Mapping landslide consequences in mountain areas: a tentative approach with a semi-quantitative procedure

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ABSTRACT: *Consequence analysis is a key aspect of anchoring assessment of landslide impacts to present and long-term development planning. Although several approaches have been developed over the last decade, some of them are difficult to apply in practice, mainly because of the lack of valuable data on the historical damages or the lack of landslide damage functions. This paper proposes a semi-quantitative procedure, based on GIS technology, to create landslide consequence maps at a 1:10,000 scale. The methodology developed within the EC-funded ALARM project (Assessment of Landslide Risk and Mitigation in Mountainous Areas) comprises two steps: the automatic identification of exposed elements (landcover/use, buildings,…) and the evaluation of their relative damage potential. The latter is evaluated on the basis of some basic criteria which allow to treat on a hierarchical basis the level of stakes (direct and indirect consequences) through the affectation of a relative value from 0 to 1. The methodology is applied on two landslide-prone catchments of Southeast France.*

Keywords: Potential damage, consequence, vulnerability, landslide, GIS technology.

RESUME : *L'analyse des conséquences potentielles d'un aléa est un des aspects essentiels de l'évaluation des impacts des glissements de terrain. Bien que plusieurs approches aient été développées dans les dix dernières années,la plupart d'entre elles sont difficiles à appliquer en pratique, principalement en raison du manque de données historiques sur les dommages observés ou sur les fonctions d'endommagement. L'objectif de cet article est de proposer une méthode semi-quantitative, fondée sur l'outil SIG, pour créer des cartes de conséquences potentielles à une échelle du 1/10 000^e^. Cette méthodologie, développée dans le cadre du projet européen ALARM, se déroule en deux étapes : (i) une identification automatique des éléments exposés (occupation et utilisation du sol, bâtiments, …) en fonction des enjeux présents sur le site et (ii) une évaluation relative des dommages potentiels. Cette dernière se combine plusieurs critères qui permettent de hiérarchiser les types enjeux (conséquences directe et indirecte) par l'affectation d'un poids relatif variant de 0 à 1. Cette méthodologie est appliquée à deux bassins de risque dans les Alpes françaises du Sud.*

Mots-clés : Dommage potentiel, conséquence, vulnérabilité, glissement de terrain, SIG.

1. Introduction

Global worldwide statistics as well as local site-specific statistics show that damage from hydro-geomorphologic processes (landslide, avalanche, and torrent flood) have risen for the last thirty years in mountains as well as in lowland areas (Alexander, 2000). This trend is linked both to an increase of the occurrence of hazardous events and to an increase of the society exposure to these events (Petrascheck and Kienholz, 2003). Today, population pressure, globalization of the economy as well as the tourism activity in the mountains are leading to an intense use of previously barely accessible or dangerous areas. Society demands ever more space (for settlement, recreation or transport), increases its vulnerability, but expects also technology to assure complete safety.

The concept of risk combines our understanding of the likelihood of a hazardous event occurring, with an assessment of its impact or potential consequence. The classical methodology for assessing and managing hydro-geomorphologic risk, and especially landslide risk, has been discussed by many authors (Varnes *et al.*, 1984, Cruden and Fell, 1997; Amatruda *et al.*, 2004; Crozier and Glade; 2005; Cascini *et al.*, 2005). Most notable is the procedure developed and reported by Fell (1997) and AGS (2000) which consists of six steps aiming at answering several basic questions (Table 1). Step 1 and Step 2 are commonly referred as the process of 'Hazard Analysis and Assessment', Step 3 is the process of 'Consequence Analysis', Step 4 is the process of 'Risk Calculation', and Step 5 and Step 6 are the process of 'Risk Evaluation'.

Table 1. *Basic questions and steps in landslide hazard and risk management (modified from Fell, 1997; AGS, 2000).*

Basic questions	Actions
1. What can cause harm?	Identification and recognition of danger
2. Where, when, how often and how can the process be generated?	Assessment of hazard (occurrence probability, magnitude-frequency)
3. What are the critical facilities, and how sensitive are they?	Analysis of consequences (values at risk and their vulnerabilities)
4. What can go wrong and how bad?	Assessment of risk (calculation of specific and total risk)
5. So what?	Assessment of risk acceptability
6. What should be done?	Mitigation of risk (if necessary)

All these assessments are qualitative in nature although there has been recently some progress towards quantitative assessments of hazard, consequence and risk (Leroi 1996; Amatruda *et al.*, 2004; Bell and Glade, 2004). However, as risk is a relative issue the assessment methods depend on the objectives, on the geographic scale of analysis, as well as on the type and amount of data available (Glade, 2002). Two analysis scales are used:

(a) the regional scale, where hazard, consequence and risk are mapped for vast areas at coarse scales (typically 1:50,000 to 1:10,000). The objective of these maps is to locate the most sensitive risk areas and to target high-risk locations for detailed risk assessments.

