Grant Agreement No.: 226479

SafeLand

Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies

7th Framework Programme
Cooperation Theme 6 Environment (including climate change)
Sub-Activity 6.1.3 Natural Hazards

Deliverable D5.3

Quantitative risk-cost-benefit analysis of selected mitigation options for two case studies

Work Package 5.1 - Toolbox for landslide hazard and risk mitigation measures

Deliverable Leader: ETHZ Revision: [4] – Final

February, 2012

Rev.	**Deliverable Responsible**	**Controlled by**	**Date**
0	ETHZ		13.09.2010
1	ETHZ		21.07.2011
2	ETHZ		21.10.2011
3	ETHZ	IIASA	22.12.2011
4	ETHZ		20.02.2012

SUMMARY

Decision making in general is a difficult issue due to the significant underlying uncertainties and complex interrelation of events and choices affecting the benefits and losses associated with decisions. Typical decision problems are subject to a combination of inherent, modelling and statistical uncertainties. This is primarily due to the fact that our understanding of the issues involved in the decision problems is often far less than perfect and that it is only possible to model the involved processes of physical phenomena as well as human interactions in rather uncertain terms. If all aspects of a decision problem would be known with certainty, the identification of optimal decisions would be straightforward by means of traditional cost-benefit analysis. Due to the existing uncertainties, it is not possible to assess the results of decisions in certain terms. There is hence no way to assess with certainty the consequences resulting from the decisions we make. However, what can be assessed is the risk associated with the different decision alternatives. Based on risk assessments, decision alternatives may then be consistently ranked on the basis of their associated utilities and benefits/losses, thereby providing a rational basis for societal decision making.

This deliverable aims to provide a framework and methodology for carrying out a risk-cost-benefit analysis that could be utilised for decision making. Further two case studies – one involving the analysis and management of risks arising from debris flow phenomenon in Barcelonnette is described and another concerned with the risk analysis and risk management for risks posed by different flow-like phenomena in Nocera Inferiore are reported.

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1 INTRODUCTION

1.1 BACKGROUND

Decision problems in natural hazards management are generally subject to significant uncertainty. This is primarily due to the fact that our understanding of the issues involved in the decision problems is often far less than perfect and that it is only possible to model the involved processes of physical phenomena as well as human interactions in rather uncertain terms. If all aspects of a decision problem would be known with certainty, the identification of optimal decisions would be straightforward by means of traditional cost-benefit analysis. Due to the existing uncertainties, it is not possible to assess the results of decisions in certain terms. There is hence no way to assess with certainty the consequences resulting from the decisions we make. However, what can be assessed is the risk associated with the different decision alternatives. Based on risk assessments, decision alternatives may then be consistently ranked on the basis of their associated utilities and benefits/losses, thereby providing a rational basis for societal decision making.

1.2 STRUCTURE OF THIS DELIVERABLE

The definitions of some relevant key terms for the analysis are provided in Chapter 2 of this deliverable. A general framework for the purpose of carrying out a risk-cost-benefit analysis that could be utilised for decision making is described in Chapter 3. In Chapter 4, a case study in Barcelonnette involving the analysis and management of risks arising from debris flow phenomenon is described. Another case study concerned with the risk analysis and risk management for risks posed by different flow-like phenomena in Nocera Inferiore is reported in Chapter 5.

2 DEFINITIONS OF KEY TERMS

The use of terms in this report adheres to the terminology presented in the SafeLand Project Handbook / Deliverable D8.1 of the project (SafeLand 2009). The definitions of some key terms are presented below:

- **Consequence –** The outcomes or potential outcomes arising from the occurrence of a landslide expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life.

- **Elements at risk –** The population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by landslides.

- **Hazard –** A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the probability of their occurrence within a given period of time.

- **Risk –** A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability and consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.

- **Vulnerability –** The degree of loss to a given element or set of elements within the area affected by the landslide hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) is affected by the landslide. Vulnerability could also refer to the propensity to loss (or the probability of loss), and not the degree of loss.

3 METHODOLOGY

3.1 FRAMEWORK FOR DECISION MAKING

If the concept of risk as the simple product between the probability of occurrence of an event with consequences and the consequence of the event is widened to also include the aspects of the benefits achieved from the decisions, risk may then be related directly to the concept of utility (von Neumann and Morgenstern, 1944 and Raiffa and Schlaifer, 1961) from the economic decision theory. A whole methodical framework is made available for the consistent identification of optimal decisions. This framework is considered as the theoretical basis for risk based engineering decision making. Based on a guideline document developed by the Joint Committee on Structural Safety (JCSS 2008), this section describes the application of such a framework for the purpose of carrying out a risk-cost-benefit analysis that could be utilised for decision making.

3.1.1 Decisions and decision maker

A decision may be understood as a committed allocation of resources. The decision maker is an authority or person who has authority over the resources being allocated and responsibility for the consequences of the decision to third parties. The intention of the decision maker is to meet some objective, the value of which is at least in balance with the resources allocated by the decision. The decision maker faces the problem of choosing between a set of decision alternatives which may lead to different consequences in terms of losses and benefits. The objective aimed for by the decision making represents the preference of the decision maker in weighing the different attributes which may be associated with the possible consequences of the decision alternatives. This needs to be done while giving due account and consideration to the preferences of the relevant societal stakeholders who will be affected by the decision.

It is thus clear that the formulation of the decision problem will depend very much on the decision maker. This makes it important to establish the stakeholders, the beneficiaries and the responsible parties for the decision problem. Each possible decision maker may have different viewpoints in regard to preferences, attributes and objectives. It is important to identify the decision maker, since the selection and weighting of attributes must be made on behalf of the decision maker. In this regard, the following general decision making levels can be identified – supranational authority, national authority and/or regulatory agencies, multinational/international private company, local authority, local private owner, private operator and specific stakeholders.

3.1.2 Attributes of decision outcomes

There are essentially three types of attributes - natural, constructed and proxy. Natural attributes are those having a common interpretation to everyone (cost in dollars, number of fatalities and other measurable quantities). For many important objectives, it is difficult or impossible to come up with natural attributes. Constructed attributes or indicators (as commonly referred to in natural hazard risk assessment literature) may be used in such cases, the underlying idea being that the attributes used must essentially define what is meant by the objective. Such attributes are made up of verbal descriptions of several distinct levels of impact that directly indicate the degree to which the associated objective is achieved and a numerical indicator is assigned to these levels. Examples of constructed attributes turning into natural attributes with time and use include the gross national product GNP (aggregate of several factors to indicate economic activity of a country) and stock market indices. Finally, there are cases where it is difficult to identify either type of attribute for a given objective. In these cases indirect measurements may be used. The attributes used to indicate the degree to which a given objective is achieved are called proxy attributes. When an attribute is used as a proxy attribute for a fundamental objective, levels of that attribute are valued only for their perceived relationship to the achievement of that fundamental objective. The decision maker will make decisions consistent with her/his values, which are those things that are important to her/him, especially those that are relevant to her/his decision.

3.1.3 Preferences among attributes and the concept of utility

Having determined the set of attributes, the objectives must be quantified with a value/utility model. This is done by means of converting the attribute values to a value scale by means of judgment of relative value or preference strength. The value scale is often referred to as a utility function. Such a utility function is generally composed of costs, benefits and losses associated with the relevant decision alternatives considered for the system. In some cases it may not appear obvious how to directly transfer different attribute values into one common value scale. To overcome this apparent problem it is possible to consider multi-attribute decision problems. However, it is emphasized that the solution to a multi-attribute will imply a weighing of the different attributes against each other and more transparency in the decision process is thus achieved by making this weighing directly.

The multi-attribute value problem is a problem of value trade-offs. These trade-offs can be systematically structured in utility functions. These are scalar valued functions defined on the consequence space, which serve to compare various levels of the different attributes indirectly. Given the utility function, the problem of the decision maker is to choose that alternative from the space of feasible alternatives that maximizes the expected utility.

The expected utility is used as a relative measure making it possible to choose between various actions. The action with the largest expected utility will be chosen from among the possible actions. Thus, no absolute criterion for the acceptability of the considered action is given from decision theory.

3.1.4 Feasibility and optimality

Different decision alternatives will imply different potential losses and potential incomes/benefits. The representation of risk in terms of expected utility facilitates decision making in correspondence with the preferences of the decision maker in accordance with the decision theory. Figure 3.1 provides an illustration of the variation of utility as a function of different decision alternatives.

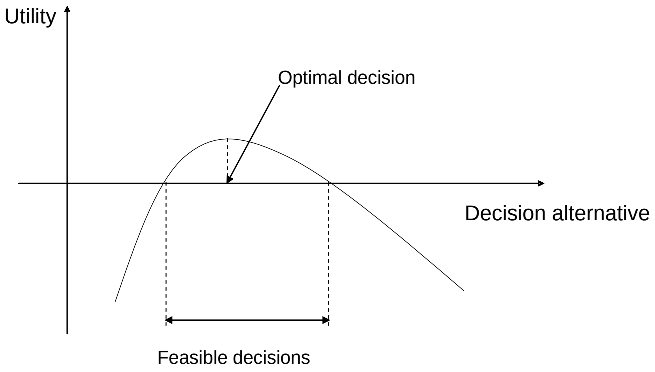

Figure 3.1 Illustration of variation of utility (expected benefit) as a function of different decision alternatives.

Decisions which do not yield a positive benefit should clearly not be chosen, wherever possible. Optimally the decision yielding the largest utility is selected but there could be constraints on the decision alternatives which are not explicitly included in the formulation of the utility function. In such cases, not all feasible decisions may be acceptable.

3.2 SYSTEM MODELLING

The definition and characterisation of a suitable system for analysis form a significant part of an engineering risk assessment and decision making problem. In general terms, a system may be understood to consist of a spatial and temporal representation of all constituents required to describe the interrelations between all relevant hazards for the system and their consequences. A system representation can be performed in terms of logically interrelated constituents at various levels of detail or scale in time and space. Constituents may either be physical components, procedural processes and human activities. The appropriate level of detail or scale depends on the physical or procedural characteristics or any other logical entity of the considered problem as well as the spatial and temporal characteristics of consequences. The important issue when a system model is developed is that it facilitates a risk assessment and risk ranking of decision alternatives which is consistent with available knowledge about the system and which facilitates that risks may be updated according to knowledge which may be available at future times. Furthermore, the system representation should incorporate options for responsive decision making in the future, depending on the knowledge available then.

It is important that the chosen level of detail is sufficient to facilitate a logical description of events and scenarios of events related to the constituents of the system which individually and/or in combination may lead to consequences. In addition to this, the representation of the system should accommodate, to the extent possible, for collecting information about the constituents. This facilitates that the performance of the system may be updated through knowledge about the state of the individual constituents of the system. In summary, the characteristics of the system hence include the knowledge about the system and the surrounding world, the boundaries of the system, the possible consequences for the system and how all these factors interrelate with the world outside the system and into the future, the available decision alternatives for the system and criteria (preferences) for assessing the utility associated with the different decision alternatives.

In a societal context, risk based decision making also needs to be understood from an intergenerational perspective. Within each generation decisions have to be made which will not only affect the concerned generation but all subsequent generations. It is necessary that the definition of the system in principle must include a full inventory of all potentially occurring consequences seen in this perspective as well as all possible scenarios of events which could lead to the consequences.

3.2.1 Knowledge and modelling of uncertainties

Knowledge about the considered decision context is an important factor for successful optimal decision making. In the real world, uncertainty or lack of knowledge characterizes the normal situation and it is thus necessary to be able to represent and deal with this uncertainty in a consistent manner. Bayesian statistics provides a basis for the consistent representation of uncertainties independent of their sources and readily facilitates for the joint consideration of purely subjectively assessed uncertainties, analytically assessed uncertainties and evidence as obtained through observations.

There exist a large number of propositions for the characterization of different types of uncertainties. It has become standard to differentiate between uncertainties due to i) inherent natural variability, ii) model uncertainties and iii) statistical uncertainties. Whereas the first mentioned type of uncertainty is often denoted aleatory (or Type 1) uncertainty, the latter two are referred to as epistemic (or Type 2) uncertainties. However this differentiation is introduced for the purpose of setting focus on how uncertainty may be reduced rather than calling for a differentiated treatment in the decision analysis. In reality, the differentiation into aleatory uncertainties and epistemic uncertainties is subject to a defined model of the considered system. Any risk assessment process requires that all uncertainties are considered and treated in a consistent manner. The relative contribution of the two components of uncertainty depends on the spatial and temporal scale applied in the model. The risk assessment should hence include a description of all relevant assumptions made in connection with the system identification, as well as the modelling of consequences and frequencies. The level and type of knowledge available to support the assumptions, as well as the modelling of consequences and frequencies, should be explicitly stated.

A related form of categorisation of uncertainties can be established on the basis of their sources. The uncertainty associated with a risk estimate stem from several sources:

- **Parameter uncertainty**, associated with input parameters, is commonly recognized and addressed in modelling approaches.
- **Conceptual model uncertainty**, concerning how the real world is represented and abstracted.
- **Modelling uncertainty**, concerning the underlying mathematical modelling and its inherent assumptions
- **Scenario/event uncertainty**: relating to whether scenarios/events representing all potential hazards have been identified and analysed.

The uncertainty in the final estimation of risk is the aggregation of all these types of uncertainties. Often the conceptual model uncertainty and the modelling uncertainty are merged and called the “model uncertainty”. The quantification of uncertainties for one scenario could then be divided into three steps:

- Quantification of uncertainties associated with the input parameters
- Assessment of the propagation of uncertainties through the mathematical or numerical model; how sensitive is the model to uncertainties?
- Quantification of the model uncertainty; how good approximation to the real world is the model? (Including uncertainty in conceptual model and numerical model)

Procedures exist for quantification of the parameter uncertainty (e.g. by statistical analyses of measurement data) and for quantification of how uncertainty propagate through the applied mathematical or numerical model (e.g. by using Monte Carlo Simulation). However the issue of quantifying the uncertainty associated with the conceptual model and numerical model is not straight forward. Here expert judgment and previous experience play an important role. Finally the uncertainty associated with choice of scenarios to be analysed is not quantifiable, but should not be disregarded. The treatment, quantification and management of uncertainties in the risk assessment, risk management and decision making processes has been dealt with in detail in the deliverables D0.3 and D5.4 of the SafeLand project (SafeLand 2011a and SafeLand 2011b).

3.2.2 System representation

The risk assessment of a given system is facilitated by considering the generic representation illustrated in Figure 3.2. A hazard is considered to be an event with the potential to cause damage to the system. For a structure, this includes extreme loads of design loads, unforeseen loads or deterioration processes. The constituents of the system can be considered as the first defence of the system in regard to the hazards. The damages of the constituents are considered to be associated with direct consequences. Direct consequences may include monetary losses, loss of lives, damages to the qualities of the environment or just changed characteristics of the constituents. Direct consequences, are thus defined as all marginal (not considering loss of system functionality) consequences associated with damages or failures of the constituents of the system. Based on the combination of events of constituent failures and the corresponding consequences, follow-up or indirect consequences may occur. Indirect consequences may be caused by e.g. the sum of monetary losses associated with the constituent failures and the physical changes of the system as a whole caused by the combined effect of constituent failures. The indirect consequences in risk assessment play a major role and their modelling should be carefully considered (Faber and Maes, 2004). Typically the indirect consequences evolve spatially beyond the boundaries of the system and also have a certain sometimes even postponed development in time.

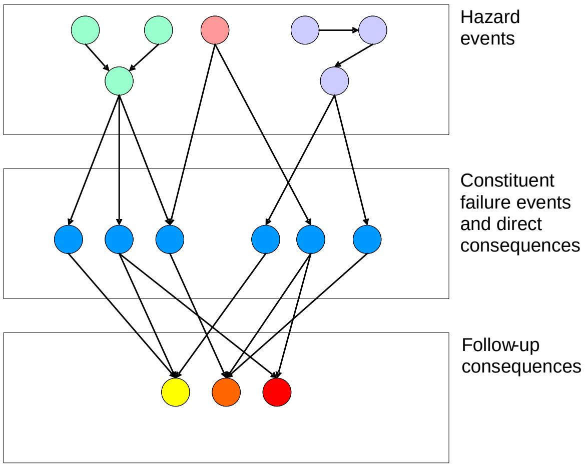

Figure 3.2 Generic system representation in risk assessment.

It should be noted that any constituent in a system can be modelled as a system itself. As an example, a system could be a road network with its constituents being bridges. The bridges, in turn, could also be systems with their constituents being structural members. This is shown in Figure 3. Depending on the required scale and level of detail in the risk assessment, the system definition, the constituents of the system, the hazards, and consequences would be different.

