Map of the intrinsic risk of avalanches for the aragonese Pyrenees by using GIS techniques

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Abstract

In the last years, an important increase in the number of trekkers that realizes winter trips in high mountain areas has been produced. This fact is involving a rise in the number of victims of avalanches. There are two main groups of variables that defines the avalanche risk level: the nivo-meteorological conditions and the terrain characteristics. The second ones are wich, due to its stable nature along the time, are easier to map. The purpose of this work is to assess the diferent geographical factors that affect on the avalanches triggering and, by combining the derived information, to extract a map of the avalanches risk that, in this case, it is restricted to aragonese Pyrenees. To this purpose GIS techniques has been used, by mixing vectorial information, Digital Terrain Models and Landsat imagery.

Keywords: *Avalanches, Risk, Geographic Information Systems, Digital Terrain Models.*

Introduction

In the last years, the number of avalanche victims has increased in a notable way. This fact has one of its origins in the practice of mountain sports, very popularized lastly. In Spain the number of victims has been estimated in four per year, with a maximum value in 1979, in which there were 11 avalanche victims.

Besides the mountaineering activities, the avalanche risk estimation is also fundamental to the country planning, as well as to the appropiate design of projects. In fact, the first work on the estimation of avalanches risk known in Spain was motivated by the construction of the Canfranc international railway station and, more recently, some similar works has been carried out to evaluate the risks on the accesses to the nearby tunnel of Somport (López *et al.*, 1997).

The mechanism that gives as result the avalanches triggering is, more or less, the following. As the sucessive snowfalls arrives in the winter station, the different snow layers are settled one after the other, each layer having its different physical properties. These heterogeneous layers are settled on the ground (or its green cover) in a way that they stay in a more or less stable state. When one or more of these layers slips quickly over other or over the ground, an avalanche occur.

It can be said that the avalanche triggering risk depends basicly on two groups of factors. On one hand some intrinsic factors derived from the nature of the terrain (slope, aspect...) and, on the other, some extrinsic factors[1], that depends on external factors, as the weather conditions (recent snowfalls, wind, temperature…). The present work is focused on the assessment of the risk that depends only on the first group of factors which, following the estimation of Julián *et al*. (2001: *p*. 120), due to its invariable nature along time, are capable of be mapped.

First of all, it must be recognized that extrinsic factors have a definite influence over the avalanche triggering risk and, in fact, near the 80 percent of the registered accidents have occurred in the next day to a severe snowfall. Nevertheless, it is clear the usefulness of have a map that warn about the terrain intrinsic risks. This kind of maps constitutes the ideal complement to the avalanche risk information from the weather services that only takes into account the extrinsic factors. With both two souces of information, people that decides to go to the mountain when the avalanches risk is not null have an important information that allows to know if its planned route runs over areas where extra careful must be taken. There are enough high mountain areas for which this kind of cartography it is already available. In Spain, Catalonia has a cartographical series (*Mapes de Zones d'Allaus*) developed by the Cartographic Institute of Catalonia in a scale 1:25,000 (but unfinished) that collect information about the intrinsic risks in the catalonian Pyrenees. Nowadays, there are no information available about this kind of cartography for other areas in Spain.

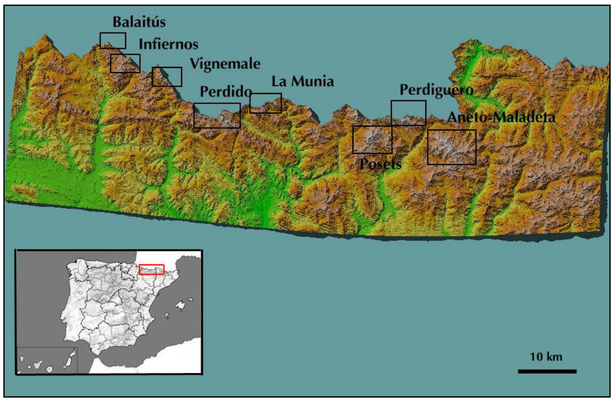

Fig. 1. Map of the working area (the aragonese Pyrenees and its surroundings) with the location and name of its mains massifs.

