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The Geological Hazard Map of Catalonia 1:25 000. A tool for geohazards mitigation

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Abstract We present the Geological Hazard Prevention Map of Catalonia 1:25000 (MPRG25M), and in detail, the procedure carried out for landslide hazard determination. As a component of the Geoworks of the Geological Institut of Catalonia (IGC), the MPRG25M is a multi-hazard map at 1:25000 scale conceived to be used for land use planning. It includes the representation of evidence, phenomena, susceptibility and natural hazards of geological processes. These are the processes generated by external geodynamics (such as slope, torrent, snow, coastal and flood dynamics) and internal (seismic) geodynamics. The information is displayed by different maps on each published sheet. 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 carry out detailed studies in case of action planning.

Keywords geohazards, mapping plan, landslides, Catalonia.

Introduction

The Parliament of Catalonia approved, by Law 19/2005, the creation of the Geological Institute of Catalonia (IGC), assigned to the Ministry of Land and Sustainability (TES) of the Catalonian Government.

One of the functions of the IGC 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”. Therefore, the IGC is in charge of making official hazard maps for such a finality. These maps comply with the Catalan Urban Law (1/2005) which indicates textually that in those places where a risk exists, building is not allowed.

The high density of urban development and infrastructures in Catalonia requires geo-thematic information for planning. As a component of the Geoworks of the IGC, 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. Geo-hazard mapping is an essential part of this information. Despite some tests have been carried out on extensive areas (Mountain Regions Hazard Map 1:50000 [DGPAT 1985], Risk Prevention Map of Catalonia 1:50000 [ICC 2003]), the MPRG25M, started in 2007, is the first mapping plan 1:25.000 which covers the whole country (Fig. 1).

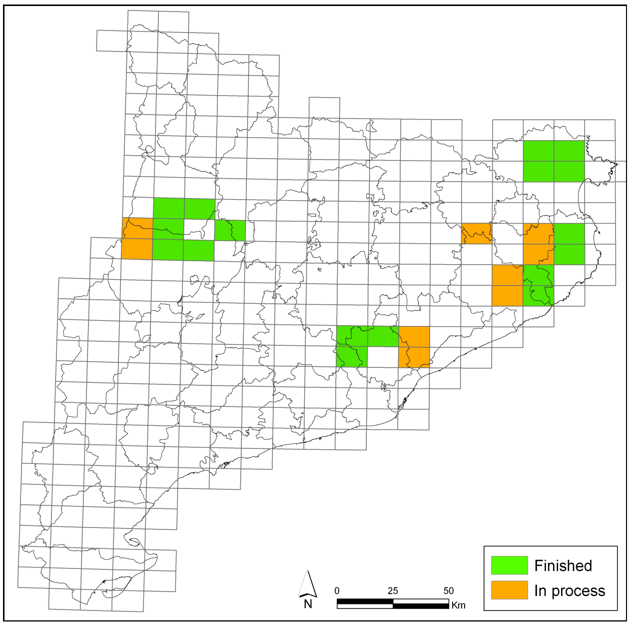

Figure 1 Map of Catalonia with the MPRG25M mapping plan: 304 sheets 1:25.000, 17 finished (11 published), 9 in progress.

The conception of the map was a major challenge. Despite the intense documentation search done at the beginning of the project, no similar works, merging such number of phenomena, at land planning scale and in a so wide area, were found.

Geological Hazard Prevention Map of Catalonia 1:25.000 (MPRGC25M)

The MPRGC25M includes the representation of evidence, phenomena, susceptibility and natural hazards of geological processes. These are the processes generated by external geodynamics (such as slope, torrent, snow, coastal and flood dynamics) and internal (seismic) geodynamics. The information is displayed by different maps on each published sheet. The main map (Fig. 2) is presented on a scale of 1:25000, and includes landslide, avalanche and flood hazard. Hazard level is qualitatively classified as high (red), medium (orange) and low (yellow). The methods used to analyze hazards basically consist of geomorphological, spatial and statistical analysis.

Several complementary maps on a 1:100000 scale show hazard caused individually by different phenomena in order to facilitate the reading and understanding of the mapped phenomena. Two additional maps for flooding and seismic hazards, represented on a 1:50000 scale, are added to the sheet.

The map is intended to enable government and individuals to have an overview of the country, with respect to geological hazards, identifying areas where it is advisable to carry out detailed studies in case of action planning. At the same time a database is being implemented. It will incorporate all the information obtained from these maps. In the future it will become the Geological Hazard Information System of Catalonia (SIRGC).