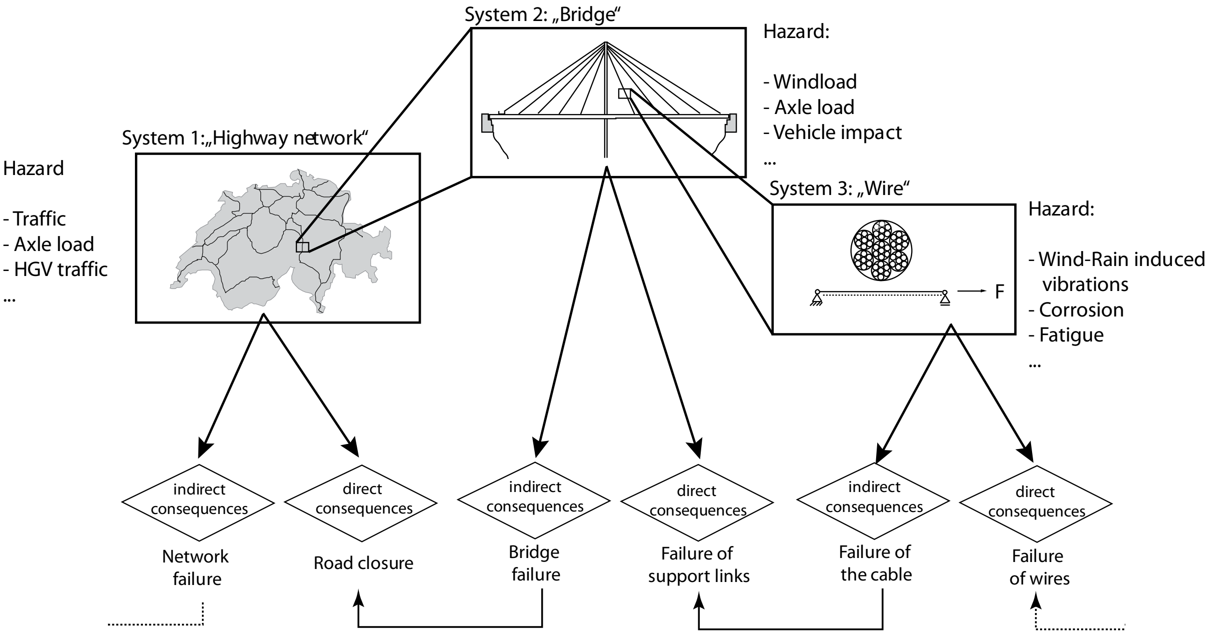

Figure 3.3 Generic system characterization at different scales in terms of hazards and consequences.

3.2.3 Hazards

The hazards acting on the constituents of a system are defined as all possible endogenous and exogenous effects with the potential to cause consequences. A probabilistic characterization of all the hazards relevant for a system requires a joint probabilistic model for all relevant effects relative to time and space.

The characteristics of hazards are very different, depending on the individual types. Effects such as technical failures, accidents, explosions, rockfall, and landslides generally could be suddenly occurring events. Floods and fire storms are generally more slowly evolving, while climatic changes are much slower. Effects like human errors and malevolence, in turn, have their own patterns over time and space. In a risk management context, the characterization of hazards must take these differences into account in order to facilitate a realistic assessment of the possible consequences as well as to allow for the identification of possible relevant measures of risk prevention and loss reduction. It is also important to note that in many risk assessments, the joint representation of several hazards is required.

For suddenly occurring events, usually the probability of the event itself is needed. Part of the safety against such events is carried by the probability that they will not occur at all. However, more characteristics or indicators are needed to facilitate the modelling of the possible consequences of the event. Considering landslides and rockfall events, typically applied indicators are the mean velocity of the movement and the volume of detachment. These characteristics or indicators are useful, because knowledge about them provide basis for assessing the potential damages caused by the hazards, such as the damages caused to buildings and infrastructure caused by the occurrence of a landslide.

3.2.4 Consequences

The consequences which may potentially be caused by different hazards are manifold and generally depend strongly on the specific characteristics of the hazard as well as the location where it occurs and the assets which are exposed. As a general rule, consequences should be assessed in regard to fatalities (loss of lives) and injuries, damages to the qualities of the environment and economic losses.

The risk assessment is greatly facilitated by considering the development of consequences as shown in the generic representation in Figure 3.2. However, in the assessment of consequences, it is useful to consider a further differentiation as illustrated in Figure 4. From Figure 3.4, it is seen that two types of indirect consequences are differentiated, namely the indirect consequences due to physical system changes and the indirect consequences caused by the societal or public perception of these. The reason for this differentiation is to indicate how risk management may efficiently be supported by risk communication. The better and more targeted risk communication undertaken before, during and after events of natural hazards is, the smaller the consequences caused by perception will be. Often traditional risk assessments focus on the assessment of direct consequences and do not attempt to model the indirect consequences by rigorous modelling. Instead, indirect consequences are generally included by somehow amplifying the direct consequences by means of a risk aversion function, the characteristics of which generally are assessed subjectively. The often more important contribution to consequences are hence commonly modelled by means of the simplest possible approximation. The approach suggested here, where consequences are differentiated into different components is meant to circumvent such excessively simplistic modelling, bringing the indirect consequences into focus and indicating the different ways they might be controlled.

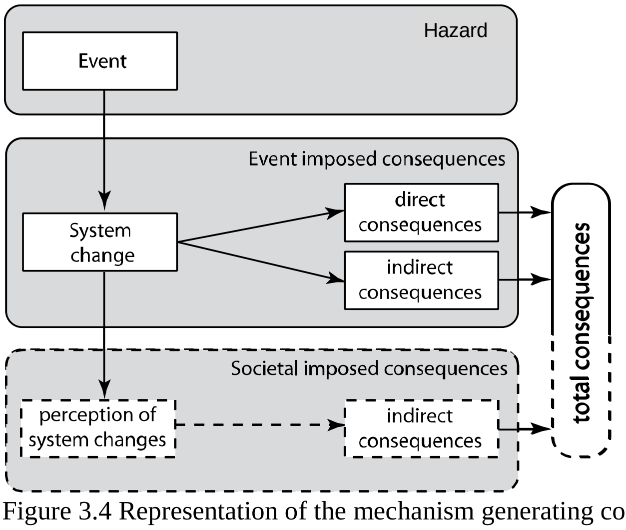

Figure 3.4 Representation of the mechanism generating consequences.

Direct consequences due to the realization of risk due to e.g. landslide hazards or the impact of the disaster can be separated into humanitarian effects, ecological effects and economic effects (Mechler, 2004). Furthermore, it may be necessary to distinguish between different risk bearers, e.g. households, private industry entities and the government as well as supranational institutions (Miller and Keipi, 2005). Each of them has different responsibilities and different options to finance losses and to decrease risk (Hochrainer, 2006). In the case of landslide risk, focus may be directed on the local government as well as households, considering landslide risk as a local hazard. Usually the (local) government/authority is responsible to finance damages to the public sector. Furthermore, additional assistance to households in case of a disaster event can be assumed (Hochrainer and Mechler, 2009). Public sector damages include asset damages to the public infrastructure, e.g. schools, roads, and bridges. Household damages can include damages to the house (partly of fully destroyed) or other inventory assets, as well as cars, the garden, or productive assets. All of these damages could be translated into monetary terms and if corresponding risk estimates are at hand, different risk measures and risk management options, including mitigation, to decrease the risk can be analysed. Ecological damages are difficult to estimate and are often measured by the change in quality of non-use values. Questionnaires or stakeholder workshops using contingent valuation methods are usually used to elicit values of consumers for these services; information from such sources can be instrumental in shaping the preferences of the concerned decision makers. Loss of life and the immediate threat to life is without doubt the most important category and deserves special attention as it is very controversial to attach numbers to it and to determine the risk bearer and responsibilities.

Indirect losses occur as a consequence of physical destruction on households, infrastructure or firms, e.g. business interruption, loss of wages, transport delays, and injuries. There is not only the question if the risk is altered in the future due to the occurrence today but also if the coping capacity to finance the losses caused due to the event are changed. As indicated in Figure 3.5, resources to cope with events can be severely affected due to previous events and may cause higher impacts even if the event is in absolute terms smaller than the one before.

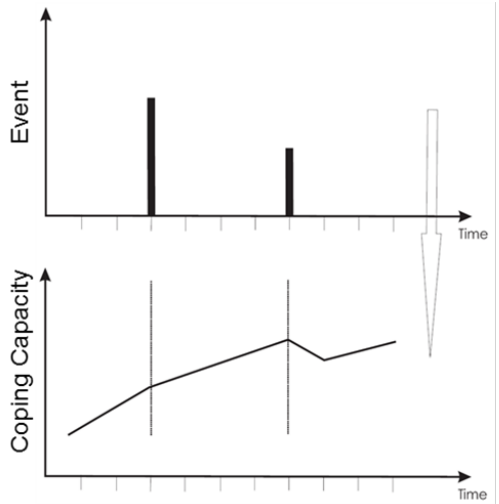

Figure 3.5 Schemata of potential dynamics of coping capacity due to multiple events.

On the household level, one can consider indebtedness levels as well as savings to be depleted in case of a severe event, making it difficult for investing in growth for the future and additionally putting them in a more risky situation to have negative long term consequences if another event occurs. Also local authorities can expect the same situation. Usually they have to divert money from the budget to finance the losses which causes important opportunity costs which have to be included in its assessment of best risk strategies. Basically, one can distinguish here between ex-post (after the event) and ex-ante (before the event happens) approaches. The latter is a pro-active strategy and therefore the risk has to be quantified. Table 3.1 show some examples of ex-post and ex-ante strategies possible for the government which can be extended/specified for local authorities or the household too.

Type	*Source*
Ex-post sources	
Decreasing expenditures	Diversion from budget
Raising government revenues	Taxation
Deficit financing *Domestic*	Central Bank credit
	Foreign reserves
	Domestic bonds and credit
Deficit financing *External*	Multilateral borrowing
	International borrowing
	Aid
Ex-ante sources	
Reserve funds	
Insurance	
Contingent Credit	
Mitigation	

Table: 3.1 Examples for loss financing for governments (Source: Mechler et al. 2009).

The possibility to finance the losses will have effects on the indirect consequences, which has to be incorporated within the cost benefit analysis to include all opportunity costs.

As an example, the consequences to be considered for the assessment of the risks on a roadway network are illustrated in Figure 3.6.

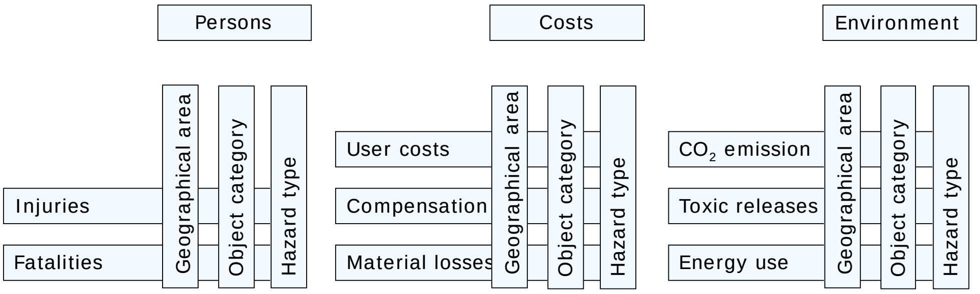

Figure 3.6 Example of different consequences to be considered in the risk assessment for a roadway network.

3.2.5 Elements at risk and their exposure to landslide(s)

A key step in quantitative landslide risk assessment is the identification of the "elements at risk" and the estimation of the outcome or "consequence" of the landslide event on these elements. In most landslide risk assessment studies reported in the literature (e.g. Agliardi *et al.* 2009, Bell and Glade 2004, Bründl et al. 2009, Cardinalli *et al.* 2002, Cassidy *et al.* 2008, Corominas *et al.* 2005, Dai *et al.* 2002, Evens *et al.* 2005, Guzzetti *et al*. 2003, Guzzetti *et al.* 2004, Hungr *et al.* 1999, Jaiswal *et al*. 2010, Lee *et al.* 2000, Lee and Jones 2004, Remondo *et al.* 2005, Wu *et al.* 1996) the elements at risk are persons, properties and infrastructure, although other consequential economic or environmental costs could also be considered.

In most landslide risk assessment studies, the focus is on the loss of human life. The expected number of fatalities depends on many factors, for example on which week-day and what time of the day the landslide occurs, whether a warning system is in place and working, etc. The potentially affected population could be divided into groups based on for example the temporal exposure to the landslide: people living in houses that are in the path of the potential landslide, locals in the area who happen to be passer-byes and tourists and/or workers who are coincidentally at the location during certain periods of the day of the year. The concept of spatial and temporal "exposure" is thus quite important in any landslide risk assessment. Lee and Jones (2004) define landslide exposure as "*the proportion of each category of element at risk expected to be effected by the landslide event*". This is similar to the United Nations International Strategy for Disaster Reduction (UNISDR) definition of exposure. Temporal exposure is important for certain classes of landslides and mobile elements at risk, such as persons and cars. The quantitative assessment of temporal exposure is more difficult and challenging than the assessment of spatial exposure.

3.3 ASSESSMENT OF RISK AND COST-BENEFIT ANALYSIS

3.3.1 Analysis and quantification of risk

The risk R_E associated with one particular event E can be assessed through the product between the probability p_E that the event takes place and the consequences c_E associated with the event, i.e.:

$$R_E = p_E \cdot c_E \tag{1}$$

Risks must be related to an appropriate time frame T, such as e.g. one year. Therefore it is often relevant to consider the risks associated with the number of a specific type of event $n(T)$ within the considered time frame T. In such a case, the above equation is appropriately written as:

$$R(T) = \sum_{i=0}^{\infty} P(n(T) = i) \cdot c_i \tag{2}$$

where $P(n(T) = i)$ is the probability of i events of the considered type within the time frame T and c_i is the consequence associated with the occurrence of the ith event.

The above equation may also conveniently be written as:

$$R(T) = E\left[n(T)\right]c \tag{3}$$

where $E\left[n(T)\right]$ is the expected number of events of the considered type within the time frame T and c is the consequence associated with the occurrence of one event. The expected number of events may be established by integration over the rate of occurrences ν as:

$$E\left[n(T)\right] = \int_T E\left[\nu(t)\right]dt \tag{4}$$

As risks are normally associated with scenarios of events, it is important to be able to quantify either the probability or the rate of occurrence of the scenarios, and this in general necessitates a probabilistic modelling involving conditional probabilities or rates respectively. A clear specification of the time reference period to which the probabilities and consequently also the risks have to be related is also necessary.

Following the assessment and evaluation of the hazards and consequences associated with the system considered for risk assessment, the ensuing risks then need to be quantified and evaluated. For this purpose, the system based on the generic representation shown in Figure 3.2 is assumed to be exposed to hazards with probabilistic characterization $p(EX_k),\ k=1,\ n_{EXP}$, where n_{EXP} denotes the number of hazards. It is assumed that the considered system includes n_{CON} individual constituents, each with a discrete set of component damage states C_{ij}, $i=1,2..n_{CON}$, $j=1,2..n_{C_i}$, where n_{C_i} is the total number of different damage states of constituent i. The probability of direct consequences $c_D(\mathbf{C}_l)$ associated with the l^{th} of n_{CSTA} possible different state of damage of all constituents $\mathbf{C}_l$, conditional on the hazard event EX_k is described by $p(\mathbf{C}_l \mid EX_k)$; the associated conditional risk is $p(\mathbf{C}_l \mid EX_k)c_D(\mathbf{C}_l)$. The risk R_D due to direct consequences, i.e. the expected value of the conditional risk due to direct consequences over all n_{EXP} possible hazard events and all constituent damage states n_{CSTA} is evaluated as:

$$R_D = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} p(\mathbf{C}_l \mid EX_k) c_D(\mathbf{C}_l) p(EX_k) \qquad (5)$$

The functionality of the considered system depends on the state of the constituents. It is assumed that there are n_{SSTA} possible different states of the constituents S_m associated with indirect consequences $c_{ID}(S_m, c_D(\mathbf{C}_l))$. The probability of indirect consequences conditional on a given state of the constituents $\mathbf{C}_l$, the direct consequences $c_D(\mathbf{C}_l)$ and the hazard EX_k, is described by $p(S_m \mid \mathbf{C}_l, EX_k)$. The corresponding conditional risk is $p(S_m \mid \mathbf{C}_l, EX_k)c_{ID}(S_m, c_D(\mathbf{C}_l))$. The risk R_{ID} due to indirect consequences is assessed through the expected value of the indirect consequences in regard to all possible hazards and constituent states, as:

$$R_{ID} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} c_{ID}(S_m, c_D(\mathbf{C}_l)) \times p(S_m \mid \mathbf{C}_l, EX_k)\, p(\mathbf{C}_l \mid EX_k)\, p(EX_k) \qquad (6)$$

The suggested risk assessment is applicable at any level of scale for the assessment of a given system. It may be applied to components, sub-systems and the system as a whole; the framework hence facilitates a hierarchical approach to risk assessment. The definition of the system in this context becomes of tremendous significance in the definition of relevant hazards and consequences. The risk assessment framework then allows for the utilization of any type of quantifiable indicators in regard to the defined hazards and consequences of the considered system.