The undeniable interest that this kind of information has and the interest of deal with the nowadays non covered areas is the origin of this work. And this is the situation for the aragonese Pyrenees (see figure 1). As a sign of the real benefit, it cannot be forgotten that near half the mortal avalanche accidents take place in the province of Huesca.

Objectives

Until the moment several approaches have been carried out to the avalanches risk mapping, although there are few works that goes more deeply into the automatization of its production. Most of these works (Julián *et al.*, 2001; the series *Mapes d'Allaus* from ICC) uses enquiries on the population or

[1] Some authors (Julián *et al.*, 2001) talk about direct or indirect criteria, respectively. Among these factors it is not included the right presence of man, which can be the key factor that trigger the avalanche when it pass over a sensible area.

photointerpretation techniques. These methodologies, although reliable, are highly time-consuming. In addition, the enquiring strategy has the great disadvantage that mountain areas, due to its inaccesibility, are just characterized by to be less walked, so the available information is really poor both in quantity and in the covered area. The aim of the present work is search for ways to speed up the generation of avalanches risk cartography allowing to work in more extensive areas, and forgetting the up to now limitation to two or three valleys. For this purpose, it will attempt to take advantage of the current posibilities that offers to us the use of Digital Terrain Models and the spatial analysis techniques by means of Geographical Information Systems (GIS).

It is expected to calibrate the obtained results following this methodology by verifying from the avalanches risk information available nowadays and fully reliable in a local range (mainly the gully or valley). It has been also collected all the available information about avalanche events (the above mentioned specific articles and newspapers) and it has been verified that the presented methodology determines a consistent risk level for these areas, for which it already have reliable information.

Materials and methods

As it has been already disclosed, the avalanche risk estimation in this work is only based on those variables that can be solely atributed to terrain, regardless of weather conditions in every moment. These variables are the following: height, slope, aspect, terrain curvature, texture and kind of ground cover (if this exist or not and the type of this green cover). All these variables are what, combined in a reasonable way and according to the fundamentals of any multi-criteria analysis, will allow to us to establish the existing risk level anywhere (to be more precise, in every pixel with a dimension of 100 meters). Among all the possibilities, the only unfeasible has been the texture due to the need of a higher resolution to estimate it (maybe lower than 5 meters, unattainable to us at the moment).

To carry out the analysis of the terrain morfometric variables, a Digital Elevation Model with a resolution of 100 meters from the Ebro Hydrographic Confederation has been used[2]. Concerning the characterization of the green cover, a Landsat TM scene has been used (resampled to 100 meters resolution) and registered to allow, in this way, the combined use with the above mentioned model. For the image processing ENVI 3.6 has been used while for the integration and its management Arcview 3.2 and ArcGIS 8.1, both from ESRI, has been used.

The herein proposed method for the avalanche risk areas location is composed of two main steps. The aim of the first step is to locate the areas in which is more likely the avalanche triggering (its head or origin), whereas a second step determines the track of the supposed avalanche, delimiting in this way the whole avalanche risk area, including the head and the downward area. In the first case, the analysis of the below described intrinsic variables was carried out; in the second one a Wolfram Research Mathematica© program was implemented to determine the suposed avalanche track assuming that the avalanche starts in any pixel with an associated risk and moves downhill, following the steepest of the 8 possible directions stored in the flow direction model, until it reaches a pixel with a slope lower than 10 degrees, being this the value what different works establishes to stop the avalanche movement (see an example in figure 2). Nevertheless, it must be reviewed that there are evidences supporting that an avalanche can partially go up to the opposed hillside.

