Landslides
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A. Puissant · M. Van Den Eeckhaut · J.-P. Malet · O. Maquaire

Landslide consequence analysis: a region-scale indicator-based methodology

Abstract Consequence analysis is, together with hazard evaluation, one of the major steps of landslide risk assessment. However, a significant discrepancy exists between the number of published landslide hazard and landslide consequence studies. While various methodologies for regional-scale hazard assessment have been developed during the last decade, studies for estimating and visualising possible landslide consequences are still limited, and those existing are often difficult to apply in practice mainly because of the lack of data on the historical damage or on landslide damage functions. In this paper, an indicator-based GIS-aided methodology is proposed with an application to regional-scale consequence analysis. The index, called Potential Damage Index, allows describing, quantifying, valuing, totalizing and visualising different types of consequences. The method allows estimating the possible damage caused by landslides by combining weighted indicators reflecting the exposure of the elements at risk. Direct (physical injury, and structural and functional damage) and indirect (socio-economic impacts) consequences are individually analysed and subsequently combined to obtain a map of total consequences due to landsliding. Geographic visualisation of the index allows the delineation of the areas exposed to any type of possible impacts that could be combined with a corresponding map displaying landslide probability of occurrence. The method has been successfully applied to analyse the present consequences in the Barcelonnette Basin (South French Alps). These maps contribute to development of adequate land use and evacuation plans, and thus are important tools for local authorities and insurance companies.

Keywords Landslide · Damage index · Direct and indirect consequences · Physical injury · Structural and function impacts · Socio-economic impacts

Introduction

Landslide risk assessment combines the likelihood of a landslide of certain magnitude to occur (i.e. landslide hazard) with an assessment of the impact or potential consequences of the hazardous event (Varnes 1984; Fell et al. 2005). Generally, for large areas where the quality and quantity of available data are too scarce for quantitative analysis, qualitative or semi-quantitative risk assessment are carried out, while for site-specific slopes that are often characterised by many observation data on hazard and past damage, detailed quantitative risk assessment should be carried out (Fell et al. 2008).

The studies focussing on regional-scale quantitative landslide hazard assessment are relatively numerous (Del Gaudio et al. 2003; Guzzetti et al. 2005; Cascini 2008; Jaiswal et al. 2011). Yet, the number of studies dealing with regional-scale (semi-) quantitative consequence analysis is still rather low (Hollenstein 2005) and standard methods are still lacking (Galli and Guzzetti 2007; Falemo and Andersson-Sköld 2011). Only during the last decade exposure and vulnerability studies started to catch up with the other steps of the risk assessment procedures (Kappes et al. 2012), which is important because, in many cases, the consequences determine the losses to a greater degree than does the hazard (Alexander 2004).

Consequences are generally defined as the outcome or potential outcome to an element at risk (EaR) arising from the occurrence of a landslide expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life (Glade and Crozier 2005). Quantitative consequence analysis requires detailed information on the vulnerability and the value (cost) of the EaR. For the term vulnerability, different definitions have emerged, often in different disciplinary contexts (Thywissen 2006; Fuchs et al. 2011). On the one hand, experts with a natural sciences and technical background generally define vulnerability as the degree of loss to a given EaR, or set of EaR within an area, affected by a hazard. Vulnerability is expressed on a scale of 0 (no loss) to 1 (total loss; UNDRO 1984) and is investigated separately from hazard in the risk assessment framework. Other definitions (e.g. CENAT 2004; Vandine et al. 2004), on the other hand, consider vulnerability and consequences as a combination and relation of exposure and hazard (e.g. spatial implicit approach; Scheuer et al. 2011). In the latter cases, exposure can thus be seen as the relationship of the EaR at risk to the landslide hazard; it is the bridging element between the natural and social scientific part of risk assessment. An example of a landslide study following the latter philosophy is the one carried out by Galli and Guzzetti (2007). With regard to consequences or loss, five different types can be distinguished: (1) physical injury, referring to the physical and/or mental health of persons; (2) physical and structural consequences, referring to the damage of buildings and infrastructures (transport lines, telecommunications and energy supply lines); (3) socio-economic consequences referring to social (person's and community's capacity to anticipate, behavioural changes, possible demographic changes) and economical direct and indirect monetary losses; (4) environmental consequences, referring to the impact on water and soil quality, wildlife and biodiversity; and (5) cultural heritage consequences, referring to the damage to historical monuments.

As consequences are measured through relative values (Birkmann 2007), the analysis depends on the nature of the assessment, on the geographic scale and on the amount of data required (Fig. 1a). Puissant et al. (2006) and Papathoma-Köhle et al. (2011) provide an overview of the possible approaches for landslide consequence and vulnerability analysis at different geographical scales (macro-, meso- and micro-scales) and for different technical objectives. These methods differ with respect to the number and type of variables, the methods of calculation and scaling (Fig. 1b).

- At macro scales (Fig. 1(b1)), the analysis is generally carried out with the objectives of strategic regional planning and is based on expert knowledge. The methodology results first, in an

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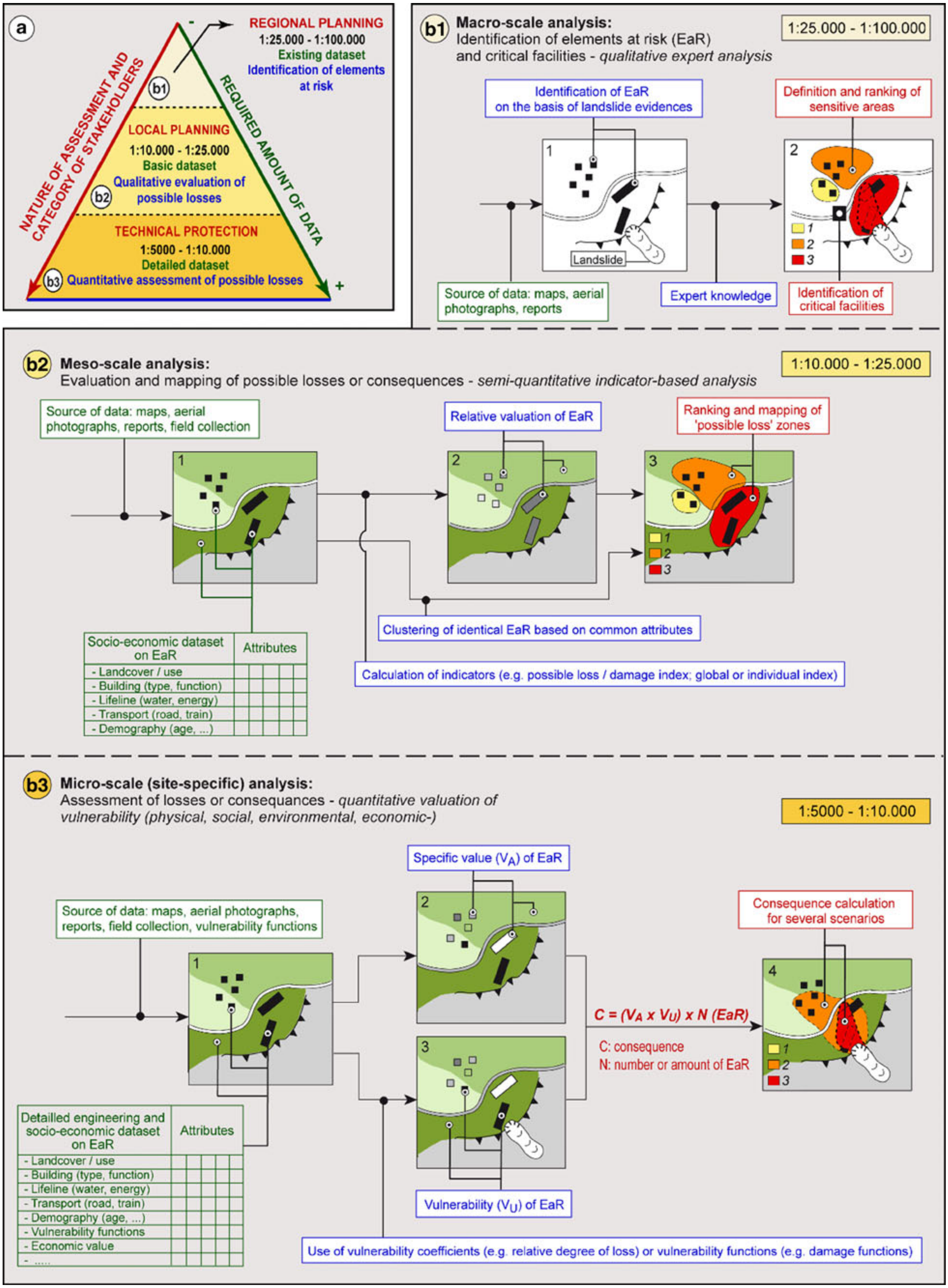

Fig. 1 Approaches used for the analysis of landslide consequences. *a* Type of analysis according to the nature of the assessment, the stakeholders, the required input data and the geographical scale; *b1*. Steps in the methods used at macro-scale; *b2* Steps in the methods used at mesoscale; *b3* Steps in the methods used at micro-scale