It should be mentioned that risks may be represented in different ways, including distribution functions of consequences, showing with what probability different ranges of consequences will occur. Other representations include density functions for risk estimates showing the uncertainty due to epistemic uncertainties. The best representation depends on the scope and purpose of the risk assessment.

In situations where the risks are to be aggregated with risks assessed in previous or other assessments, it is important that the risks are represented in a consistent manner and possible dependencies between the independently assessed risks are carefully accounted for in the aggregation.

3.3.2 Indicators of risk and updating of knowledge

Risk indicators may be understood as any observable or measurable characteristic of the system or its constituents containing information about the risk. If the system representation has been performed appropriately, risk indicators will in general be available for what concerns the hazards as well as the direct consequences and the follow-up/indirect consequences to the system. For the risk assessment in the context of landslide and rockfall hazards, suitable risk indicators could be quantities related to the triggering event, the process of the landslide/rockfall that has been triggered, damages to buildings and infrastructure, fatalities and injuries, damages to the qualities of the environment, economic losses, and socio-economic consequences.

The presented risk assessment and decision framework facilitates a Bayesian approach to risk assessment through the use of risk indicators. In a Bayesian framework for risk assessment, such indicators play an important role as they readily enable the updating of probabilities and information required in the risk assessment whenever new knowledge or information about the system becomes available. As an example, the updating of the probability $P(C_{ij})$ that a constituent i of the system is in a particular state j given the indicator e is considered. Using the Bayes' rule of probability, the updated probability $P(C_{ij}|e)$ can be expressed as:

$$P(C_{ij}|e) = \frac{P(e|C_{ij})P(C_{ij})}{P(e|C_{ij})P(C_{ij}) + P(e|\overline{C_{ij}})(1 - P(C_{ij}))} \tag{7}$$

where $P(e|C_{ij})$ is the likelihood of the indicator.

3.3.3 Comparison and ranking of decision alternatives based on prior, posterior and pre-posterior decision analysis

The basis for preference ordering of different decision alternatives $\mathbf{a} = (a_1, a_2, .., a_{n_d})^T$ for a given decision problem concerning a system is the corresponding risk or more generally the corresponding expected utility $E\left[U(a_j)\right],\ j = 1, 2, ..n_d$:

$$E\left[U(a_j)\right]=\sum_{i=1}^{n_{O_j}} p(O_i \mid a_j) u(a_j, O_i) \qquad (8)$$

where $E[\cdot]$ is the expectation operator, n_{o_j} is the number of possible outcomes O_i associated with alternative a_j, $p(O_i \mid a_j)$ is the probability that each of these outcomes will take place (given a_j) and $u(a_j, O_i)$ is the utility associated with the set (a_j, O_i). This presentation assumes a discrete set of outcomes but can straightforwardly be generalized to continuous sample spaces.

Depending on the state of information at the time of the decision analysis, three different analysis types are distinguished, namely *prior analysis*, *posterior analysis* and *pre-posterior analysis*. The simplest form of the decision analysis is prior analysis. In a prior analysis, the risk (or expected utility) is evaluated on the basis of statistical information and probabilistic modelling available prior to any decision and/or activity. The representation of uncertainties is hence made on the basis of the existing information about the different variables in the analysis; however, as the realisations concerning the decision and/or activity have not occurred yet, the probabilistic modelling involves both aleatory and epistemic uncertainties. The distribution parameters used to quantify uncertainties in variables are initially modelled by prior distribution functions. The prior decision analysis is illustrated by a simple decision tree in Figure 3.7. The optimal decision is identified as the alternative with the maximum utility. Prior decision analysis thus forms the basis for the simple comparison of utilities associated with different activities and may therefore be applied for purposes of ranking and optimization.

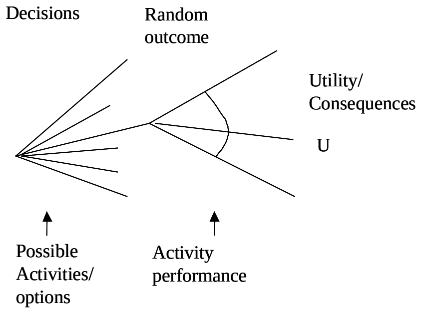

Figure 3.7 Decision/event tree for prior and posterior decision analysis.

Posterior decision analysis is in principle of the same form as the prior decision analysis, however, changes in the branching probabilities and/or the consequences in the decision tree reflect that the considered problem has been changed as an effect of e.g. risk reducing measures, risk mitigating measures and/or collection of additional information. The posterior decision analysis provides a means for the utilization of new information in the decision analysis – referred to as updating. By the application of the Bayes' theorem (see e.g. Lindley

1976) the prior distribution functions, assessed by any mixture of frequentistic and subjective information, are updated and transformed into posterior distribution functions.

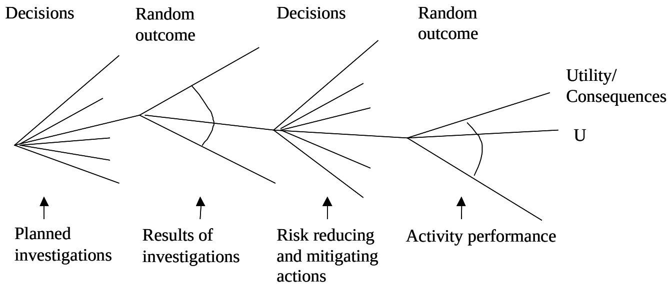

Figure 3.8 Decision tree for pre-posterior decision analysis.

The third type of decision analysis is the pre-posterior analysis and may be illustrated by the decision tree shown in Figure 3.8. Using pre-posterior decision analysis, optimal decisions in regard to information collection activities which may be performed in the future can be identified. Pre-posterior decision analysis is described in Raiffa and Schlaifer (1961) and Benjamin and Cornell (1970). The principle behind the pre-posterior decision analysis is that the outcomes of planned information collection activities are assumed to follow the prior probabilistic model of uncertainties. Based on these assumed outcomes and taking into account any uncertainties associated with the observation and/or interpretation of the outcomes, posterior decision analyses are performed. The corresponding risks are thereafter weighed with their probability of occurrence, again based on the prior probabilistic modelling. The pre-posterior decision problems may hence be seen as a series of posterior decision problems for which the optimal solutions are averaged out over the entire prior uncertainty, with the analysis made before new information is actually collected. The formulation of each of the posterior decision problems is based on an updated probabilistic model of the prevailing uncertainties assuming a given ‘outcome of nature’.

The theoretical basis framework for decision making outlined above may be readily applied for the identification of optimal decisions in regard to risk analysis and management. In addition to this it is also possible and worth considering to formulate the decision problems as explicit functions of information (through risk indicators) concerning the hazards and consequences which may become available at future times. Thereby the risk analysis and management process can be adapted to the available knowledge at any given point in time and optimized accordingly.

3.3.4 Risk reduction and mitigation

The various possibilities for collecting additional information in regard to the uncertainties associated with the understanding of the system performance as well as for changes in the characteristics of the system can be considered to comprise the total set of options for risk treatment. The risk treatment options may, in the context of risk based decision making, be considered as the available decision alternatives. Risk treatment is decided upon for the purpose of optimizing the expected utility achieved by the decision making. Following the previously suggested framework for risk assessment, risk treatment can be implemented at different levels in the system representation, namely in regard to the hazard, the direct consequences and the indirect/follow-up consequences.

The options for risk treatment can be assessed and evaluated in terms of their risk reducing effect, i.e. their efficiency R_{RE}. This may be simply assessed through the reduction of total risks achieved through the measure ΔR divided by the cost of the measure C_R, i.e.:

$$R_{RE} = \frac{\Delta R}{C_R} \qquad (9)$$

By assessing the efficiency of different measures of risk reduction, a prioritization of measures may be established for what concerns reduction of hazards, reduction of direct consequences as well as reduction of indirect/follow-up consequences associated with the system.

3.3.5 Risk acceptance and assessment of costs and benefits using life safety investment criteria

In addition to risks due to economic losses, the decision maker has to take into account also the risks to persons, as well as potential damages to qualities of the environment. Whenever decision alternatives, on the basis of risk assessments, have been identified and ranked by comparing the expected value of utility, the risks must be considered in regard to their acceptability. It is useful to differentiate between tangible and intangible risks, i.e. risks which may easily be expressed in monetary terms and risks which are not. Intangible values concern fatalities / loss of lives, injuries and damage to the qualities of the environment.

One possibility to provide a unified framework to assess the costs and benefits of risk mitigation measures is to transform all direct and indirect risks into monetary terms. Afterwards a probabilistic cost benefit analysis is applied. The basic measure here is the *exceedance probability*. An exceedance probability curve indicates the probability that at least an amount specified in monetary terms is lost in a given year. A typical exceedance probability curve can be constructed as depicted in Figure 3.9. Here the horizontal axis shows the magnitude of the loss in monetary terms (US dollars) and the vertical axis depicts the annual probability that the losses will exceed this level; details on constructing exceedance probability curves in the context of catastrophe models may be found in Grossi and Kunreuther (2005) and Hochrainer (2006). The area under the exceedance probability curve is the referred as the average annual loss. Risk reduction measures typically decrease the vulnerability of the system/structure and therefore reduce the expected loss. Graphically, the risk reduction measure shifts the exceedance probability curve to the left and therefore reduces the average annual loss.

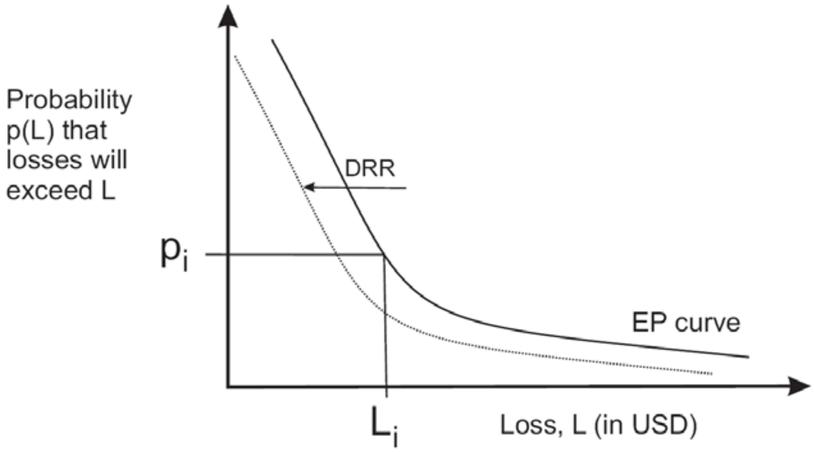

Figure 3.9 Example of an exceedance probability curve and risk reduction effect.

For the system/asset/structure under consideration, the relevant measures for reducing losses from the hazards in question need to be selected. Then exceedance probability curves need to be constructed for the system with and without the risk reduction measure in place; this should also include indirect effects. Benefits can be quantified through reductions in the average annual loss after measures have been applied to the system and discounted over the relevant time horizon. The cost estimates of each risk reduction measure have to be derived from various sources. Combining these estimates, a *benefit-cost ratio* (B/C ratio) can then be computed. The most attractive risk reduction measure from an economic standpoint is the one with the highest B/C ratio assuming there are no budget constraints with respect to the cost of the investment. Using the B/C ratio as the metric captures the concept of the complex interactions of three main components that affect the final decision: vulnerability of the system, the hazard level of the area, and the cost of the measure considered.

In addition to the probabilistic benefits and costs of decreasing risk, e.g. to withstand hazards, the impact of possible changes in the discount rate and time horizon over which the expected benefits on the analysis needs to be considered. It is also important to take note of the assumptions underlying such an analysis. Firstly, the consideration of climate change would likely increase the benefits of the selected risk mitigation measures. Secondly, the cost-benefit analyses performed via the expected value means that the household assumes zero risk aversion; if the householder were more risk averse then this would increase the economic benefit of risk reduction investment. Such risk aversion has to be assessed usually by case to case studies.

The identification of acceptable decisions based on the assessment of the associated risk and benefits and the life safety criteria is now considered through an example. In Figure 3.10, decisions are considered in terms of a continuous parameter *p*. The utility function here could be considered as a combination of the benefits, losses and costs associated with the decision alternative. From this perspective, it is clear that only a certain range of the decision parameter *p* will yield a positive utility; this range corresponds to feasible decisions. An example could relate to the choice of the thickness of the plate of a rockfall protection gallery. There is a certain choice of the thickness of the plate associated with the maximum utility and where increments of benefits, losses and costs are in balance; this refers to the optimal decision alternative shown in Figure 3.10 as *p**.

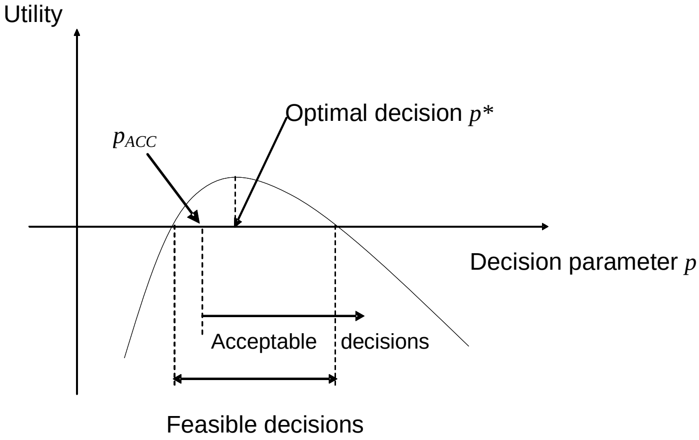

Figure 3.10 Identification of acceptable and optimal decisions.

Having identified the optimal decision *p**, it is necessary to check whether this decision is admissible from a societal perspective. In Figure 3.10, the value of the decision parameters which exactly corresponds to the societal preferences in regard to investments into life-saving activities need to be assessed; this value of *p* is called p_{ACC}. It is important to notice that acceptability thus not only depends on the level of risk itself but also the efficiency of risk reduction. Focus is thereby directed not only on the highest sources of risks but moreover on the risk reduction activities with the highest efficiency.

Rational risk acceptance criteria in the context of societal decision making may then be derived on the basis of socio-economic considerations. In this context, the issue of concern relates only to involuntary risks. It is assumed that risk reduction is associated with reallocation of societal economic resources. In the context of societal infrastructure with a life time typically in the order of decades or centuries, it is expedient that such economic resources are allocated with the highest possible efficiency and with due consideration of intergenerational acceptability. At the level of societal decision making, an efficient life-saving activity may be understood as a measure which in the most cost effective manner reduces the mortality or equivalently increases the statistical life expectancy.

The incremental increase in life expectancy through risk reduction, the corresponding loss of economic resources, measured through the Gross National Product (GNP) together with the time used for work, all assessed for a statistical life in a given society, can be considered to form the most important building stones for the assessment of the efficiency of risk reduction measures. Based on these demographical indicators, the Life Quality Index (LQI) facilitates the development of risk acceptance criteria (Nathwani et al. 1997; Nathwani et al. 2009). The underlying idea of the LQI is to model the preferences of a society quantitatively as a scalar valued social indicator, comprised by a relationship between the GDP per capita g, the life expectancy at birth e and the proportion of life spend for earning a living w. Based on the theory of socio-economics, the Life Quality Index can be expressed in the following principal form:

$$L = g^q e \tag{10}$$

Here the parameter q is a measure of the trade-off between the resources available for consumption and the value of the time of healthy life. It depends on the fraction of life allocated for economic activity and furthermore accounts for the fact that a part of the *GDP* is realised through work and the other part through returns of investments. The parameter q is assessed as:

$$q = \frac{1}{\beta}\frac{w}{1-w} \tag{11}$$

In the above equation, β is a constant taking into account that only part of the GDP is based on human labour, the other part is due to investments and other activities. Every risk mitigation measure influences the value of the LQI. The consideration that any investment into life risk mitigation should lead to an increase of the LQI leads to the following risk acceptance criteria that could be used to assess the net life safety benefit from decision alternatives concerning risk mitigation options for the system:

$$dL = \frac{\partial L}{\partial g} dg + \frac{\partial L}{\partial e} de \geq 0 \tag{12}$$

or

$$\frac{dg}{g} + \frac{1}{q}\frac{de}{e} \geq 0 \text{ or } -dg \geq \frac{g}{q}\frac{de}{e} \tag{13}$$

A given measure with the purpose of reducing risks of life implies an allocation of dg and a corresponding increase of life expectancy $d\ell$. Based on the above equations, the relationships between dg and dl which lead to increases in the LQI may be determined which in turn can be utilized for assessing the corresponding probability of different types of failures of relevance for a considered system; this probability may then be utilized, for instance, as a target value for structural design or assessment purposes.

