals of this publication are first to present some results of the recently established inventory; and second to show some experiences on the susceptibility analysis and the resulting maps.

2 STUDY AREAS

2.1 *Situation*

Four study areas have been selected in this work. All of them are located at the South flank of the Central-Eastern Pyrenean mountain range, which limits France and Spain and enclaves the Principality of Andorra. The situation of the study areas is shown in Figure 1 and main characteristics of each area are listed in Table 1. The four study areas cover about 2850 km^2 and represent in a perfect way the different regions of the Central-Eastern Pyrenees affected by sliding and flowing phenomena.

2.2 *Geologic and climatic settings*

From a geological point of view, the Pyrenees are divided into two sectors: the Axial Pyrenees and the Pre-Pyrenees (Muñoz, 1992). On one side, the study areas Andorra, NE Catalonia and NW Catalonia are located in the Axial Pyrenees, where igneous and metamorphic rocks are cropping out, principally covered by colluvium or glacial deposits. On the other side, the study area called Central Catalonia is located in the Pre-Pyrenees, where sedimentary rocks (limestone, sandstone, marls etc.) crop out, covered by a soil layer of colluvial origin or glacial deposits.

The climatic conditions in the Central-Eastern Pyrenees are affected by three factors: the Mediterranean Sea, the west-winds from the Atlantic Ocean and the orographic effect. The yearly precipitation ranges from 850 mm to 1200 mm. Dryness and

Table 1. Characteristics of the study areas. Three in Catalonia (CAT) and one in Andorra.

Study area	Area (km^2)	Elevation (m asl)	Lithology (principal rock type)
Central CAT	1040	600–2600	sedimentary
NW CAT	1012	1600–3000	igneous and metam.
NE CAT	338	1400–2900	igneous and metam.
Andorra	468	1600–2900	igneous and metam.

