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EDITOR'S NOTE

Translation: Frédéric Leone, Marion Cole

AUTHOR'S NOTE

This study took place within the framework of the MOPERA research programme (Modélisation Probabiliste pour l'Évaluation du Risque Avalanche – Probabilistic modelling of avalanche risk assessment) funded by the ANR 2009, programme « Risques Naturels : Compréhension et Maîtrise » (Natural risks: comprehension and mastery). We would like to thank the GIS service of the Hautes-Alpes' Conseil Général (general council) for the availability of the "events" database and the reviewers of this article for their suggestions.

1 Road accessibility is particularly strategic for the upkeep of economic activities but also for rescue interventions. In the French Alps, accessibility is reduced, particularly at the bottom of the valley, and it may be further degraded by various natural hazards. In this regard, avalanches are a considerable threat because, other than the victims and direct damage they may cause, they often incur roads being cut off over more or less prolonged periods at a time of year when networks are already considerably altered by seasonal closures. What sometimes results is a territorial fracture which affects mountain societies in particular and the stakes linked to touristic economy.

2 In the avalanche domain, as in other natural hazards', traditional risk assessment methods, very often hazard-centred, are gradually evolving towards methods taking into account the presence of stakes of various natures (human, material, functional) associating different forms of vulnerabilities (Eckert *et al.*, 2012, Leone *et al.,* 2010, Leone & Vinet, 2006). Vulnerability is defined as a propensity to damage or dysfunction which can be measured by damage intensity, expressed in rates or probability of destruction/death (D'Ercole, 1994; Leone *et al.*, 1996; Reghezza, 2006). In the avalanche domain, such measures are still very empirical and are presented as damage matrixes or curves which provide the level of damage expected for each type of hazard according to the phenomenon's magnitude (pressure exerted by the particular avalanche) (Barbolini *et al.*, 2004). Existing practical applications mainly concern risk mapping for urbanism (Keylock *et al.*, 1999) and road risk assessment.

3 Most work on avalanche-related road risk assessment is based on Wilhelm's work (1997). He provided practical formulas of death rate estimation according to the intensity of traffic, the average number of passengers per vehicle, the traffic's speed and the length of the exposed road section. Calculations can apply to a single corridor, or a longer road section crossed by several corridors, by adding them up. Classic applications of such procedures concern the comparison of different treatment strategies of the great Alpine cols' winter viability (permanent or temporary closures, building permanent protections such as tunnels, etc.). Various refined models were suggested, concerning hazard modelling (Wastl *et al.*, 2011; Zischg *et al.*, 2005b), the potential monetization of losses (Rheinberger *et al.*, 2009), or even considering additional risk for vehicles stopped by roads being cut off during their transit (Hendrikx et Owens, 2009). In every case, the acuteness of risk assessment is highly dependent on the quality of the avalanche hazard estimation in terms of the exposed sections' length and the intensity of potential impacts. However, many countries refer to it: Switzerland (Margreth *et al.*, 2003), Austria (Zischg *et al.*, 2005a), Norway (Kristensen *et al.*, 2003), etc., taking into account possible local specificities (national characteristics of the vehicle fleet for instance).

4 In the French Alps however, using this type of method is not very widespread, even though historical information concerning avalanche activity is particularly abundant, although spread out (cf part 2). This lack of interest may be explained by the considerable limit of such methods, notably that they are only interested in the direct consequences of avalanche impacts, disregarding the consequences of accessibility loss, which are often more important.

5 The eminently geographical problem of territorial accessibility linked to natural risks relies on several notions proper to risk geography or transport geography. Thus it can bind different approaches yet under exploited in the perspective of crisis management support. Let us note the studies of IRD geographers who tried to analyse accessibility as an essential component of territorial vulnerability facing crises, but didn't go so far as developing quantitative assessment methods based on the graph theory for example (D'Ercole & Metzger, 2009; Demoraes and D'Ercole, 2009; Metzger *et al.*, 2011). By contrast, other scientists have recently applied these theories to natural risks (Chang, 2003; Gleyze, 2005; Nabaa, 2011), without formalising a territorial conception of risk confronting the notion of direct to indirect risk areas, via accessibility. Recent work undertaken in Mayotte for the tsunami risk (Leone *et al.*, 2013) or in the Alps for debris flow (Leone *et al., 2011*), tend to formalise this territorial approach of risk based on deterministic models

(for a given scenario of road closures) and not according to a closure risk analysis as suggested here for avalanches.

