Avalanche hazard mapping plan for the Catalan Pyrenees

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ABSTRACT: The avalanche cartographic information collected up to present for the Catalan Pyrenees pointed out the existence of localities at risk because of this hazard. It was therefore considered necessary to initiate a hazard mapping plan for all those localities at risk. The final objective of these works is to reduce the risk by fostering the improvement of civil protection plans, to plan protection works and to manage urban planning in hazardous areas. The project was defined in three stages: (1) preparation of the knowledge bases, (2) establishing the methodology and regulations, and (3) map production. The first stage consisted in identifying basic information needs and fulfilling them. To do this, different tasks were carried out. They comprised the characterization of Pyrenean major avalanches, the improvement of knowledge about Pyrenean snow climates, an exhaustive search of historical data, the accomplishment of dendrochronological analyses in forested avalanche paths, and the calibration of the Swiss avalanche dynamics model Aval-1D with the Pyrenean conditions. The second stage determined the number of localities that should be considered for avalanche hazard zoning. Besides, methodological specificities were defined. To this end, the work was performed in a pilot area where different zoning methodologies implemented in the Alpine countries were compared (France, Switzerland, Italy and Austria), and the analysis of the results led to the establishment of the zoning methodology. At present, the third phase of the avalanche hazard mapping plan has begun, with the completion of the first maps which are already in production. On the whole, we expect to perform hazard mapping for twenty localities where avalanche risk is significantly high.

KEYWORDS: Pyrenees of Catalonia, avalanche hazard mapping, hazard zoning, risk.

1 INTRODUCTION

Every winter, avalanches affect leisure sports activities, ski resorts, roads and infrastructures in most cases located above 1500 m a.s.l., in the Catalan Pyrenees. Less frequently, avalanches can affect populated areas, below these elevations. The work done in obtaining historical information about avalanches through population enquiries and historical archival research has revealed the occurrence of avalanches that affected localities in the past, most of which have not been repeated with equal magnitude to the present (Rodés, 1999, Garcia et al., 2006, Oller et al., 2006; Rodés and Miranda, 2009). However, in the recent past, during a major episode from 6 to 8 February 1996, two major avalanches caused damage to a mountain hostel in eastern Catalan Pyrenees and on 31 January 2003, another avalanche completely destroyed a house in Pleta de Vaquèira residential area, in western Catalan Pyrenees. Nowadays, we know that, total or partial destruction of isolated houses and even entire villages occurred in the past (Figure 1). Only in the 1855 episode at Val de Toran, there were up to 57 casualties, most of them because avalanches destroyed the houses where the people had taken refuge. In this episode, the destruction of 58 houses was reported (Garcia et al., 2006). If, on the one hand, we consider that these avalanches can happen again, and on the other, we consider the strong increase in soil occupation experienced since the seventies of the last century (Apellániz et al., 2008) we can conclude that the avalanche risk is significant.

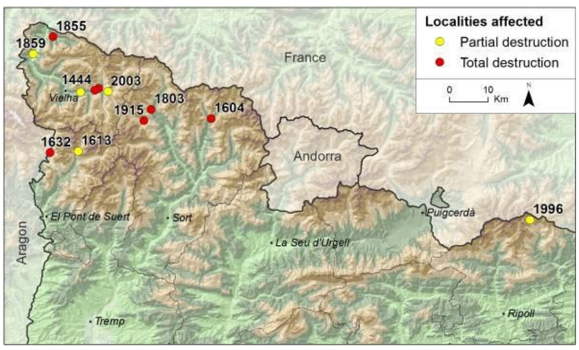

Figure 1. Catastrophic avalanches and year of occurrence in the Catalan Pyrenees, registered in the Avalanche Database of Catalonia (BDAC).