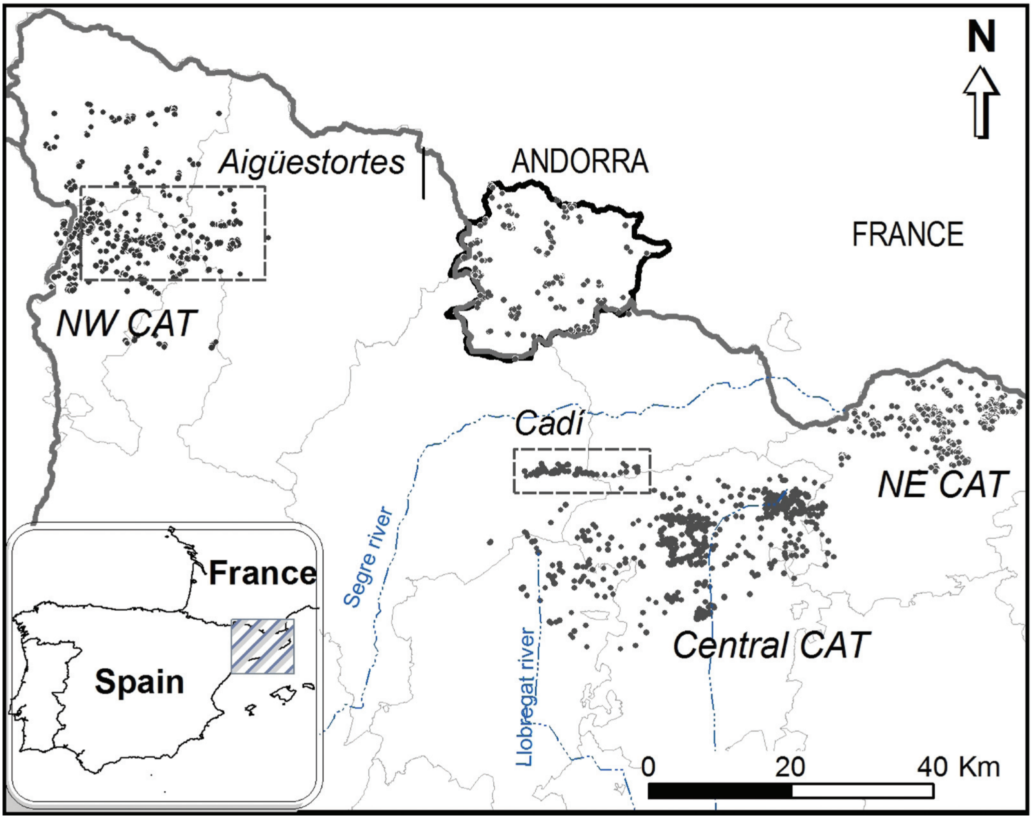


Figure 1. Situation of the selected study areas and visualization of the inventory points. The two specific study zones Aigüestortes and Cadí are shown by rectangles of dashed lines.

convective storms are common in summer, while advective with sometimes long-duration rainfalls characterize autumn and winter. The most critical rainfalls for the triggering of shallow slides and debris flows are short rainstorms with high intensity in summer and long-lasting rainfall episodes with medium intensities in autumn (Corominas et al., 2002; Hürlimann et al., 2003).

3 METHODS AND DATA AVAILABLE

3.1 *Methods*

The first step was the collection of the different information available in digital or analog formats. Some inventories were created in the 1980thies on topographic maps during field surveys, but at least some (not very exact) coordinates could be found for all the entries. More recent inventories were made by standard interpretation of paper aerial photographs with different scales and qualities (Portilla, 2013) and 2D or pseudo 3D interpretation of digital ortho-photos (Hürlimann et al., 2012).

In the second step all the existing data have been merged in a unified information tool, which was ARCGIS by ESRI. The inventories have been harmonized, compared and duplicated entries were eliminated. Finally, more than 800 were duplicated, which resulted in 2262 final events (Table 2). This high amount of duplicates entries (almost a third) can be explained by the fact that several inventories covered the same areas and especially the area Central CAT has been analyzed by different persons.

Most entries were represented with a single point, but some of them contained polygons as spatial information. Therefore, the polygons were transformed into points using the highest elevation in the polygon as reference.

The susceptibility analysis was carried out by overlaying the points on two types of terrain units: grid cells and first-order catchments. The terrain units for the grid-cell analysis contained the following information: i) elevation of the 5 × 5 m Digital Elevation Model (DEM), ii) morphometric parameters derived from the DEM (slope angle and curvature), and iii) additional geospatial information on geology and also the land cover, which includes the vegetation types. The DEM and the other information were obtained from the official websites of the Catalan administration. For the 1st order catchment analysis, morphometric parameters like average slope, Melton Ratio, Relief Ratio etc. were calculated for the different catchment polygons using the DEM. The Melton Ratio is defined as the catchment relief (maximum altitude minus minimum altitude) divided by the square root of the catchment area, while the Relief Ratio is the catchment relief divided by the catchment length (along longitudinal axis). In addition, information on both land cover and geology classes were incorporated by determining their percentages inside the catchment polygons.

Table 2. Number of entries collected in the different inventories of the four study areas.

Study area	# of initial entries	# of final entries	final entries per km^2
Central CAT	1917	1250	1.2
NW CAT	630	512	0.5
NE CAT	294	317	0.9
Andorra	183	183	0.4
GLOBAL	3024	2262	0.8

The final susceptibility analysis of the governing factors included simple methods like the visualization and interpretation of histograms as well as bi-parametric plots. Statistical tools were only applied at very specific test sites.

In the next step, the susceptibility matrices were defined using simple bi-parametric relations to classify each terrain unit in one of four susceptibility classes. Finally, different maps were created and a preliminary validation of the susceptibility zonation was performed.

3.2 *Data available*

The database not only includes slides and flows induced by individual thunderstorms with limited extension, but also events triggered by the catastrophic rainfall episodes of 1940, 1963 and 1982. In fact, these MORLEs (multiple occurrence of regional landslide events) incremented considerably the total amount of entries, because they included hundreds of flows and slides.