[2] http://oph.chebro.es/CARTOGRAFIA/FICHAS/mdt200.htm

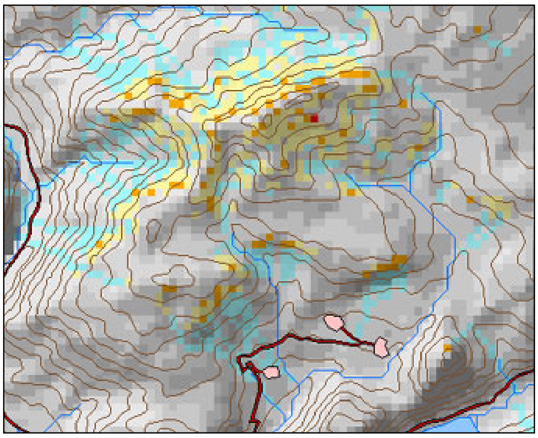

Fig. 2. Excerpt from the final results in the determination of the avalanches head with the associated risk, in yellow-to-red colors (see table 6) and the path of avalanches (showed in cyan).

Once these ideas are clarified, each of the variables considered in this work are described now: it is described the effect of each variable on the avalanche risk, the importance of each variable on the final risk estimation (obviously, not all the variables have the same level of significance) and the numeric estimation of the risk that the adopted value by each variable involve. This last information has been included in the next tables by using the available statistical information (mainly from the Cartographic Institute of Catalonia) or a justified estimation, if no data were available. In this way, it begins from the simple hypothesis which stand that a strong correlation exists between the observed frequency of avalanches, showed in the statistical information, and the risk (likelihood) of occurrence.

1. The height

It is clear that avalanches only occur over the snow level, directly related to the freezing level (the height to which temperature has lowered to reach zero degrees Celsius). In the case of Pyrenees, during winter station the freezing level is placed around 1700 meters (García-Ruiz, *et al.*, 1985; Creus, 1987).

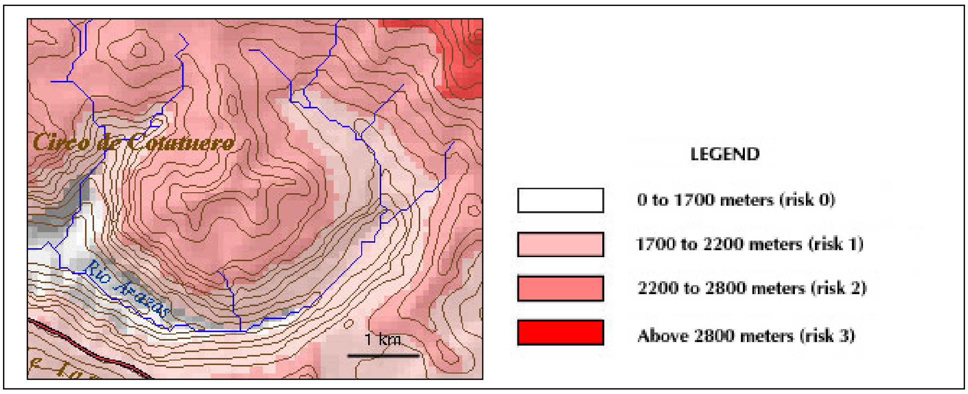

Fig. 3. Excerpt from the risk map according to the height.

To that effect, given the almost null possibility of an avalanche triggering below a height of 1700 meters, these areas have been not considered in the current study (and, in accordance, a null weight has been given for it, see table 1 and figure 3).

Table 1. Conversion from height to risk.

Height (meters)	Risk
< 1700	0
1700 – 2200	1
2200 – 2800	2
> 2800	3

2. The slope

Among all the variables, the slope is, without dubt, the one that has more influence on the avalanche risk. This is easy to understand since an avalanche is only a snow mass moving downhill so the gravity and the friction will be the forces that will decide if the avalanche will occur or not. On the other hand, in all the existent bibliography concerning this matter it is accepted that the critical slope for the avalanche triggering range from 25 to 45 degrees. Lower slopes contribute to reach the needed stability to cancel in the practice the chance of an avalanche event[3], while higher slopes allows continuous "purges" (that is, small slides of snow that prevent the formation of the big amounts of snow necessaries to trigger a considerable avalanche).