(b) the local scale, where hazard, consequence and risk are computed for individual landslides at fine scales (typically 1:5000 to 1:1000). The objective of these computations is to quantitatively assess occurrence probabilities and magnitudes of hazardous events, as well as to evaluate the direct and indirect consequences (physical, social, environmental and economic) of the hazard (Giacomelli *et al.*, 2005) in order to implement planning procedures or mitigation works.

If several technologies and procedures exist for landslide hazard assessment (Aleotti and Chowdhury, 1999; Carrara *et al.*, 1999) less attention has been given (i) to the identification of the people, facilities and resources exposed to a danger, and (ii) to the quantitative and reproducible assessment of the consequences in case of hazardous events (e.g. question 3 in table 1). Proposing a methodology integrating data from multiple sources to analyse and map consequences at macro and meso scales is therefore the objective of this work.

Landslide consequence assessment is significant for on-going and future planning exercises. It is a way of measuring which people, facilities and resources are potentially vulnerable, where they are located and what might be the strategy to reduce this vulnerability. Standardized methods for landslide consequence assessment and mapping are lacking for three reasons. First, landslide hazard is characterized by insufficient statistics of past landslides losses and fatalities (Schuster and Fleming, 1986) and by the absence of reference event of a given landslide type for a certain region (Wong *et al.*, 1997) compared to other type of hydro-geomorphic hazards. For example, consequences from earthquakes or flooding are normally determined based on an assumption that future events will follow a pattern similar to the past. Thus, given enough data from past events, the consequences can easily be determined. However, many landslide hazards have no or limited historical-event precedents upon which the consequences can be properly assessed, particularly for rare or extreme events that can have the largest impact on society.

Second, impacts of hazardous events can be quite diverse according to the type of movement. It is clear from Figure 1 that a building can face several types of solicitations of different magnitudes; estimating its potential damage and its vulnerability with engineering vulnerability functions is therefore a complex task difficult to apply in practice and necessitating detailed engineering databases (Léone *et al.*, 1996).

Third, consequence assessments suffer of the unavailability of robust social, economic or patrimonial values on the elements at risk and on their vulnerabilities for several regions (Glade, 2003).

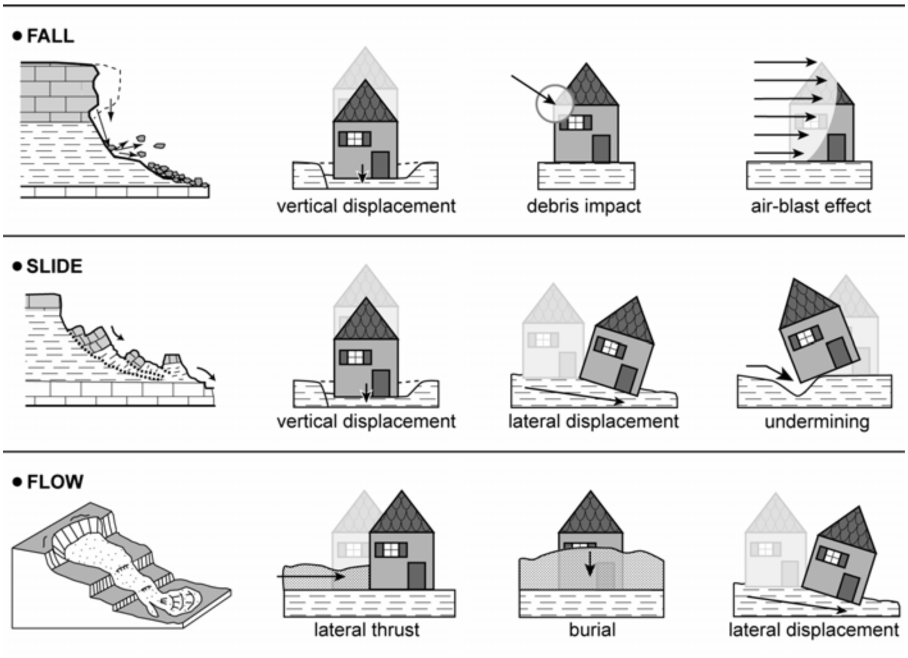

Figure 1. *Types of hydro-geomorphic hazards -fall, slide, flow- and associated major type of impact and solicitation on an element at risk (modified from Léone et al., 1996).*

This research reviews the available methods of consequence analysis and proposes a general methodology to assess and map landslide consequences on the regional scale through the development of a composite index. As will be discussed hereafter, the proposed methodology is very general in scope, uses the best available information to locate the high-sensitive areas, and can be applied independently of the type of landslide hazard and the type of environmental and socio-economic context. The methodology has been developed within the framework of the EU-funded project ALARM '*Assessment of Landslide Risk and Mitigation in Mountain Areas*' -http://ivm9.ivm.vu.nl/alarm/- (Silvano, 2003) and has been applied to a landslide-prone catchments in the South French Alps.