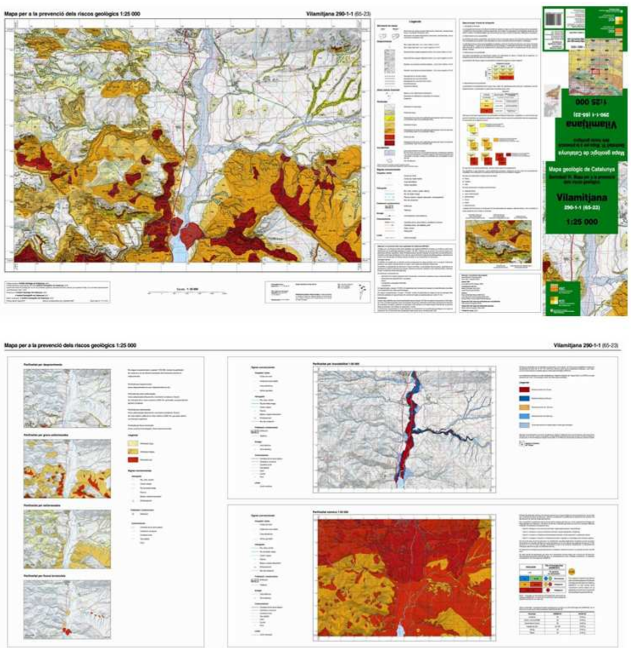

Figure 2 First published sheet (front and back), Vilamitjana (65-23), in 2010.

For hazard evaluation, maximum homogeneity and reproducibility in the mapping procedure is intended, in order to extrapolate it to the entire territory. It consists of a geomorphological approach complemented with GIS analysis and statistical modeling. Terrain susceptibility, frequency, magnitude, and hazard for each different phenomena, are the parameters to be obtained. Of course, expertise is important throughout the entire process. The procedure followed in the main map consists of three steps: (1) catalogue of phenomena and evidences, (2) susceptibility determination, and (3) hazard determination.

The catalogue of phenomena and evidence is the base of the further susceptibility and hazard analysis. 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 (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 in 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.

In a second step, areas susceptible to be affected by the phenomena are identified from the starting zone to the maximum extent determinable at the scale of work. Their limits are drawn taking into account the catalogue of phenomena and geomorphological indicators of activity, and from the identification of favourable lithologies and morphologies of the terrain. This phase includes the completion of GIS and statistical analysis to support the determination of the starting and run-out zone. It can be extensively applied with satisfactory results with regard to the scale and purpose of the map.

Finally hazard is estimated on the basis of the analysis of the magnitude and frequency (or activity) of the observed or potential phenomena. Susceptibility areas are classified according to the hazard matrix represented in Fig. 3. Hazard zones are represented as follows: areas where no hazard was detected (white), zones with low hazard (yellow), medium hazard zones (orange), and areas with high hazard (red).

		FREQUENCY / ACTIVITY		
		Low	Medium	High
INTENSITY	Low	Low	Low	Low
	Medium	Low	Medium	Medium
	High	Medium	High	High

Figure 3 Hazard matrix (based on Altimir et al. 2001).

In order to obtain an equivalent hazard for each phenomenon, an effort was made to equate the parameters that define them. The same frequency/activity values were used for all phenomena, but magnitude values were adapted to each of them.

Each hazard level contains some considerations for prevention (Fig. 4). These considerations inform about the need for further detailed studies and advise about the use of corrective measures.

	PREVENTION	
HAZARD	Detailed studies	Hazard management
Not observed	-	-
Low	Recommendable	Necessary in certain cases
Medium	Essential	Necessary in many cases
High	Essential	Necessary in most of the cases

Figure 4 Prevention recomendations.

Hazard from each phenomenon is analyzed individually. The main challenge of the map is to easily present the overlapping hazard of different phenomena. A methodology identifying that this overlap exists has been established with this objective in mind. It indicates what the maximum overlapped hazard is (Fig. 5), but in any case, without obtaining new hazard values.

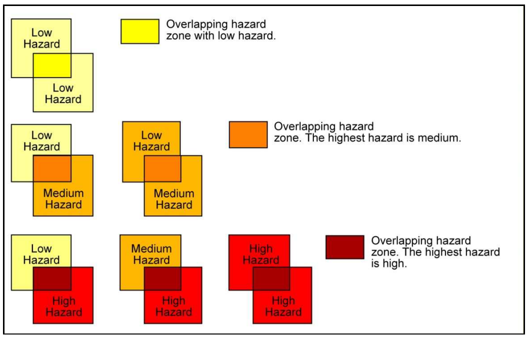

Figure 5 Multi-hazard representation.