Table 2. Conversion from slope to risk.

Slope (degrees)	Risk
< 25	0
25 – 30	15
30 – 35	40
35 – 40	20
40 – 45	20
> 45	10

[3] Only in certain cases wet snow avalanches could occur in slopes lower than 25 degrees.

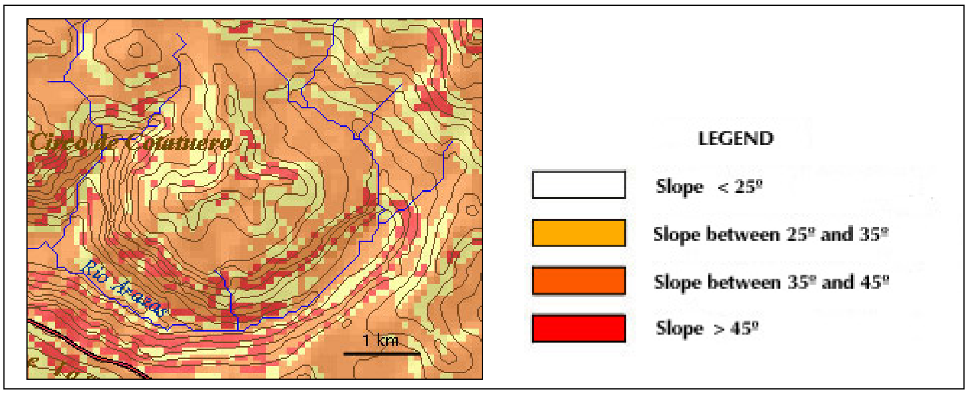

Fig. 4. Excerpt from the risk map according to the slope.

The used non-lineal increase of the risk according to the slope is one of the reasons why this work could be considered innovative (see table 2 and figure 4). Indeed, the increase in the risk is different from 35 to 45 degrees than from 25 to 35 degrees, and so is reflected by the ICC statistics (http://www.icc.es/allaus/estad211.html). Due to this situation, the avalanches percentage in every interval of slopes it has been taken into account to estimate the risk. In this way, for instance, if the 40% of registered avalanches occurred in an area which slope values are between 30 and 35 degrees, the risk value it has been taken equal to 40 and so on.

3. The aspect

Concerning this variable, it is interesting to start with a mention to some authors (Julián *et al.*, 2001: 122) that consider the aspect as an extrinsic variable because of its clear connection with the nivo-meteorological conditions. The present methodology asumes that, despite this connection exists, it is indisputable that situations in wich one can affirm that there is no influence neither from wind nor Sun's radiation —and, consequently, from the aspect— on the analyzed terrain are really limited and, therefore, the aspect can be considered as acting on the avalanche risk in a relatively constant way (independently of the extrinsic factors).

The performance of this variable is due to two different factors interacting: the prevailing wind direction and the Sun's path along the day. Concerning the first variable, the prevailing wind in the Pyrenees latitude is from the west, although in high mountain areas, as in this case, the direction can be slightly conditioned by orography (for instance, the valley breeze prevailing during the day or the channelization of the wind in the valley direction). Because of this prevailing direction, hillsides with an eastern component (the leeward hillsides), are which will accumulate a greater snow depth, difficult to become stable, allowing the formation of windslabs (which cause the 70% of the avalanche accidents).

