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A regional methodology for rockfall hazard assessment in the hazard prevention map of Catalonia 1:25,000. A geomorphological approach

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ABSTRACT: One of the functions of the Cartographic and Geological Institute of Catalonia (ICGC) is to "study and assess geological hazards, including avalanches, to propose measures to develop hazard forecast, prevention and mitigation and to give support to other agencies competent in land and urban planning, and in emergency management". To accomplish these functions, the ICGC began the Geological Hazard Prevention Map of Catalonia (MPRG25M) in 2007. The MPRG25M is designed as a multi-hazard map, indicating the overlapping of different hazard zones in the same area. This article presents the methodology developed for assessing the rockfall hazard. The analysis includes two steps: (a) estimating the magnitude-frequency relationship of the events and (b) estimating the travel distance, based on the angle of reach. The evaluation is done in areas previously identified as susceptible. Susceptibility is defined by the combination of lithology with slope angle. Rockfall frequency and magnitude is obtained by field work with rockfall inventory, activity features, activity evidence and the identification of favorable terrain morphologies. The subsequent processing of these data includes the angle of reach analysis, which determines the area affected by the rock fall trajectories and the degree of hazard. This analysis is systematic and uniform for the whole of the territory to obtain comparable results.

1 INTRODUCTION

1.1 *Legal framework*

The Parliament of Catalonia approved, by Law 2/2014, the creation of the Cartographic and Geological Institute of Catalonia (ICGC), before Geological Institute of Catalonia (IGC), assigned to the Ministry of Land and Sustainability of the Catalonian Government.

One of the functions of the ICGC is to «study and assess geological hazards, including snow avalanches, to propose measures to develop hazard forecast, prevention and mitigation and to give sup-port to other agencies competent in land and urban planning, and in emergency management». Therefore, the ICGC is in charge of making official geological hazard maps for such finality. These maps comply with the Catalan Urban Law (Law Decree 1/2005) which defines that in those places where a risk exists, building is not allowed.

1.2 *Geohazard mapping*

The high density of urban development and infra-structures in Catalonia requires geothematic information for planning. As a component of the Geoworks of the ICGC, the strategic program aimed at acquiring, elaborating, integrating and disseminating the basic geological, pedological and geothematic information concerning the whole of the territory in the suitable scales for the land and urban planning. Geohazard mapping is an essential part of this information. Despite some tests have been carried at regional scale (Mountain Regions Hazard Map 1:50,000 [DGPAT 1985], Risk Prevention Map of Catalonia 1:50,000 [ICC 2003]), the

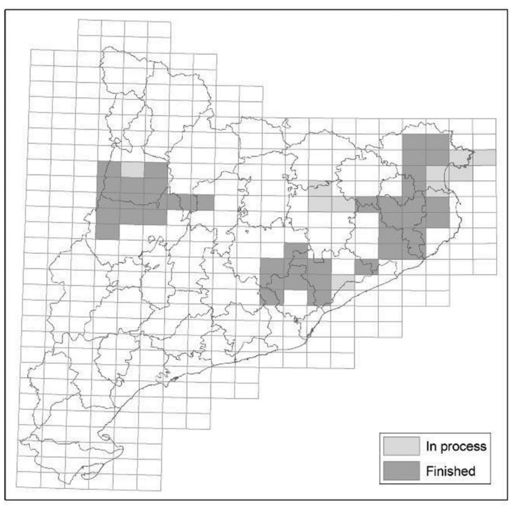

Figure 1. MPRG25M progress map: 304 sheets 1:25,000, 41 finished and 10 in progress.

Geological Hazard Prevention Map of Catalonia (MPRG25M), started in 2007, is the first mapping plan 1:25,000 which covers the whole of Catalonia, 32,144 km^2, comprising of a total amount of 304 sheets (Fig. 1). Nowadays, 10 sheets are in process and 41 have been completed. 32 sheets of these have been published in GeoPDF and 28 in vector format (ICGC 2015a).