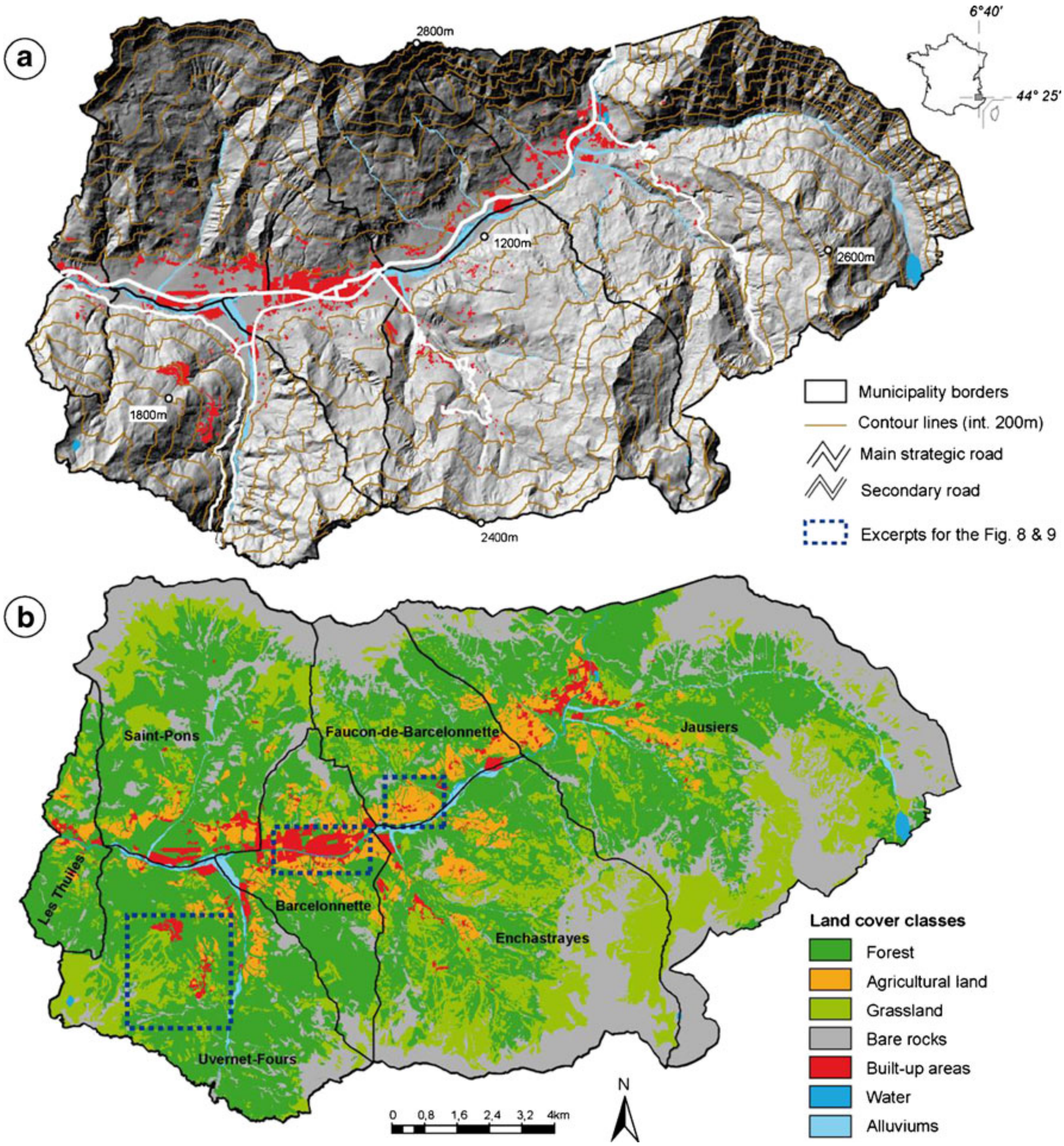

Fig. 2 Physio-geographic characteristics of the study area including **a** the relief and the location of the municipalities; **b** the land cover/use observed in 2010

inventory of the EaR and of the critical facilities and second, in a qualitative ranking of their value. The EaRs are classified in categories (according to territorial plans, building and population distribution, strategic elements such as fire and rescue buildings, hospitals and nursing homes, schools, lifelines and transport lines). Only the EaRs directly affected by an active landslide are inventoried. Then their value (in terms of a monetary true value or in terms of a relative cost) is expressed as the sum of the intrinsic value of each element by distinguishing properties and goods, economic activities and human life. This methodology is used in practice for the implementation of the regulatory natural hazard risk maps in France ('Plan de Prévention des Risques Naturels, PPRn'; MATE/METL 1999) and in Switzerland ('Carte des Dangers Naturels'; BUWAL/BWW/BRP 1997).

- At mesoscales (Fig. 1(b2)), the analysis is generally carried out with the objectives of local planning (e.g. municipality level) and reproducible semi-quantitative indicator-based methods are used. Within this approach, landslide consequences are expressed in terms of possible losses (or damage) by composite indices. Two categories can be distinguished:

  – Global indicators for which possible losses are valued either by the clustering of EaR with identical characteristics using statistical or morphological techniques (Maquaire et al. 2004; Papathoma-Köhle et al. 2007) in order to delineate zones of homogeneous assets, or by empirical formulas in which the EaR are classified by using a relative scale of values adapted to the characteristics of the area (Blong 2003; Fuchs et al. 2007; Kaynia et al. 2008). This approach

Fig. 3 Example of damage and consequence of several landslide types on categories of EaR observed in the study area in the last decade

is useful for vast areas where it is difficult to collect and analyse data for each individual element;

- Individual indicators for which possible losses are computed by loss utility functions. This approach is highly flexible for adaptation to complex environmental contexts in order to determine the global cost of the losses (Bonnard et al. 2004; Malet et al. 2006).

- At micro-scales (Fig. 1(b3)), the analysis is conducted for site-specific technical prevention (e.g. design of protective measures) using quantitative methods for the valuation of physical, social, environmental and economic vulnerability factors. This approach uses detailed datasets and statistical techniques for the quantification of probabilistic losses (Li et al. 2010). Assuming that the EaR and their respective value have been identified, the vulnerability of a given element is defined by the following:

  - The use of 'vulnerability coefficients' representing the degree of loss to a given element or set of elements for events of different magnitude (Varnes 1984; Leroi 1996). The coefficients can be relative and defined using a qualitative scale such as 'no damage,' 'some damage,' 'major damage' and 'total loss,' or can be expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss is the value of the damage relative to the value of the property; for persons, it is the probability that a particular life will be lost, given the person(s) affected by the landslide (Glade 2003). This method, sometimes called 'analytical vulnerability analysis,' requires detailed statistics on the past damage (Petrascheck and Kienholz 2003) and impacts (French et al. 2011).
  - The use of 'vulnerability functions' representing the interactions between the damaging event and the EaR through damage or fragility curves expressing the possible resistance of the elements to an impact (Barbolini et al. 2004; Haugen and Kaynia 2008; Akbas et al. 2009; Li et al. 2010; Mavrouli and Corominas 2010a, b; Quan Luna et al. 2011). Léone et al. (1996) distinguishes structural damage functions (for properties), physical injury functions (for persons) and operational damage functions (for socio-economic activities). The method is difficult to apply in practice because it needs good engineer knowledge on the elements' resistance which is often very long to acquire.

In most cases, a pure quantitative assessment is difficult. This is due to the complexity of the problem (i.e. consequences are dynamic and comprise environmental, economic, demographic, political, cultural, and psychological dimensions; Twigg and Bhatt 1998), the lack of sufficient statistics on past landslide fatalities and losses (especially affecting private properties), and the absence of documented reference events of a given landslide type for the studied region (Glade 2003; van Westen et al. 2006; Petrucci and Gullà 2010). Therefore, Puissant et al. (2006) elaborated a semi-quantitative region-scale indicator-based method, called Potential Damage Index (PDI). The proposed indicator has been developed to be flexible enough and generic to be applied to regions with diverse risk exposure and socio-economic specificities, and applicable at different spatial scales, (i.e. macro- and mesoscales; 1:100,000 to 1:10,000). The objectives of the consequence maps are to locate the most sensitive areas and to target possible high consequence locations for detailed risk assessments. The PDI method allows estimating physical injury, structural and functional damage and socio-economic effects from an EaR evaluation. Given that such datasets originally only contains a limited set of building and infrastructure indicators (i.e. building type, function and height; land use, land cover and lifelines for instance), this study aims at generalising the PDI methodology in order to improve the determination and mapping of the potential direct and indirect consequences of hazardous landslide events on individual facilities and resources at the regional scale. The method is applied for assessing the present landslide consequences on a mountain territory in the South French Alps.

Study area: the Barcelonnette Basin, South French Alps

The study area is the Barcelonnette Basin, a 200-km^2 area covering the municipalities of Saint-Pons, Barcelonnette, Faucon-de-Barcelonnette, Enchastrayes, Uvernet-Fours, Jausiers and Les Thuiles in the department 'Alpes-de-Haute-Provence' (Fig. 2). The altitude ranges from 1,100 m at the outflow of the River Ubaye up to more than 3,000 m on the highest summits surrounding the catchment.