The final inventory incorporates 2262 entries, which are defined as points or polygons. About 1000 events are related to the important 1982 rainstorm that principally affected the Central part of Catalonia (study area Central CAT). After the occurrence of this catastrophic MORLE, several research groups and authorities have been gathering data (Gallart and Clotet, 1988; Baeza and Corominas, 2001; Santacana et al., 2003), which herein were merged and checked. Regarding NE Catalonia, the MORLE associated with the 1940 extreme rainfall was recently analyzed (Portilla, 2013) and provided more than 300 events for the present database. The other entries were mostly obtained from individual studies carried out by the UPC-team, master or PhD students, companies and authorities.

The overall dataset of the final inventory is illustrated in Figure 1, where the four study areas are clearly visible.

4 RESULTS

4.1 *Analysis of preparing factors*

4.1.1 *Terrain unit: Grid cell*

In this research task, the governing factors for the initiation of debris/earth flows and shallow slides were analyzed using the dataset including the three Catalan study areas (Central CAT, NW-CAT and NE-CAT with a total of 2079 entries). All the different morphometric factors and parameters regarding lithology and land cover were studied using grid cells as terrain units. The results of the grid-cell based analysis showed that the slope angle, where the events started, was the most significant factor. Other morphometric factors provided some trends, but without the clear differentiation observed for the slope angle. Figure 2 illustrates the distributions of the slope angle for the three study areas, individually and as entire dataset. While slope angles between 30 and 35º are the most frequent in the entire dataset, some difference can be observed comparing the three areas. The area NE-Catalonia is characterized by most frequent values ranging from 20 to 30º and the area NW-Catalonia by values between 35 and 40º. Thus, some regionalization effects have to be taken into account investigating morphometric factors like the terrain inclination. The existence of events at very low slope angles may be explained by the precision of some inventories (especially the older ones carried out in the 1980th and published on 1:50000 paper maps).

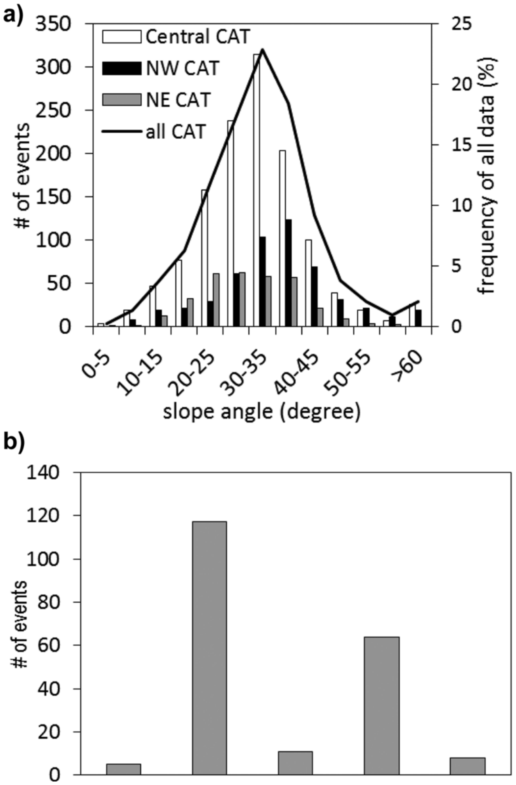


Figure 2. a) Slope angle of the initiation points of flows and slides for the three Catalan datasets. b) Influence of the land cover, which includes the vegetation type, at the initiation points of debris flows in the study zone Aigüestortes of NW-CAT area.