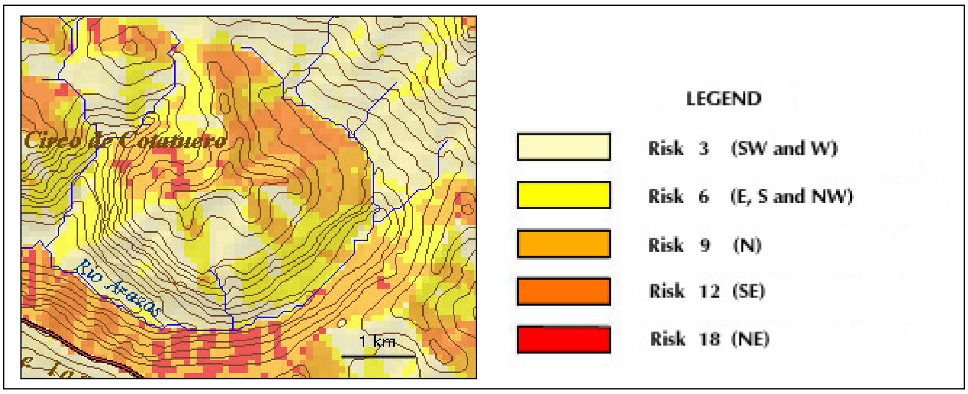

Fig. 5. Excerpt from the risk map according to the aspect.

On the other hand, as it is well known, in the North Hemisphere the Sun travels the sky following a path almost always at the south of the observer. Because of this fact, the north faces keeps the snow mantle colder and compacter than the other faces. Moreover, it must be taken into account that, in the special case of wet snow avalanches —usual in the spring—, it is in the south faces where the avalanches risk is higher (due to the snow fusion and the decrease in friction caused by the pressure rise inside the pores of the snow mantle). All these matters, as well as the statistics published by ICC[4] has lead to the estimation shown in the table 3, with the maximum risk levels in northeast, north and southeast aspects (see also the figure 5).

Table 3. Conversion from aspect to risk.

Aspect	Risk
N	9
NE	18
E	6
SE	12
S	6
SW	3
W	3
NW	6

4. The curvature

It is accepted that convex surfaces cause an unstable situation in the snow mantle, allowing the appearance of fractures due to stress, while concave surfaces favour the snow accumulation and its stabilization.

[4] These statistics can be consulted on the web page http://www.icc.es/allaus/estad28.html

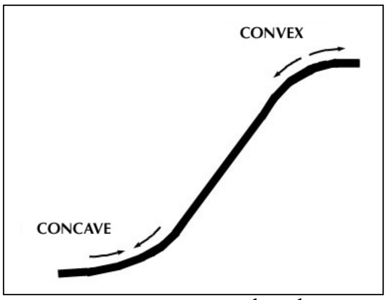

Fig. 6. Hillside profile. The stress on convex areas makes the snow mantle more unstable.

On the other hand, as it is well known, there are different surface curvature parameters according to the selected criterion for the surface section. Some authors, as Maggioni *et al*. (2002), uses plane curvature, but here the profile curvature has been chosen, understanding that defines clearly the existence of stress forces in the truly interesting direction, that is, the hillside direction (in which the main involved force acts: the one of gravity). Indeed, the vertical —the one of the potential avalanche advance— is the truly significant direction concerning the snow mantle unstabilization (see figure 6), offering a breakage section in the most harmful direction, the one perpendicular to the avalanche movement.

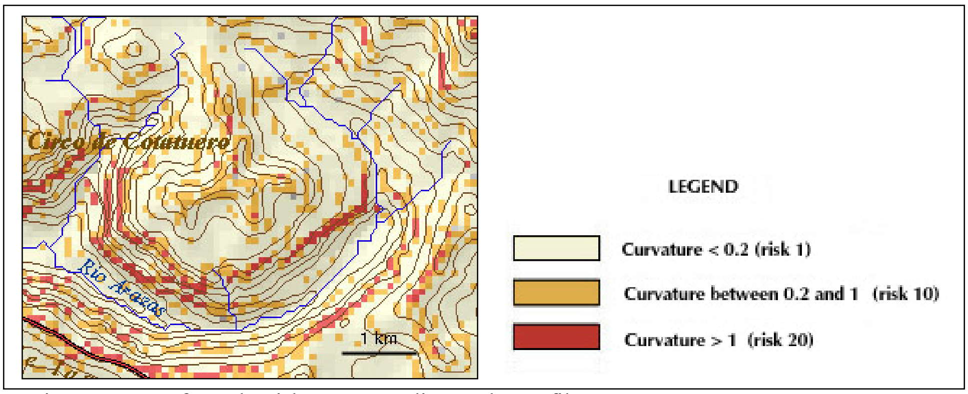

Fig. 7. Excerpt from the risk map according to the profile curvature.