2. Concepts of landslide consequence assessment and review of existing methods

Cruden and Fell (1997) have defined the term ‘consequence’ as the resulting or potential outcomes arising from the occurrence of a hazardous event expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life. It is the product of the value of the elements at risk and of its vulnerability (Amatruda *et al.*, 2004). Several methods of consequence analysis (Figure 2) have been developed over the last decade, especially for earthquake and flooding. By vocabulary extension, most of these methods uses the term ‘vulnerability assessment’ instead of ‘consequence assessment’.

Although vulnerability is an intuitively simple notion, it is surprisingly difficult to define and even more difficult to quantify (Cutter, 1996; Glade, 2003). Two ways of understanding vulnerability are currently dominant (Hufschmidt *et al.*, 2005):

- Geoscientists and engineers use the term to describe the susceptibility of population, buildings and engineering works, economic activities, public service utilities, infrastructure and environmental features with respect to the nature of the hazard. Vulnerability reflects therefore the level of damage representing the degree of loss to a given element at risk.
- Human and social scientists, in contrast, define vulnerability as the potential for attributes of a system to respond adversely to the occurrence of hazardous events. Vulnerability represents therefore the ability of social groups to anticipate, cope with, resist harm and recover from the impact of a hazard afterwards (Wisner *et al.*, 2004). This definition corresponds with the way ‘resilience’ (e.g. the inverse of the vulnerability) is understood today (D’Ercole, 1994; Alexander, 2003).

As consequence is a relative issue, the measuring methods depend on the nature of the assessment, on the geographic scale, and on the amount of data required (Figure 2a). The methods differ with respect to the number and type of variables, the method of scaling, the weighting and other criteria.

At macro scales (Figure 2b-1) analysis of landslide consequence is commonly based on expert knowledge. The methodology results first in an inventory of the elements at risk and the critical facilities and second in a qualitative ranking of their value. The elements 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, power lifelines, main roads, etc). Only the elements directly affected by an active landslide are inventoried. Then their value (in terms of a monetarily 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 in France for the implementation of the ‘*Plan de Prévention des Risques*’ (MATE/METL, 1999), or in Switzerland for the ‘*Carte des Dangers Naturels*’ (BUWAL/BWW/BRP, 1997).

At meso scales, landslide consequence is evaluated more sophistically by reproducible qualitative or semi-quantitative methods (Figure 2b-2). Within this approach, landslide consequence is expressed in terms of potential loss (or damage) by composite indices. Index-based methods have been used for a long time in a wide variety of disciplines to measure complex, multi- dimensional concepts that cannot be observed or measured directly. Generally the index is the composite of several indicators. Two types of indices can be distinguished (Crosta *et al.*, 2001):

- global indices for which potential damage is computed by empirical formulas, such as those proposed by Del Pretre *et al.* (1992). The elements at risk are classified by using a relative scale of values adapted to the characteristics of the area. This approach is useful for vast areas where it is difficult to collect and analyse data for each individual element;
- individual indices for which potential damage is computed by loss utility functions (Crosta *et al.*, 2001). This approach implies a better flexibility and adaptation to complex situations to determine the global cost of the losses (Bonnard *et al.*, 2004).

At micro scales and for site-specific analyses, landslide consequence is evaluated more quantitatively by using vulnerability factors including physical, social, environmental and economic components (Figure 2b-3). Within this approach, direct or indirect effects can also be evaluated (Glade, 2003). This approach uses detailed datasets and complex multi-criteria models (Mejia-Navarro and Garcia, 1996). Again, assuming that the elements at risk and their respective value have been identified, the vulnerability of a given element is defined by:

(a) the use of '*vulnerability coefficients*' representing the degree of loss to a given element or set of elements for events of different magnitude (Varnes *et al.*, 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 damage (Petrascheck and Kienholz, 2003).

(b) the use of '*vulnerability functions*' representing the interactions between the event and the elements at risk. Léone *et al.* (1996) distinguishes structural damage functions (for property), physical injuries 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 building resistance which is often very long to acquire.