2 METHODOLOGY

The MPRG25M is designed as a multi-hazard map, indicating the overlapping of different hazard zones in the same area (Oller et al. 2011). The MPRG25M is a 1:25,000 scale map where whole of the Catalan territory will zoned according to geological hazard. The purpose of this tool is to support urban, road and infrastructure planning. The map is intended to enable government and individuals to have an overview of the territory, with respect to geological hazards, identifying areas where it is advisable to do detailed studies in case of action planning. The main challenge of the map is the graphic representation for the easy reading of the overlapping hazard of the different phenomena.

This article presents the methodology used for assessing the rockfall hazard.

The MPRG25M includes the representation of activity evidence, phenomena, susceptibility and level hazard of geological processes considered. These are the processes generated by external geodynamics (such as slope, torrential, snow, coastal and flood dynamics) and internal (seismic) geodynamics.

The MPRG25M mapping procedure, for each phenomena represented on the map, consists of three steps: firstly, preparing a catalogue of phenomena and activity evidence, based on information obtained from the collection and analysis of available historical documentation, analysis and photointerpretation of old and recent aerial photographs, on field surveying and on population inquiries. Secondly, determination of the susceptibility to slope or cliff failure (starting zone) and the maximum extent determinable at the scale of work (runout zone). Thirdly, hazard assessment based on the analysis of the magnitude and frequency (or activity) of the observed or potential phenomena (Oller et al. 2011).

3 ROCKFALL HAZARD ANALYSIS

Rockfall hazard analysis (Fig. 2) includes two main steps: (a) estimating the magnitude-frequency relationship of the events and (b) estimating the travel distance, based on the angle of reach (Corominas 1996). The evaluation is done in areas previously identified as susceptible. Susceptibility is defined by the combination of lithology with slope angle. Rockfall frequency and magnitude is obtained by field work. The subsequent processing of these data includes the angle of reach analysis, which determines the area affected by the rock fall trajectories and the degree of hazard. This analysis is systematic and uniform for the whole of the territory to obtain comparable results.

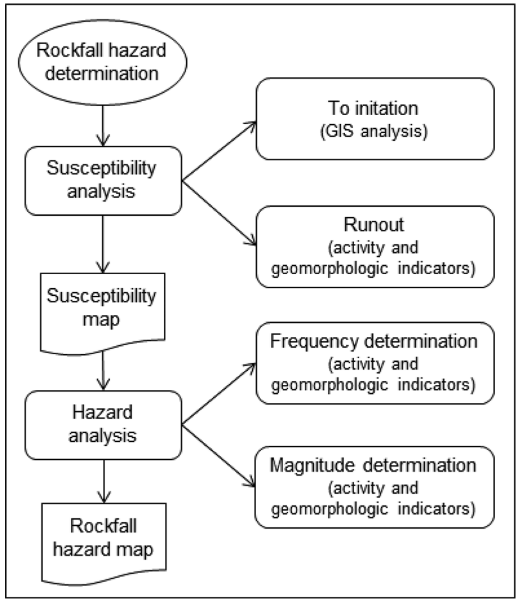

Figure 2. Rockfall hazard determination process.

3.1 *Rockfall inventory and activity evidence*

The catalogue of phenomena and activity evidence is the base of the further susceptibility and hazard analysis. It consists of a geomorphologic approach and it comprises the following 4 phases: (1) Bibliographic and cartographic search: the information available in archives and databases is collected. (2) Photointerpretation: carried out on vertical aerial photos of flights from different years (1945, 1957, 1977, 1985, 2003, etc.). The observation of the topography and the vegetation allows the identification of areas with signs of instability coming from the identification and characterization of events that occurred recently or in the past, and from activity indicators. (3) Field survey: checking and contrasting on the field, the elements identified in the previous phases. Field analysis allows a better approach and understanding, and therefore identifying signs and phenomena not observable through the photointerpretation. (4) Population inquiries: the goal of this stage is to complement the information obtained in the earlier stages, especially in aspects such as the intensity and frequency. It is done through a survey to witnesses who live and/or work in the study areas.