The actual land cover/use is the result of the presence of severe hydro-geomorphological processes in connection with important changes in human activities in the last centuries with high

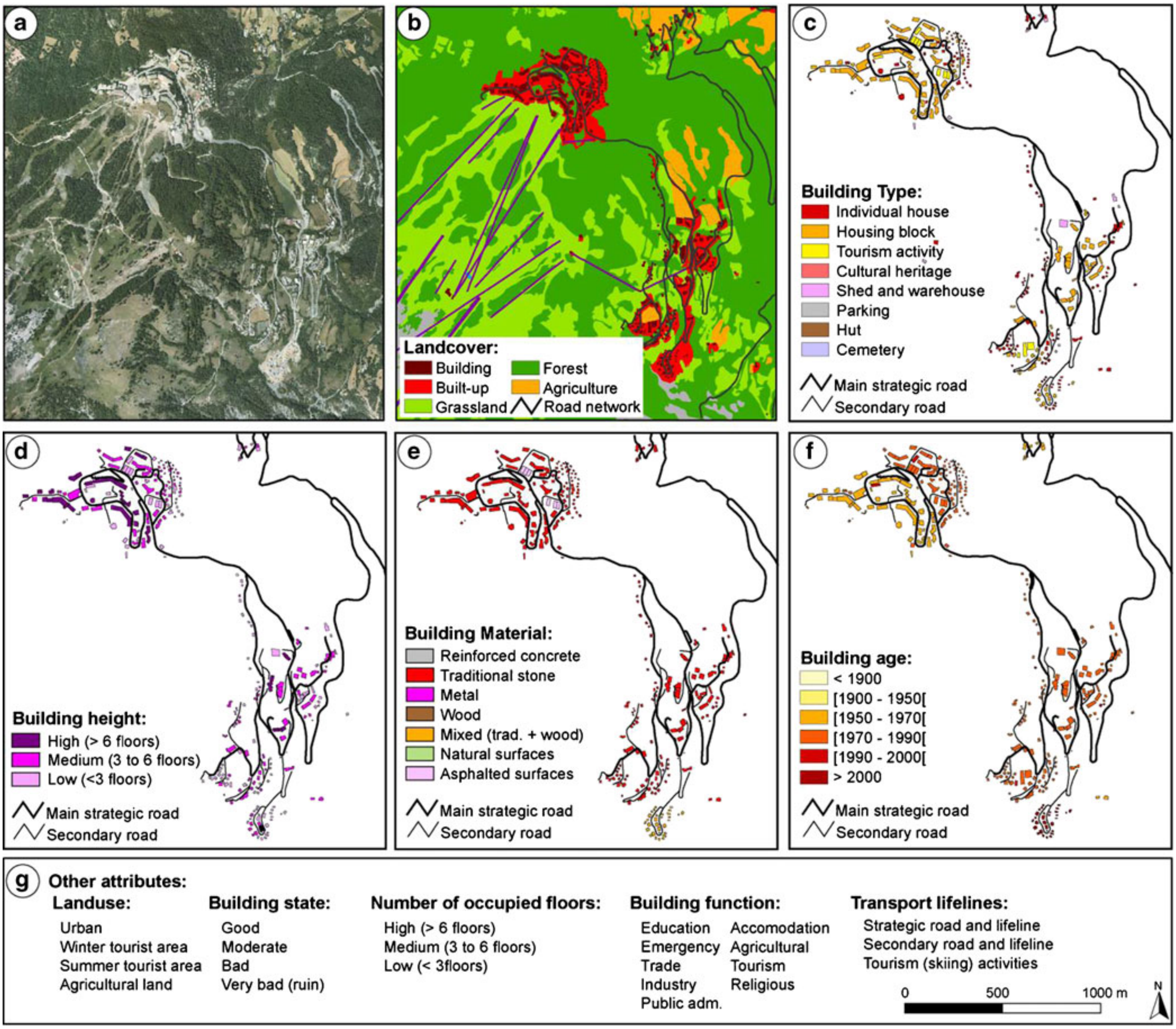

Fig. 4 Examples of the database on EaR constructed for the Barcelonnette Basin, with an excerpt of the ski resort of Pra-Loup at the South–West. **a** Orthophotograph of 2007; **b** Land cover in 2010. **c** Building type. **d** Building height. **e** Building construction material. **f** Building age. **g** List of attributes collected for each category of EaR

deforestation rate and the introduction of agricultural practices till the eighteenth century. In the nineteenth century, reforestation and dam building for torrent correction marked the landscape as a result of landslide activities and torrential events largely threatening the human activities. After the Second World War, urbanisation and progressive agricultural abandonment are the main drivers of changes in the land cover and land use. For instance, the number of inhabitants was around 18,000 in the beginning of the nineteenth century and has quickly decreased due the rural exodus. In 2009, the population is around 8,000 inhabitants and is concentrated along and around the Ubaye River. Barcelonnette is one of the less populated districts in France with a low population density (<10 inhabitants km^{-2}). At present, land cover classes account more than 40 % of forest, around 20 % of bare rocks and grassland and 5 % of agricultural lands (Fig. 2).

The area has an important administrative, touristic, commercial and communication role. Most economic activities are situated in the municipalities along the Ubaye River (Fig. 2a, b). Only touristic activities, especially winter tourism, are concentrated on the hillslopes (Fig. 2b) with the ski resorts of Pra-Loup and Sauze/Super-Sauze on the territory of Enchastrayes. Apart from houses, the region contains several administrative buildings, schools, hospitals, shops, hotels, ski infrastructures and industrial parks. The most important lifeline is the main road ensuring the relation with Italy.

Due to its predisposing geological structure consisting of limestones and sandstones overlying sensitive clay shales (i.e. black marls), the hillslopes are affected by severe gullying, shallow landslides, large deep-seated landslides, debris flows and rockfalls (Malet et al. 2005), and among 70 % of the slopes can be classified as prone to mass movements (Kappes et al. 2011). As a

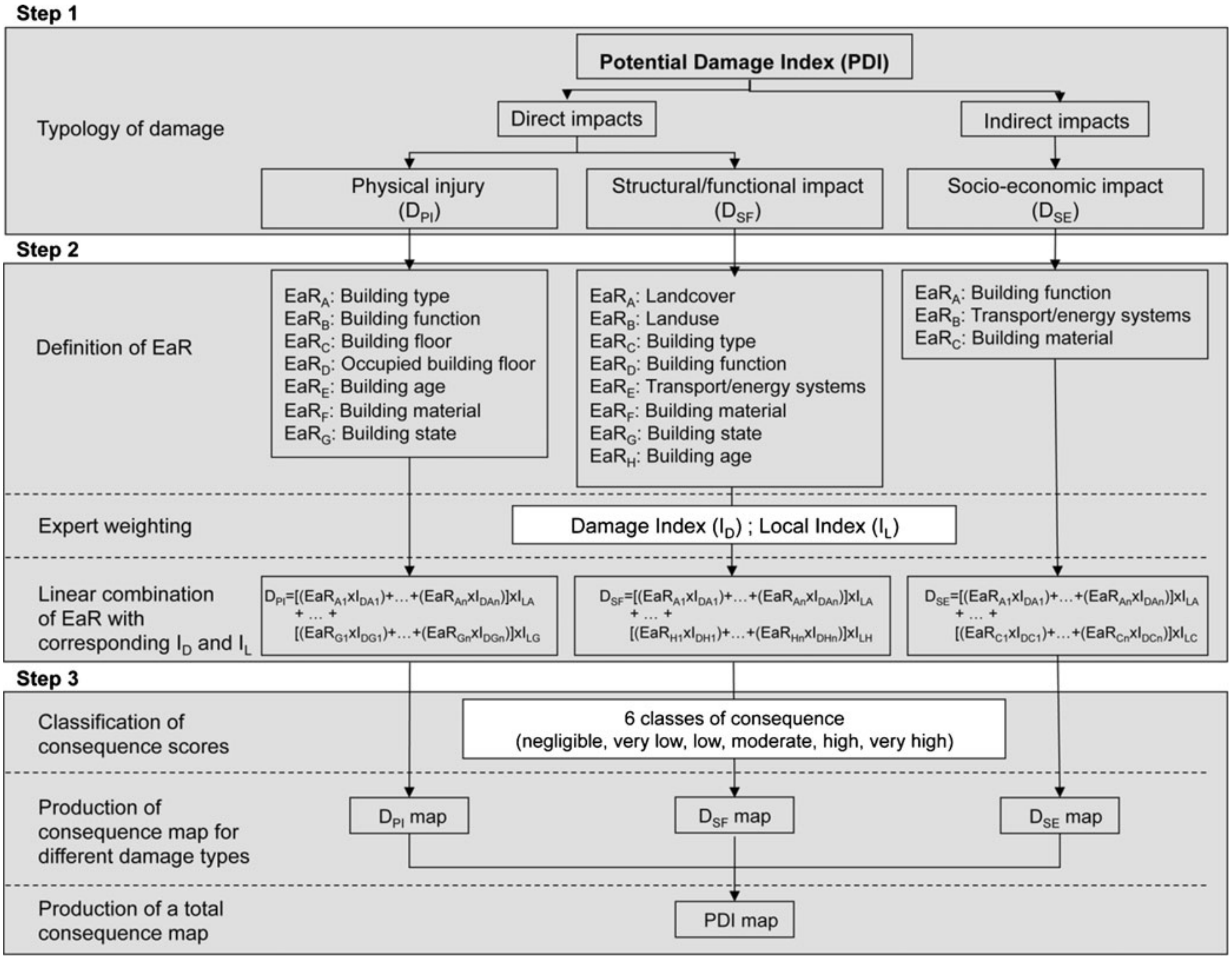

Fig. 5 Framework for the calculation of the Potential Damage Index (*PDI*) to estimate consequences at a regional scale

consequence, the recent development of urbanisation and tourism activities has led to an intense use of previously unoccupied and most of the time landslide susceptible slopes.