(c) the use of multi-criteria models to evaluate a synthetic vulnerability expressing the capacity of response of a society to potential crises (D'Ercole, 1994; Chardon, 1999). This method, which necessitates the collection of a large quantity of socio-economic data, has never been applied in practice due to incomprehension between the stakeholders and the scientific community (D'Ercole, 1994).

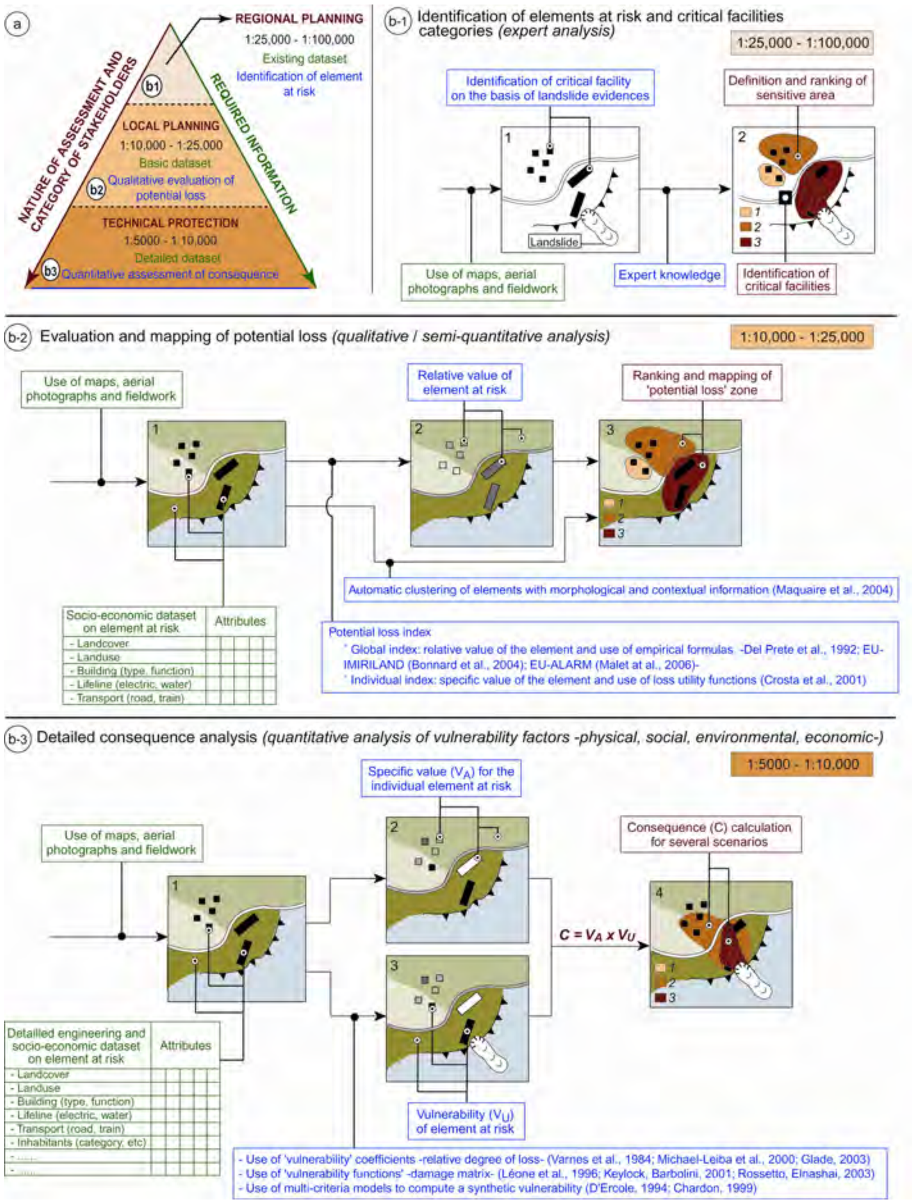

Figure 2. *Approach used in assessing landslide consequence* ***a.*** *Type of analysis according to the nature of assessment, the stakeholders, the required input data and the geographical scale* ***b-1.*** *Steps in the methods used at macro scale* ***b-2.*** *Steps in the methods used at meso scale* ***b-3.*** *Steps in the methods used at micro scale.*

To overcome some of the limitations associated to the above mentioned approaches, a method for locating and mapping highly-sensitive areas over large territories is proposed. The methodology originally developed for meso scales (1:10,000 to 1:25,000) is very general in scope and versatile to be applicable for several types of environment (largely-visited mountain areas, densely-populated valley floors, urban areas, etc). The method is index-oriented because of the ability of indices to synthesize a vast amount of diverse information into a simpler, more usable form. The straightforwardness of a composite index makes the information easily accessible to the general public, technicians, local and regional planners, insurance companies, government agencies and other potential users.