The assigned risk values according to profile curvature are shown in the table 4 and an example is shown in the figure 7.

Table 4. Conversion from curvature to risk.

Curvature	Risk
< 0.2	1
0.2 – 1	10
> 1	20

5. The texture or roughness

This parameter acts favouring or preventing the snow sheet anchoring and hindering, in this way, its movement. So, rough surfaces (for instance, boulder debris) favour the better stabilization of the fallen snow sheets, while smooth surfaces (as the high mountain pasture, for instance) are prone to suffer slides.

Provided the limited spatial resolution of the available information, this variable cannot be taken into account, however a variable with a similar behaviour has been included in the analysis, the green cover. This is described in the next section.

6. The green cover

As already has been advanced in the previous section, the type of green cover existing on the ground (its height and density) has an effect that can favour or prevent the avalanches triggering. The role developed is similar to the one of texture, favouring the proping up of snow sheets if there are bush or tree species or, preventing its stabilization if there are pastures. Some works (McClung, 2001: 228) come to state that the 90% of avalanches occur on terrain with a green cover which average height is lower than 2 meters.

In fact, in the same way happened with the zones below 1700 meters height, the chance of an avalanche triggering on forested areas is almost null, so these areas has been ignored in this study (by assigning to these areas a null weight, see table 5).

To estimate the green cover a Landsat scene has been used, carrying out the calculation of the Normalized Difference Vegetation Index (NDVI), because this index is the most used nowadays. The available image is dated at January 28th, a date, in principle, with a high risk of avalanches, so represents an appropiate information, except for the drawback that, by detecting the chlorophyl levels in leafs, the NDVI will cannot detect the decidouos forests. As it is known, the NDVI range from –1 to 1, corresponding the negative values, more or less, to water regardless its state (water surfaces, snow/ice cover or clouds), while the lower positive values show poorly developed vegetation (bare soil o pastures) and the high positive values show more developed areas (dense forests). The criterion used for the classification and the corresponding risk values are shown in the table 5, while an excerpt of the model of risk due to ground cover can be seen in figure 8.

Table 5. Conversion from type of cover to risk.

Cover	NDVI	Risk
Water/ice/snow surface	-1 – 0	20
Rocks/bare soil	0 – 0.1	10
Pasture	0.1 – 0.3	30
Forest	0.3 – 1	0

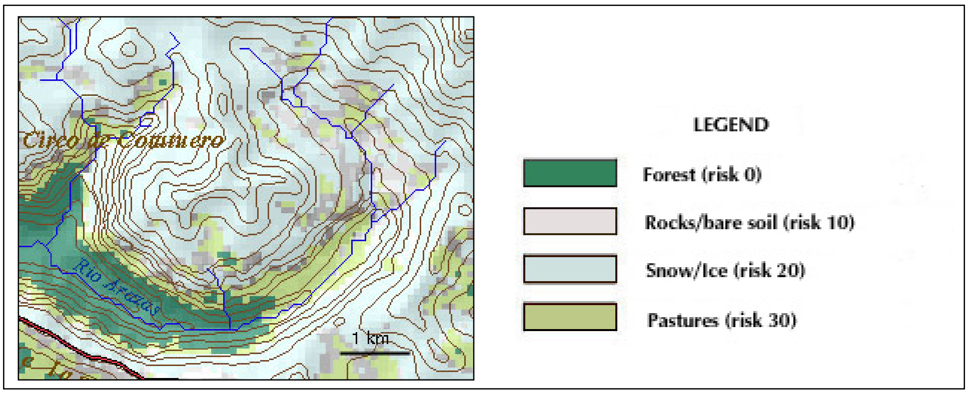

Fig. 8. Excerpt from the risk map according to the existing cover.