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With the goal of reducing avalanche risk, in 2004, the Geological Unit of the Cartographic Institute of Catalonia (UG-ICC, currently IGC), defined the Avalanche Hazard Mapping Plan for the Pyrenees of Catalonia (PZTSPA). The Avalanche Hazard Map (MZA), produced between 1986 and 2006, provided the first avalanche susceptibility map at a 1:25.000 scale, for the whole territory (Oller et al., 2005). The starting in 2005 of the Avalanche Database of Catalonia (BDAC), allowed to store the information of recorded avalanches (susceptible areas and avalanche events from historical/witness sources and field observation) in a single repository, which offers an environment for permanently updating and consultation, at a more detailed scale. In the present, the BDAC is hosted, maintained, and fed by the Geological Institute of Catalonia (IGC). For urban management and civil protection, it is necessary to use detailed cartography at a local scale which for a geological hazard is at least 1:5,000. Consequently, following the example of the Alpine countries, it was considered necessary to carry out the PZTSPA to provide the urban planning authority (DGTOU) with the basic documentation for prevention and protection of localities with an identified risk.

Hazard mapping is an essential tool for the prevention of geological hazards and, particularly, for urban planning (OFAT et al., 2001). For snow avalanches the first maps were made in Switzerland during the sixties (Frutiger, 1970) and other countries such as France, Austria, Italy, the United States or Canada, applied a similar methodology. The first regulations that raised the hazard zoning as we know it today appeared in the early eighties (eg. OFF-IFENA, 1984). In Catalonia, official hazard mapping exists only for flooding. The uses allowed in flood areas are regulated by the Regulations of the Planning Act, approved by Decree 305/2006, 18 July. For the remaining geohazards, the IGC is working together with the Urban Planning Department of the Catalan Government ("Direcció General d'Ordenació del Territori i Urbanisme de la Generalitat de Catalunya", DGOTU) to define hazard zoning according to geological hazards, being coherent, consistent and objective, and governing permissible uses in urban plans, according to the Urban Planning Law of Catalonia (DL 1/2005 26 July) and associated Regulations (D. L. 305/2006 18 July). Under this law, development and building in risk areas are forbidden. The PZTSPA was born for this purpose, to identify hazard and therefore risk for the Pyrenean municipalities where susceptibility was identified. While these locations do not have a protection against avalanches to diminish risk, the maps are essential for Civil Protection emergency plans.

The avalanche hazard areas have traditionally been defined in terms of return period and impact pressure (Mears, 1992). The methodology is based on zoning the terrain in two or three classes: high (red colour), medium (blue) and low (yellow). These maps are usually associated to regulations and, therefore, they are mandatory. They imply a building ban in high hazard areas, building with restrictions in the case of medium hazard, and minor constructive restrictions in the case of low hazard. The procedure to determine hazard consists on terrain analysis, analysis of recent and of reconstructed avalanches from damage to vegetation or structures, and historical data. Numerical computation is performed in the final phase of the analytical process and after calibration using available data. Its weight depends on the existence of such data (Freer & Schaerer, 1980; Mears, 1992; McClung & Schaerer, 2006).

In Catalonia, the first hazard maps (ZTSPA) were carried out to plan and protect infrastructures and for urban planning in 1997 by the UG-ICC. The Swiss zoning methodology was applied from the beginning to the end of phase 2 of the PZTSPA because in our opinion it was the most solidly introduced in its territory. These first zonings had a recommendation character because they were not followed by urban laws. The PZTSPA served to analyze the methods used in different Alpine countries to define a methodology for the Catalan Pyrenees based on criteria that justify these methodologies.

2 METHODOLOGY

The project PZTSPA was defined in three stages: (1) preparation of the knowledge bases (2004-2011), (2) establishment of the methodology and regulation (2009-2010) and (3) map production (2012-??).

The first stage consisted in identifying the needs of basic information, to obtain, store and use it. A first objective was the implementation of the Avalanche Database of Catalonia (BDAC; Oller et al., 2005) to neatly store all information collected from the beginning of the project in 1986 (Furdada, 1990). In this database, mapping and alphanumeric format data are introduced from terrain analysis, field winter observation, inquiries to population, and historical documentation. The event log allowed, on the one hand, a first characterization of major avalanche episodes in the Catalan Pyrenees, and on the other hand, the calibration of the

Swiss numerical model FL-1D from the Aval-1D programme (Oller et al., 2010).