Many different types of damage related to landslides have been observed on EaR in the last decade, ranging from burial of houses from debris flows and mudflows, debris impacts on houses and bridges from debris flows and rockfalls, lateral displacement of houses from slow landslides, and debris impacts on roads and infrastructures from shallow debris slides and rockfalls (Fig. 3).

Materials and methods

Construction of an adapted geospatial database of elements at risk

For mountain areas, geospatial databases on EaR and relevant indicators of exposure are generally not available. Hence, prior to any kind of consequence analysis, this basic information needs to be collected. The database created for the Barcelonnette Basin contains the EaR considered relevant for assessing physical injury, structural and functional damage and socio-economic impacts at a 1:10,000 scale. The categories of EaR are buildings, lifelines (consisting in transportation and energy systems), land cover and land use (Léone et al. 1996; Alexander 2004) which are described by a series of attributes to characterise their sensitivity to landslide impacts (Fig. 4).

Among the categories of EaR, buildings are most discriminant for the identification of damages (French et al. 2011), especially for physical injury, which for this study is only evaluated inside buildings. The building location is extracted from the French database BD TOPO® (2004) of the French topographic survey (IGN) completed by the analysis of aerial photographs. Several building attributes (i.e. building type, function, number of floors, number of occupied floors, age, state and construction material; Fig. 4) are mainly obtained from a detailed field survey using tablet-PC and PDA GIS mapping, and completed with other sources (e.g. multi-temporal aerial photographs, Google Earth and Street View analyses). Information on the transportation systems (roadways) and energy systems (electric power networks) are taken from BD TOPO®. For roadways, a distinction is made between the main strategic regional roads and the local roads. For the energy systems, the strategic power lines (high voltage electricity transmission network; ≥150 kV) are differentiated from the secondary power lines (moderate and low voltage electricity transmission network; ≤150 kV). The location of the ski lifts and main sports and leisure facilities is obtained from aerial photographs and topographic maps. Land cover and land use are obtained from aerial photographs of 2007 (Fig. 4b), and a distinction between zones occupied with winter and summer tourist infrastructures is proposed.

Calculation of the potential damage index

As the objective is to establish a flexible and generic indicator-based methodology to be applied at different spatial scales, the PDI focuses on both direct and indirect damage. The PDI considers that the specific EaR can be characterised by a possible degree of destruction caused by landslides of unspecified type. In that approach, different degrees of destruction caused by different types of landslide impact (burial, flooding, push or failure) are not taken into account in the methodology. This assumption is compliant with the scale of applicability of the index and the French regulation on risk mapping. The calculation flowchart for the construction of the PDI is schematised in Fig. 5 and consists of three different steps.

The first step identifies the predominant damage observed for the area on the most relevant stakes. The choice of the stakes has been elaborated through discussion meetings with the local risk managers (i.e. ONF-RTM service) and corresponds to the national

DIRECT IMPACTS

PHYSICAL INJURY (D_{PI})

I_{D_s}	I_{D_w}	Building type	I_L=1
1.00	1.00	Housing	
0.70	0.80	Tourism activity	
0.30	0.30	Cultural heritage	
0.50	0.50	Shed and warehouse	
0.20	0.20	Parking	
0.10	0.10	Hut	
0.00	0.00	Cemetery	

I_D	Number of floor	I_L=2
1.00	> 6	
0.85	3-6	
0.70	< 3	

I_{D_s}	I_{D_w}	Building function	I_L=2
1.00	1.00	Education	
0.95	0.95	Emergency	
0.90	0.90	Trade	
0.90	0.90	Industry	
0.70	0.70	Public administration	
0.80	0.80	Accommodation	
0.40	0.40	Agricultural	
0.60	0.80	Tourism	
0.20	0.20	Religious	

I_D	Building state	I_L=2
1.00	Good	
0.70	Moderate	
0.20	Bad	
0.00	Very bad (ruin)	

I_D	Building age	I_L=2
1.00	> 1990	
0.90	1970-1990	
0.70	1950-1970	
0.50	1900-1950	
0.30	< 1900	

I_D	Material	I_L=2
1.00	Reinforced concrete	
1.00	Traditional	
0.40	Metal	
1.00	Wood	
1.00	Mixture	
0.40	Natural	
0.20	Coated, parking and asphalted surfaces	

I_{D_s}	I_{D_w}	Number of occupied floors	I_L=1/3*
0.50	1.00	> 6	
0.70	0.70	3-6	
1.00	1.00	< 3	
0.00	0.00	0	

STRUCTURAL AND FUNCTIONAL IMPACT (D_{SF})

I_D	Land cover	I_L=2
0.35	Pasture	
0.30	Forest	
0.15	Grass	
0.10	Water	
0.05	Bare rocks	

I_D	Land use	I_L=4
1.00	Urban	
0.80	Winter tourist area	
0.50	Summer tourist area	
0.25	Arable land	

I_D	Building type	I_L=1
1.00	Housing	
0.80	Tourism activity	
0.30	Cultural heritage	
0.50	Shed and warehouse	
0.20	Car park	
0.10	Hut	

I_D	Building function	I_L=3
1.00	Education	
0.95	Emergency	
0.90	Trade	
0.90	Industry	
0.70	Public administration	
0.80	Accommodation	
0.40	Agricultural	
0.80	Tourism	
0.20	Religious	

I_D	Transport and energy systems	I_L=2
1.00	Strategic road /energy line	
0.80	Secondary road/energy line	
0.80	Servicing road	
0.60	Skiing activities	
0.10	Tracks	

I_D	Material	I_L=2
1.00	Reinforced concrete	
1.00	Traditional	
0.40	Metal	
1.00	Wood	
1.00	Mixture	
0.40	Natural	
0.20	Coated and asphalted surfaces	

I_D	Building state	I_L=2
1.00	Good	
0.70	Moderate	
0.20	Bad	
0.00	Very bad (ruin)	

I_D	Building age	I_L=2
1.00	> 1990	
0.90	1970-1990	
0.70	1950-1970	
0.50	1900-1950	
0.30	< 1900	

INDIRECT IMPACTS

SOCIO-ECONOMIC IMPACT (D_{SE})

I_D	Building function	I_L=3
1.00	Education	
0.95	Emergency	
0.90	Trade	
0.90	Industry	
0.70	Public administration	
0.80	Accommodation	
0.40	Agricultural	
0.80	Tourism	
0.20	Religious	

I_D	Transport and energy systems	I_L=4
1.00	Strategic road/energy line	
0.80	Secondary road/energy line	
0.80	Servicing road	
0.60	Skiing activity	
0.10	Tracks	

I_D	Material	I_L=2
1.00	Reinforced concrete	
1.00	Traditional	
0.40	Metal	
1.00	Wood	
1.00	Mixture	
0.40	Natural	
0.20	Coated and asphalted surfaces	

* *1: Faucon, Jausiers, Saint-Pons, Les Thuiles*
3: Barcelonnette, Enchastrayes, and Uvernet-Fours

I_L = Local Index
I_D = Damage Index
I_{D_s} = Damage Index for summer season
I_{D_w} = Damage Index for winter season

Fig. 6 Damage Index (I_D) (for the winter and summer seasons) and Local Index (I_L) assigned to the attributes of the EaR. The values are attributed according to the local situation in the study area

Table 1 Correlation coefficients (R) of the building attributes used in the geospatial database of EaR in combination with their p values for testing the hypothesis of no correlation

Building	Type	Function	Occupied floor	Floor	Material	State	Age
Type	1	0.6728	0.7509	0.3400	0.1685	0.2915	0.1135
		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Function		1	0.5626	0.2489	0.0724	0.350	0.2293
			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Occupied floors			1	0.1353	0.2518	0.2585	0.1369
				<0.0001	<0.0001	<0.0001	<0.0001
Floors				1	0.0840	0.1232	−0.1148
					<0.0001	<0.0001	<0.0001
Material					1	*0.0027*	−0.0759
						0.8602	<0.0001
State						1	0.4068
							<0.0001
Age							1

p values smaller than 0.05 indicate that the correlation is significant and are represented in normal font

regulations described in the French Risk Mapping Methodology (PPRn; MATE/METL 1999). As underlined before, instead of distinguishing categories of consequences, a distinction between damage is proposed as follows:

1. To people consisting in any type of mechanical trauma to the body caused by landslides; this category of damage is called 'physical injury' (D_{PI});
2. To buildings, lifelines and human activities over a relative limited time period; this category of damage is called 'structural and functional impact' (D_{SF});
3. To socio-economic activities characterised by possible consequences diffuse in time and possibly far away for the damaging event; this category of damage is called 'socio-economic impact' (D_{SE}).