3.3.6 Perception and communication of risk

Different individuals in society perceive risks differently, depending on their own situation in terms of to what degree they may be affected by the hazards, to what degree they are able to influence the risks and to what degree the risks are voluntary. Generally risks are perceived more negatively when stake holders feel more exposed, when they feel they have no influence and they feel they are exposed to risks involuntary.

Another aspect is related to how adverse events are perceived by individuals and groups of individuals in society when and after such events take place. Again, this depends on the perspective of the affected individuals and groups of individuals. Furthermore, the occurrence of adverse events and the way the information about such events is made available will affect the perception of risks in general but also in many cases trigger actions which have no rational basis and only adds to the societal consequences of such event.

Due to the effects of the perception of risk, it is generally observed that different individuals and groups of individuals have different attitudes in regard to what risks can be accepted. Risk averse and risk prone attitudes are observed, which simply refers to the effect that risks are assigned different tastes depending on these characteristics. Whereas such behaviour is a private matter for individuals of society, it leads to an uneven distribution of risks, if exercised in the context of societal decision making and this is clearly unethical and not rational.

The perception of risks may be significantly influenced by information about the risks themselves. Information can and should be used as a targeted means of reducing potential losses caused by reactions to events beyond what is rational, seen in the perspective of normative decision making. Being provided with transparent information in regard to the nature of hazards, possible precautionary actions, information on how risks are being managed and the societal consequences of irrational behaviour reduces uncertainties associated with the understanding of risks of individuals. This, in turn, adds to rational behaviour and thereby reduces follow-up consequences.

3.4 LARGE SCALE INDICATOR BASED RISK MODELING

Large scale risk assessment and management of a system requires a systematic and consistent representation and management of information for a typically complex system with a large number of constituents and/or sub-systems. Such representation must enable a rational treatment and quantification of the various uncertainties associated with the constituents as well as the system. The consistent handling of new knowledge about the system and its constituents as and when it becomes available and its use in the risk assessment and decision making process is also essential. Further, the numerous dependencies and linkages that exist between different constituents of the system need to be systematically considered. The above requirements and considerations necessitate the use of generic risk models for the assessment and management of risks and their implementation through tools such as Bayesian Probabilistic Networks (BPNs) and Influences Diagrams (IDs).

3.4.1 Generic risk models

The idea behind the application of generic risk models is to identify categories of assets (such as categories of buildings) for which the risk assessment model has principally the same structure. Models are then formulated for each category but with incorporation of the indicators characterizing hazards and consequences; the establishment of such models could be done using Bayesian Probabilistic Networks (BPN) for instance. In this way the individual generic risk models can be made specific for a given asset (e.g. building) by relating the risk model to the asset through the information of the indicators stored in a data base. Besides providing a very efficient means for risk assessment, the use of this approach for large scale risk assessment also facilitates a consistent modelling of the relevant dependencies between the parameters which influence the risk. It is very important to include such dependencies in the risk modelling process owing to their possibly significant influence on the results of the risk assessment.

Indicator-based risk models may be divided into two main groups:

- Deductive: measurement of risk is hazard specific and based on disaster impact data
- Inductive: measurement of risk is based on underlying factors which influence a community's ability to deal with, and recover from an impact. Such methods are less hazard specific or hazard independent

The indicators may be expressed at a specific geographical scale (local, regional or global scale) or at a specific organizational level (e.g. individual, household and community level). Indicator models may serve as an alternative to Geographical Information System (GIS) based approaches (give a risk estimate based on indicators) or as a model applied within a GIS tool. Typically, deductive models are put into GIS models to assess the direct losses, while inductive models are used as stand-alone models to assess indirect losses.

3.4.1.1 Bayesian Probabilistic Networks (BPN)

Bayesian Probabilistic Networks (BPN) are constructed on the principles of causality and interrelationships between considered events and variables of interest. Graphical representations of such causally interrelated events are called causal networks. Briefly, the steps involved in the construction of a BPN are:

- Formulation of causal interrelations of events leading to the events of interest (consequences), in terms of nodes (variables) connected by edges (arrows).
- Assigning to each variable a number of discrete mutually exclusive states.
- Assigning probability structures (tables) for the states of each of the variables
- Assigning consequences corresponding to the states represented by the network.

BPNs are designed to facilitate the modelling of common cause or dependency phenomena that are characteristic of a typically complex system with a large number of constituents and/or sub-systems. They also provide an enormously strong tool for decision analysis, including prior analysis, posterior analysis and pre-posterior analysis together with the use of generic risk models. The hierarchical approach to risk assessment as facilitated by the framework described in the previous sections is also supported by the use of BPNs.

Details regarding the development and use of BPNs can be found in Jensen (2001). The use of Bayesian Probabilistic Networks (BPNs) has proven to be efficient in several risk assessment applications for natural hazards (Faber et al., 2007; Bayraktarli et al., 2005 and Schubert et al., 2005).

3.4.2 Geographical Information systems (GIS) in risk assessment

Generally, the hazards relating to natural hazards as well as the possible ensuing consequences can be considered to depend strongly on the specific geographical location of the occurrence of the event. For this reason, the use of Geographical Information Systems (GIS) needs to be considered in the context of a risk assessment and analysis process. The indicators of relevance for the characterization of hazards and consequences associated with the system may be related to the models of the real world which form the basis for the risk assessment, considering the hazards, vulnerability and the robustness of the considered system. The risk assessed from these models and related to the real world through the indicators can then be managed by means of various risk reduction actions. The use of a GIS platform serves as a database for storing and managing the information required for the risk management process and strategy optimization. The data stored in the different layers of a GIS data base may then be directly utilized in the modelling of the risks for the system.

4 CASE STUDY AT SITE 1 - BARCELONNETTE

4.1 SYSTEM IDENTIFICATION AND SITE DESCRIPTION

4.1.1 Geographical boundaries for the study area

The Faucon torrent (Barcelonnette Basin, South East France): a torrent prone to debris flow risks

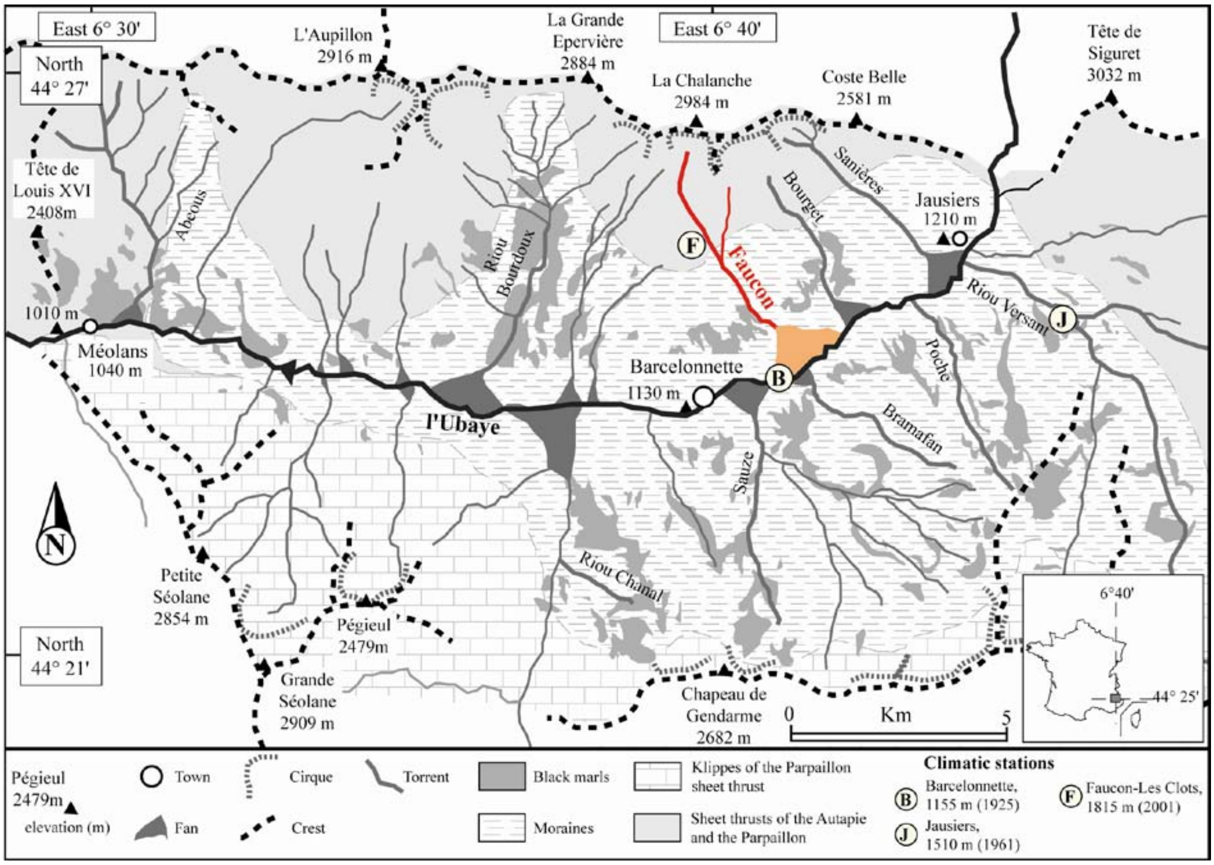

Figure 4.1 Location of the Faucon catchment in the Barcelonnette basin (South French Alps).

The Faucon torrent evolves (44°25'N, 6°40'E) in a steep forested watershed with an area of 10.5 km² which rises to 2984 m above sea level. Local slopes are steeper than 25°, reaching 80° at the highest elevations. The higher parts of the massif consist of two sheet thrusts of faulted sandstones and calcareous sandstones. Slopes below this consist of Callovo-Oxfordian black marls, covered by various quaternary deposits which exhibit a sandy-silt matrix, may include boulders up to 1-2 m in size and are between 3 and 15 m thick.

The incised channel has an average slope of about 20°, ranging from 80° in the headwater basin to 3° on the alluvial fan, and is approximately 5500 m in length. Channel morphology is characterized by two main types of cross-section, a V-shaped profile with a steep channel, a flat-floored cross profile between steep slopes.

The Faucon torrent has formed a 2 km² debris-fan, which spreads across the Ubaye valley floor. It has a slope gradient ranging from 2 to 9°. The fan consists mostly of cohesion-less and high-permeable debris (debris-flows strata and/or torrential deposits). The Faucon stream has a classical torrential flow regime associating: (1) peak discharges in spring (snow melting) and in autumn (high precipitations) and, (2) a high variability in summer according to the occurrence of storms.

Since 1850, fourteen debris flows have occurred in the Faucon torrent. Two major events occurred in 1996 and in 2003. About a hundred check dams were built on the torrent since the 1890's to prevent flooding but only a half of them are still efficient, two main types of check dams can be observed: (1) concrete check dams, (2) dry stone check dams.

Figure 4.2 The two main types of check dams in the Faucon torrent: (A) photograph of a masonry check dam (Champerousse torrent); (A) photograph of a concrete check dam (Faucon torrent).

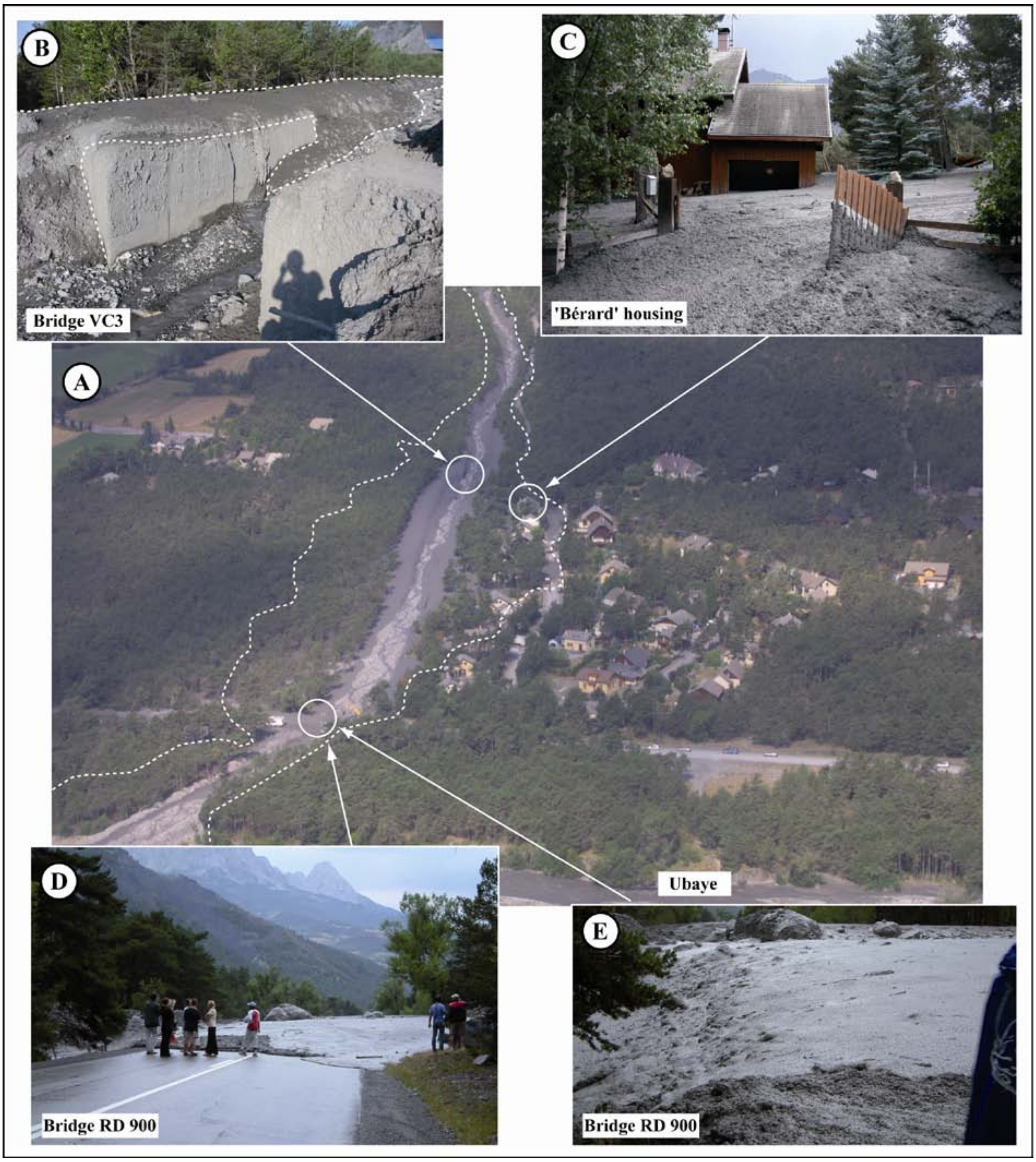

Figure 4.3 Spreading of the 2003 debris flow on the Faucon torrential fan. (A) Aerial view of the Faucon fan (courtesy from Michel Peyron). (B) The VC3 Bridge completely destroyed. (C) A house overflowed. (D) The end of the debris-flow event at the RD 900 Bridge. (E) View of the ‘fresh’ debris-flow deposit at the RD 900 Bridge.

4.1.2 Temporal limitations for the assessment of risks

The risk analysis has to be performed on the basis of the analysis of past events. For the entire Barcelonnette basin, a database of mass movements has been built by the Service de *Restauration des Terrains en Montagne* (RTM), a branch of the French Forest Office which is in charge of risk management in the mountain departments of France; this database has been completed by academic research works.

Concerning the Faucon torrent, 45 debris flows/floods have been recorded since 1732. Figure 4.4 shows the temporal repartition of these events over the last 300 years. The figure shows an strong increase of debris flows since 1960. Nevertheless it is always very dangerous to make an interpretation of such data due to the problems of validation of archives and/or lack of data.