At the same time, the participation in research projects focused on the development and use if the dendrochronological methodology (ALUDEX, OAPN 11/2003 and AVDENPYR) allowed to reconstruct major events that occurred during the last decades and to learn more about the parameters of frequency/magnitude in the studied areas. Several avalanche paths were selected according to the potential information related to avalanche activity stored in tree rings.

During this stage, progress was made also in the nivological zoning of the Pyrenees. Data from 75 weather stations was analyzed and the most representative series in relation to their location, elevation, time extent, continuity and quality were selected. They were validated and used to obtain the statistical values of snow height at 24 and 72 h and the total snow depth for reference return periods of 10, 30, 100 and 300 years. This data is essential to the application of numerical models for avalanche dynamics and to design protection structures.

During the second stage, we determined the number of locations where it would be necessary to perform the ZTSPA. In this regard, the BDAC spatial information was crossed with vulnerable elements in the topographic map 1:5,000 (ICC). In order not to leave any doubtful locality out, the runout distance obtained from the statistical model (Norwegian α-β statistical model; Lied and Bakkehöy, 1980) with the parameters obtained by Furdada (1996), was added to the inventory layer (figure 2).

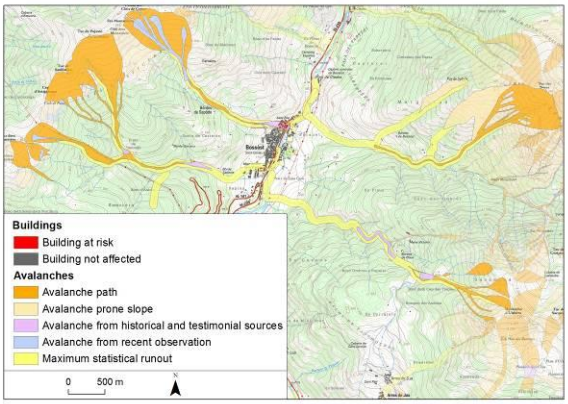


Figure 2. Analysis performed to identify the localities where the ZTSPA had to be applied.

Forty-one localities at risk were identified (Figure 3). We distinguished two priorities. With priority 1, twenty sites where historical or observational information overlapped the site. With priority 2, an amount of 21 sites, where overlapping occurs owing to the extent obtained from the statistical model, but there is no historical or observational evidence.

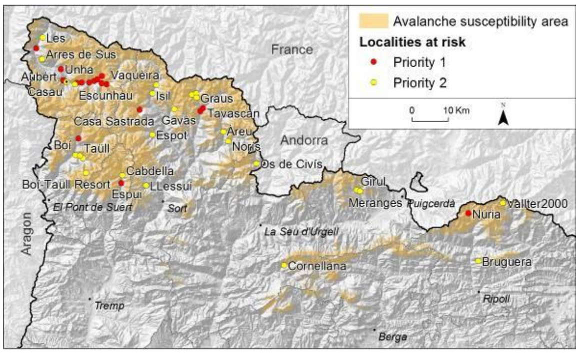


Figure 3. Localities at risk identified by crossing the vulnerable elements of the 1:5.000 topographic map with the avalanche susceptibility layer.

Also in the course of the second stage, we defined the scale of work and methodological specificities such as reference events, the hazard matrix or the numerical simulation models to use. To this end, we worked in a pilot area within the municipality of Naut Aran (Val d'Aran, western Catalan Pyrenees) with the advice of the WSL Institute for Snow and Avalanche Research SLF. In this work, the different zoning methodologies implemented in four alpine countries (France, Switzerland, Italy and Austria) were compared and analyzed in depth with the aim of designing the most appropriate zoning methodology to Catalan specificities (Janeras et al., 2011).

To guide the administration and technicians in the preparation of such maps in a consistent way throughout the country, requirements were written for the elaboration of avalanche hazard maps (REZTSPA). The requirements document shows which are the steps to follow: (1) basic literature search, (2) terrain analysis, (3) historical and testimonial search, (4) nivological analysis, (5) reconstruction of the reference avalanche scenarios (6) avalanche simulation, (7) avalanche hazard zoning and (8) recommendations and proposal of protection works. The allowable uses for the three hazard classes were defined in collaboration with the DGOTU.