6 In order to partially resolve such shortcomings, and retrospectively assess the physical, functional and human vulnerability of road networks to avalanche risk in the French Alps, the first stage of our study consisted in geo-referencing and harmonising in a GIS, the information given by the main databases available on avalanche consequences in the three French Alpine departments (Alpes-de-Haute-Provence, Hautes-Alpes, Alpes-Maritimes). This enabled us to identify avalanche impacts on roads since 1937, to measure their frequency, their geographical distribution, their gravity and the nature of direct and indirect damages. A second research step falls within an approach of road network functional disturbance risk assessment. It is translated by the construction of indexes set up on the scale of sections combining indicators of closures and functional values appreciating the importance of each section in the network's global functioning. Thirdly, the identification of vulnerable and/or exposed sections enabled us to map the isolation risk of certain parts of the territory and associated populations on a regional scale. This last stage of the research resorted to graph-based modelling and research algorithms of the shortest paths from three big cities of these three Alpine departments: Grenoble, Marseille and Nice.

Avalanche types and damage processes

7 The avalanche phenomenon is generally defined as a rapid flow of snow down a sloping surface. This very general definition encompasses extremely varied phenomena according to the type of triggering or the flow dynamics, which are closely linked to the state of the snow (Ancey *et al.*, 2006). Dynamics wise, there are two types of avalanches: sluffs or loose snow avalanches (a mixture of low density snow and air) and dense avalanches. Among the latter, an additional distinction between dry and wet snow (presence of liquid water) may be useful.

8 Despite the rather precise localisation of the most dangerous avalanche prone sites and the set-up of protection measures, cases of extensions beyond CLPA (Carte de localisation des Phénomènes Avalancheux – avalanche phenomena localisation map) historical contours are relatively frequent. Deposits (dense phase) resulting from such great avalanches can obstruct considerable lengths of network and incur important clearing difficulties on threatened sections. Wet snow avalanches in particular are responsible for most road closures. Even when they only lead to localised obstructions due to the often important channelization of their flow, clearing up is often long because of the snow's high density. It is the dense phase of snow and rocky and vegetable debris transported that cause most damage on roads. For sluff type avalanches, the blast effect affects the road less but often damages additional equipment. Let us also note the indirect damage caused during the clearing of snow by machines that must work in emergency with very low visibility.

Methodology

Construction of geodatabases

9 This research relies on the constitution of a Geographic Information System (GIS) covering all three studied departments. Some data comes from public organisations (INSEE, IGN, RTM/ONF), other data is provided by local authorities. They cover several themes and were subjected to a time-consuming compilation, integration, harmonisation and validation work, in the field particularly. Two local scale topographic and demographic referentials were used:

- The IGN route500 vectorial database (2010) which represents the main roads with a precision of 100 m. It differentiates 5 classes of roads for speed calculations (highways, main roads, regional roads, local roads and access roads). It also informs us of the main roads' winter closures.
- INSEE (2012)'s gridded population database provides the number of permanent residents per km^2 and was established from a specific use of fiscal files. Additional data on the periods of cols' usual closures or certain secondary roads, were provided by various sources (Internet, regional councils, Topo IGN DB, testimonies).

10 Most of our work consisted in setting up a new database of the impacts of avalanches on the road network of the three departments between 1937 and 2011. This base merges the information from three main sources which we had to georeference manually, case by case, after checking and removing duplicates. A total of 1,042 usable impacts were censured and located. 60% of the data came from the EPA base (Enquête Permanente sur les Avalanches- permanent survey on avalanches) managed by the Irstea. The EPA is a chronicle of events of over near 4,000 corridors, sometimes since the early 20th Century, describing avalanches' physical characteristics and incurred damage or disturbances. The duration and quality of series has already proved its worth in other studies, notably the analysis of risk for urbanism including avalanche protection designs (Eckert *et al.*, 2007; Naaim *et al.*, 2010) or to establish the link between avalanche activity and climate (Jomelli *et al.*, 2007; Castebrunet *et al.*, 2012), but never for the quantification of road risk. The rest of the data was provided by the ONF's RTM service (Restauration des terrains en montagne – mountain terrain restoration) (34%) and the GIS service of the Conseil Général des Hautes-Alpes (6%). The produced "impacts" base was coded in such a way as to differentiate the intensity of physical and functional damage on the road network according to an original typology, whilst keeping a descriptive field on the nature of such impacts.

11 The areas exposed to avalanches, also used in the following part of our research (*cf* 4th part) were extracted from the CLPA (Carte de localisation des Phénomènes Avalancheux – avalanche phenomena localisation map), also managed by the Irstea. This regularly updated mapping censures the maximal spatial extensions observed (testimonies and archives) or supposed (photo-interpretation) on the quasi totality of the Alps (Bonnefoy *et al.* 2010; Robinet and Bonnefoy, 2013). Although widely used locally to establish Risk Prevention Plans of mountain towns, its potential for the quantification of road risk on a regional scale has only recently been acknowledged and used (Tacnet *et al.*, 2013).