To identify the hazard level and the phenomena that causes it, especially in overlapping areas, an epigraph is assigned (Fig. 6). This epigraph consists of two characters, the first in capital letters, indicates the value of hazard (A for high hazard, M for medium hazard and B for low hazard), and the second, in lower-case, indicates the type of phenomena (*d* for rockfalls, *s* for slides, *x* for flows, *a* for avalanches and *f* for subsidence and collapses). The higher the overlapping, the longer the epigraph will be.

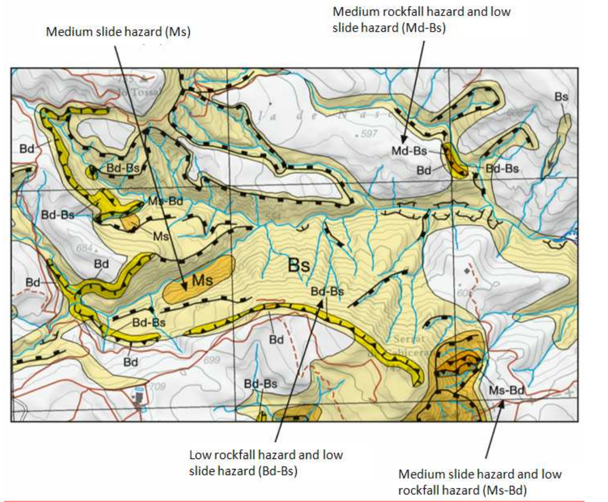

Figure 6 Example of multi-hazard representation. This figure is part of the explanatory information of the map (original scale: 1:25000).

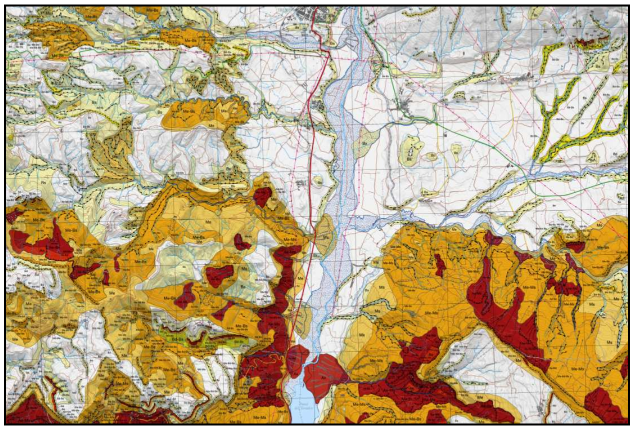

Figure 7 Main map 1:25000, which includes landslides, avalanches, sinking and flooding according to geomorphologic criteria.

Landslide hazard analysis procedure (main map)

On the map, landslides are classified as rockfalls, slides, and torrent flows (based on Varnes 1978). Slides include translational, rotational, complex, and shallow slides, and earth flows. Torrent flows include debris flows. In fact, we are dealing with quite different phenomena, which are controlled by different factors, and have different type of motion. Consequently the treatment applied to each one of them is specifically adapted.

As explained before, the analysis process includes the susceptibility and hazard analysis (Fig. 8).

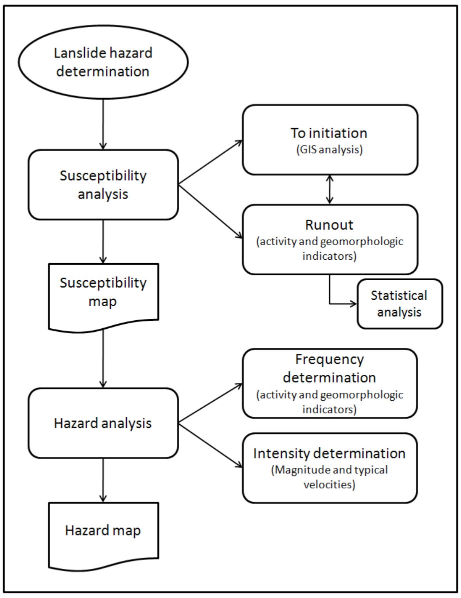

Figure 8 Lanslide hazard determination process.

Susceptibility analysis

The first step is to obtain the susceptibility. It is done by crossing lithology with slope inclination according to Tab. 1. This is obtained through GIS analysis by crossing the geological map 1:25.000 with the slope map obtained from the digital terrain model 5x5 m (ICC) (Fig. 9). For such a purpose the geological map is automatically processed and converted into a superficial deposits map. From this map susceptible lithologies are identified, listed in Tab. 1. Combining it with their critical slope inclinations, a first approach to susceptibility to iniciation for slides is obtained. For rockfalls a simpler classification is used in order to detect rocky slopes (45-70º) and escarpments (>70º), for any kind of rock (bedrock or engineering soil) (Tab. 2).