In this paper, the methodology for (1) the index-oriented method is detailed and (2) some results on the Sauze and Faucon torrential basins, a landslide and debris-flow prone catchments located in the French South Alps, are presented and discussed.

3. Methodology

The index-oriented method to evaluate landslide potential consequences (damage) combines the identification of the elements at risk (or stakes) and of their value with a semi-empirical model. Stakes are defined as a relative value scale of the exposed elements (Maquaire *et al.*, 2004). The proposed method uses three steps.

The first step is to define a typology of the main stakes observed in mountain area. These consequences represent (i) the people in their physical integrity '*physical injury*' (C_{PI}), (ii) the direct effects on buildings, infrastructures and human activities limited in time '*direct structural and functional effect*'(C_{SF}) and (iii) the effects on socio-economic activities characterized by extra-local consequences and diffuse in time '*indirect socio-economic effect*'(C_{SE}).

The second step is building a database of the exposed elements for each type of stake. Each element is described by some attributes which are ranked through an expert weighting. A relative value called '*damage index*' (I_D) is then allocated to the elements for each stake (Figure 3). The relative importance of each stake can also be weighted in order to take into account the objectives of the study or the local socio-economic context of the region. This index is called '*local index*'(I_L).

The third step consists in defining a mathematical model to create a quantitative expression of vulnerability. A linear combination of the exposed elements for each stake associated to their respective indices (damage and local index) allow to evaluate the potential landslide consequences for each type of consequences (C_{PI}, C_{SF}, C_{SE}) and finally a total potential consequence (C_T).

To be used in practice, the methodology is based on the use of commercial databases, on the digital processing of aerial and satellite imagery, and on GIS technologies.

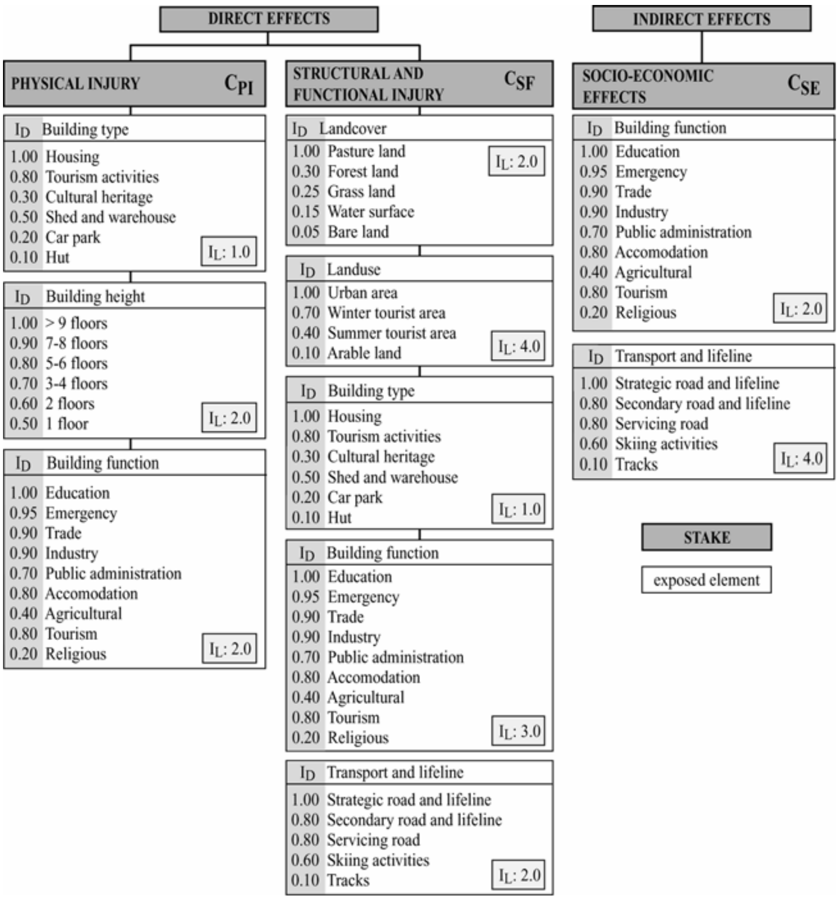

Figure 3. *Proposed relative values (damage and local index) of several exposed elements for respectively **a.** Stake 'Physical injury' (C_{PI}), **b.** Stake 'structural and functional potentials effects' (C_{SF}), and **c.** Stake 'socio-economic effects' (C_{SE}.).*