Modelling road accessibility with graphs

12 According to Bavoux *et al.* (2005), a location's accessibility is the degree of ease with which this location can be reached from one or more other locations, using part or all of the existing means of transport. Graph theory, used in computing or economy, is particularly interesting in the transport field. Indeed, the transformation of a "real" road network into a graph provides multiple applications. If the graph theory simplifies the network visually, it is most useful in the calculations and graphic representations of accessibility above all. First of all, the network must be turned into a graph, which is a mathematical object composed of nodes and arcs. The nodes (points) can be associated to the intersections of a network, and the arcs (links) are associated to road sections. The graph must faithfully render the urban road hierarchy and thus distinguish different types of roads that make up the network (Appert & Chapelon, 2008). Within the framework of road networks, it is important to assign values to graphs. Indeed, the start and finish locations are located in space and do not necessarily have the same weight: roads have different speeds and capacities. Each arc is characterised by its length in kilometres and by the automobile circulation velocity allowed on the infrastructure it represents, respecting Highway Code.

13 The road graph used for the applications which follow was built using the IGN's DB Route500. Consequently, it only serves the main conurbations, some villages but all touristic resorts. Accessibility calculations were realised with the RouteFinder® tool designed for the creation and use of accessibility maps in a GIS MapInfo® environment. The itineraries were defined leaving from Grenoble, Marseille and Nice respectively, towards each mesh of the inhabited territory and potentially isolated by one or more avalanches. This choice is justified regarding the volume of touristic stakes drained by these conurbations, of departures or transit, over winter periods of high frequentation and thus presenting a maximal population isolation risk. They were calculated according to the fastest routes given by the Dijkstra (1959) algorithm provided by the RouteFinder® application. The three accessibility scenarios rely on a degraded road graph, in winter viability conditions, over main roads only, with 14 cols out of 24 closed, and without going through Italy. We consider that the smaller secondary mountain roads, particularly the communal and forest ones, are unusable in winter, and not adapted to road flows from the neighbouring big cities. The applied circulation velocities were adapted from Chapelon (1996) from the work undertaken by the CETE in the east for the alternative itinerary analysis tool (ANITA). In the end, we kept 5 classes of velocities ranging from 40 to 110 km/h according to the types of roads proposed by the Route500 base.

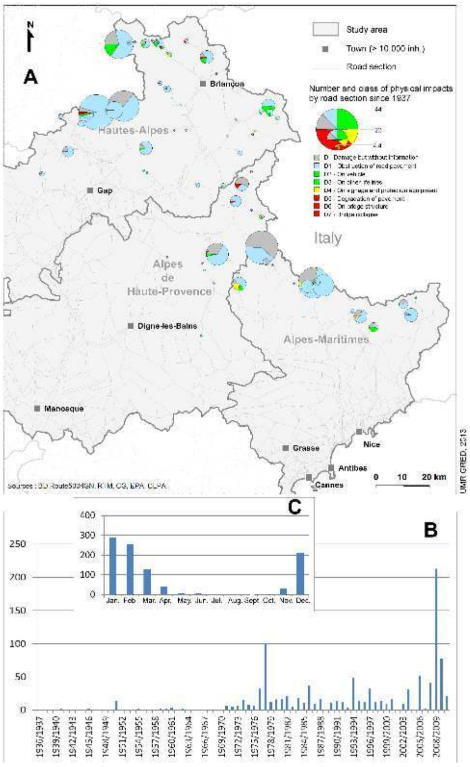
Direct and indirect impacts of avalanches (1937-2011)

Temporal and geographic distribution

14 The annual distribution of impacts displays a net increase during our study period. In all likelihood, this is more symptomatic of the improvement of data gathering than of an increase of avalanches. The 1970s threshold is particularly noteworthy, when information gathering became gradually systematised (figure 1B). The distribution distinguishes seasons where the number of impacts was far higher than average, often due to abundant

snowfall. The most remarkable are 1950/1951, 1977/1978 and 2008/2009. In opposition, some seasons had very few impacts (1988/1989, 2004/2005) or were even spared like in 2000/2001. Moreover, this distribution actually conceals very short crisis periods during which very numerous impacts occurred. Thus, the temporal distribution of impacts over 73 years shows that the months of January, February and December are by far the most concerned (figure 1C). According to our data, December 2008 had the most impacts on the road network in the three studied departments.

Figure 1. Spatiotemporal distribution of physical impacts of avalanches on the main road network (1937-2011)



A: BY ROAD SECTION, B: BY WINTER SEASON, C: MONTHLY

15 The distribution of impacts per mountain range shows important spatial differences and a high representation of Champsaur and Mercantour, in particular on the network open in winter for the latter (figure 1A). On another scale, the most concerned towns in relative value are Isola (06), Abriès (05), La-Chapelle-en-Valgaudemar (05) and Villar-Loubière (05) with a record for the last one established at 82 impacts for 10 km of roads open in winter. The road sections the most affected by avalanche phenomena belong to great road axes such as the route du Lautaret (N91) or de Barcelonnette (D900), or impasses (Valgaudemar, Vallouise or Haut-Queyras valleys), or going through cols (Vars) and lead to resorts (Isola 2000). The hardest hit section open in winter in 73 years (44 impacts) is located between Saint-Maurice-en-Valgaudemar and Villar-Loubière in the Hautes-Alpes. Crosscutting the impacts DB with the IGN's road TOPO DB determines the type of roads comprised in the avalanches contours. It appears that the events censured are equally spread out between local and inter-communal networks (51%) and regional and main networks (49%). This result can be explained by the fact that the main roads, although fewer, are often open in winter and the events are better classified.