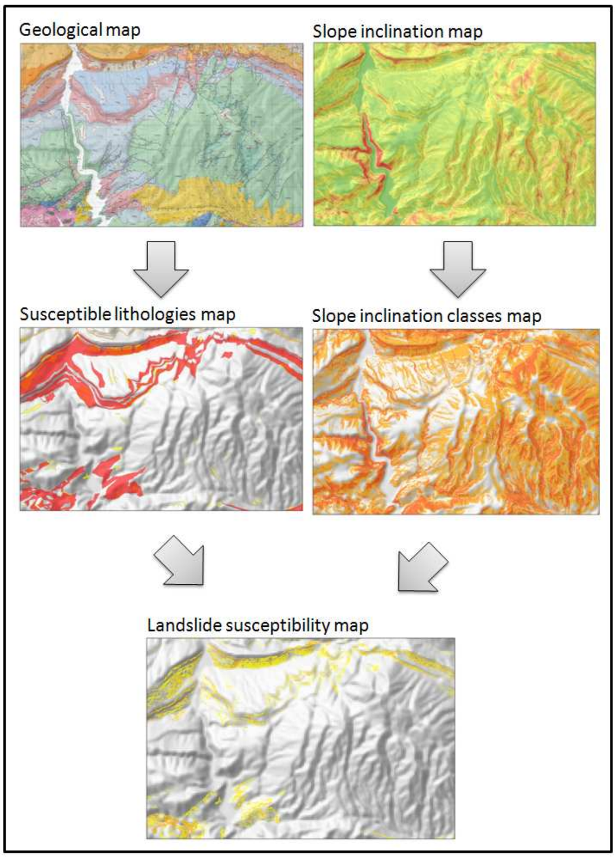

Figure 9 Process to obtain landslide susceptibility to initiation.

Table 1 Parameters used for obtaining slides and debris flow susceptibility to initiation.

Lithologies	Slope angle	Susceptibility
Scree slopes, and uncohesive clastic units in general	> 30º	Moderately high
Superficial deposits and claystone units in general	> 25º	
Superficial deposits and plastic claystone units and slided materials	> 15º	Very high
Plastic claystone units and slided materials	>8º	Extremely high

Table 2 Susceptibility to initiate rockfall. It combines slope angle and lithology.

Lithology	Slope angle		
	> 70º (Escarpment)	70º- 45º (Rocky slope)	45º- 35º
Bedrock	High	Medium	
Engineering soils	High	High	
Non cohesive deposits/ scree slopes	High	High	Low

This procedure identifies the terrain susceptible to develop the phenomena. To identify the terrain susceptible of being affected by the different phenomena, the inventory is essential. With the inventory, a first map that includes starting, track and runout susceptible terrain is drawn. Tab. 3 shows the activity and geomorphological indicators considered for the different types of phenomena.

Table 3 Activity and geomorphological indicators used for determining susceptibility to a given phenomenon.

Indicators	Rockfalls	Slides	Torrent flows
activity indicators	-Scars of recent and old rockfalls	-Slide scars -Scarps -Undrained depressions -Marshy areas -Tilted trees	-Erosion rate on unstable deposits in the catchment area
geomorphological indicators	-Individual rockfall events -Individual blocks and deposits at the foot of the escarpment -Escarpment -Scree slopes	-Badland areas -Creep areas -Solifluction areas -Rock slide deposit -Mass slide deposit	-Torrent fan -Debris flow deposits -Levees -Unstable deposits in the catchment area (tills, slides)

To validate the susceptibility on the one hand and in order to improve the inventory during field work, on the other hand, 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, the expert validates or rejects it.

For rockfalls a further analysis is done in order to improve the susceptibility map. The event inventory is checked with the reach angles defined by Corominas (1996), shown in Table 5. This is done systematically by using the CONEFALL1.0 software (Quanterra 2011), 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 (Tab. 4).

Table 4 Maximum angles of reach (Corominas 1996). Starting volumes are determined from photointerpretation and field observation.

Rockfall volume (m^3)	Angle of reach value (absence of obstacles, in º)
1-10	48-40
10-100	40-33
100-1000	33-26
>1000	<26

For debris flow, the availability of unstable material on the catchment slopes and its capacity to generate this kind of phenomena is evaluated. (Tab. 5).