Results

Once all the parameters affecting the avalanche risk has been connected (by means of a multiplication), the final risk level range from 0 to 1,296,000, although the studied zone do not exceed a level of 864,000. Provided that does not seems natural to consider a final risk level determined only by one of the five parameters taken into account, a threshold level has been defined in 3000 instead of 1, resulting from the application (multiplication) of some minimum risk values for all the considered parameters (1 for the height, 10 for the slope, 3 for the aspect, 10 for the curvature and 10 for the ground cover). Concerning the intermediate values that set the bounds to the three defined risk levels (null, moderate, high and very high), these has been defined by assuming a lineal variation in the risk to all the variables except for the aspect, for which, by means of a minimum-square adjustment, an exponential function has been obtained (see figure 9) to define its variation ($Risk = 2.1918\ e^{0.2463\,x}$, been x the aspect datum position after be ordered in a increasing risk way). The legend of the map with its risk levels and every defined interval can be consulted in the table 6.

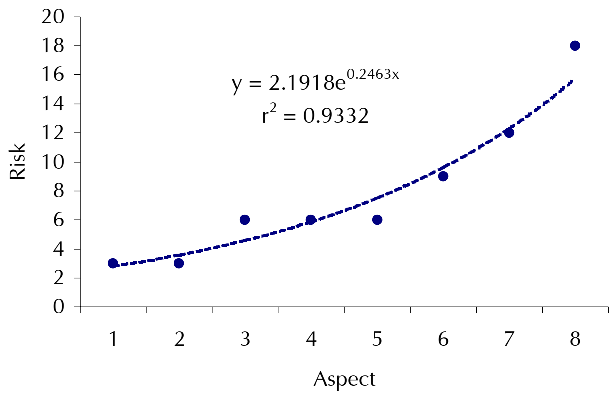

Fig. 9. Exponential adjustment that defines the risk levels according to the aspect (including the function expression and its correlation coefficient).

Table 6. Risk levels in the map and its legend.

Risk Index	Risk Level	Legend
0 – 3000	Null	
3000 – 45653	Moderate	
45654 – 280229	High	
280230 – 1296000	Very High	

To verify the achieved results it has been chosen to check it with the historical data of avalanches (those avalanches from which there are a record and enough information, mainly from the Cartographic Institute of Catalonia[5]). Indeed, provided that avalanches are a recurrent event (wherever an avalanche occurred it is likely that occur again and, consequently, the area in question constitutes a risk focus), it is natural to believe that, if those areas where an avalanche have happened are not shown by the obtained results, the latter would be discussed without excuses. On the contrary, if a reasonable percentage of registered avalanches has been detected by means of the present methodology, this could be considered correct. To that effect nearly all the discussed cases (92%) have corroborated the level of risk here estimated. As examples, it can be mentioned those of Gerber Lake on January 3th, 1998 (with a risk index estimated in 108,000/High), the Rius Pass/Mount Sarrahera on January 25th, 2003 (with a risk index estimated in 96,000/High) or the Escornacrabes gully in the Beret Massif on February 17th, 2002 (with a risk index estimated in 432,000/Very High)[6].

The results achieved also show coherence with previous works related to more local areas (Julián *et al.*, 2001) which estimate a higher avalanche risk, for instance, in the north slope of the Pineta Valley, the south slope of Canal Roya and the Custodia mountains (Julián *et al.*, 2001) or the Secras gully near the Canfranc railway station (López *et al*. 1997).