Besides the slope angle, another important influence on the occurrence of slides and flows was observed in the land cover. In the following, we present the results for the Aigüestortes region, located in the NW-CAT area (Figure 1), where a clear influence of the land cover type in the initiation of the 205 observed debris flows is visible (Figure 2). Especially the scree deposits seem to be susceptible, but also meadow is characterized by a high frequency of events. The initiation points in scree deposits are mostly manifested by the so-called “firehose effect” (Godt & Coe, 2007). This initiation mechanism of debris flows was observed many times in the aerial photographs of recent years, available in colors and at 1:5000scale.

4.1.2 *Terrain unit: 1st order catchment*

In the following, we present the results obtained when analyzing the governing factors for debris-flow occurrence at the north flank of the Cadí mountain range. This range is located in the study area of Central CAT (see Figure 1) and is characterized by a high debris-flow activity. A total of 58 catchments have been studied and divided into “active” ones (debris flows have been observed) and “not active” ones (no debris flows observed).

The occurrence of debris flows was investigated by the interpretation of 11 sets of aerial photographs taken between 1956 and 2012 (Mico, 2014). This photo-interpretation showed that 24 catchments can be classified as “active” and 34 as “not active”.

Different governing factors were analyzed revealing that the most significant ones were on one side the two morphometric parameters Melton Ratio, M, and the Relief Ratio, R and on the other side the land cover, which includes the vegetation type (Figure 3).

Since this analysis was carried out using the 1st order catchment as terrain units, the presence of scree deposit inside the polygon, Sr, was taken as reference factor.

The results clearly show that debris-flows occur in catchments with a presence of scree deposits higher than 10%. However, a better distinction between active and not active catchment can be represented by a threshold line represented by the following equation:

$$Sr = 25\text{–}20\ M \tag{1}$$

Therefore, the combination of a morphometric parameter indicating the “energy” of a catchment due to its morphologic characteristics with a second parameter representing the sediment availability seems to be the best option to predict the debris-flow occurrence. Regarding the morphometric parameter, here we showed the Melton Ratio, but results indicate that also the Relief Ratio reveals good outcomes.

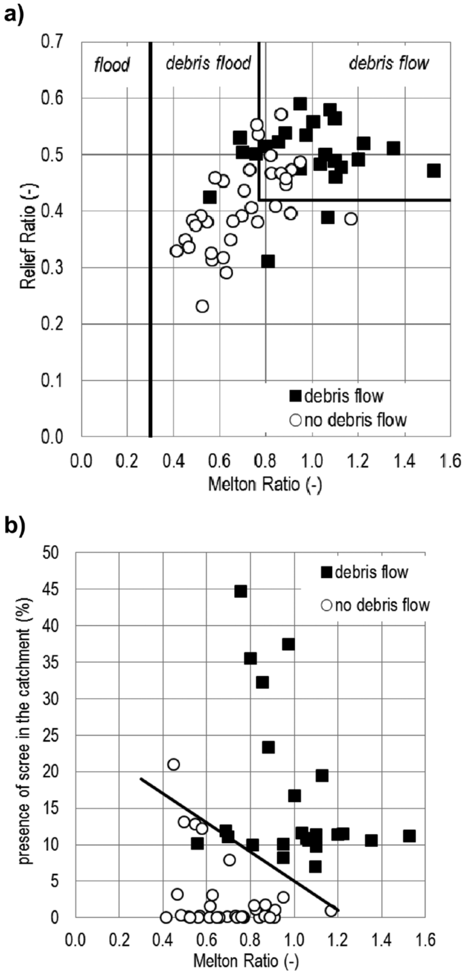


Figure 3. Debris-flow occurrence in the Cadí test zone. a) The effect of Melton Ratio and Relief Ratio including the classification of Wilford et al. (2004). b) The effect of Melton Ratio and the presence of scree deposits (bottom). Straight line represents the threshold line given by Eq. (1).

4.2 *Susceptibility zonation*

In the second part of the study, preliminary matrices were defined in order to create susceptibility maps at regional scale. Statistical techniques were only applied to some specific and localized test sites and thus the matrices were mostly established by knowledge-driven approaches using both the results obtained from the analysis of the governing factors and expert criteria. In general, four to five value ranges of the two selected parameters were combined in the matrices in order to determine the resulting susceptibility class. Four different susceptibility classes were finally defined including very low, low, medium and high susceptibility.