Table 5 Susceptibility determination criteria for debris flows.

Magnitude class	Criteria
Low	With little or no availability of material in the catchment and channel (surface covered by moveable material less than 5%) or slope of the basin below the 10º
Medium	Availability of moveable material in the basin and channel (surface covered by moveable material between 5 and 25%) and slope of the basin between 10º and 20º
High	abundant availability of moveable material in the basin and the channel or large landslides (surface covered by moveable material over 25%) and slope of the basin higher than 20º

Hazard analysis

Hazard analysis is attained specifically for each phenomenon according to the hazard matrix by combining frequency/activity with intensity values (Fig. 3). Bearing in mind the scale of the map, these parameters are given as an order of magnitude in a logarithmic scale. Frequency is assigned to repetitive phenomena as rockfalls and debris flows. Activity is assigned to slides as non repetitive phenomena but with a long stabilization process (Tab. 6).

Table 6 Frequency / activity parameters (based on a synthesis from Mather et al. 2003).

F/A class	Frequency	Activity	Age	Preservation
High	<50 years	Historic. Active or reactivable	<100 years	Good
Medium	50-500 years	Dormant young. Inactive but reactivable	100-5000 years	Medium
Low	>500 years	Dormant mature/old. Inactive	>5000 years	Bad

However, taking into account the scale of the work, it would be unlikely to have enough data to determine the return periods for a particular slope, so that an estimate of the frequency according to the abundance of indicators and their activity is performed. In the case of slides, it is generally difficult to establish frequency beyond 100 years. For this reason the frequency/activity of the movements must be considered taking into account the preservation of the phenomena and the abundance of activity evidence.

A practical criterion is shown in Tab. 7. In 1956 the first available photographic flight was made over Spain (Servicio Geográfico del Ejército 1956). This flight provided the first aerial images of the country and it is usually used as a starting point. Comparing these images with the present ones, it is possible to observe changes indicating recent landslide activity.

Table 7 Activity based on photointerpretation by comparing recent and old aerial photographs.

Activity	Activity indicators
Low	Without indicators
Medium	Activity indicators before 1956
High	Activity indicators after 1957

For rockfalls, frequency is obtained from the percentage of scars existing on the escarpment, the number of recent identifiable events, and the existence of blocks of rock at the foot of the escarpment.

Intensity is indirectly obtained through magnitude estimation, and is defined as a function of landslide volume and expected velocity, which is considered an intrinsic characteristic of each type of phenomenon (Cardinali et al. 2002). In Tab. 8, a classification of magnitudes for slides and debris flows is shown.

Table 8 Intensity parameters for slides and debris flows (slow to rapid moving landslides).

Phenomena	Intensity		
	High	Medium	Low
Slides and debris flows	>2000 m^3	800 - 2000 m^3	<800 m^3

For rockfalls, the height of the escarpment is incorporated for obtaining magnitude (Tab. 9).

Table 9 Rockfall magnitude for bedrock based on starting volumes and height of the escarpment (fast moving landslide).

Magnitude	Height of the escarpment (or height of the starting zone)		
Estimated starting volume	<10 m	10 – 100 m	>100 m
<1 m^3	Low	Medium	Medium
1-10 m^3	Medium	High	High
> 10 m^3	High	High	High

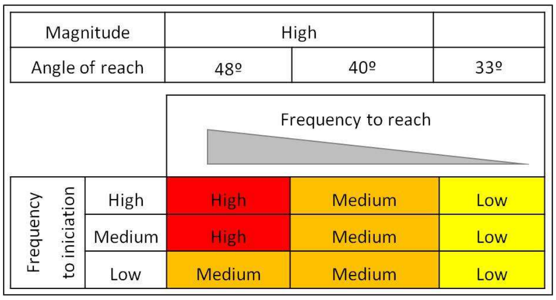

Figure 10 Example of hazard zoning for expected rockfall of 10-100 m^3.

Once frequency and intensity are determined, hazard level can be obtained from the hazard matrix shown in Fig. 3.

Final remarks

The target of the MPRG25M is to give an overview of the territory at 1:25000 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 plan has just started and has shown that some methodological limitations have to be reviewed. A line of applied research is working in parallel to the project in order to improve methodologies and quality of results (e.g. Abancó et al. 2009).

Geohazard information is dynamic. For this reason, a database is being implemented. It will incorporate all the information obtained for the elaboration of these maps, and information coming from the geohazard surveillance service of the IGC. In the future it will become the Geological Hazard Information System of Catalonia (SIRGC).

Acknowledgments

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