Direct and indirect damage typology

16 Damage due to avalanche impacts on the road network is generally minor. However, damage on annex equipment and road structures may be far more serious. In avalanche cases, the most important type of damage is the obstruction of the road. This type represents at least 69.5% of censured damage events. Material damage affects mainly additional networks (5%), annex equipment (1.7%) and vehicles (1.5%). Let us note the very low part of damage to the road in itself (0.7%), lower than damage to road infrastructure (1%). This is because undermining linked to avalanches is very rare.

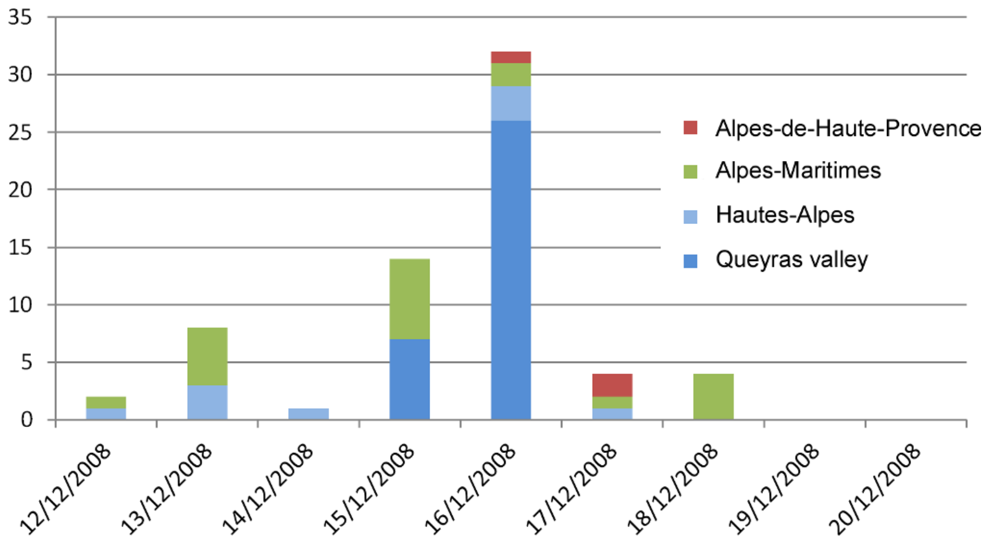
17 The different road network managers set up warning systems, preventive avalanche triggering and network closure in order to protect users. Thus, deaths linked to avalanches on road networks are extremely rare. Only 11 deaths were censured since 1937 over the three studied departments.

18 According to our analysis, 79% of events led to functional disturbances such as the interruption of circulation, but there is great uncertainty as to the duration of such closures: 54% of cases correspond to closures without duration indications, at least 5% to a road traffic interruption over several hours and 5% to several days. This high disturbance is explained by the type of dominant physical damage (obstruction), by the simultaneity of events in avalanche periods and by certain transport difficulties of clearing machines in areas that are often not well equipped.

The December 2008 avalanche surge

19 In between 14th and 20th December 2008, following an “eastern flux” meteorological phenomenon, snowfall was very abundant on the mountains bordering Italy, particularly on the Queyras where the accumulation over two days reached up to 300 cm at Ristolas, 150 cm at St Véran and Montgenèvre and 100 cm at Névache. The snowfall, accumulated on an already thick coat following the bad weather of 10th and 11th December, came with strong winds thus giving record values with 2.30 m of snow at Saint-Véran. This meteorological event caused a considerable concentration of high amplitude avalanches in the valleys of La Tinée, Névache and Queyras especially. They flowed over the CLPA’s spatial contour (Eckert *et al.*, 2010). Thus, 34 events justified a modification of the CLPA in seven towns of the Queyras (Gaucher *et al.*, 2009).

Figure 2. Number of avalanche impacts on the road network during the December 2008 avalanche surge.



20 The great avalanches of 15th and 16th December were responsible for the main road closures, in particular in the Hautes-Alpes (Queyras) and the Alpes-Maritimes (figure 2) (Ocana & Escande, 2009). Very many avalanches spread to the roads, cutting them over lengths reaching up to 400 m (“la Fourche” avalanche at Abriès). During this crisis, over three thousand people, residents or tourists, were isolated for several days. The situation was particularly critical in the Queyras where the population’s spreading required emergency evacuations, and in the Tinée valley where road closures isolated over 1,500 people, mainly tourists, during six days. It was only on 19th December in Queyras and 20th December in Isola 2000 that road connections were reopened, ending the crisis situation.