After this process the inventory includes the location and mapping of rockfalls (starting, runout zone and maximum extent), activity indicators, potential detached volume, height of the cliff, volume of fallen blocks and volume of unstable blocks. All this information is collected cartographically (Fig. 3) and supplemented with data sheets about singular points and population inquires. All rockfall map elements are codified in 72 categories for further susceptibility analysis and hazard determination.

3.2 *Susceptibility determination*

Preliminary susceptibility is determined from GIS analysis by crossing lithologic and slope inclination layers. Lithological layer is obtained from the geological map 1:25.000 (ICGC 2015a). Slope layer is obtained from the digital terrain model 5 × 5 m (ICGC 2015b). From this, the land is classified to detect steep slope (35º–45º), rocky slopes (45–70º) and cliffs (>70º), for any kind of rock. This classification is refined by identifying favorable structures to produce rockfalls (Table 1).

This procedure identifies the terrain susceptible to develop the phenomena. For identify the terrain susceptible of being affected by rockfalls, the inventory is essential. With the inventory, a first map that includes starting and runout susceptible terrain is drawn. The main activity and geomorphological indicators considered are: individual rockfall events, scars (of recent and old rockfalls) and individual blocks and deposits at the foot of the escarpment.

The event inventory is checked with the reach angles modified by Corominas et al. (2010) based on Corominas (1996), shown in Table 2. This is done systematically by using the CONEFALL1.0 software (Quanterra 2003), which can be broadly applied to obtain maximum reach boundaries in function of observed or expected rockfall volumes. This procedure allows for another approach, by contrasting the map based on terrain indicators with the one based on the statistically obtained angles of reach.

On the one hand, to validate the susceptibility and on the other hand, in order to improve the inventory during field work, the susceptibility map and the inventory map are compared, with a search for activity indicators in areas where susceptibility was identified. If evidence corroborates automatic susceptibility, it is confirmed. If no evidence is found, expertise validates or rejects it.

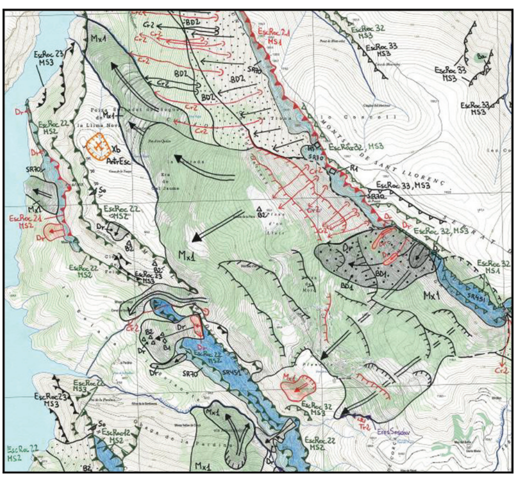

Figure 3. Fragment of the phenomena and activity evidence map. Includes rockfall, slides and flows information.

Table 1. Susceptibility to initiate rockfalls. It combines slope angle and lithology.

	Terrain slope		
Lithology	>70º Cliff	70–45º Rocky slope	45–35º Steep slope
Hard rock with favorable structural setting	High	High	Medium
Hard rock	Medium	Medium	Low
Alternating hard and soft rocks with favorable structural setting	High	High	Low
Engineering soil	High	High	Medium

Table 2. Maximum angles of reach. Correlation between the volume of the potential rockfall, the volume of the rock blocks accumulated on the slope, and angle of reach. Volumes are determined from photointerpretation and field observation.

Magnitude (Estimated starting volume) m^3	Volume (Individual rock blocks observed) m^3	Angle of reach °
< 10	< 2	48–40
10–100	2–5	40–33
100–1000	5–50	33–26
> 1000	> 50	< 23

3.3 *Hazard assessment*

To assess hazard, it is necessary to define the volume of the largest characteristic rock block of the sector concerned (magnitude), the area affected by the trajectory of the blocks and the probability of occurrence of this characteristic rockfall (frequency). The hazard matrix, based on Altimir et al. 2001, classify the hazard as high (red), medium (orange) and low (yellow) (Fig. 4). In the main map areas where no hazard was detected are represented in white. The upper frequency boundary is 50 years, justified by the return period of the rains responsible for major flooding and widespread landsliding in Catalonia, which is between 40 and 70 years (Corominas et al. 2010). To set the boundary for low frequency (return period of 500 years) we used a logarithmic scale, because it minimizes the uncertainty in its assessment in the absence of many historical records exceeding 100 years. In the same way, bearing in mind the scale of the map, the magnitude parameter is given as an order of magnitude in a logarithmic scale.