3.1 *Identification of exposed elements*

In Europe, only the largest urban cities have spatial databases in which the exposed elements are carefully described. They are usually provided by the national mapping agency of each country. This is often not the case in the mountainous areas where this basic information has to be collected. The exposed elements generally considered as relevant at a 1:10,000 scale to evaluate the stakes are (Léone *et al.* 1996):

- *landcover/landuse* which gather *natural and semi-natural surfaced areas* such as forests (coniferous or broadleaved trees), agricultural lands, grasslands, wetlands and open-areas without any vegetation and *artificially surfaced areas* such as car parks, camp sites or leisure areas;

- *buildings which* refer to man-made objects (residential block, individual house/chalet, warehouse, etc.) built either in highly resistant structure (concrete, breeze-block, stone) or medium resistant structure (steel, wood). Each type of object is associated to one or several urban functions (residential, commercial, industrial, and agricultural);

- *lifelines* which correspond to different type of networks (power, water, sewerage), the transport of essential supplies, as well as the infrastructure essential to the basic economy (motorway, national road, municipality road, etc.). Elementary human-made objects supporting lifelines (electric lines, ski lifts) are integrated in this category.

Among these exposed elements, buildings (according to their heights or their number of liveable floors) and transport lifelines (according to the number of traffic lanes) are the most discriminant for the identification of the stakes. Indeed, the size and the number of buildings, and their spatial distribution allow to estimate the potential number of casualties, the structural damages, and the functional disturbances that may affect the socio-economical activities. Furthermore, the identification of transport lines is useful to locate different networks, usually established at the edge or beneath the road.

A semi-automatic procedure, detailed in Maquaire *et al.* (2004), is used to locate these elements at a 1/10,000 scale. This procedure is based on digital processing of aerial and satellite imagery, and on GIS technologies.

3.2 *Value calculation: definition of 'damage index' (I_D) and a 'local index'(I_L)*

The damage index (I_D) is defined according to the potential losses undergone by the exposed elements if they were affected by a landslide; therefore, the intensity of the hazard is not taking into account for calculating the index. Figure 3 indicates the values used for I_D on a scale from [0-1]. For example, the I_D values for the stake 'structural and functional effects' and the exposed elements 'landcover' is defined in line with the local state value o the landcover parcels collected from the local planners. As well, for the exposed element 'lifelines', the I_D value is derived from the expected perturbations that may arise from their destruction. This approach has been also used by Glade (2003).

The local index (I_L) is defined for each type of exposed elements (Figure 3) by taking into account the socio-economic and environmental characteristics of the study area. For example, the economic activities of the Enchastrayes village are highly dependent on summer and winter tourism activities. In consequence, a high local index (4.0) is used for the 'landuse' exposed element because the tourism infrastructure has to be preserved (chairlift, ski-tow, …).

Therefore, the methodology does not require the collection of a large quantity of socio-economic data based on the value of the exposed elements or on the value of the damage relative to the value of the property. In fact, these data do not exist for most of the mountain areas or are often very heterogeneous and difficult to collect. Moreover, the methodology is versatile and may be adapted to many different situations (type of exposed elements, weighting -I_D and I_L-) in order to take into account the local situation of the area or to propose several scenarii for management or planning. The combination of the potential consequences (C_{PI}, C_{SF}, C_{SE}) allows to evaluate a total potential consequence index C_T expressed in five classes (Table 2).

Total Consequence	**Definition**
C0 : negligible	No consequence on the exposed elements
C1 : very low consequence	Minor consequences on building and lifelines Liow, local and short-time perturbations of the human activities
C2 : low consequence	No casualties. Low to moderate consequences on building and lifeline. Moderate perturbations of the human activities during a few days to a few weeks.
C3 : moderate consequence	Low or serious casualties due to high damages on buildings. Moderate to high perturbations of human activities. High, direct or indirect consequences on the local territory, during a few months.
C4 : high consequence	Serious casualties or deaths due to the total destruction of buildings. Very high, direct or indirect consequences, that can not managed locally. Domino consequences are expected.

Table 2. C*lasses of total potential damage (CT) defined for the study area (according to French PPR procedure 'Plan de Prévention des Risques').*

4. Results: mapping landslide consequences

The proposed methodology is tested on the Sauze and Faucon torrential basins, two landslide and debris-flow prone catchments located in the French South Alps. Figure 4 presents the total potential landslide damage (S_T) map over these areas. It also shows the cumulated curve of C_T for which thresholds defined the classes (C0 to C4).