Environmental and cultural damage are not included so far in the processing.

The second step consists in selecting the EaR and their attributes concerned for estimating each category of damage. To each attribute, an attribute value, called Damage Index (I_D), reflecting its importance is allocated (Fig. 6). The values are assigned through expert knowledge and reflect the possible losses (mainly in terms of costs) if the EaR would be impacted by a landslide. In detail, for each EaR, the I_D is attributed on the basis of either the economic value of the

Table 2 Experiments of D_{PI} calculation for the winter season (D_{PI_W}) produced to investigate the sensitivity of the PDI to input variables

Name	Combination of building attributes
D_{PI_W}	All variables: Building function, Building type, Number of occupied floors, Building material, Building type, Building state, Building age, Number of floors
Exp_1	Building function, number of occupied floors, building material
Exp_2	Building function, number of occupied floors, building material, building age
Exp_3	Building function, number of occupied floors, building material, building state
Exp_4	Building function, number of occupied floors, building material, building age, building state
Exp_5	Building function, number of occupied floors, building material, building age, building state, number of floors
Exp_6	Building type, number of occupied floors, building material
Exp_7	Building type, number of occupied floors, building material, building age
Exp_8	Building type, number of occupied floors, building material, building state
Exp_9	Building type, number of occupied floors, building material, building age, building state
Exp_10	Building type, number of occupied floors, building material, building age, building state, number of floors
Exp_11	Building function, number of occupied floors, building material, building type
Exp_12	Building function, number of occupied floors, building material, building type, building state

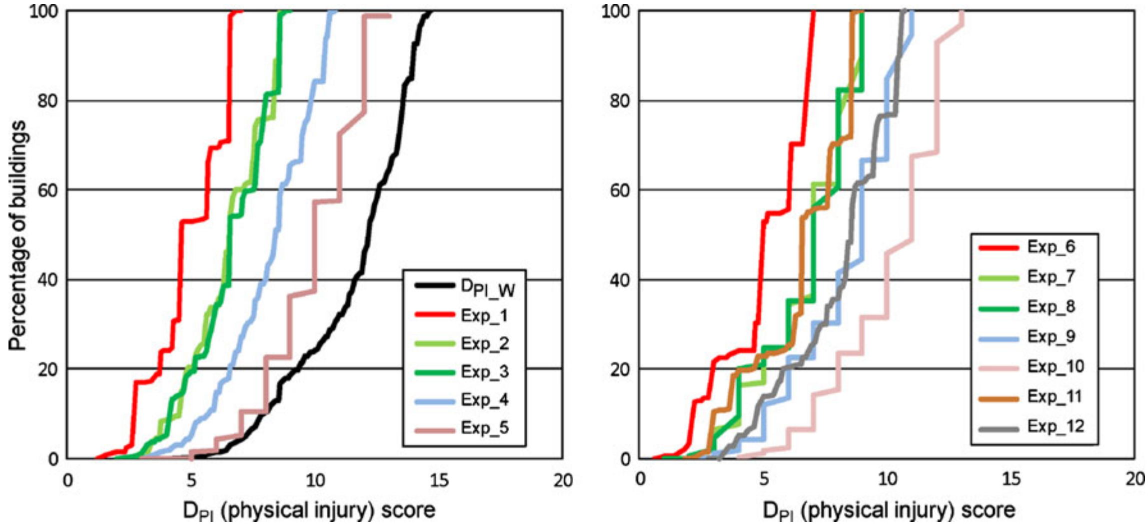

Fig. 7 Classified physical injury (D_{PI}) scores for the ski resort area of Pra-Loup (see location on Fig; 2) testing different combinations of building attributes (Table 2)

land (census data), the market value of the building (census data), the presence of generic public in a building (visitors, buyers, students, etc.), the rate of occupancy of the building, etc. For the estimation of physical injury, it is not possible to include information on the number of persons occupying a building because this information is currently not available. Instead, the number of building floors and the number of occupied building floors are used. A maximum of four persons (i.e. a family) per floor is assumed. By assigning a high I_D index to buildings occupied by the most fragile persons (i.e. school and hospitals), the fact that not every person within the region is equally vulnerable is taken into account.

Apart from the I_D index, a local index (I_L) is defined in order to take into account the local socio-economic context of the region, the purposes of the assessment (i.e. prevention, emergency management) and the various end users having specific needs (i.e. local authorities, emergency services). A high I_L value is, for example, attributed to building function and to lifelines. The main reasoning behind this is that for the tourism activity in the regions, these lifelines are of major importance. Disruption of roads towards ski resorts and of ski lifts will have a major impact on the occupation of the buildings in the resorts.

The I_D and I_L indices have been assigned through discussion meetings with the local stakeholders. The proposed values are therefore not subjective but reflect the local socio-economic situation of the study area at a certain time.

The PDI method can take into account the fact that consequence is a dynamic element and varies with time (season, night/day). However, no differentiation between expected consequences at different time of the day or of the year is made in the case study analysis. Given the importance of winter and summer tourism, it is decided to only produce different physical injury maps for summer and winter. More detailed assessments are not possible given the lack of information on mobility of the population. A quantitative expression of consequences is then calculated using a multi-criteria model. For the three types of damage (step 1), a weighted linear combination of the attributes of the EaR and their associated I_d and I_l indices allows calculation of a score for D_{PI}, D_{SF} and D_{SE}; their sum corresponds to the total potential damage PDI.

Finally, the third step consists in classifying the obtained scores for D_{PI}, D_{SF} and D_{SE} and in constructing a classified PDI map in six classes.

Results and discussion

Sensitivity of attributes for the construction of the potential damage index

Figure 6 indicates that both the D_{PI} and D_{SF} sub-index contain several building attributes. The cross-correlation analysis has been performed on more than 1,000 buildings, and the correlation matrix (Table 1) confirms that almost all indicators are correlated. Therefore, a sensitivity analysis of the PDI to changes in the number and type of building attributes is carried out to identify the most relevant attributes to collect in the field and to remove eventual completely redundant indicators. Among a full list of attributes, and taking into account the local characteristics of the study area, the results of the sensitivity analysis allows to guide the expert in charge of the assessment for optimising the creation of the EaR database in the case of time and budget constraints.

Only the sensitivity analysis of D_{PI_W} (winter season) is presented because D_{PI}, D_{SF} and D_{SE} have many attributes in common. Apart from the complete model including all building attributes listed in Fig. 6, 12 other combinations of attributes are evaluated (Table 2). Experiments Exp_1 to Exp_5 are identical to combinations Exp_6 to Exp_10 with the only difference that building function is replaced by building type.

As such, the effect of correlation between building type and function can be assessed. The effect of using either building age (Exp_2, Exp_7) or building state (Exp_3, Exp_8), or both of them (Exp_4, Exp_9) is further evaluated. Finally, the two last combinations (Exp_11, Exp_12) contain a reduced set of building indicators.

Analysis of the cumulative frequency curves of D_{PI_W} scores calculated for each building using the different combinations of attributes (Fig. 7) show that the steps in these curves are generally different from one combination to another which suggested