Loss of accessibility as a measure of territorial vulnerability

Dysfunction risk index

21 In a decision-making and prevention context, the functional disturbance risk of a road network can be defined as a closure probability combined to a functional value. The latter appreciates the strategic or functional importance of this section as regards the rest of the road network (Leone *et al.*, 2011). Within this study, we suggest an experimental index of dysfunction (IRd) which is the result of the multiplication of a closure index (Ic) with a functional value corresponding here to the minimal length of diversion of the exposed section avoiding a col closed in winter (Ld in km). This length was calculated via the road graph built on our study area. Each risk index variable was brought between 0 and 1, as a result of a division with its maximal value. For each section:

$$IRd\ (0\text{-}1) = Ic * (Ld / Ld\_max)$$

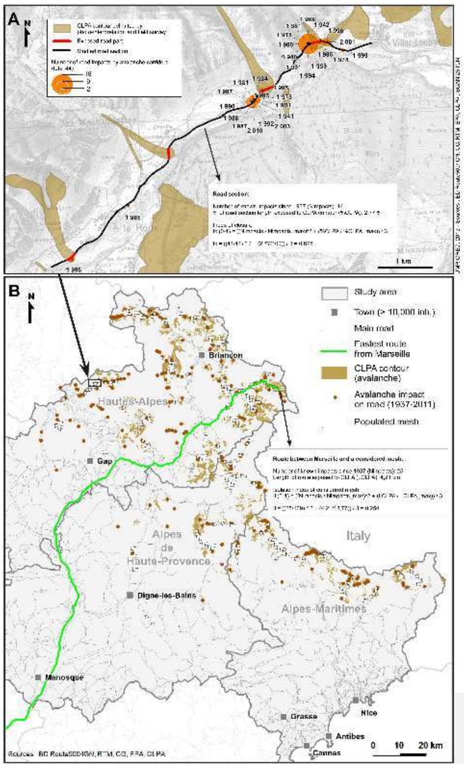
22 The closure indexes (Ic) of the 203 exposed sections were determined empirically by adding the number of known impacts since 1937 (Nimpacts) with the percentage of length of exposed section, meaning crossing a CLPA contour delimitated by land

photointerpretation and analysis (%CLPA). A coefficient of 2 was affected to the first variable to reinforce the weight of the vulnerability remarked (the damage) compared to the exposure. For each section:

Ic (0-1) = ((Nimpacts / Nimpacts_max)*2 + (%CLPA / %CLPA_max)) / 3

23 Figure 3A illustrates the calculation principle by taking the most impacted section as an example, located between Saint-Maurice-en-Valgaudemar and Villar-Loubière in the Hautes-Alpes. This measure of exposure to avalanches takes up the principle of empirical methods renowned in mapping of susceptibility to landslides. These methods combine and hierarchize part of the factual data on historical damages (or events) and part of the factors of predispositions giving the hazard contour (Chassagneux *et al.*, 1998; Sri Hadmoko D., 2009).

Figure 3. Index calculation principles: (A) closure (Ic) on the most impacted road section (between Saint-Maurice-en-Valgaudemar and Villar-Loubière in the Hautes-Alpes), (B) isolation (Ii) of a populated mesh of the valley of Queyras (Ristolas) from Marseille on the fastest route

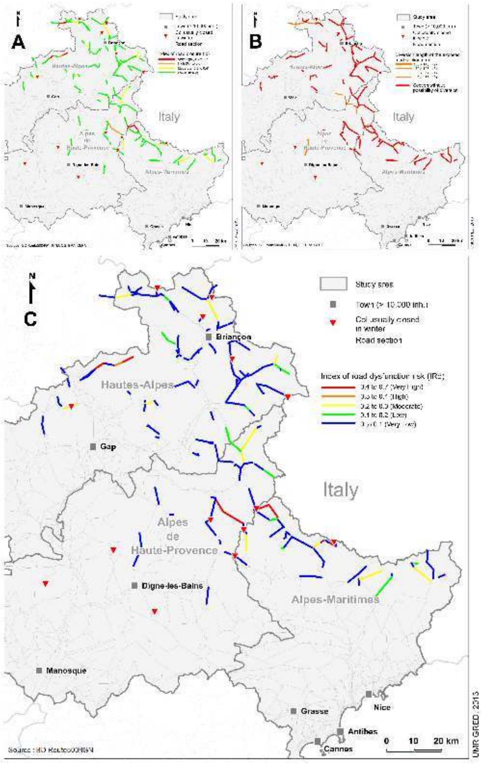


24 The maximum number of impacts is of 44 and the maximal percentage of section length exposed to a CLPA is of 100. The longest known diversion is of 143 km (Ld_max). An arbitrary value of 286 km (twice the maximum value) was allocated to sections disposing of no possibility of diversion (143 sections) to make their great functional and strategic values stand out, since they are unavoidable.