Figure 5 details the consequence maps: the structural and functional consequence map C_{SF} highlights the stakes related to the spatial extension of the ski domain, the urban area and the arable land; the direct physical injury map C_{PI} classes the buildings by their potential number of casualties; finally, the indirect socio-economic map C_{SE} shows the potential consequences related to transport, lifelines and tourism activities.

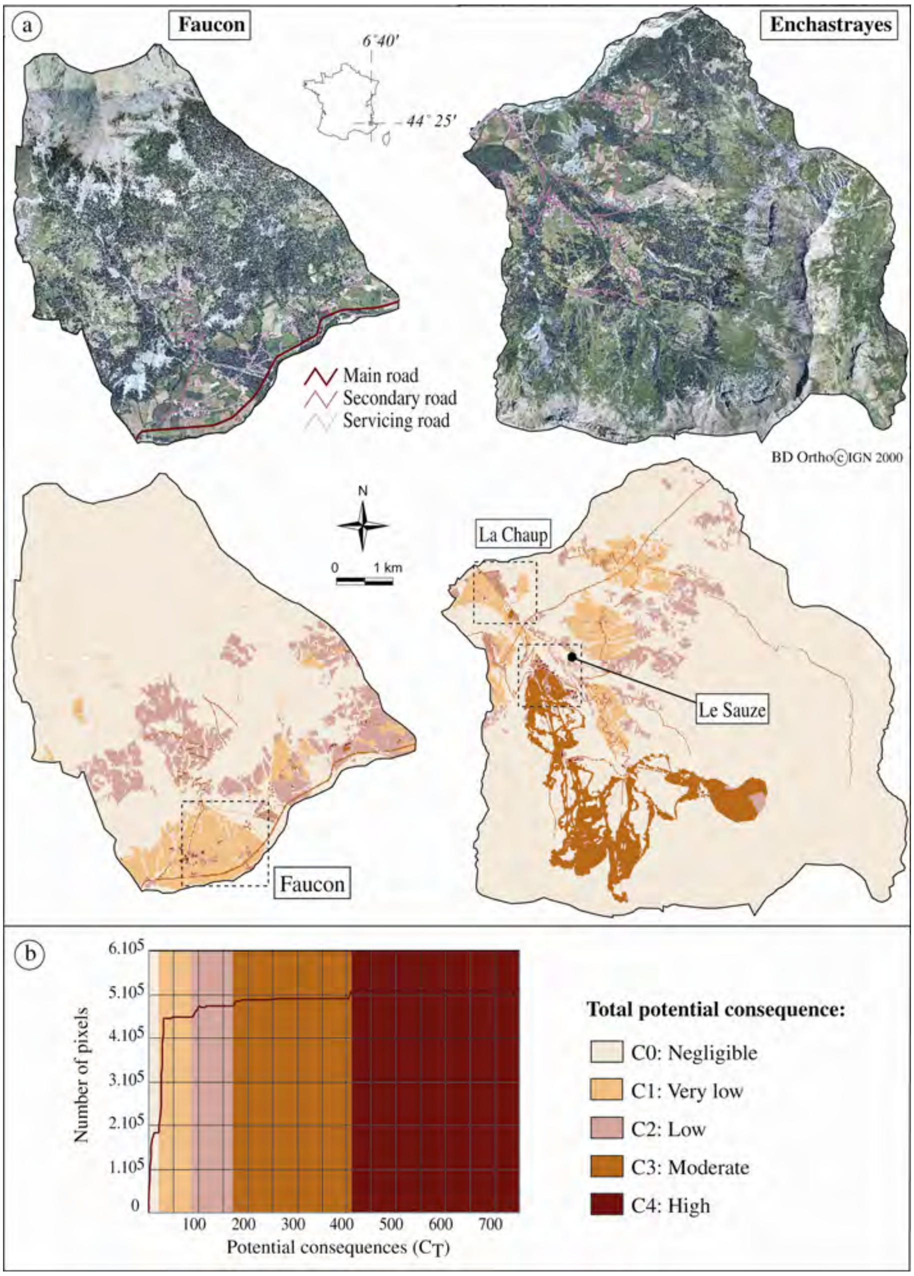

Figure 4. *(a) Orthophotos of the both study areas (Barcelonnette Basin – South Alps) and total potential consequence map; (b) cumulated curve used to define the classes.*