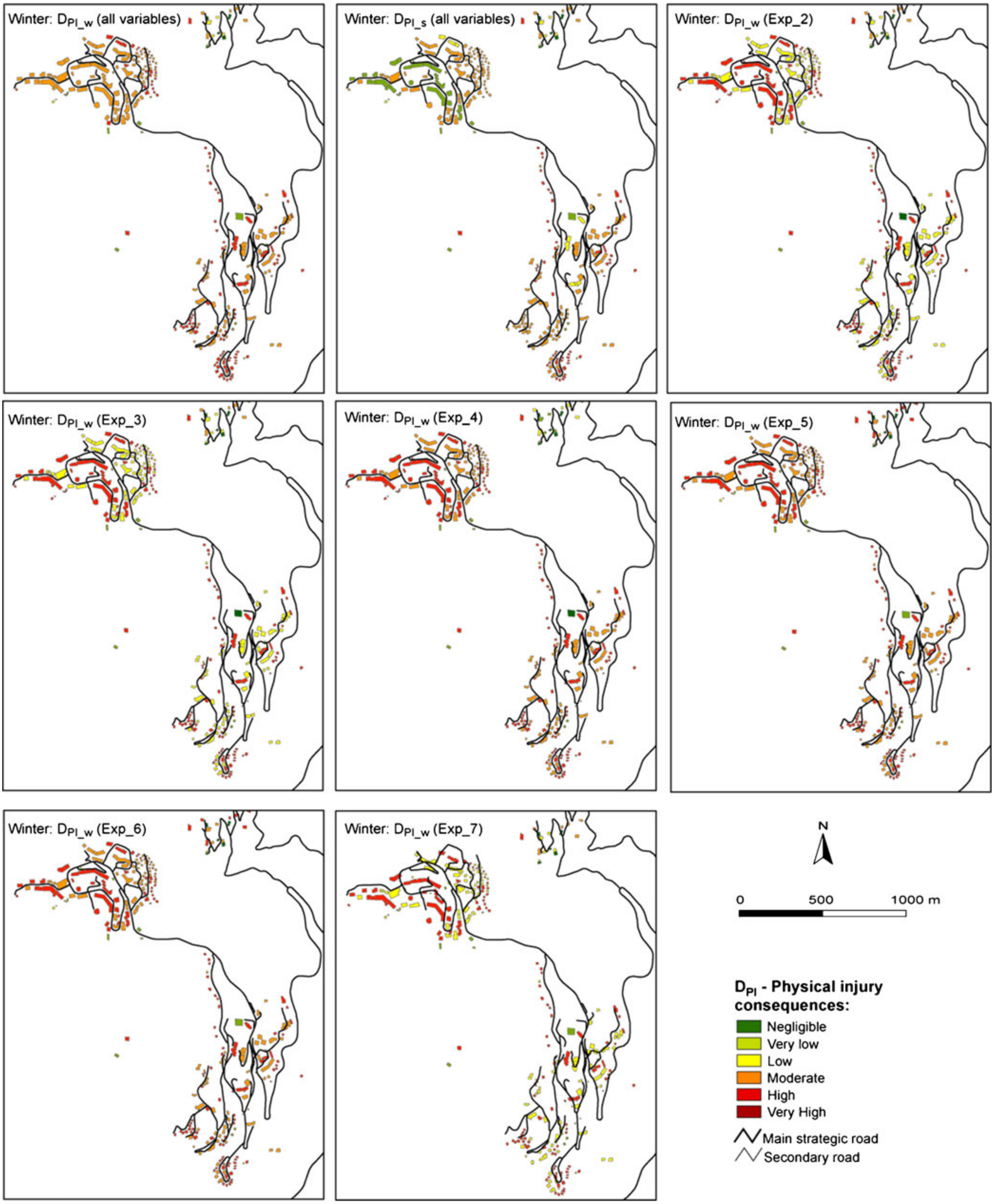

Fig. 8 Maps of classified physical injury (D_{PI}) scores for the ski resort area of Pra-Loup (see location on Fig. 2) testing different combinations of building attributes (Table 2). Quantiles classification is used

that the classified D_{PI_W} maps of each combination could look different.

Figure 8 shows some example maps for the ski resort of Pra-Loup focussing on the correlation between building function and

Table 3 Classes of potential damage (PDI) defined for the study area (according to the French regulation on landslide risk mapping; PPRn - Mouvements de Terrain)

Potential damage	Definition
Negligible	No consequence on the EaR.
Very low	Minor consequences on building and lifelines. Low, local and short time perturbations of human activity.
Low	No casualties. Low to moderate consequences on building and lifelines. Moderate perturbations of human activity during a few days to a few weeks.
Moderate	Low or serious casualties due to high damages on buildings. Moderate to high perturbations of human activity. High, direct or indirect consequences on the local territory, during a few months.
High	Serious casualties or deaths due to the total destruction of buildings. High, direct or indirect consequences that cannot be managed locally. Domino consequences are expected.
Very high	Serious casualties or deaths due to the total destruction of buildings. Very high, direct or indirect consequences that cannot be managed locally. Domino consequences are expected.

The PDI is interpreted in five categories (from negligible to very high) to be compliant with the class number and definition used in the PPRn

type (R^2=0.67; Table 1) on the one hand and between building age and state (R^2=0.41; Table 1) on the other hand. The maps are classified using quantiles, i.e. all classes contain 20 % of the buildings.

Due to the correlation between building type and building function, moderate to strong agreement between the classified D_{PI_W} maps of Exp1 with Exp6 and Exp_2 with Exp_7 (Fig. 8) is observed for the study area. Hence, although the steps in the cumulative curves of D_{PI} scores are not strictly corresponding (Fig. 7), classification using quantiles generally results in relatively similar maps. This is not true for combinations testing the presence of building state and age. The D_{PI_W} maps using only one or both of these attributes are not similar. This is illustrated in Fig. 8 which shows clear differences between, for instance the D_{PI_W} maps of Exp_2, Exp_3 and Exp_4.

These experiments learn that none of the combinations of building attributes results in a classified D_{PI_W} map completely identical to the map obtained from the combination of all building attributes. Hence, semi-quantitative approaches based on attribute combination are susceptible to (1) the type and amount of attributes included, (2) the quality of the data collection and (3) the expert-based knowledge concerning the local socio-economic setting of the study area (necessary for the identification of the main stakes, and thus the construction of the geospatial database of EaR and the assignment of I_D and I_L value).

For the Barcelonnette Basin study case, inter-correlated attributes were chosen to be included in the analysis, because even though correlated, they all provide a relevant contribution to the final potential damage estimate. Performing correlation and sensitivity analyses on the test area at the beginning of the consequence analysis study is, however, useful to get insight into the contribution of individual building attributes to the damage estimate. As an example, old buildings (i.e. attribute age) might be in a good state (i.e. attribute state) but still their foundation might be different from the current building code.

The maps obtained with the different combinations of attributes have been discussed with the local stakeholders in order to identify the more preferable one according to the French regulations and to their assessment methodology. In general, the finding was that the best applicable damage map is the worst-case scenario in order to be compliant with the precautionary principle stated in the French regulation.

Potential damage index maps

Using the framework described above (Fig. 5; Fig. 6), the PDI has been calculated for the whole Barcelonnette Basin for two different scenarios (winter and summer periods). Continuous D_{PI}, D_{SF} and D_{SE} scores were obtained and classified. The distribution of obtained damage values over the study area is investigated and class boundaries in accordance with the French regulatory law on

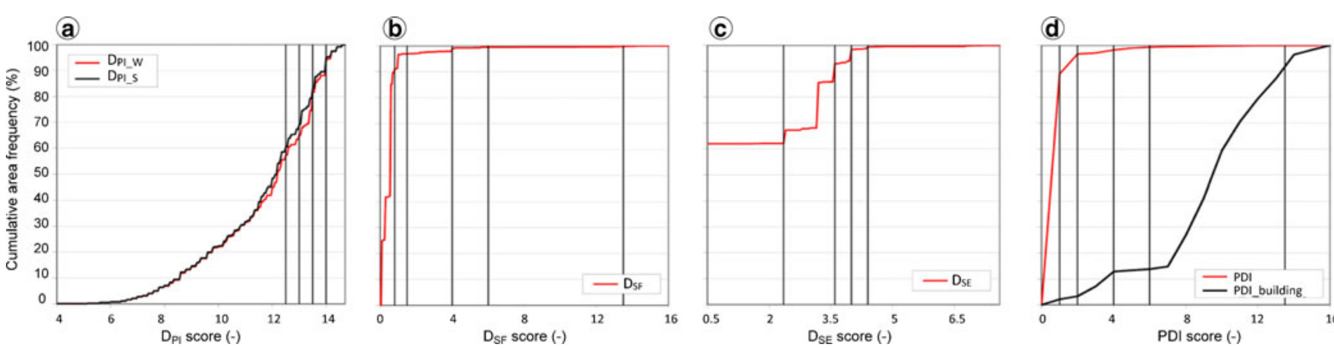

Fig. 9 Cumulative curves of scores obtained for: **a** physical injury in winter (D_{PI_W}) and summer (D_{PI_S}), **b** structural and functional impacts (D_{SF}), **c** socio-economic impacts (D_{SE}) and **d** total potential damage (*PDI*). These curves are used to classify the damage maps. Whereas the *Y-axes of* D_{PI_W}, D_{PI_S} and $PDI_{\_building}$ include only the areas covered by buildings, *Y-axes of* D_{SF} and D_{SE} include the complete study area. A threshold classification of the cumulative curve is used. The *black vertical lines* indicate the boundaries used in the classified PDI maps