The susceptibility was firstly analyzed in the study zone Aigüestortes using the two terrain units (grid cells and 1st order catchments). In addition, the Cadí mountain range was selected to elaborate susceptibility maps using 1st order catchments as terrain units.

4.2.1 *Susceptibility zonation using grid cells*

The susceptibility matrix for Aigüestortes zone, located in the NW-Cat test area (see Figure 1) combines four intervals of slope angles with four types of land cover types (Figure 4a). This matrix was directly applied to a 5 × 5 meter grid of the slope angles and geospatial information on land cover using GIS-techniques.

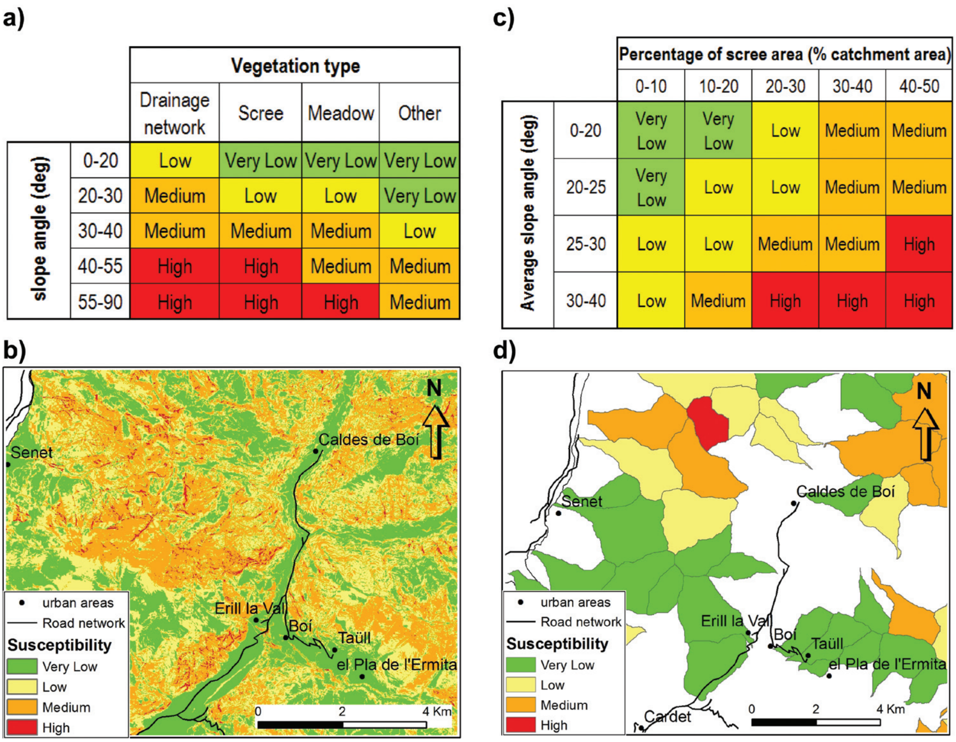
The resulting susceptibility map of the Aigüestortes study zone is shown in Figure 4b and gives a good example of a regional zonation using grid cells as terrain units. The susceptibility map indicates that the valley floors are classified as very low, while main slopes are mostly attributed to have medium susceptibility. Only a minor amount of cells are classified as high susceptible.

A simple validation of the susceptibility map was carried out by overlaying the observed points of debris-flow initiation on the zonation, which included the four susceptibility classes. This validation revealed very positive results and showed that 26% of all debris flows started in the high, 58% in the medium, 14% in the low and only 2% in the very low susceptibility class.