Upon completion of stages 1 and 2, the third stage of the PZTSPA is currently being done with the first maps already in production, for sites with priority 1.

3 RESULTS

The project has contributed to improve the understanding of the avalanche and snow behaviour in the Pyrenees, and to the establishment of the foundations to produce the ZTSPA.

To characterize the avalanche dynamics we worked with a set of 522 major avalanches, avalanches that exceed their normal size causing damage to forest and infrastructure in its proximity (Schaerer, 1986). Most of these avalanches occurred in the twentieth and early twenty-first centuries, although a few took place before. Normally, they are size 3 or bigger, according to the Canadian size scale to which an impact pressure above 100 kPa is attributed (McClung and Schaerer, 2006). It should be noted that these are mainly dry snow avalanches, with or without a powder part (81%), while the wet snow constitute a 17% (Figure 4). We must mention the occurrence of slushflows during the winter 1997-1998 (Furdada et al., 2000), a rare phenomenon in the Pyrenees, according to current knowledge, and it was considered as a separate case. There were differences in the extent of avalanches in relation to their geographic distribution. This result was achieved by calculating the α angle, or angle of reach. The α angle varies from 15° to 50° (McClung and Mears, 1991), with lower values corresponding to more continental and extreme avalanches. The minimum values (up to 16º) werd recorded in the Oceanic climate region, “Aran-Franja nord de la Pallaresa”, and in the Mediterranean-influenced climate, “Ter-Freser” region, in the easternmost part. In the interior regions, with an intermountain or transitional climate, the angle is higher, with minimum values ranging from 18 to 21° (Figure 5). Such variations could be due to differences within the return period of snowfalls related to each climatic variety.

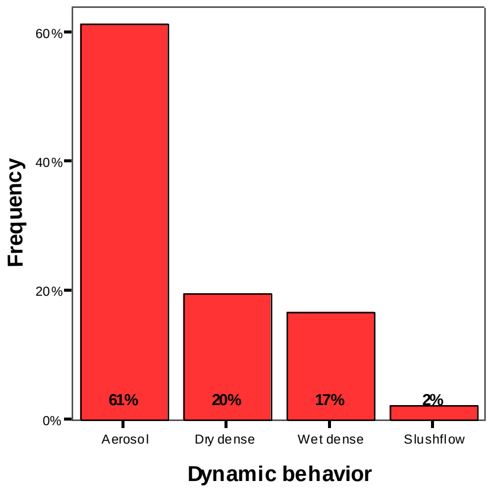


Figure 4. Dynamic behaviour of major avalanches recorded.

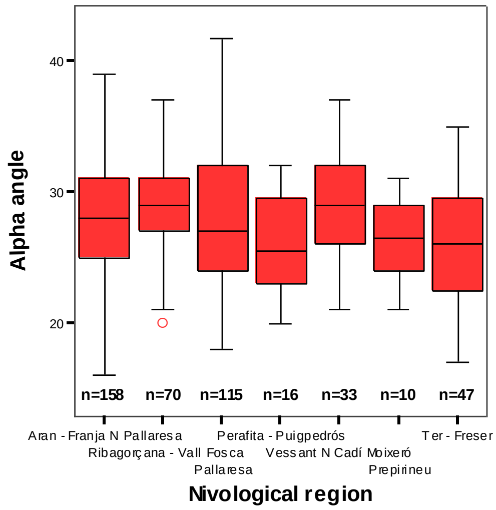


Figure 5. α angle values in relation to the nivological region (from west to east).

In relation to the calibration of the numerical model Aval-1D (Oller et al., 2010), it was concluded that a good fit is obtained by applying the friction coefficients established for the Alps, to the Pyrenees, for high frequency avalanches (T=30). For low frequency avalanches, there was not enough accurate data for calibration. Climatically it could be reasonable a little adjustment of the elevation threshold for the application of the friction coefficients, but the uncertainty in the input parameters was greater than the possible error in the result from the use of such coefficients. With respect to this, we didn’t find significant differences between the analyzed avalanches in eastern and western Catalan Pyrenees. Consequently, for the application of Aval-1D in the Pyrenees, we recommend using the coefficients established for the Alps, but whenever possible, it is advisable a prior calibration for greater reliability.