25 The closure indexes obtained are comprised between 0 and 0.7 (figure 4A). The highest values (>=0.4) concern a dozen sections located mainly in the valleys of Valgaudemar and Haute-Romanche (05), Bachelard (04), Haute Tinée and on the road of the col de la Bonette and Isola 2000 towards the col de la Lombarde (06). The resulting IRd index distinguishes the most risky sections that are in theory those presenting the highest

probability of incurring the highest functional prejudice, expressed in course distance lengthening (figure 4C). The same classification can be found in IRd and Ic because of the impossibility of diversions of roads located in the bottom of the valley, except for the valley of the Haute-Romanche that has a bypass itinerary of 137 km (figure 4B). The IRd indexes do not integrate the value of the road section's use, an element that could relativize the functional impact of a closure for the community. However, displaying road hierarchy accounts for this both functional and useful impact.

Figure 4. Dysfunction risk index by road section (IRd) (C) crossing a closure index (Ic) (A) with the minimal length of diversion of the exposed section (Ld) (B)

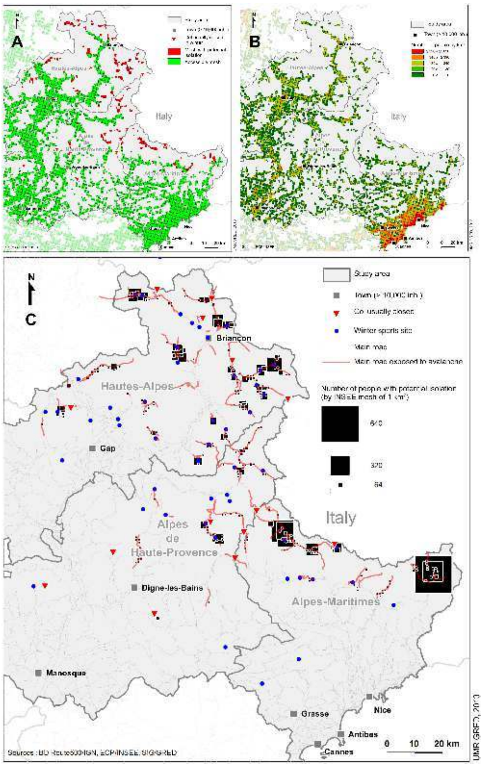


Territorial isolation risk index

26 Territorial accessibility degradation is a consequence of network closures that can be modelled via graphs. Accessibility being defined for well-defined start and finish locations, first we selected all the meshes of territory that could be isolated, i.e. totally deprived of road access in the event of an avalanche from great regional cities, in normal winter viability conditions, which is with 14 closed cols (figure 5A). To do so, we removed from the graph all road sections that had at least one impact since 1936 and/or crossing at least one CLPA contour. This extreme deterministic scenario isolated 0.83% of the resident population out of the three departments (11,215 inhabitants, figures 5B and 5C). The results are close to the situation experienced in December 2008, which once modelled gives an equivalent of 4,502 inhabitants. The 6 most impacted towns, in terms of isolated meshes, are in ascending order respectively: Isola (06), Arvieux (05), Allos (04), Saint-Paul (04), Tende (06,) Saint-Etienne-de-Tinée (06). In associated population, the equivalent classification shows: Pelvoux (05), Isola (06), Vallouise (05), Allos (04), Tende (06), Saint-Etienne-de-Tinée (06). These results do not include the winter touristic frequentation

which is very important in sectors that can be isolated; sectors that include over 20% of winter sports sites of the three departments (19 out of 103).

Figure 5. Permanent resident population potentially isolated in case of an avalanche (C), with territory meshes potentially isolated (A) and population censured by INSEE (B)



27 In order to hierarchize the isolation risk of these portions of the territory, we proceeded to the calculation of an isolation risk index (IRi) which is the result of the multiplication of an isolation index (Ii) of each mesh by its resident population (Pop). This index was also brought between 0 and 1 by dividing each variable by its maximal value. For each mesh or associated itinerary:

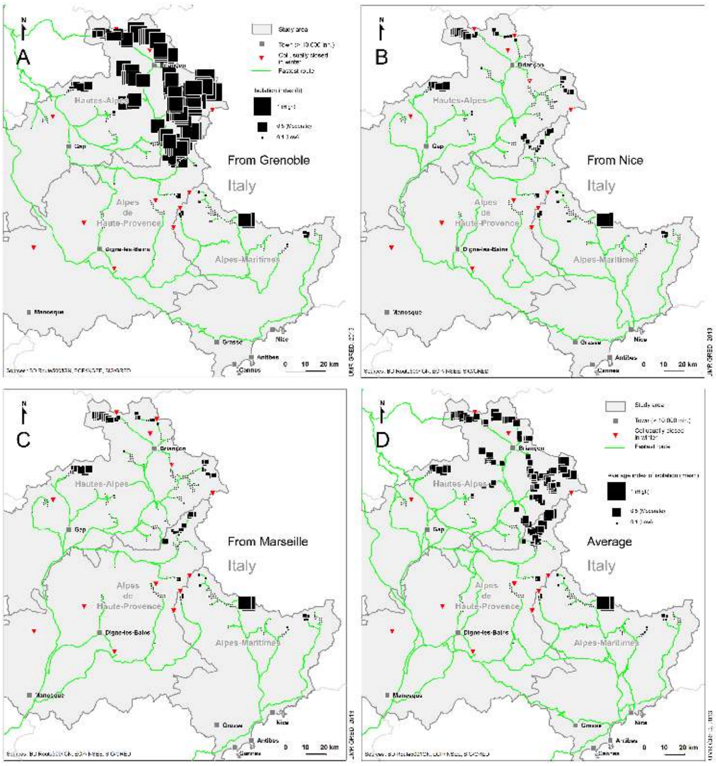
IRi (0-1) = Ii * (Pop / Pop_max)

28 The isolation indexes (Ii) of the 311 potentially isolated meshes were determined empirically by adding the number of known impacts since 1937 to the total length of road crossing a CLPA contour (LCLPA in km) (*cf* figure 3b for the method). These values were calculated in an iterative way with the road graph for each itinerary linking the meshes and three main cities of Grenoble, Marseille and Nice, in a normal winter viability situation with 14 closed cols, and according to the fastest itineraries (933 itineraries, figures 6A, B, C). Yet again, a coefficient of 2 was applied to the first variable to reinforce the weight of the vulnerability remarked (the damage) as regards the exposure. For each mesh or associated itinerary:

Ii (0-1) = ((Nimpacts / Nimpacts_max)*2 + (LCLPA / LCLPA_max)) / 3

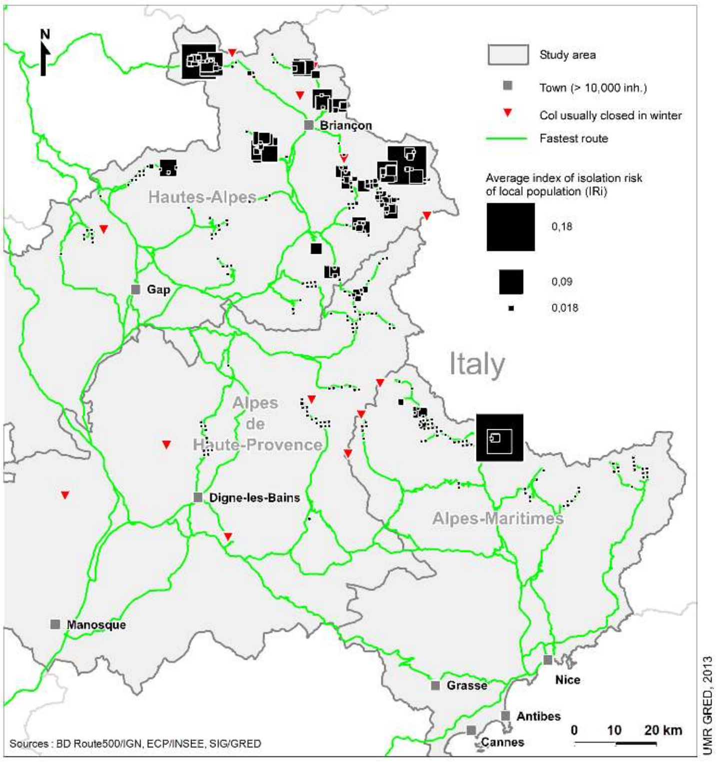
29 The maximum number of impacts on an itinerary is of 109 and the maximal length of CLPA crossed is 13.77 km. The most populated mesh includes 634 inhabitants (Pop_max). Each mesh was then allocated the average of Ii and IRi (figures 6D and 7 respectively).

Figure 6. Isolation index of territorial meshes (Ii) leaving the three big cities (A: Grenoble, B: Nice, C: Marseille, D: average index)



30 Towns showing the most meshes of high average probability of isolation are in ascending order La-Chapelle-en-Valgaudemar (05), Névache (05), Ristolas (05), Abriès (05), Isola (06) and Saint-Paul (04). The population corresponding to these meshes is of 426 inhabitants and the highest average isolation risk index values are obtained by ascending order in the towns of la Grave (05), Abriès (05) and Isola (06). These portions of the territory present the highest probability of isolation of the highest number of resident people (figure 7). Let us note that this isolation risk increases in winter, since the meshes concerned correspond to three touristic resorts, providing a total of 9,300 beds.