4.2.2 *Susceptibility zonation using 1st order catchments*

Two studies will be presented for the case of 1st order catchments as terrain units: on one side the Aigüestortes zone, which is the same one as the one used above in the grid-cell based map; and, on the other side the Cadí mountain range (see Figure 1 for locations).

Regarding the Aigüestortes zone, the susceptibility matrix combines the following two parameters: the average slope angle of the catchment and the per-


a)

slope angle (deg)	Vegetation type			
	Drainage network	Scree	Meadow	Other
0-20	Low	Very Low	Very Low	Very Low
20-30	Medium	Low	Low	Very Low
30-40	Medium	Medium	Medium	Low
40-55	High	High	Medium	Medium
55-90	High	High	High	Medium

c)

Average slope angle (deg)	Percentage of scree area (% catchment area)				
	0-10	10-20	20-30	30-40	40-50
0-20	Very Low	Very Low	Low	Medium	Medium
20-25	Very Low	Low	Low	Medium	Medium
25-30	Low	Low	Medium	Medium	High
30-40	Low	Medium	High	High	High

Figure 4. Preliminary susceptibility matrices and resulting zonation for the Aigüestortes test zone located in the NW-Cat area. Susceptibility matrix (a) and zoom of the resulting map (b) using grid cells as terrain unit. Susceptibility matrix (c) and zoom of the resulting map (d) using 1st order catchments as terrain unit.

centage of scree deposit inside the catchment (Figure 4c). This matrix was applied to all the 1st order catchments previously calculated from the digital elevation model using GIS-techniques, the HEC-geoHMS tool and a user-defined threshold condition for the initiation of the drainage network.

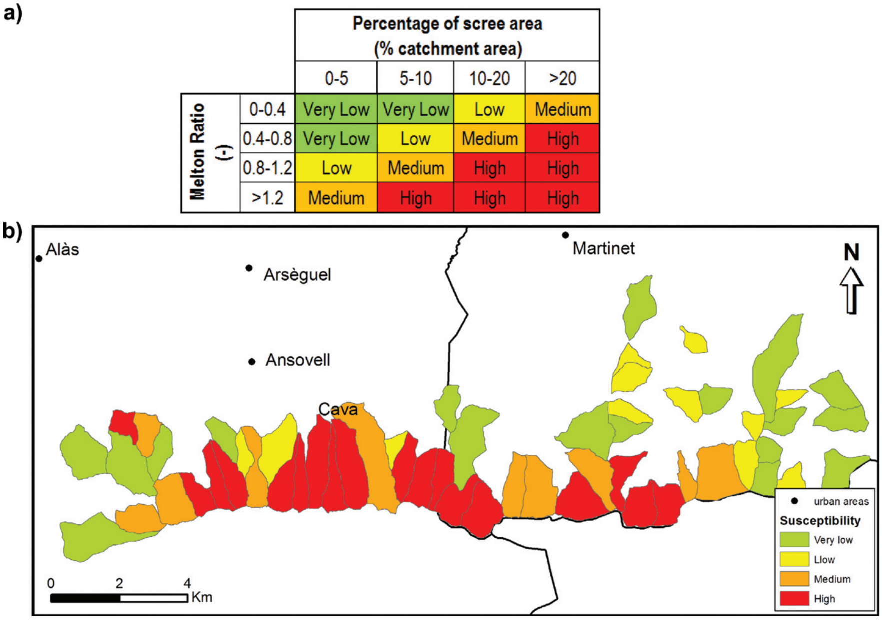
The resulting susceptibility map (Figure 4d) looks very different from the one created using grid cells. On one side, the terrain units are much larger and thus the interpretation of the susceptibility seems to be easier. On the other side, some parts of the study area cannot be covered by the polygons of the 1st order catchments and thus lack of information. This lack of a continuous coverage of the terrain by 1st order catchments can be explained by the fact, that many catchments do not fulfill our threshold condition for the definition of the starting point of the hydrologic network.