Data obtained from dendrochronological analysis in six avalanche paths distributed along the Pyrenees of Catalonia allowed to establish the methodology and identify and reconstruct older major avalanche episodes at regional and local scale, undetected from classical sources (Muntán et al., 2004, 2009). The amount of registered events increased by 60% for the studied avalanche paths and in most cases, its extent could also be established (Fig. 6). Dendrochronology proved to be a complementary technique that provides information on magnitude and frequency of avalanches not easily obtainable from other sources (Muntán et al., 2010). This methodology has begun to be applied in the ZTSPA process, in avalanche paths adjacent to forest.

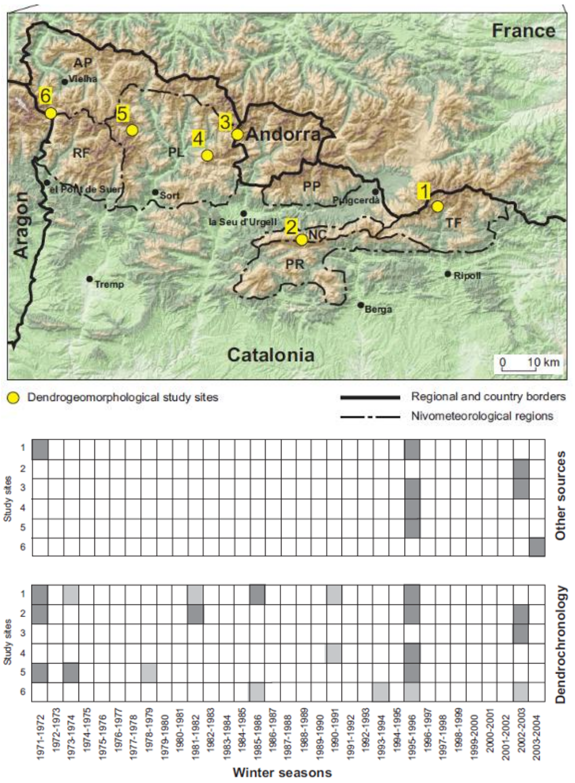


Figure 6. Avalanche paths where dendrochronological technique was applied (map) and reconstructed events (charts). The upper chart shows the events recorded in the BDAC. The lower chart shows the events obtained from dendrochronology (60% more). Darker squares represent major avalanches (Muntán et al., 2009).

Regarding the nivological zoning of the Catalan Pyrenees, we obtained values for snow depth requiring return periods (10, 30, 100 and 300 years). Given the paucity of temporarily long data series from high altitude, an analysis and a selecting process of the most representative values to make a map of recent and total snow depth distribution is currently under process. This map will spatially show the recommended values for the simulation and design of avalanche protection works.

	HS			DH3dd			HN72			HN24		
	30 anys	100 anys	300 anys	30 anys	100 anys	300 anys	30 anys	100 anys	300 anys	30 anys	100 anys	300 anys
Arinsal	247	306	360	89	102	114	102	118	132	74	84	93
Baquèira-1800	254	303	347	136	165	190	151	181	208	101	122	140
Baquèira-2500	367	445	516	114	141	165	146	181	213	105	129	152
Boí	329	399	462	109	129	147	139	165	189	75	87	98
Boí-Taüll	274	330	381	117	142	165	119	144	166	67	79	89
Bonaigua	363	421	474	109	126	142	124	146	166	75	89	101
Cadí Nord	231	275	314	99	120	139	105	125	143	55	63	71
Cap del Reg	138	170	199	84	101	117	94	114	132	64	77	89
Comalada	256	299	338	93	106	118	97	111	123	59	67	75
Estana	54	67	77	53	65	75	68	85	100	41	50	58
Grau Roig	242	289	332	121	146	168	133	157	179	79	93	106
Malniu	129	154	176	90	107	122	111	133	152	68	79	90
Núria	159	193	224	87	102	115	99	117	133	68	80	91
Ordino	250	289	324	95	110	124	141	165	187	90	104	117
Pal	161	196	228	78	92	104	111	132	152	68	83	96
Pastuira	198	230	268	111	134	155	117	138	158	76	90	104
Port del Comte	103	122	138	58	69	78	83	100	115	49	58	66
Portainé	319	392	457	124	154	181	130	161	189	91	112	131
Sasseuba	238	272	304	83	96	107	90	105	117	48	53	57
Ulldeter	168	205	239	120	146	170	124	148	169	89	108	126
Vallter	282	359	429	130	163	192	132	164	193	85	105	123