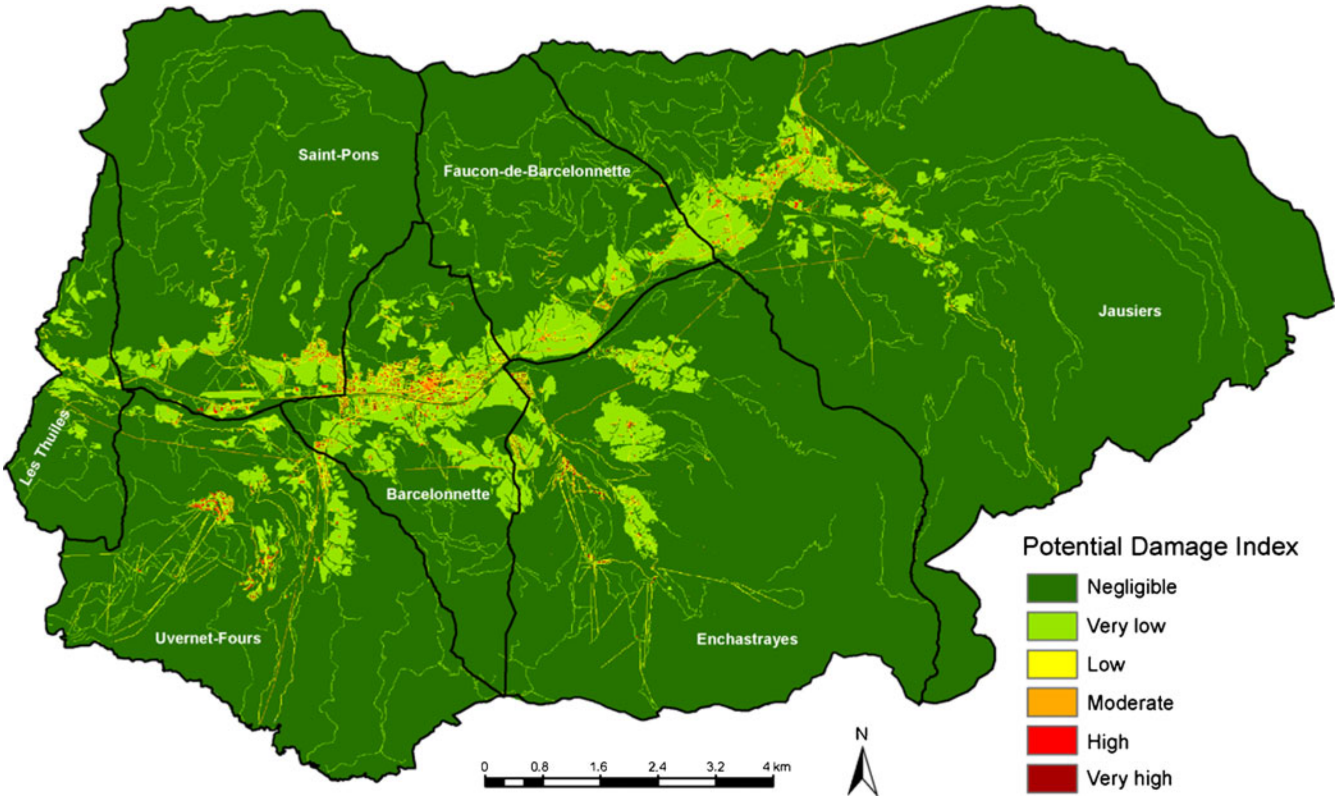

Fig. 10 Potential Damage Index map produced for the winter season for the whole Barcelonnette Basin. Class boundaries are derived from the analysis of Fig. 9 and Table 3

landslide risk mapping (Plan de Prévention des Risques: Mouvements de Terrain (PPR); Table 3) are defined.

Generally, the damage classes high and very high contain only a limited percentage of grid cells (Fig. 9) because, in accordance with the PPR, consequences vary between different types of buildings and roads. The classified D_{PI} and D_{SE} maps have five classes, while the D_{SF} map consists of six classes. For this last map, no satisfying results were obtained with five classes, because it was difficult to differentiate roads from agricultural area without losing the necessary differentiation between buildings. The difficulty of classifying D_{SF} is clear from its cumulative curve which does not show clear steps.

The PDI map is obtained for the whole Barcelonnette Basin (Fig. 10) by summing the classified D_{PI}, D_{SF} and D_{SE} maps and subsequent reclassification. Excerpts of PDI maps of the centre of Barcelonnette, the ski resort of Pra-Loup and the housing of Le Bérard on the torrential fan of the Faucon creek are shown in Figs. 10, 11 and 12. The detailed maps of all indices for the centre of Barcelonnette, the housing of Le Bérard at Faucon-de-Barcelonnette and the ski resort of Pra-Loup are also shown in Figs. 10, 11 and 12, respectively. The PDI map of the centre of Barcelonnette (Fig. 11(a_1)) reflects the probability of having injured persons in a building, and shows lower values in the centre, because most buildings there have a commercial function or are partly used for storing goods, and many are not or only partially used as residence.

The D_{PI} maps of the ski resort of Pra-Loup (Fig. 12) confirm that the PDI method allows distinguishing between estimated D_{PI} in winter (D_{PI_W}; Fig. 12(a_1)) and summer (D_{PI_S}; Fig. 12(a_2)). Due to the higher amounts of tourists in wintertime, more persons are expected to be injured if a building is damaged due to landsliding.

The D_{SF} maps show that destruction of each of the buildings will result in high reconstruction costs. This is mainly due to the fact that the buildings are well maintained, built relatively recently and have a touristic function. The D_{SE} maps show, in general, moderate economic damage to all buildings. High and very high damage are attributed to main road and principal lifelines only. However, as especially winter tourism is the main economic activity of the region, indirect losses to damaged hotels as well as to unattainable hotels suffering from closure of the main strategic road or the ski infrastructures can be high.

Figures 11 and 12 show also the possible structural and functional damage. Unsurprisingly, very high to moderate D_{SF} scores, comprising urbanised built-up areas respectively with and without buildings are highlighted.

Conclusions and perspectives

In this study, a method for estimating and mapping potential damage caused by landsliding (PDI) applicable at different spatial scales (i.e. macro- and mesoscales; 1:100,000 to 1:10,000) is presented and tested. The proposed indicator has been developed to be flexible enough and generic to be applied to regions with diverse risk exposure and socio-economic specificities, and it is designed to be independent of the type of landslide causing the damage.

The method includes the creation of a detailed geospatial database on attributes of elements at risk, and an evaluation of the model sensitivity to changes in the combination of attributes is proposed. Special attention is given to the classification of the potential damage maps. The PDI method allows calculation of an index for physical injury, structural and functional impacts and socio-economic impacts.