Again, a simple validation of the resulting susceptibility map was carried out and showed even better results than in the grid-cell based map. In this map using 1st order catchments, 60% of all debris-flow initiation points were situated in catchments classified with high susceptibility, 20% with medium, 19% with low and only 1% with very low susceptibility. A detailed look on the very low cases showed that they were in catchments with an average slope angle between 20 and 25º and 0–10% scree deposits.

Regarding the Cadí mountain range, a slightly different susceptibility matrix was defined. Here, the average slope of the 1st order catchment was substituted by the Melton Ratio. Thus, the morphometric parameter Melton ratio was combined with the percentage of scree deposits inside the catchment (Figure 5a).

The susceptibility map created for the Cadí mountain range shows that many 1st order catchments are classified with medium and high susceptibility, which coincides with the observations that this zone has a very high debris-flow activity.

The validation of the results indicated that no debris-flow activity has been observed in any of the catchments classified with low or very low susceptibility (true negative). In contrast, one or more debris flows have been detected in most (86%) of catchments classified with medium or high susceptibility (true positive). Only in one catchment defined as high susceptible no activity has been observed (false positive).


a)

Melton Ratio (-)	Percentage of scree area (% catchment area) 0-5	5-10	10-20	>20
0-0.4	Very Low	Very Low	Low	Medium
0.4-0.8	Very Low	Low	Medium	High
0.8-1.2	Low	Medium	High	High
>1.2	Medium	High	High	High

Figure 5. Preliminary susceptibility matrix (a) and resulting zonation (b) for the Cadí study zone located in the Central-Cat area using 1st order catchments as terrain unit.

5 CONCLUSIONS

The present work shows preliminary results on the susceptibility assessment of rainfall-triggered flows and slides in the Central-Eastern Pyrenees. In a first step, different inventories have been merged into a global dataset, which represent each event by a single point or by a polygon with an associated point. In a second step, the preparing factors for the flows and slides have been analyzed in a GIS. Finally, susceptibility matrices have been defined in order to create maps using two different types of terrain units (grid cells and 1st order catchments).

The merging of the different inventories was not an easy task, since the old datasets lacked of precision and detailed description. Nevertheless, a total of 2262 entries could be gathered and georeferenced in the final database.

The analysis of the most important preparing factors confirmed that slope angle between 25 and 45° are the most susceptible morphologic conditions, while the existence of scree deposits also favors the occurrence of shallow failures and especially the initiation of debris flows. These results refer to the analysis carried out at grid cells. In addition, the most susceptible morphometric factor in 1st order catchments revealed to be the mean slope angle, Melton ratio or Relief ratio.

The definition of the susceptibility matrices focuses on debris flows and showed that the best selection of the two input parameters was the one that includes on one side a morphometric parameter and on the other side another parameter referring to the sediment availability. The finally selected morphometric parameters include the slope angle for the grid-based analysis and the average slope angle or Melton ratio for the analysis using the 1st order catchment. In addition, the sediment availability was approximated by the land cover in the grid cell and the percentage of scree deposit in the 1st order catchment.

A preliminary susceptibility zonation was performed in two study zones (Aigüestortes and Cadí mountain range), where debris flows are the most common process. The validation of the generated susceptibility maps showed that the results are consistent with the observed activity. This conclusion is promising, especially when considering the simplicity of the zonation, which is based on a two-parameter matrix with four final susceptibility classes.

Another important point is the adequate selection of the terrain units used for the zonation. The comparison of the two resulting susceptibility maps in the Aigüestortes study zone showed that a zonation based on 1st order catchments seems to have an easier interpretation. This aspect is of special importance, if the final map is utilized by land-use planners or other stakeholders. However, the maps created by this type of terrain units do not cover the entire study area

The results of the present study are preliminary, but represent a useful help for the administration in order to define guidelines for the launch of susceptibility or hazard maps at regional scale. However, the matrices should be adapted to each study area, since an important effect of regionalization has been observed in the global inventory of the Central-Eastern Pyrenees.

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