Figure 7. Snow depth values for 30, 100 and 300 years return periods.

Concerning the definition of the ZTSPA, work in the pilot area allowed to test the different methodologies applied in Switzerland, Italy, Austria and France. In order to make a comparative analysis of results from the different methods, hazard was classified into high, medium and low. Figure 8 shows the results according to the four methods in terms of affected area, taking as benchmark the start of the runout zone. Major restriction zones were homogenized in red (in general, building ban); intermediate restriction sites, in blue (building permitted under strict partial restrictions), and finally in yellow, areas of minor organizational restrictions.

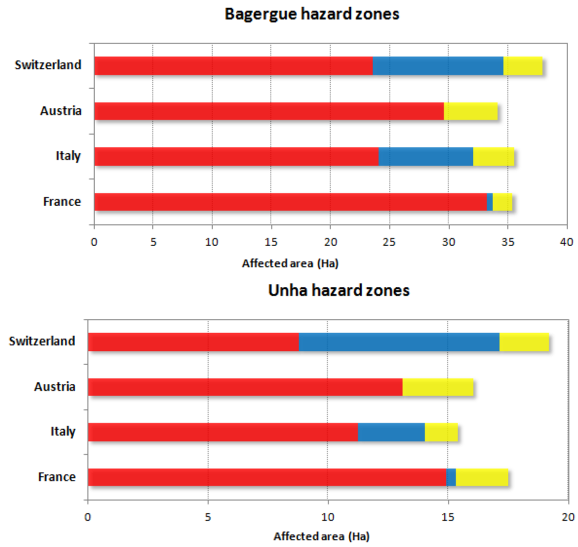


Figure 8. Terrain extent according to hazard classes obtained for Bagergue (up) and Unha (down) depending on the methodology used.

We can see how, despite the analyzed locations have different terrain configurations, they maintain proportionality in the results. Swiss zoning takes the higher extent, but zoning is gradual in the direction of the avalanche, so that the red area is the smallest. The second largest is the French zoning, but on the contrary, it is less gradual, showing maximum extent of the red zone. Finally, Austrian zoning has the distinction of being bicolour, with a great expanse of red zone, only exceeded by the French map, and a smaller global area. Comparison of results helped to understand what the differences represent in terms of hazard extent depending on the methodology.

From this comparative experience and the discussion of criteria justifying the different methodologies, the considerations that finally will define the zoning matrix (Figure 9) are pointed out. (1) Simple zoning is advisable, with few classes, considering the division into three degrees of hazard optimal. (2) The high pressure limit to plot the red zone adopted was 30 kPa level. This pressure limit is the most commonly accepted and is considered the maximum demandable for a reinforced housing. (3) In some cases the avalanche return period of 100 years proved to be insufficient as the area of maximum extent. It was therefore preferable to work with the avalanche of 300 years. Thus, it was considered necessary to work with two reference scenarios (T=30, T=300). (4) Low hazard (yellow) was considered to be an option for situations where exceptional avalanches have a high degree of uncertainty due to unawareness and lack of information. The French concept of maximum credible avalanche (AMV) was incorporated, because it did not rely only on the results from calculation of extreme situations.