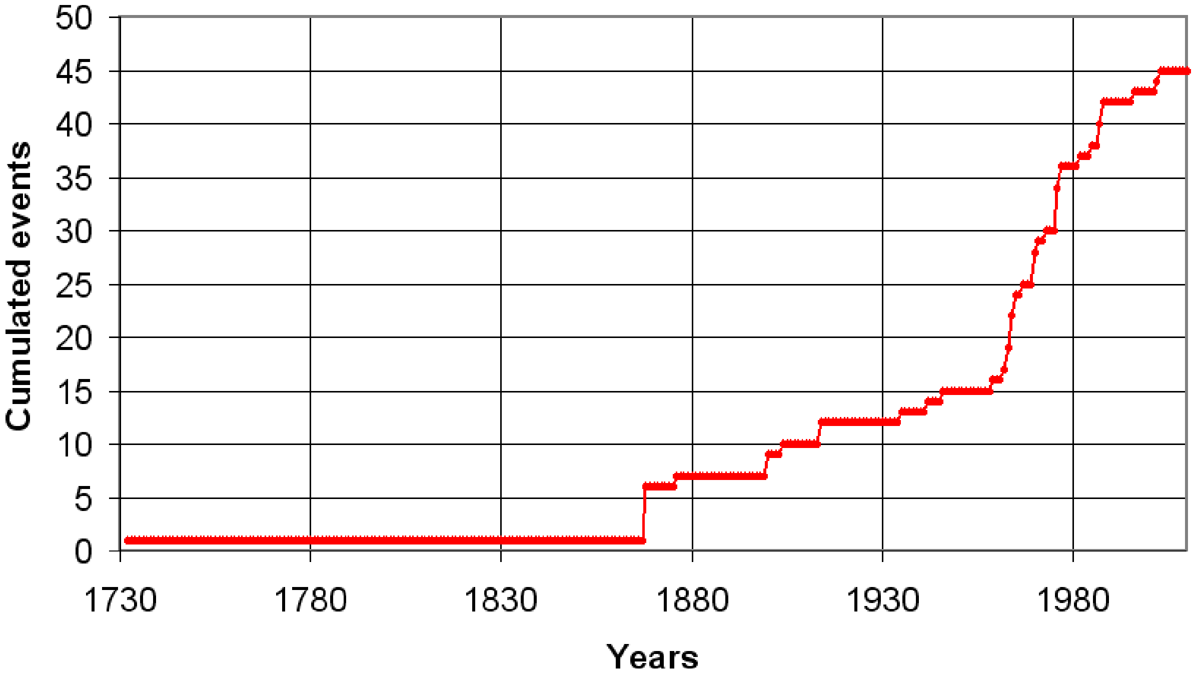

Figure 4.4 Cumulated frequencies of debris-flows events in the Faucon torrent over the period 1730-2010.

The data associated with these events do not exhibit the same level of accuracy and quality; only a few of them (1996, 2002 and 2003) are well documented in terms of their discharge, volume, rheology, flooding areas, damages. A PPR[1] has been built for the Faucon torrent in 2002 (Figure 4.5). The PPR is produced based on expert analysis and knowledge; the risk map is usually prepared with the help of both field works (recognition of phenomenon and

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[1] PPR: “Plan de Prévention des Risques” is an official french document where a town is cut in several areas according to the level of risk : Red Zone: no possibilities to built, Blue Zone: possibility to built under several conditions (mitigation), White zone: possibility to built without any limitations.

mapping) and compilation and analysis of archives. Sometimes some additional works are used in order to increase the accuracy of the map (hydraulic empirical equations for instance).

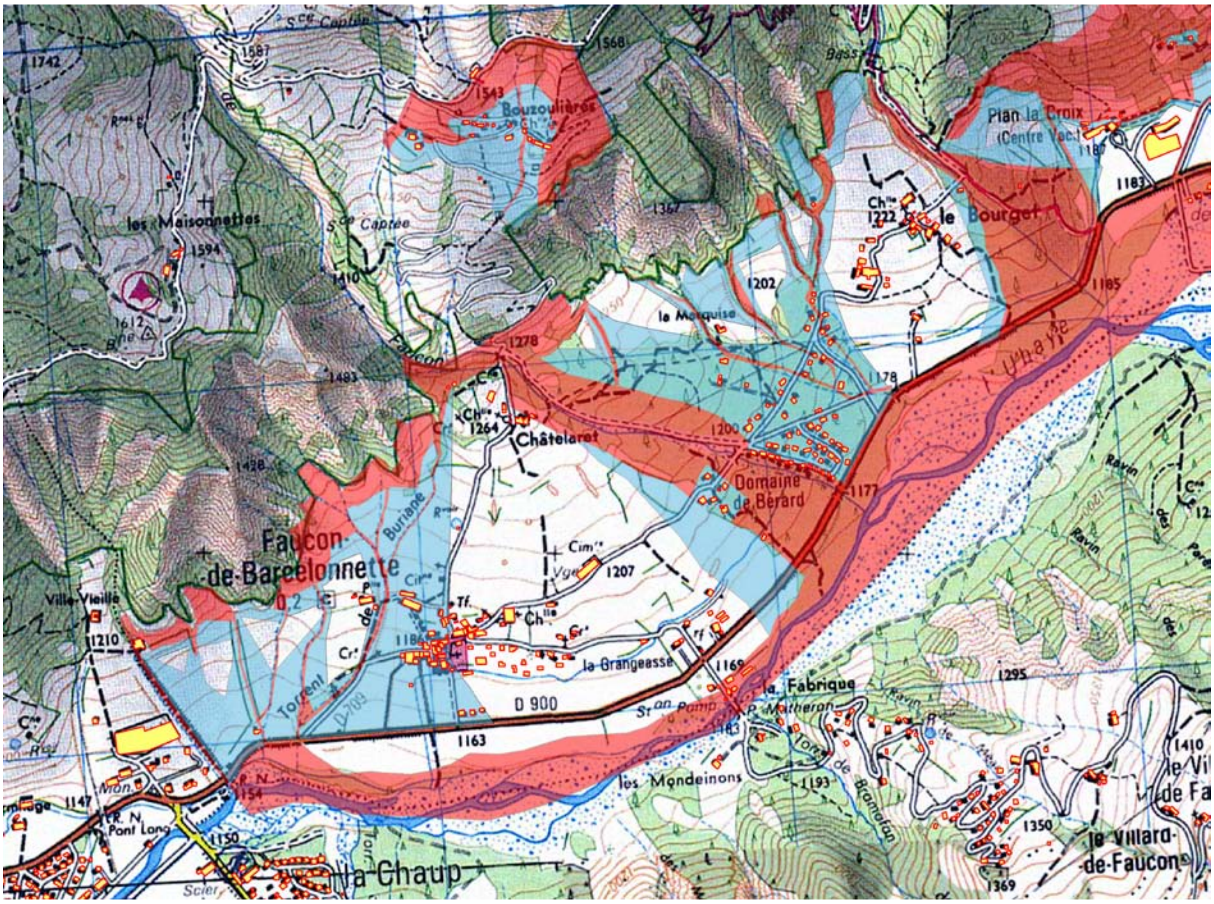


Figure 4.5 Sample of the PPR of the Faucon de Barcelonnette town.

4.2 DECISION MAKERS AND STAKEHOLDERS

4.2.1 Identification of decision makers and stakeholders

The decision makers and stakeholders are:

- the Service de *Restauration des Terrains en Montagne* (RTM), a branch of the French Forest Office which is in charge of risk management in the mountain departments of France (Haute-Savoie, Savoie, Isère, Hautes-Alpes, Alpes de Haute Provence, Alpes-Maritimes, Pyrénées-Orientales, Ariège, Haute-Garonne, Hautes-Pyrénées, Pyrénées Atlantiques);
- the municipalities of Faucon-de-Barcelonnette and Barcelonnette, represented by their mayor;

- the mountain community ‘Communauté des Communes de la Vallée de l’Ubaye, CCVU’ which is a cluster of several municipalities along the Ubaye river;
- the Prefecture of Alpes-de-Haute-Provence, which is the representative of the National State in the Department;
- The Conseil Général “Alpes-de-Haute-Provence”, which is in charge of the regional politics on natural and technological risks in the Department.

4.2.2 Rationale for options ranking and decision optimization

The RTM engineers and technicians are in charge of the PPR. They usually rank the different risk zones according to their expertise and knowledge. There are no official ranking methods; usually some methods are proposed in official guidelines. These methods differ according to the type of hazard, the type of data, etc.

Nevertheless, some of the steps are common to all the hazards:
- the scale of the final document is 1/25,000;
- the data are mapped and analysed with an ONF-RTM GIS Platform (ArcView);
- they will produce one map per hazard or process (e.g. snow avalanches, landslides, debris flows, rockfall, etc.) and then combine them all in order to produce a multi-hazard (risk) map.

In order to build the risk map they combine (1) a forest map, (2) a hazard map and (3) a stake map. For the hazard classification, they will combine a simple approach with single criteria and a relative index based on the process intensity (e.g. the discharge or the volume for a debris flow) rather than the spatial and temporal frequencies.

For ***debris flows and torrential floods***, the RTM office cuts the torrent in several areas according to several criteria:
- the bed slope;
- the material availability (scouring and entrainment);
- the geometry of the bed and the possibility to have temporal sedimentary storage area;
- the minimal length of an area is 250 m.

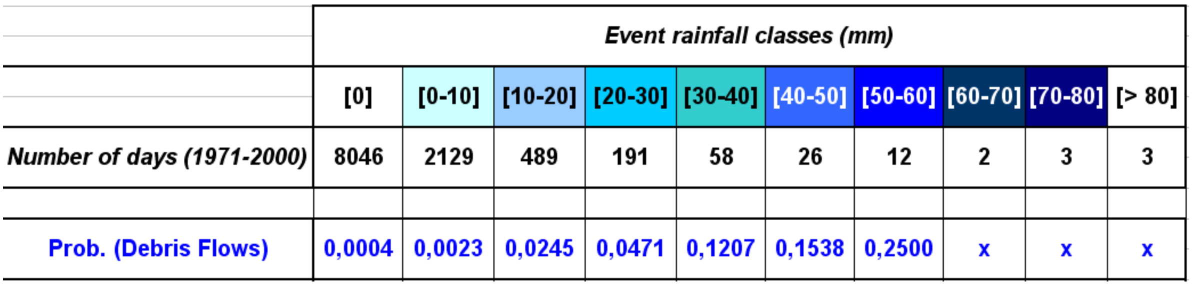
For ***landslides***, the RTM office classifies the landslide according to their depth (> or < to 2 meters).

4.3 DOCUMENTATION OF HAZARDS

The debris flow hazard in the Faucon catchment can be summarized as a list of key elements:

- Since 1850, 14 debris-flows and 31 torrential floods have been recorded. Then the return periods for debris flows and torrential floods are respectively 1 event each 11 years (debris flows) and 1 event each 5 years (floods);

- Two main triggering mechanisms have been observed in the Faucon watershed: fluidization of a landslide (more or less 10,000 m^3 volume) like in 1996, or erosion of screes (more or less, 5000 m^3 volume) like in 2003. In both case, the scouring during the runout was very intense (95,000 m^3 in 1996, and 85,000 m^3 in 2003).
- According to a climatic/historical analysis, a probabilistic assessment of debris-flows triggered by rainfall has been done. The results are summarized in the table below. The probabilities are respectively 0.12, 0.15 and 0.25 for 30, 40 and 50 mm daily rainfall;



	Event rainfall classes (mm)									
	[0]	**[0-10]**	**[10-20]**	**[20-30]**	**[30-40]**	**[40-50]**	**[50-60]**	**[60-70]**	**[70-80]**	**[> 80]**
Number of days (1971-2000)	**8046**	**2129**	**489**	**191**	**58**	**26**	**12**	**2**	**3**	**3**
Prob. (Debris Flows)	**0,0004**	**0,0023**	**0,0245**	**0,0471**	**0,1207**	**0,1538**	**0,2500**	**x**	**x**	**x**

- According to historical data, field works and numerical modelling results, the hydraulic characteristics of debris-flows in the Faucon watershed can be evaluated as follows:
  Mean volume[2] ranges from 75.10^3 to 95.10^3 m^3;
  Maximum volume ranges from 40.10^3 to 300.10^3 m^3;
  Maximum peak discharge ranges from 750 $m^3.s^{-1}$ to 1250 $m^3.s^{-1}$;
  Maximal velocity ranges from 5 to 10 $m.s^{-1}$;

As a synthesis, a scenario can be established with such characteristics:

- ***Triggering mechanisms:*** Landslide fluidisation (volume 10,000 m^3). The landslide (Champerousse landslide) located in the upper part of the Faucon watershed can be used for this scenario;
- ***Runout:*** Debris flow runout (scouring volume 90,000 m^3 for a runout track of approximately 3000 m. The rheological characteristics will be representative of such kind of cohesive debris flow (Bingham or Herschel-Bulkley, see Remaître *et al.* 2005b).
- ***Spreading:*** Total volume of the debris-flow spreading on the fan: 100,000 m^3.

Additional information on the Faucon torrent and associated debris flow events can be found at http://eost.u-strasbg.fr/omiv and in the following references (Remaître, 2006, Remaître et al., 2005a, 2005b, Remaître et al., 2008, Remaître & Malet, 2010).

4.4 DOCUMENTATION OF VULNERABILITY

Three major events have occurred in the two last decades; two debris flows in 1996 and 2003 and one torrential flood in 2002 (Remaître, 2006; Remaître et al., 2005a, 2008, 2009).

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[2] The volume corresponds here to the total volume of the event (material + water).

The 1996 event: On Monday August 19, 1996, between 4:00 and 6:30 p.m. in the middle Ubaye valley, a debris flow was triggered by an intense and local thunderstorm. Indeed no rainfall was recorded by the pluviograph located at the Faucon alluvial fan. Several inhabitants provided eye-witness descriptions of debris flow. They describe flowing masses of the mud-boulder debris, first moving with pulsating waves "slower than a running man", and then rushing downward at high speed. According to eye-witnesses and the French Forest Office, the total duration of the event was about 2 ½ hours. The total volume was estimated between 75,000 and 100,000 m^3 (Remaître, 2006).

The debris flow caused moderate damage and the main road across the alluvial fan was cut for several hours. The cost of the event has been estimated to 75,000€ (cleaning of the channel, building of a new wood bridge at the upper part of the fan, cleaning of 3 gardens located near the torrent).

The 2003 event: On Monday August 5, 2003, between 6:00 and 8:00 p.m., a debris flow occurred. This event has been triggered on two specific spots on the east flank of the Faucon catchment: the Trois Hommes area, and the upper part of the Champerousse torrent. For both cases, the morphology of the source area corresponds to a strong incision in scree slopes. The volume of the Trois Hommes debris-flow ranged approximately from 4000 to 5000 m^3, while the volume of the material in the source area of Champerousse ranged from 6000 to 7500 m^3. Unlike the Trois Hommes event, all the material did not reach the Faucon torrent; in fact 3000 m^3 of material has been trapped by the check-dams network. The observations at the Trois Hommes slope and the Champerousse torrent indicate that the source volume ranges from 7500 to 9500 m^3, a value of 8500 m^3 can be considered.

Field measurements and evidences of the residents indicate that the event evolved into 5 surges, for a time interval ranging between 2 and 5 minutes. These debris-flow surges filled the channel progressively; the last surge overflowed and caused the occlusion of the VC3 Bridge. Eyewitnesses indicate that the debris-flow height of the last surge reached 5 to 6 m. Most of the debris spread over the left bank, causing some substantial damages on five houses. Some residents were in their houses as the overflowing occurred but remained uninjured. The thickness of the debris deposits ranged from 1.0 to 2.0 m. Moreover, the debris flow also breached the main road of the valley; the traffic was stopped during several hours and remained difficult for three weeks while authorities cleaned the channel and the fan. The total volume of debris-flow deposits was estimated to be 45,000 m^3 on the debris fan and 15,000 m^3 in the upper channel.

The cost of the event has been estimated to 1.5 to 2 million € (cleaning of the channel, building of a new concrete bridge at the upper part and the lower part of the fan, cleaning of 7 gardens located near the torrent and 3 houses, building of new dikes at the fan and 9 check dams near the triggering area).

A database is available for the elements at risk in the Faucon torrent. This database comprises different kind of information:

- Location;
- Year of building;
- Type of building and associated functions (housing, companies, administrative);
- Geometry of the building (area, height, perimeter, etc.);
- Characteristics of the buildings (building material (concrete, wood, dry stones…), number of floors, number and exposition of windows);
- Number of inhabitants per buildings (and also domestic animals) for several periods (during the period with a lot of tourists (winter and summer) and during the low season).

4.5 LISTING OF SELECTED RISK MITIGATION MEASURES

4.5.1 The Faucon torrent (Barcelonnette B)

The Faucon torrent is equipped with 82 check dams; see Table 4.1 for their detailed characteristics. Two types of check dams have been constructed: concrete check dams and masonry. The approximate value of the check dams is respectively 100,000 € for the concrete check dams, and 60’000 € for the masonry check dams.