The most appropriate procedure to determine the frequency and magnitude of rockfall would be from the analysis of the recorded events (Fig. 5) However in most cases it is not possible to have enough data to determine return periods, or representative data of output volumes. Thus, the frequency and magnitude are determined based on the following features: (i) recent observed rockfalls; (ii) density and size distribution of rockfall scars; (iii) number and volume of fallen blocks. According these features starting zones are classified as zones with many indications of instability, with indications of instability or with a few indications of instability. The final frequency matrix is obtained from this classification and the height of the cliff (Table 3).

The magnitude is determined from the block susceptible to detach, based on the direct observation, the size of rockfall scars (related rock disconti-

		FREQUENCY		
		Low	Medium	High
MAGNITUDE	Low	Low	Low	Low
	Medium	Low	Medium	Medium
	High	Medium	High	High

Figure 4. Hazard matrix depending on the intensity and frequency or activity.

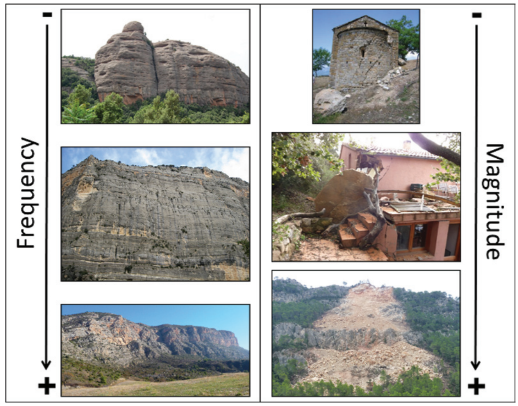

Figure 5. Examples of scarps low to high frequency (left) and examples of rockfalls low to high magnitude (right).

Table 3. Rockfall initiation frequency based on evidences and height of the escarpment.

	Height of the escarpment (or height of the starting zone)		
Evidences	<10 m	10–100 m	>100 m
Many indications of instability	Medium	High	High
Indications of instability	Low	Medium	High
Few indications of instability	Low	Low	Medium

Magnitude		Medium		
Angle of reach		40°	33°	30°
		Frequency to reach		
Frequency to inciciation	High	High	Medium	Low
	Medium	Medium	Medium	Low
	Low	Medium	Low	Very Low

Figure 6. Example of hazard zoning for expected rockfall of 10–100 m^3.

nuities) or the correlation of individual rock blocks observed on the slope (Table 2). Four categories are established, less than 10 m^3, from 10 to 100 m^3, from 100 to 1000 m^3, and higher than 1000 m^3.

To determinate the area potentially affected by the rockfall trajectories is defined according the angle of reach (Table 2). The methodology introduces the frequency of reach which allows clas-

Table 4. Rockfall reach frequency based on the volume of the expected event and the angle of reach.

	Angle of reach					
Rockfall Volume m^3	≥ 40°	≥ 33°	≥ 30°	≥ 26°	≥ 23°	≥ 21°
< 10	Med.	Low				
10–100	High	Med.	Low			
100–1000	High	High	High	Med.	Low	
> 1000	High	High	High	High	Med.	Low

**Med.* means Medium.

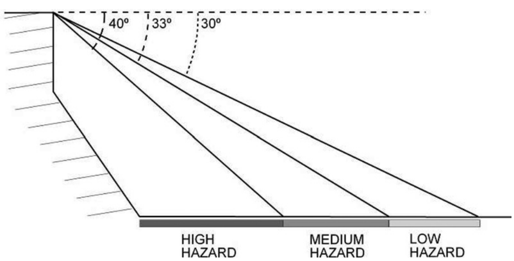

Figure 7. Hazard boundaries based on the angle of reach for a 10–100 m high cliff, many instability evidences and potential rockfall volumes between 10–100 m^3.