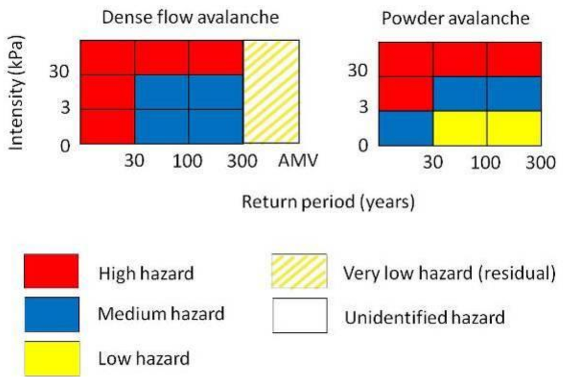
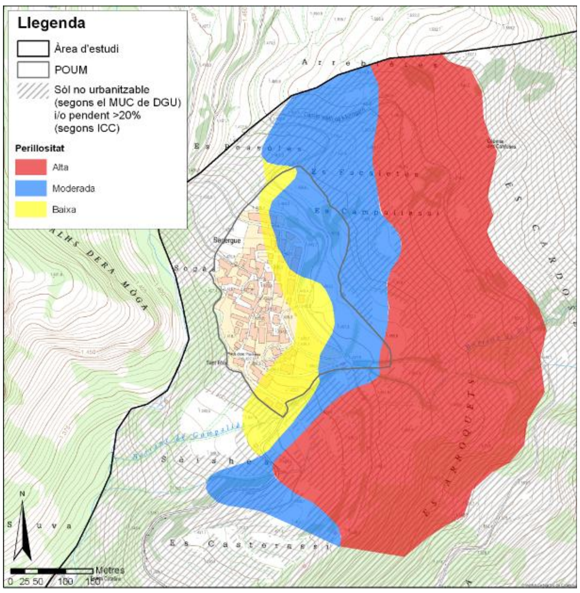


Figure 9. Hazard matrix adopted for the Catalan Pyrenees for the ZTSPA.

The result of the application of the matrix adopted for the Catalan Pyrenees can be viewed in figure 10 for the villages of Bagergue and Unha, both in the pilot area.



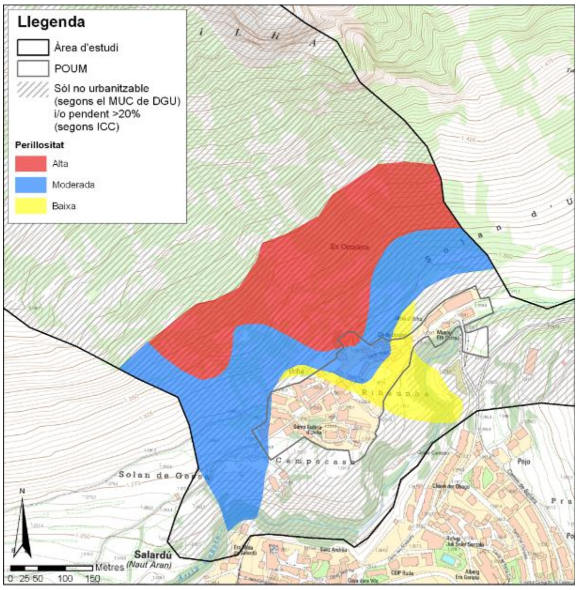


Figure 10. ZTSPA applied to the villages of Bagergue (up) and Unha (down), both in the municipality of Naut Aran (Val d'Aran, western Catalan Pyrenees)

4 CONCLUSIONS

The PZTSPA has served to set a methodology, to define an avalanche hazard matrix and a procedure to perform the ZTSPA homogeneously and comparable in the Catalan Pyrenees. Similarly to the Swiss methodology three hazard classes were established, but incorporating the concept of maximum credible avalanche (AMV) of the French methodology.

Simultaneously, the PZTSPA has given a boost in understanding avalanche dynamics and nivological behaviour in the Catalan Pyrenees. While it has increased the volume of information about past events, it has improved the knowledge on geographical distribution, return periods and intensity of avalanches as well as the return periods of snowfalls and snow depths.

The ZTSPA will reveal risk at urban scale in localities susceptible of being affected by avalanches. The results will be essential to manage civil protection in emergency situations and to prioritize the development of protection works to progressively reduce this risk.

In the future this methodology will serve for a better management of new urban planning.

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