N°	Type	Distance to Dam 1 (m)	Toe elevation (m)	Top elevation (m)	Height (m)	Width min. (m)	Width max. (max)	Status
1	Concrete	0	1271	1272	1.80	8.00	12.00	Good
2	Concrete	312	1311	1318	7.00	2.80	20.00	Good
3	Masonry	345	1319	1320	0.50	3.00	18.00	Good
4	Concrete	357	1321	1330	8.70	8.20	29.80	Good
5	Concrete	426	1334	1344	9.00	5.00	19.50	Good
6	Concrete	486	1348	1349	1.00	8.00	8.00	Good
7	Concrete	500	1350	1356	5.80	8.80	25.00	Good
8	Concrete	560	1361	1371	9.40	6.00	16.40	Good
9	Concrete	583	1374	1377	3.00	5.00	18.00	Good
10	Concrete	596	1376	1377	0.50	5.00	11.00	Buried
11	Concrete	616	1378	1381	2.70	3.10	11.90	Damaged
12	Concrete	706	1392	1400	7.70	7.20	23.00	Damaged
13	Concrete	760	1405	1414	8.80	6.00	24.00	Damaged
14	Concrete	787	1415	1423	8.00	5.20	19.00	Damaged
15	Masonry	809	1426	1427	1.00	5.00	5.00	Destroyed
16	Masonry	815	1427	1427	0.00	5.00	5.00	Destroyed
17	Masonry	854	1435	1435	0.00	4.00	4.00	Destroyed
18	Masonry	947	1460	1463	3.00	5.50	5.50	Destroyed
19	Masonry	978	1469	1469	0.00	4.20	4.20	Destroyed
20	Masonry	1000	1477	1477	0.00	4.00	4.00	Destroyed
21	Masonry	1006	1483	1483	0.00	4.00	4.00	Destroyed
22	Masonry	1024	1490	1498	7.80	11.50	29.00	Damaged
23	Masonry	1038	1498	1503	4.30	6.00	20.50	Damaged
24	Masonry	1064	1507	1510	2.50	3.50	9.00	Damaged
25	Concrete	1157	1525	1530	4.60	4.50	12.50	Damaged
26	Concrete	1164	1531	1535	4.00	6.00	16.00	Good
27	Concrete	1169	1536	1538	1.80	7.50	19.00	Good
28	Masonry	1186	1539	1541	1.60	1.50	3.50	Destroyed
29	Masonry	1219	1543	1549	6.00	6.70	10.40	Good
30	Concrete	1248	1548	1557	9.50	6.00	16.40	Good

31	Masonry	1311	1566	1569	3.00	3.50	13.00	Good
32	Concrete	1334	1568	1574	5.20	4.50	16.50	Good
33	Concrete	1372	1578	1584	5.50	5.50	16.00	Good
34	Concrete	1397	1585	1588	2.70	5.00	18.00	Good
35	Concrete	1562	1623	1628	5.00	10.00	20.00	Good
36	Concrete	1567	1628	1630	2.00	10.00	20.00	Good
37	Concrete	1585	1632	1634	2.10	12.00	22.00	Good
38	Masonry	1625	1635	1635	0.00	4.00	15.00	Destroyed
39	Masonry	1775	1667	1667	0.00	4.00	4.00	Destroyed
40	Masonry	1785	1668	1668	0.00	5.00	5.00	Destroyed
41	Masonry	1809	1672	1675	2.60	6.00	14.60	Damaged
42	Concrete	2000	1704	1712	8.50	7.00	27.00	Good
43	Masonry	2021	1711	1712	1.40	9.00	22.00	Buried
44	Masonry	2042	1715	1715	0.00	11.00	25.00	Destroyed
45	Masonry	2366	1777	1777	0.00	25.00	25.00	Destroyed
46	Masonry	2373	1780	1780	0.00	25.00	25.00	Destroyed
47	Masonry	2410	1788	1788	0.00	10.00	10.00	Destroyed
48	Concrete	2514	1813	1816	2.80	5.00	16.50	Good
49	Concrete	2524	1817	1819	2.70	5.30	21.00	Good
50	Concrete	2545	1821	1825	3.50	5.00	18.60	Good
51	Concrete	2562	1825	1828	3.00	5.00	16.50	Good
52	Concrete	2579	1828	1830	2.40	5.00	25.00	Good
53	Concrete	2597	1833	1837	3.20	5.00	18.00	Good
54	Concrete	2621	1840	1842	3.10	5.00	19.00	Good
55	Concrete	2637	1845	1847	1.40	5.00	14.70	Good
56	Concrete	2658	1848	1852	3.40	5.00	15.50	Good
57	Concrete	2683	1851	1857	5.50	6.00	31.00	Good
58	Concrete	2806	1882	1886	3.90	5.00	12.00	Good
59	Concrete	2824	1887	1890	3.50	5.00	29.00	Good
60	Masonry	2870	1895	1895	0.00	25.00	25.00	Destroyed
61	Masonry	3114	1952	1954	3.00	6.00	15.00	Damaged
62	Masonry	3364	2031	2032	1.00	8.20	15.00	Damaged
63	Masonry	3383	2035	2035	0.00	8.50	12.00	Destroyed
64	Masonry	3454	2050	2051	1.00	9.00	18.50	Damaged
65	Masonry	3470	2053	2054	1.50	13.00	16.80	Damaged
66	Masonry	3544	2071	2074	2.00	3.50	3.50	Damaged
67	Masonry	3645	2093	2095	2.20	9.00	15.00	Damaged
68	Masonry	3661	2101	2101	0.00	11.70	29.00	Destroyed
69	Masonry	3681	2103	2106	3.00	11.00	25.00	Damaged
70	Masonry	3770	2126	2126	0.00	4.00	7.00	Destroyed
71	Masonry	3776	2127	2130	2.50	8.00	15.00	Damaged
72	Masonry	3807	2135	2135	0.00	12.50	12.50	Destroyed
73	Masonry	3825	2141	2143	2.20	4.50	12.00	Destroyed
74	Masonry	3842	2145	2149	3.50	6.00	18.00	Damaged
75	Masonry	3886	2158	2162	4.00	9.00	15.00	Damaged
76	Masonry	3898	2163	2167	4.00	4.50	18.50	Good
77	Masonry	3924	2173	2176	3.00	3.00	8.00	Damaged
78	Masonry	3939	2177	2178	0.50	6.00	15.00	Destroyed
79	Masonry	3955	2181	2184	2.50	6.00	16.00	Damaged
80	Masonry	4108	2226	2233	5.50	10.00	18.00	Good
81	Masonry	4197	2295	2300	4.50	6.00	7.00	Good
82	Masonry	4306	2364	2370	6.00	5.00	5.50	Good

Table 4.1 Detailed characteristics of check dams in Faucon torrent

The torrential fan is equipped by dykes on both side of the torrent. These dykes have been built during 2004 and 2006, after the last large debris flow in 2003.

A detailed map of the Faucon watershed area showing the different mitigation structures that include check dams and the dykes is provided in Figure 4.6.

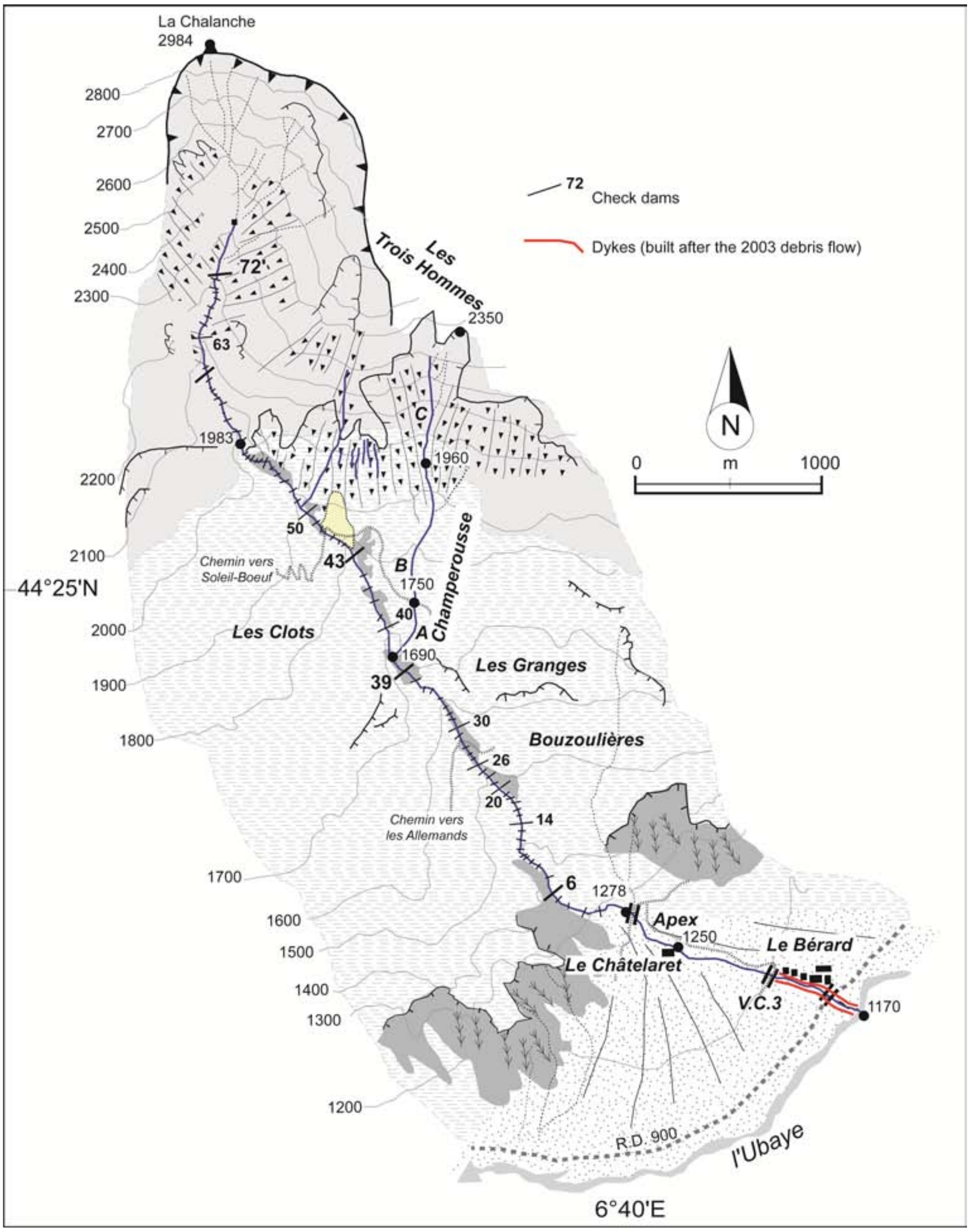


Figure 4.6 Map showing the check dams and dykes in the Faucon watershed area.

4.5.2 Influence of check dams characteristics on the debris flow magnitude according modelling scenarios

The discussion in this section is based on Remaître et al. (2008). The JDFM-1D, developed by van Asch (van Asch et al., 2004), is used to simulate the run-out of the debris flow. The constitutive equation used in the model is a simplified 2-parameters visco-plastic rheology. The model uses the Janbu force diagram to resolve the force equilibrium equations; a Bingham fluid rheology is introduced and represents the resistance term. The JFDM-1D model can take into account the amount of material entrained by the flow along the path (scouring) in order to increase the final volume deposited. According to Rickenmann et al. (2003), the intensity of the scouring is assumed to be a function of the integrated mean shear stress of the debris-flow mixture which passed through sections of the torrent, and is controlled by the slope gradient, the volume and the density of the mixture which enters this section. Therefore, breaking the energy of the flow in the earlier stage of the debris-flow event kinematics would reduce the total amount of entrained material. A complete description of the model can be found in van Asch et al. (2004) and Remaître et al. (2008).

The model has been calibrated both on the debris-flow events that occurred in 1996 and 2003 at the Faucon stream. Influence of the check dams on the debris-flow intensity is quantified taking into account several check dams configurations (number and location) as input geometrical parameters.

For each modelling test, the same triggering scenario has been used based on the observations after the 2003 event. A volume of 5000 m^3 of material has been considered, which corresponds to one of the source area (Trois Hommes area). The rheological characteristics of the debris-flow material cannot be changed during the run-out. Therefore, we considered that the flow exhibits visco-plastic behaviour for the entire simulation. The source area is located at the upper part of the profile while the check point location corresponds to the upper part of the fan where the flow-track shows a clear flattening of the slope gradient. The run-out distance is approximately 4000 m.

In the model, the chains of check dams influence the intensity of the debris-flow through topographic variations of the flow track (slope angle). For the scenario A, the height of check dams corresponds to the height observed in the field in July 2003. For the scenarios B and C, a 5m height has been considered for all the check dams. Three main run-out scenarios have been tested (Figure 4.7):

- Scenario A: effect of the check dams on the intensity of the 2003 debris-flow. This scenario is a kind of “back analyses”. We compare modelling results for two configurations of debris-flow pathway; a profile with no check dams (A1), and the profile with the check dams observed before the 2003 debris-flow event;

- Scenario B: effect of the location of check dams on the intensity of a debris flow. Three configurations of check dams location were tested: check dams located in the upper part of the torrential pathway (B1), in the middle part (B2) and in the lower part (B3);

- Scenario C: effect of the number of check dams on the intensity of a debris flow. Three configurations of check dams were tested: a profile with 10 check dams (C1), a profile with 20 check dams (C2) and a profile with 30 check dams (C3).

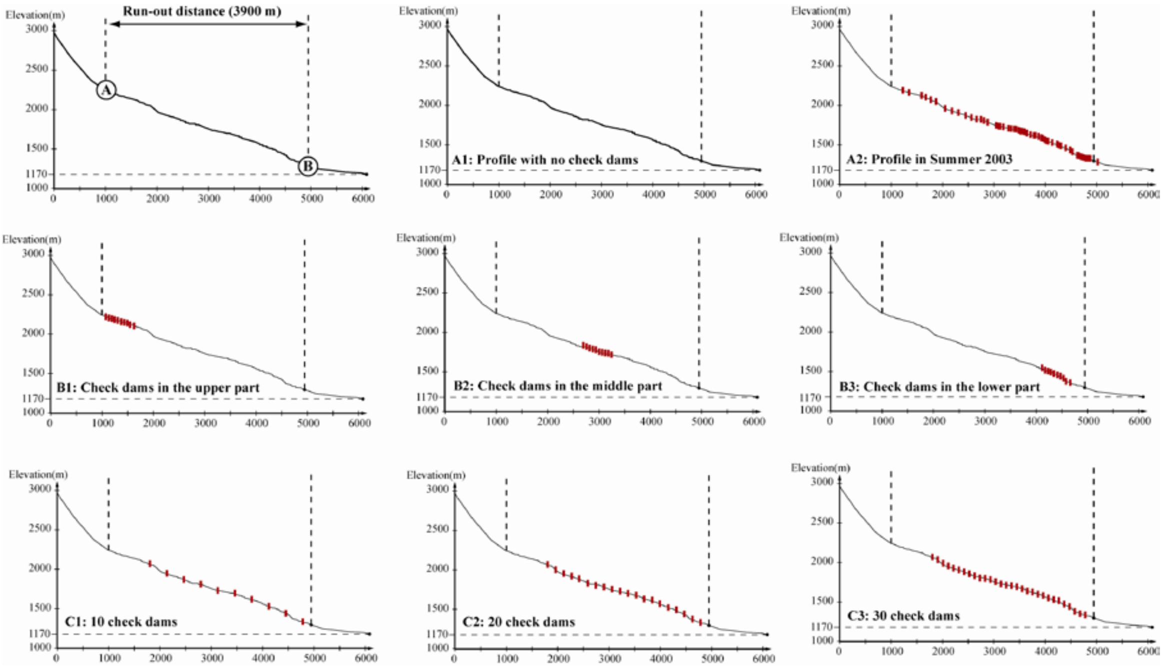


Figure 4.7 Settings of the three modelling scenarios. The bed profile corresponds to those of the Faucon torrent.

For each scenario, the maximal flow height, the maximal velocity and the total volume of debris where analysed and compared (Figure 4.8). For the scenario A, logically, the intensity of the debris flow is decreasing when the torrent is equipped with check dams. The maximum flow height is decreased from 5.95 m (A1: no check dams) to 2.21 (A2: 75 check dams), while the maximum velocity is decreased from 1.58 m.s-1 (A1) to 0.53 m.s-1 (A2). The total volume of the debris-flows is decreasing from 69,000 m^3 (A1) to 33,000 m^3 (scenario A2).