Figure 7. Average index of isolation risk of territorial meshes (IRi) from Grenoble, Nice and Marseille, combining the isolation index (Ii) and the permanent population



Conclusion and perspectives

31 This research, based on the avalanche risk's spatial and quantitative analysis, informs the vulnerability of a territory on a regional scale on the basis of its road network's exposure. Direct risk was studied retrospectively through the analysis of road impacts over more than seventy years. Indirect risk was assessed prospectively via indexes of network closures and population isolation. This enabled us to valorise exceptional historical data that was yet underexploited in risk geography and use the potentiality of road graphs provided by the IGN for accessibility calculations. It is a rather innovative approach in the avalanche field where nearly all road vulnerability assessment works are limited to the direct consequences of impacts on the network.

32 The new databases produced are georeferenced and adapted to a geographical interpretation of damage on roads. We encourage the pursuing of their development and fulfilment, notably by integrating more numerous and elaborate socio-economic data that will gradually refine the obtained indicators. For example, the proposed damage typologies should in the future estimate more precisely the direct and indirect costs; taking their inventory on a regional scale is always a real challenge. Starting from these databases, a possible statistical approach to assess direct annual costs attributable to avalanches on the road network would be to multiply the average costs of each intensity of damage by their annual frequency. This implies to better take inventories of average costs, which is our study's weakness. Moreover, the macroeconomic analysis of indirect costs accountable to the territorial isolation could occur on the basis of scenarios on a local (valleys) or regional (mountains) scale, by accumulating activity losses, additional

costs linked to possibly longer trajectories, rescue costs or dealing with isolated people (supplies, treatment) etc. The accumulation of all these costs, per studied site, could fuel a cost/benefits analysis appreciating the economic opportunity of certain avalanche prevention measures, by estimating the amount of avoided damage.

33 However, the exploratory part on risk indexes is already an important step forward. It moves away from a hazard-centred avalanche risk approach to look at human and territorial stakes of this risk, by including for the first time the indirect consequences on a scale of an important part of the French Alps. The conclusions and maps obtained, although widely improvable, can be of some interest to risk managers. Indeed, unlike other studies treating functional vulnerability of road networks facing natural threats (Gleyze, 2005; Nabaa, 2011), this cartographic approach can associate spatialized and adjustable socio-economic stakes to the network, in volume and nature, in previously defined and connected meshes at risk.

34 For example, the potentially isolated stakes studied here correspond to the resident population censured by the INSEE on a gridded base. But we can imagine other assessments taking in account temporal population variations (day / night or school holidays / not holidays), or other socio-economic indicators such as the number of days / skiers or the daily turnover of ski resorts. It is also possible to change the scale by refining the road network considered (IGN Topo DB for example) merging it with a finer territorial grid. The associated isolation risk assessment will be even more precise on the geographical aspect. Conversely, data can be aggregated to smaller scales to express indexes and losses of accessibility on the valley, mountain or variable administrative entity scales (communal, administrative districts, departments, etc.).

35 An important progress perspective also concerns the improvement of assessment of avalanche triggering probabilities and consequent network closures, assessed in a simple and empirical way in this work. The latter could be improved by using digital models of avalanche propagation (Naaim *et al.,* 2004) and/or refining the temporal assessment on the basis of already documented evolutions of the regional avalanche activity in answer to climate change (Eckert *et al.,* 2013). Such perspectives could refine accessibility loss scenarios and accompany a reflexion with deciders on locally-developed response strategies to reinforce the resilience of mountain territories with high touristic stakes but with reduced accessibility.

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ABSTRACTS

Road accessibility is highly strategic for the maintenance of economic activities but also for the emergency services. In mountains, snow avalanches are a particularly strong threat because, in addition to the victims and direct damage, they cause a loss of accessibility more or less prolonged when the networks are already strongly altered by seasonal closures. Specifically, risk to traffic roads caused by snow avalanches has been very rarely assessed at a regional scale. To assess the physical, human and functional vulnerabilities of road networks in three Alpine departments (Alpes-de-Haute-Provence, Hautes-Alpes, Alpes-Maritimes), the first step of this research was to geo-locate and harmonize within a GIS all information sources about the consequences of avalanches on roads. This allowed identifying the road impacts of avalanches since 1937, to characterize the intensity and typology of damages and to evaluate the functional vulnerability of networks. The second step was to produce simple risk indexes of dysfunction and isolation at this regional scale. These indicators were modeled using the graph theory in a GIS framework, integrating avalanche activity indicators derived from the past activity with the road network. The obtained output maps should facilitate the decision support for crisis management and a comparative spatial analysis at the regional scale.

INDEX

Keywords: snow avalanches, vulnerability, risk, traffic roads, accessibility, mapping, Alps

AUTHORS

FRÉDÉRIC LEONE

UMR GRED, Université Montpellier 3

ALBERT COLAS

UMR GRED, Université Montpellier 3

YANN GARCIN

UMR GRED, Université Montpellier 3

NICOLAS ECKERT

UR ETGR, Irstea / Université de Grenoble Alpes

VINCENT JOMELLI

UMR LGP, 8591 CNRS / Université Paris 1

MONIQUE GHERARDI

UMR GRED, Université Montpellier 3