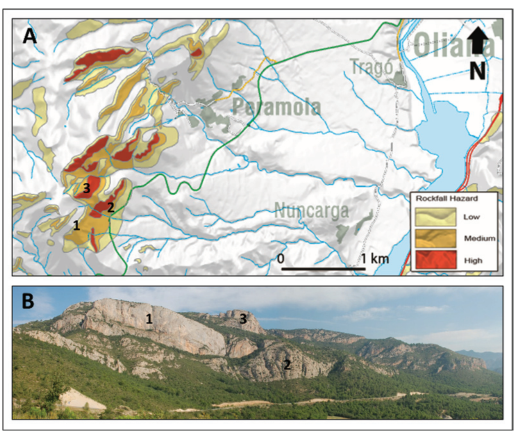

Figure 8. A. Rockfall hazard map. Example of Peramola (67–24) sheet. Point 1, Tossal de Sant Marc, has medium as a maximum hazard degree, point 2, Costa de l'Arengada, has high hazard and point 3, Roc de les Dues, has high hazard (Discussion in the text). B. Panoramic view of points 1, 2 and 3.

sify the land between the starting zone and the maximum reach boundary according the angle of reach for each rockfall magnitude. Due to the scale of mapping and always on the side of safety, the maximum reach boundary limit becomes larger according to a new angle of reach classifying this area with low hazard (Table 4). To this purpose, the CONEFALL1.0 program is used. It is designed to calculate the area for each hazard degree.

Once frequency and magnitude are determined for each starting zone (cliffs, rocky and steep slopes), hazard level can be obtained from four hazard matrix (Fig 6), each one as a function of their corresponding expected rockfall volume.

Figure 7 shows, as an example, a schematic profile with the hazard analysis of a cliff with a height between 10 and 100 meters, with many instability features and potential rockfall volumes between 100 and 1000 m^3.

Figure 8 shows the final rockfall hazard map, obtained with the methodology presented in this contribution. In this figure, points 1, 2 and 3 are distinguished as an example. Point 1, Tossal de Sant Marc, is a cliff with evidences of instability, 10 to 100 m height and 10 to 100 m^3 potential volumes to detach, thus has medium hazard degree. Point 2, Costa de l'Arengada, is a cliff with many evidences of instability, 10 to 100 m height and 10 to 100 m^3 potential volumes to detach, thus has high hazard degree. Point 3, Roc de les Dues, is a cliff with many evidences of instability, 10 to 100 m height and less than 10 m^3 potential volumes to detach, thus has high hazard degree.

4 CONCLUSIONS

The target of the MPRG25M is to give an overview of the territory at 1:25,000 scale, with respect to geological hazards, identifying areas where it is advisable to carry out detailed studies in case of urban or infrastructure planning.

The methodology developed for determining the rockfall hazard on the MPRG25M, in which it is ranked as high, medium and low, allows us to obtain homogeneous and comparable results for the whole territory.

The method is based on an exhaustive catalog of phenomena and activity evidence which, together with the identification of the output zones and arrival of rockfalls, allows the realization of very reliable susceptibility maps. Although there are areas without a complete recorded events catalog, the methodology presented in this work allow determine the magnitude and frequency from other indications as a density and size distribution of rockfall scars and number and volume of fallen blocks.

The different classifications presented (height of escarpment, potential volumes to detach, and frequency boundaries) are based on logarithmic scale, because it minimizes the uncertainty and allows a homogeneous cartography at regional scale.

Subsequently, based on the potential volumes to mobilize and frequencies of departure and arrival, the land is zoned according to the hazard by rockfalls. Note that the hazard level is determined from the output frequency of rockfalls and the reach frequency based on the reach angle obtained from statistical data.

After 41 sheets completed of the Geological Hazard Prevention Map of Catalonia (MPRG25M), the methodology presented has been useful for determining the rockfall hazard for different types of terrain, from the orographic point of view (from step mountains to large depressions with incised rivers) or lithological (from hard rock to soft rock).

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