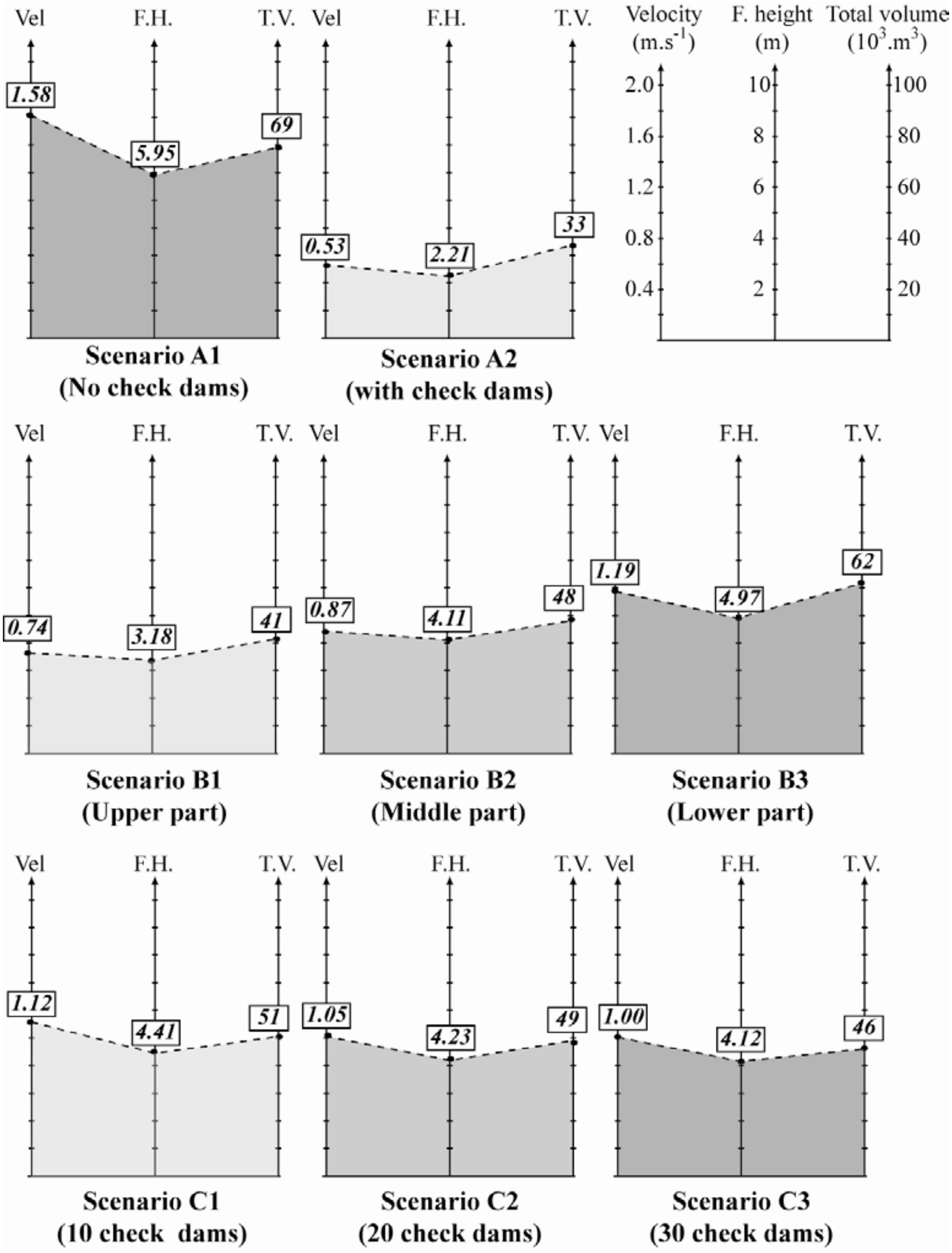


Figure 4.8 Results of the three modelling scenarios.

The run-out modelling results for the Scenario C show a decrease of the flow intensity. The decrease is particularly strong between the scenario A1 (no check dams) and the scenario C1 (10 check dams): decreasing of the maximal velocity, the maximal flow height and the volume are respectively 29% (1.58 to 1.12 m.s-1), 25% (5.95 to 4.41 m) and 26% (69,000 to 51,000 m^3); while the decreasing is gently moderate when the number of check dams is increasing (scenarios C1, C2 and C3). For instance, between the C1 and the C3 scenarios,

decreasing of the maximal velocity, the maximal flow height and the volume are respectively 11% (1.12 to 1.00 m.s-1), 7% (4.41 to 4.12 m) and 10% (51,000 to 46,000 m^3).
The comparison of the debris-flow intensities for the three cases (B1, B2 and B3) shows that the location seems to have a strong influence on the debris-flow intensity. Indeed, the differences are significant between the B1 scenario (dams located on the upper part) and the B3 scenario (dams located on the lower part): decreasing of the maximal velocity, the maximal flow height and the volume are respectively 37% (1.19 to 0.74 m.s-1), 36% (4.97 to 3.18 m) and 33% (62,000 to 41,000 m^3).

4.5.3 Debris flows spreading modelling on the Faucon torrential fan

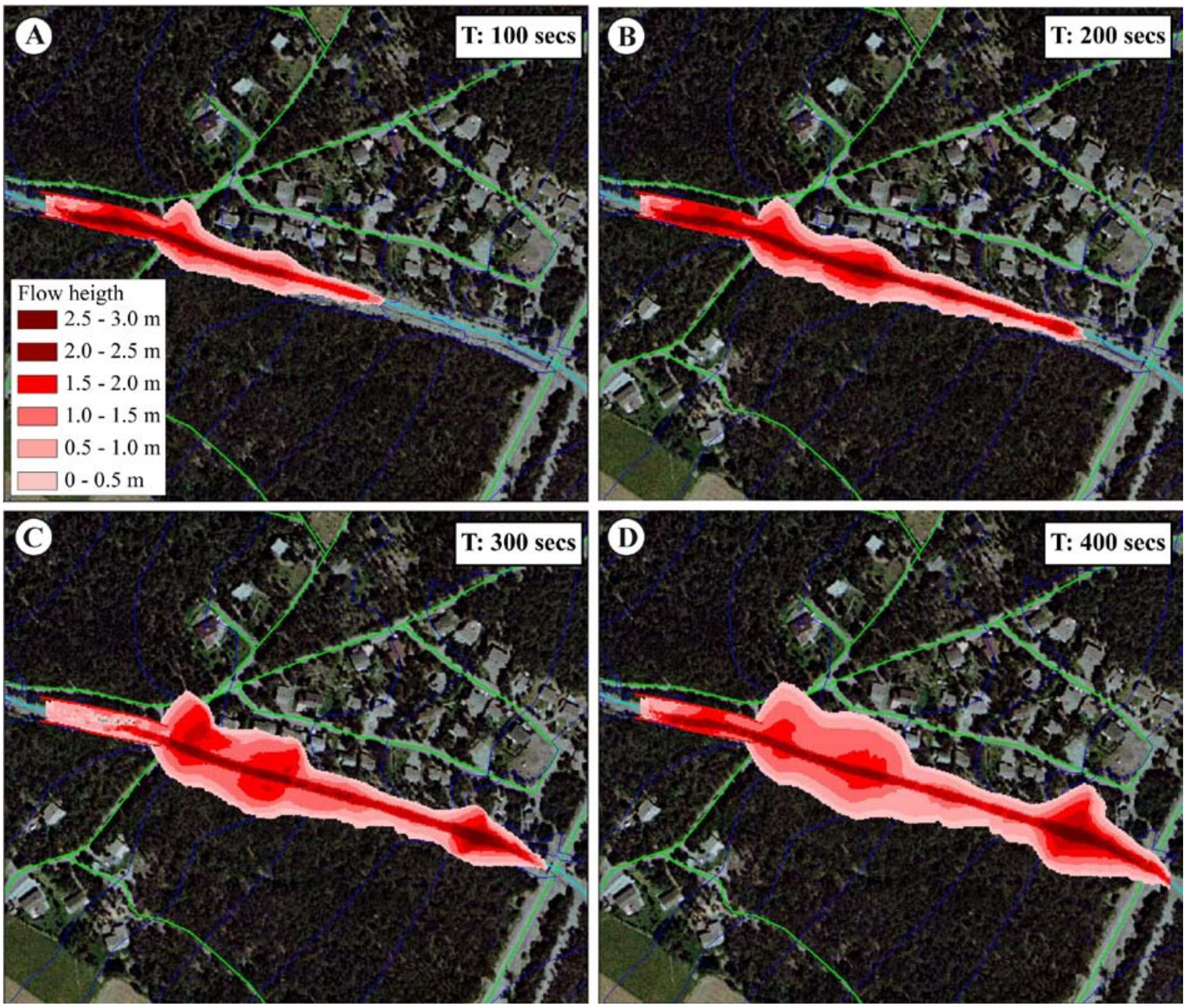


Figure 4.9 Example of Cemagref 2D output maps at the Faucon fan.

The discussion in this section is based on Remaître (2006). The complete description and the constitutive equations of the model can be found in Laigle and Coussot (1997), Laigle and Marchi (2000), and Remaître (2006). This model considers one phase for the computation of runout of visco-plastic materials with a Herschel-Bulkley (HB) rheology. It is based on the conservative form of the steep-slope shallow water equations which are solved using a finite volume technique. A hydrograph can be specified as boundary conditions. The Cemagref model is valid only for materials where the fine fraction is large enough to lubricate contacts between grains. Coussot (1994) has specified that a clay fraction greater than 10% is necessary so that debris flow material may be assumed to behave like a Herschel-Bulkley fluid. In this case, the rheological tests and the shape of lobes in the field are consistent with visco-plastic behaviour, well represented by a Bingham or Herschel-Bulkley model. Inputs have been gathered both on field and laboratory.

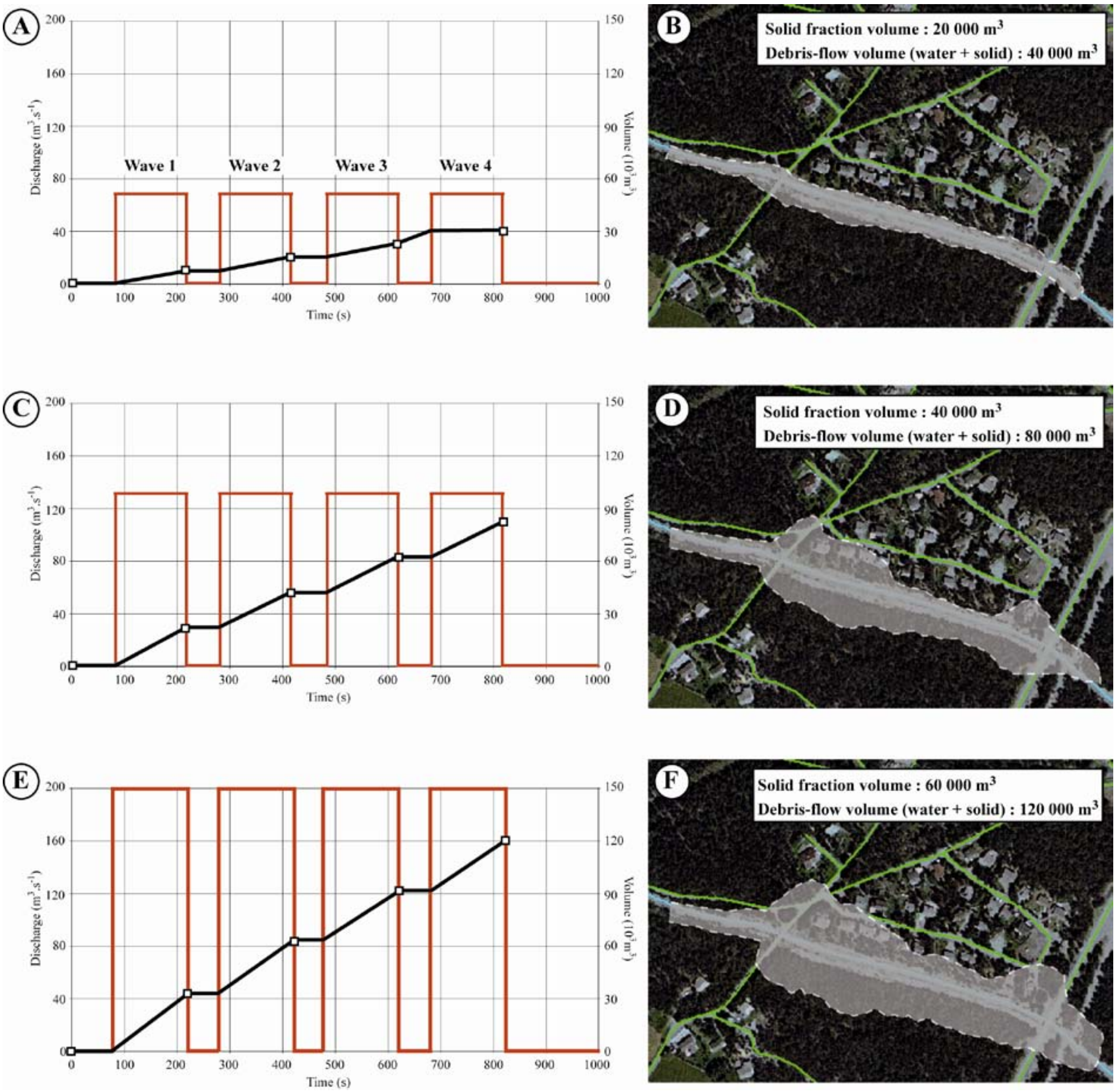


Figure 4.10 Evaluation of the minimal debris-flow volume in order to overflow the alluvial fan according the simulation with the Cemagref-2D code.

The model has been previously calibrated and validated for several flow-like landslide events that have occurred in the Barcelonnette basin (Malet et al., 2005; Remaître et al. 2005b). For this stage, the model has been calibrated on the flow height of the 1996 and the 2003 events at Faucon stream. Calibration results are quite consistent with field observations for the flow height, while velocities are underestimated of a factor two.

The minimal volume in order to produce overflowing on the fan has been evaluated. It was assumed that an overflowing occurred when the simulated flow height was higher than the height of the torrential bank. For these simulations, the 2003 debris-flow rheological characteristics were used and 4 volumes (40, 60, 80 and 120.10^3 m^3) were tested. The primary objective was to define some critical spots where overflowing could occur. Results shown in Figure 4.10 indicate that the upper part of the fan (from 0 to 600 m in horizontal distance) is not very sensitive to overflowing except for a very large volume (greater than 80 000 m^3). However, the lower part of the fan (typically near Bridge 2) is threatened by overflowing for a volume up to 60 000 m^3. Below Bridge 2, torrential banks are not higher enough to ensure that any overflowing will occur. Moreover, at this point, the torrential track narrows from approximately 4 to 3 m, decreasing the flow section.

4.6 EVALUATION OF CONSEQUENCES

4.6.1 Identification and collection of information for relevant infrastructure

The exposed elements considered of interest for the analysis of debris flow risks at the Faucon catchment at a 1:10,000 are (Puisssant et *al.* 2006):

- *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 the estimation of 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.

4.6.2 Considered direct consequences/losses – damages to infrastructure and loss of lives

In the case of the Faucon catchment, a methodology for consequence analysis combining estimation of the direct consequences/potential damages to infrastructures and loss of lives, and the indirect consequences in terms of socio-economic impact have been assessed jointly by developing vulnerability indexes (Puissant et al., 2006). The methodology is described below.

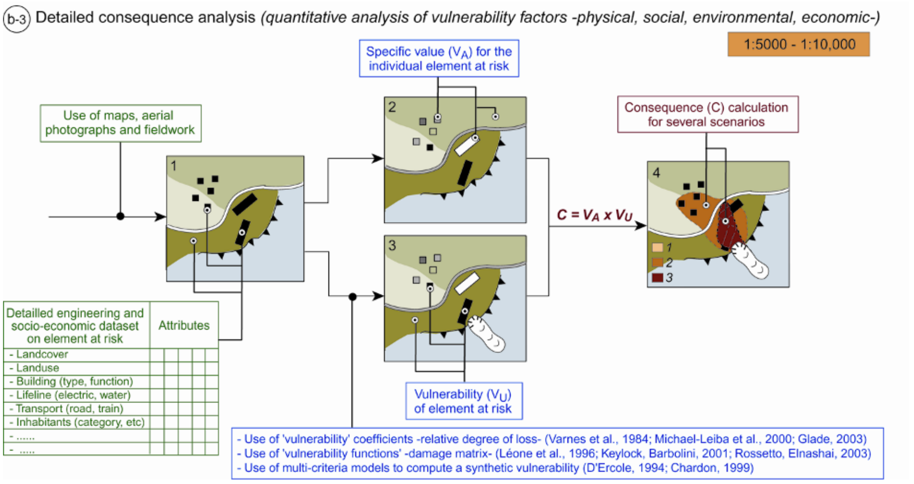


Figure 4.11 Approach used in assessing landslide consequence at the Faucon catchment, ands steps used in the analysis.