Once the results were verified, the edition phase of the map of avalanches risk was carried out by using the information described up to now and a cartographical background that allowed the unequivocal identification of every place. In view of the model resolution, the allowed scales for the final map was established between 1:50,000 and 1:150,000, although the one that offers a better reading is the 1:100,000 scale (in two DIN A1 sheets). On the other hand, with the aim of simplify the map reading and, provided that this is not an orientation map, but a consultation map, it has been considered that the geographical information to be included could must be minimum. It has been added to the map, specifically, the relief information (as level lines and shading), the hydrographic network, the main communication routes, as well as the main names (the main water courses, the most significant mountain ranges, the relevant peaks and towns and so on). An excerpt from the resulting map can be seen in the figure 10.

[5] This information has been very useful because of the fact that, despite this work is focused only on the province of Huesca, some coverage inside the contiguous provinces (Navarra and Lleida) exists.
[6] All these cases are described in the ICC web page (http://www.icc.es/allaus) inside the section *Accidents per allaus*.

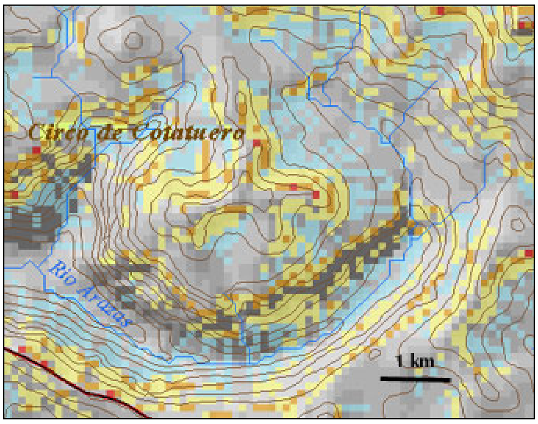

Fig. 10. Map of risk according to the combination of all the variables.

Conclusions

The unquestionable usefulness of Digital Terrain Models for the avalanches risk estimation has been checked, revealing the importance of improving its resolution and accuracy.

As already has been set out, provided that the available information had a limited spatial resolution, the final map will have as basic spatial unit a 100-meter side square, which results really poor for the evaluation of some parameter (the case of texture has been mentioned) and, therefore, the risk of avalanches of a lower size is impossible to estimate in practice[7]. Whereas, other parameters has been benefited from this low resolution, as is the case of curvature estimation, which is more suitable to estimate at a medium scale because the curvature effects at a small scale are less significant on avalanche triggering. Nevertheless, from our point of view, the resulting information is unquestionably worth, among other reasons because this kind of avalanches, bigger and therefore more destructive, are which this methodology is able to detect.

On the other hand, this work also reveal the important support offered by this kind of maps, both for the trekkers and the technicians responsible for the land planning. In the first case to be capable of evaluate in advance the risk of the planned route (according to the avalanche risk forecast of weather services[8]) and, in the second, to evaluate the potential danger if changes in the current land use planning are carried out or new infrastructures are built (tunnels, skiing resorts and so on).

Consequently, in the case of existing an (extrinsic) avalanche risk forecast between moderate (2) and high (4) and, provided that the map shows the foreseeable avalanche triggering areas, if the route planned by the mountaineers cross a place located downward from a intrinsic risk area (for instance, High or Very High), these mountaineers could consider if it is really advisable or not to start the initially planned activity or if it is better to choose an alternate route.

Finally, it is fundamental to clarify that this work does not at all intends to replace the experience in the avalanches risk estimation. People who decide to accomplish a trail across areas with significant amounts of snow must to know which are the playing variables or the signs of avalanche danger, as well

[7] Nevertheless, according to ICC data, only 39% of avalanches will be included in this group.
[8] For instance, according to the forecast of INM (the Spanish National Weather Institute) in its web page http://www.inm.es/cgi-bin/nevadas.cgi.2002?ccaa=arn&producto=p18t or the ICC, http://www.meteocat.com /marcs/marcos_previsio/marcs_pirineu.htm.

as to interprete it to get the final and indisputable estimation of the risk level. To that effect, the now presented cartography does not constitutes a decisive information but an ideal complement to the weather information and the experience in high mountain, which as a last resort is the essential guarantee of a safe activity.

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