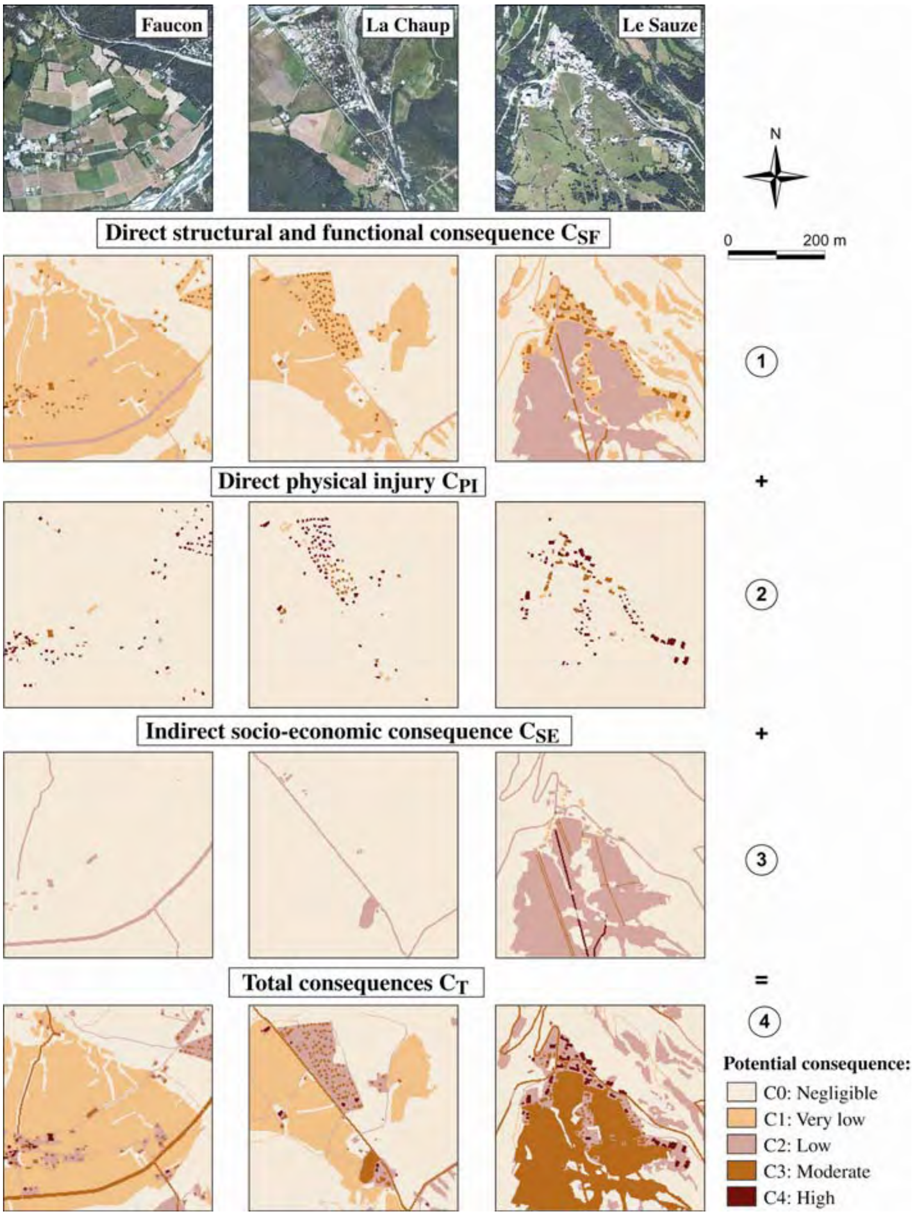

Figure 5. *Example of the direct structural and functional potential consequence map C_{SF} (1), direct physical injury map C_{PI} (2), indirect economic consequence map C_{SE}, (3) and total consequence C_T (4) simulated with by the semi-quantitative model. Examples of the Faucon village, La Chaup hamlet and Sauze ski resort.*

5. Conclusion

This research reviews the methods of landslide consequence analysis and proposes a general methodology to assess and map (at macro to meso scales) landslide consequences through the development of a composite index of potential consequences (e.g. vulnerability). The proposed methodology is very general in scope, uses the best available information to locate the high-sensitive areas, and can be applied independently of the type of landslide hazard and the type of environmental and socio-economic context.

The method is index-oriented because of the ability of indices to synthesize a vast amount of diverse information into a simpler, more usable form, and to represent in a cartographic form. The straightforwardness of this composite index makes the information easily accessible to the general public, technicians, local and regional planners, insurance companies, government agencies and other potential users.

At this stage of development of the procedure, it is premature to recommend this index as the basis for drawing strong policy conclusions. It may however be considered together with other quantitative and qualitative indicators, to assess and map vulnerability and their policy implications.

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