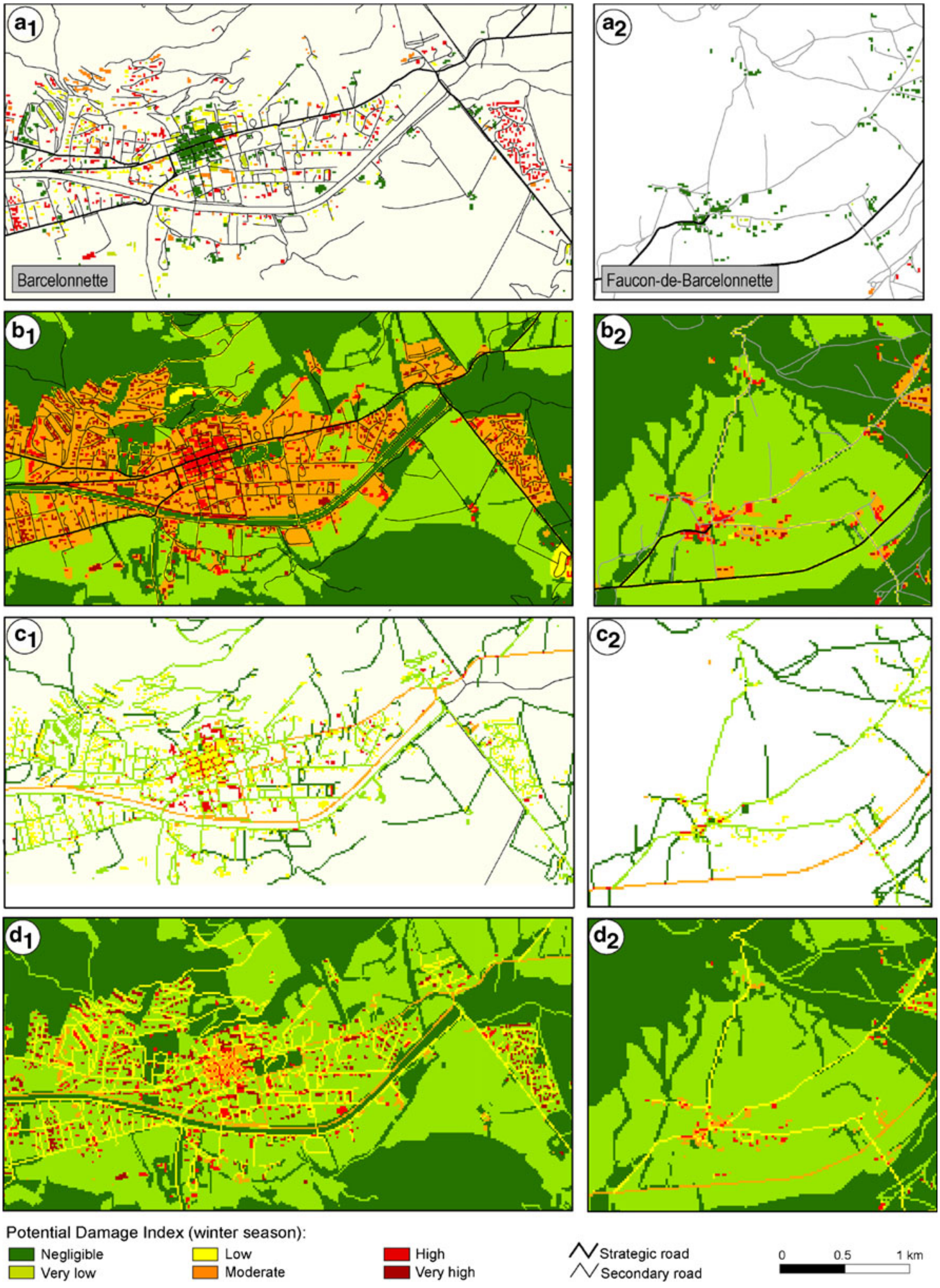

Fig. 11 Potential Damage Index map produced for the winter season for the centre of Barcelonnette and the housing of Le Bérard at Faucon-de-Barcelonnette. Class boundaries are derived from the analysis of Fig. 9 and Table 3. *a₁* D_{PI} map for Barcelonnette; *a₂* D_{PI} map for Faucon-de-Barcelonnette; *b₁* D_{SF} map for Barcelonnette; *b₂* D_{SF} map for Faucon-de-Barcelonnette; *c₁* D_{CE} map for Barcelonnette; *c₂* D_{CE} map for Faucon-de-Barcelonnette; *d₁* PDI map for Barcelonnette; *d₂* PDI map for Faucon-de-Barcelonnette

The indicator maps (i.e. D_{PI}, D_{SF}, D_{SE} and PDI) can be used for purposes such as land use planning and emergency management decision-making in terms of risk reduction. The method has been elaborated through discussion with various categories of stakeholders (local authorities, risk planners) in the study area, and other stakeholders (rescue teams, individuals and insurance companies) may have interest in consulting and using such type of maps with a straightforward and easily understandable information.

One of the advantages of the method is that the indices are flexible and allow the creation of scenarios of possible consequences (e.g. summer or winter season) by modifying the values of the attributes of EaR. The Local Index (I_L) allows for accounting of differences in main economic activities throughout the study area. Due to its flexibility, the method can probably also be applied to other natural hazards occurring in the region (i.e. floods, snow avalanches; Kappes et al. 2011) by implementing slight modifications of both the attributes of the exposed elements and the I_D and I_L indices assigned to these attributes. A possible limitation of working with a flexible indexing method is its subjectivity (i.e. the results are highly depending on the expert knowledge which is necessary to select the correct set of attributes of EaR and their I_D and I_L indices), but this subjectivity is believed to be quite reduced if the index values are discussed and assigned by the local stakeholders.

The sensitivity analysis only focussed on physical injury and the combination of attributes. Effects of either small changes in the values allocated to the attributes or errors in the EaR geospatial database were not investigated so far. This analysis showed that such semi-quantitative method is sensitive to the input data, because different combinations of attribute result in different classified potential damage maps. Carrying out a correlation analysis on a test area at the beginning of a consequence analysis study allows for ranking attributes according to their importance for damage estimation. Such a ranking enables selection of a limited set of relevant attributes (i.e. building type, function, number of floor and state for this scale of analysis) in the case money or time constraints hamper detailed data collection.

Further, in the perspective of automating the method, collection of these important attributes from airborne/spaceborne products will be a major challenge in the coming years. Automating the construction of EaR geospatial database is highly necessary because generally only a limited set of attributes can be collected from census data or digital topographic databases available through regional or national cartographic services (Catani et al. 2005; Zêzere et al. 2008). For instance, currently, building height can be automatically derived from airborne LiDAR surveys or even the analysis of stereoscopic very high resolution satellites images; as well, multi-temporal analysis of airborne photographs allow automatic extraction of information on building age.

By definition, persons, buildings, lifelines or socio-economic activities are only at risk when they are located in a hazardous area. Therefore, future studies will focus on the combination of the

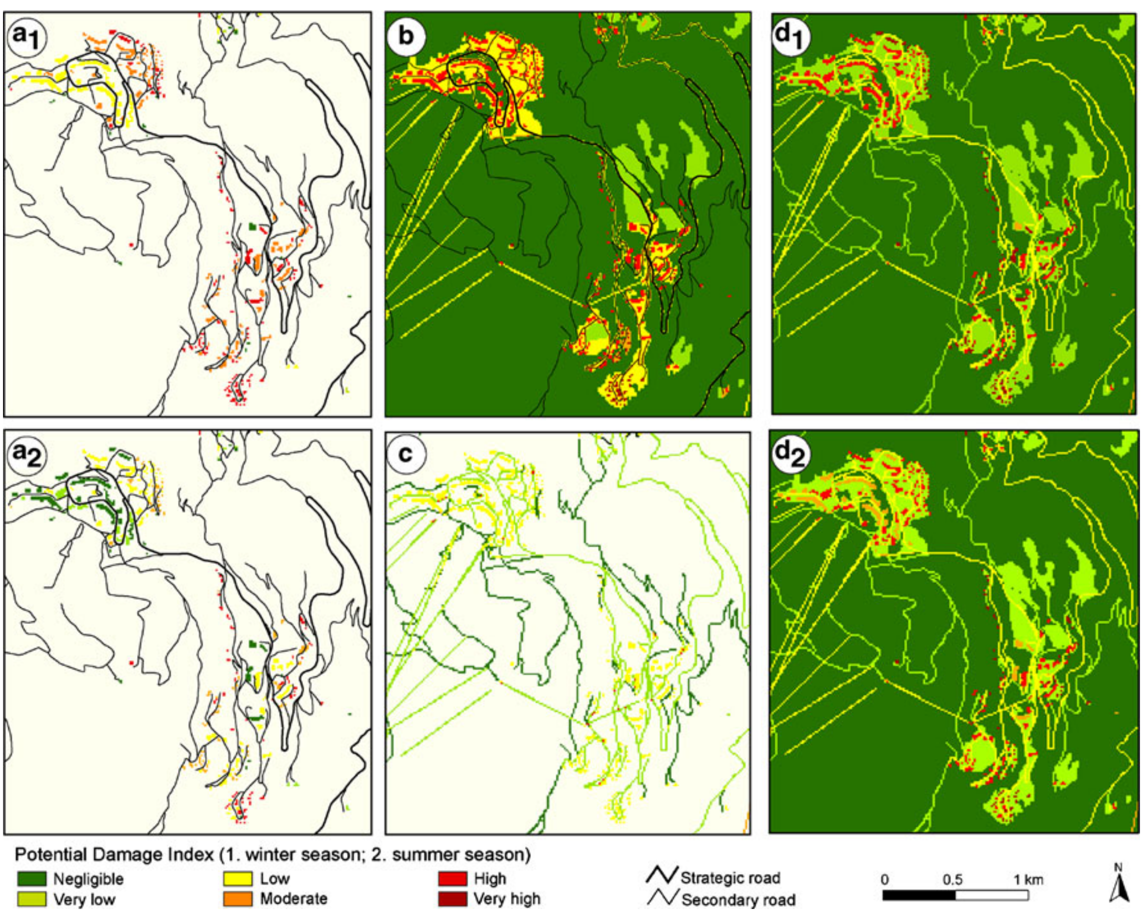

Fig. 12 Potential Damage Index map produced for the winter season (scenario 1) and for the summer season (scenario 2) for the ski resort of Pra-Loup. Class boundaries are derived from the analysis of Fig. 9 and Table 3. a_1 D_{PI} map for the winter season; a_2 D_{PI} map for the summer season; b D_{SF} map; c D_{CE} map; d_1 PDI map for the winter season; d_2 PDI map for the summer season

presented potential damage maps to landslide susceptibility/hazard assessments available for the region (Thiery et al. 2007; Kappes et al. 2011). In this context, it is important to realise that the estimated D_{PI}, D_{SF}, D_{SE} and PDI indices represent the total damage. It would be possible to estimate partial damage only in case information on landslide intensity is available. Depending on the intensity, the total damage values should then be multiplied with a value between 0 and 1. In order to obtain a complete estimate of future consequences, further research will also focus on quantitative modelling of future building and lifelines locations starting from the available 2,100 land cover/use map and taking in account the French building code and environmental protection measures.

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A. Puissant
Laboratoire Image, Ville, Environnement, CNRS UMR 7362,
Université de Strasbourg, 3 rue de l'Argonne,
F-67083 Strasbourg, France
e-mail: anne.puissant@live-cnrs.unistra.fr

M. Van Den Eeckhaut
Institute for Environment and Sustainability, Climate Risk Management Unit, Joint Research Centre (JRC), European Commission, IT-21027 Ispra, Italy

J.-P. Malet (✉)
Institut de Physique du Globe de Strasbourg, CNRS UMR 7516, Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, 5 rue Descartes,
F-67084 Strasbourg, France
e-mail: jeanphilippe.malet@unistra.fr

O. Maquaire
Laboratoire Géographie Physique et Environnement, CNRS UMR 6554, Littoral, Environnement Télédétection et Géomatique,
Université de Caen-Basse-Normandie,
Esplanade de la Paix, F-14032 Caen, France