Definition of the relevant stakes

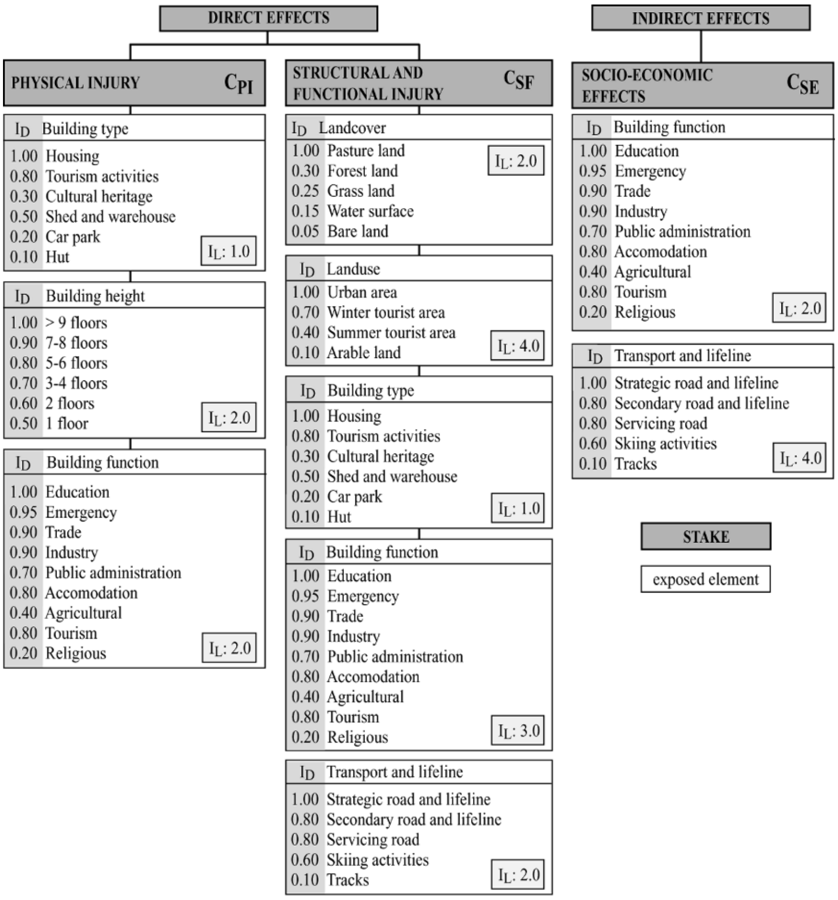
The index-oriented method to evaluate landslide potential consequences (damage) combines the identification of the elements at risk (or stakes) and of their value with a semi-empirical model. Stakes are defined as a relative value scale of the exposed elements (Maquaire *et al.*, 2004). The proposed 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 4.12). 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.



DIRECT EFFECTS

PHYSICAL INJURY C_{PI}

I_D	Building type
1.00	Housing
0.80	Tourism activities
0.30	Cultural heritage
0.50	Shed and warehouse
0.20	Car park
0.10	Hut

I_L: 1.0

I_D	Building height
1.00	> 9 floors
0.90	7-8 floors
0.80	5-6 floors
0.70	3-4 floors
0.60	2 floors
0.50	1 floor

I_L: 2.0

I_D	Building function
1.00	Education
0.95	Emergency
0.90	Trade
0.90	Industry
0.70	Public administration
0.80	Accomodation
0.40	Agricultural
0.80	Tourism
0.20	Religious

I_L: 2.0

STRUCTURAL AND FUNCTIONAL INJURY C_{SF}

I_D	Landcover
1.00	Pasture land
0.30	Forest land
0.25	Grass land
0.15	Water surface
0.05	Bare land

I_L: 2.0

I_D	Landuse
1.00	Urban area
0.70	Winter tourist area
0.40	Summer tourist area
0.10	Arable land

I_L: 4.0

I_D	Building type
1.00	Housing
0.80	Tourism activities
0.30	Cultural heritage
0.50	Shed and warehouse
0.20	Car park
0.10	Hut

I_L: 1.0

I_D	Building function
1.00	Education
0.95	Emergency
0.90	Trade
0.90	Industry
0.70	Public administration
0.80	Accomodation
0.40	Agricultural
0.80	Tourism
0.20	Religious

I_L: 3.0

I_D	Transport and lifeline
1.00	Strategic road and lifeline
0.80	Secondary road and lifeline
0.80	Servicing road
0.60	Skiing activities
0.10	Tracks

I_L: 2.0

INDIRECT EFFECTS

SOCIO-ECONOMIC EFFECTS C_{SE}

I_D	Building function
1.00	Education
0.95	Emergency
0.90	Trade
0.90	Industry
0.70	Public administration
0.80	Accomodation
0.40	Agricultural
0.80	Tourism
0.20	Religious

I_L: 2.0

I_D	Transport and lifeline
1.00	Strategic road and lifeline
0.80	Secondary road and lifeline
0.80	Servicing road
0.60	Skiing activities
0.10	Tracks

I_L: 4.0

STAKE

exposed element

Figure 4.12 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}.).

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 4.12 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 of 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 XX) by taking into account the socio-economic and environmental characteristics of the study area. For example, the economic activities of the Faucon 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.

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 scenario for management or planning. The combination of the potential consequences (C_{PI}, C_{SF}, and CSE) allows the evaluation of a total potential consequence index C_T expressed in five classes (Table 4.2).

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 cannot managed locally. Domino consequences are expected.

Table 4.2 Classes of total potential damage (CT) defined for the study area (according to French PPR procedure ‘Plan de Prévention des Risques’).

Results: mapping landslide potential consequences

Figure 4.13 presents the total potential landslide damage (S_T) map over the area. It also shows the cumulated curve of C_T for which thresholds defined the classes (C0 to C4).
Figure 4.14 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.

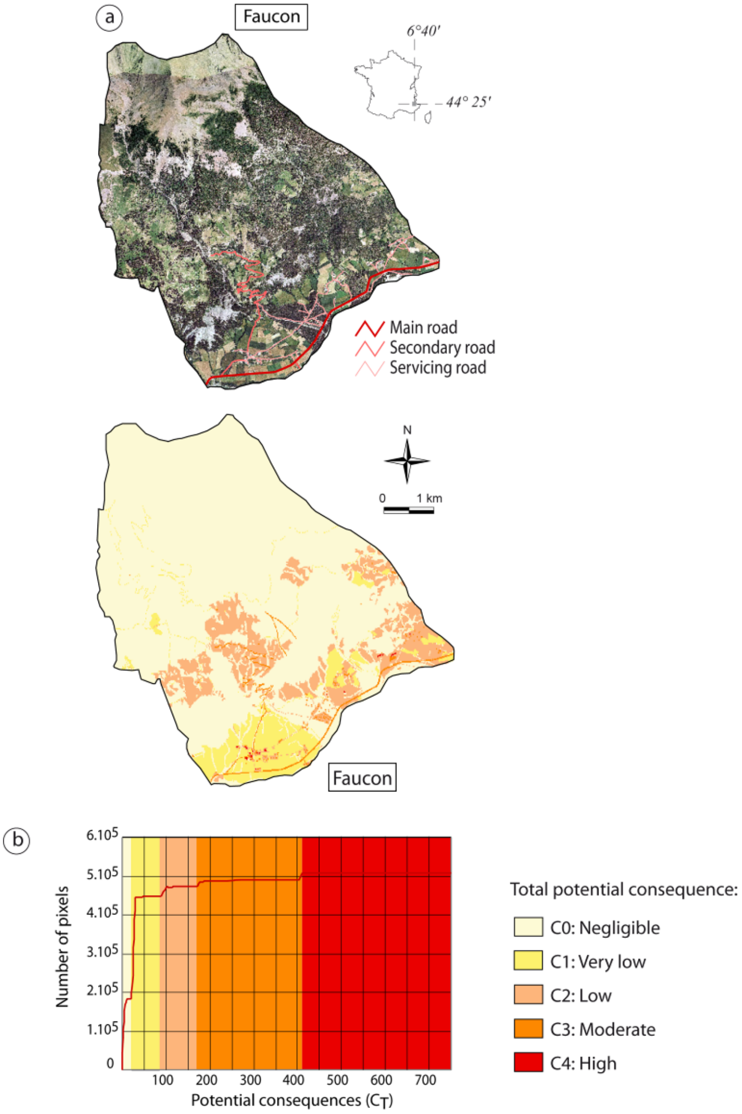


Figure 4.13 (a) Orthophotos of the study area of the Faucon catchment and total potential consequence map; (b) cumulated curve used to define the classes (in Puissant et al., 2006).

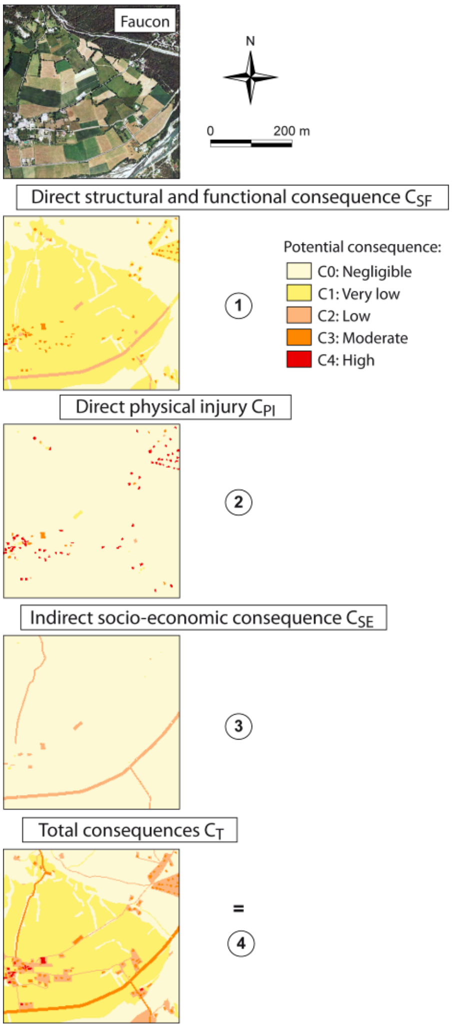


Figure 4.14 Example of the direct structural and functional potential consequence map C_{SF} (1), direct physical injury map C_{PI} (2), indirect economic consequence map C_{SE}, (3) and total consequence C_T (4) simulated with by the semi-quantitative model. Examples of the Faucon village (in Puissant et al., 2006)

Results: mapping landslide vulnerability in a multi-hazard approach

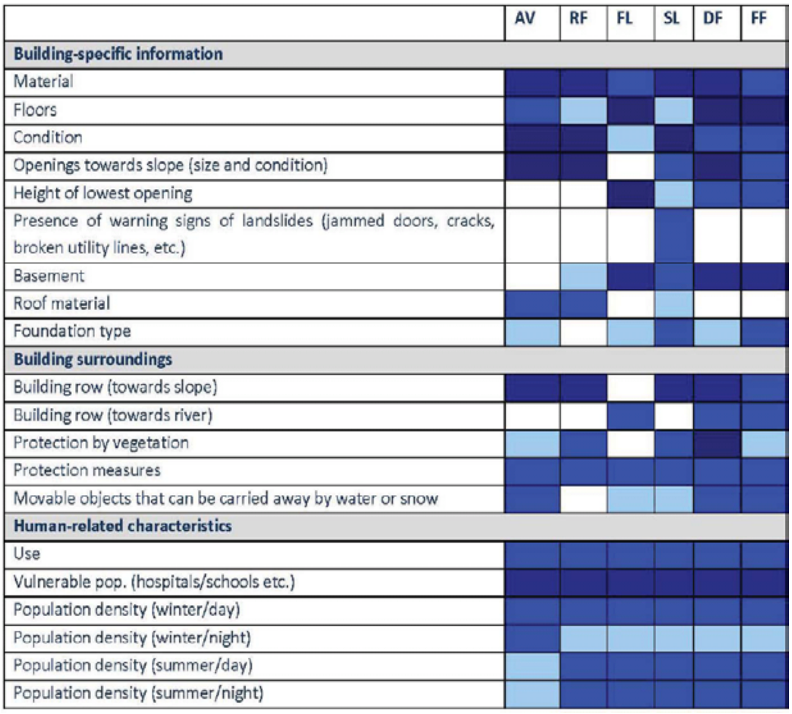
In order to complete the analysis, the potential consequence assessment has been extended with the development of an approach of vulnerability analysis, on the basis of the PTVA model developed for tsunami assessment (PTVA: Papathoma Tsunami Vulnerability Assessment; Papathoma and Dominey-Howes 2003). The model includes the following steps:

- Step 1: Identification of the study area and the relevant hazards;
- Step 2: Selection of vulnerability indicators and data collection (Table 4.3);
- Step 3: Weighting of indicators and Relative Vulnerability Index (RVI) assignment for every building.

The RVI is applied according to the following formula:

$$RVI = \sum_{1}^{m} w_m \cdot I_m s_n \tag{14}$$

with the weights w_1 to w_m for the vulnerability score $I_m S_n$ $(s_1\text{-}s_n)$ for each indicator I_1 to I_m.



	AV	RF	FL	SL	DF	FF
Building-specific information						
Material	█	█	▒	█	█	▒
Floors	▒	░	█	░	█	█
Condition	█	█	░	█	▒	▒
Openings towards slope (size and condition)	█	█		▒	█	▒
Height of lowest opening			█	░	▒	▒
Presence of warning signs of landslides (jammed doors, cracks, broken utility lines, etc.)				▒		
Basement		░	█	▒	█	█
Roof material	▒	▒		░		
Foundation type	░		░	▒	░	▒
Building surroundings						
Building row (towards slope)	█	█		█	█	▒
Building row (towards river)			▒		▒	▒
Protection by vegetation	░	▒		▒	█	░
Protection measures	▒	▒	▒	▒	▒	▒
Movable objects that can be carried away by water or snow	▒		░	░	▒	▒
Human-related characteristics						
Use	▒	▒	▒	▒	▒	▒
Vulnerable pop. (hospitals/schools etc.)	█	█	█	█	█	█
Population density (winter/day)	▒	▒	▒	▒	▒	▒
Population density (winter/night)	▒	░	░	░	░	░
Population density (summer/day)	░	▒	▒	▒	▒	▒
Population density (summer/night)	░	▒	▒	▒	▒	▒

Table 4.3 Selection of vulnerability indicators for mountain hazards observed in the Faucon catchment and their importance (AV: snow avalanche, RF: Rock fall, FL: Flood, SL: Shallow Landslide, DF: Debris flow, FF: Flash Flood, Light blue: Less important, Middle Blue: Important, Dark Blue: Very Important)

The objective is to have an indicator based vulnerability assessment approach for multi-hazards. The innovative aspect of the methodology is its flexibility, as we consider not only vulnerability "to" different hazards but also vulnerability "for" a range of users according to their objectives. The results show that the methodology can provide information to different stakeholders in order to identify hotspots and focus their efforts in specific buildings and areas, however, it also demonstrates the need for more data regarding the indicators themselves and better documentation of damage assessment.

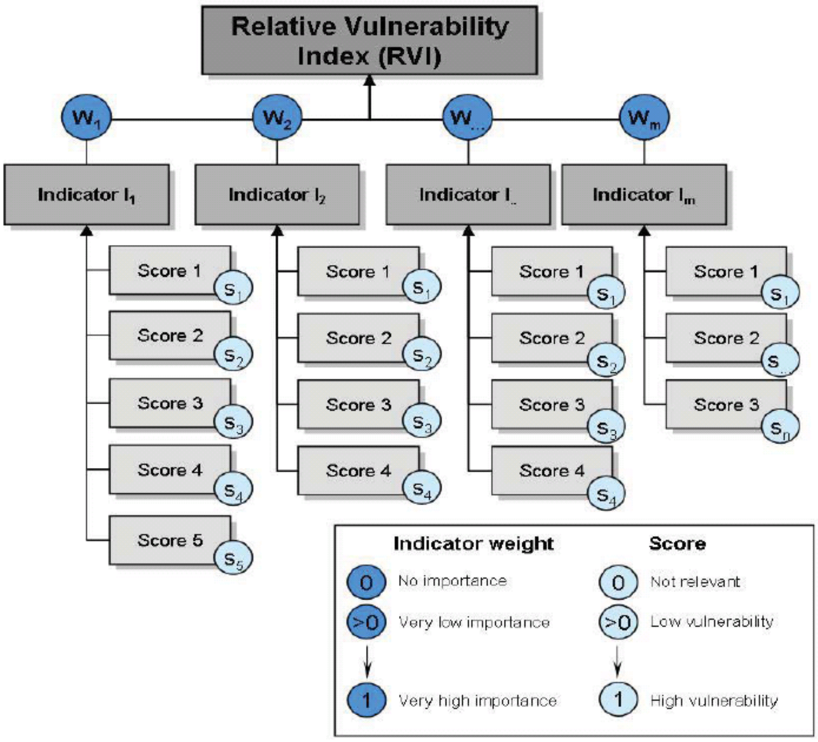
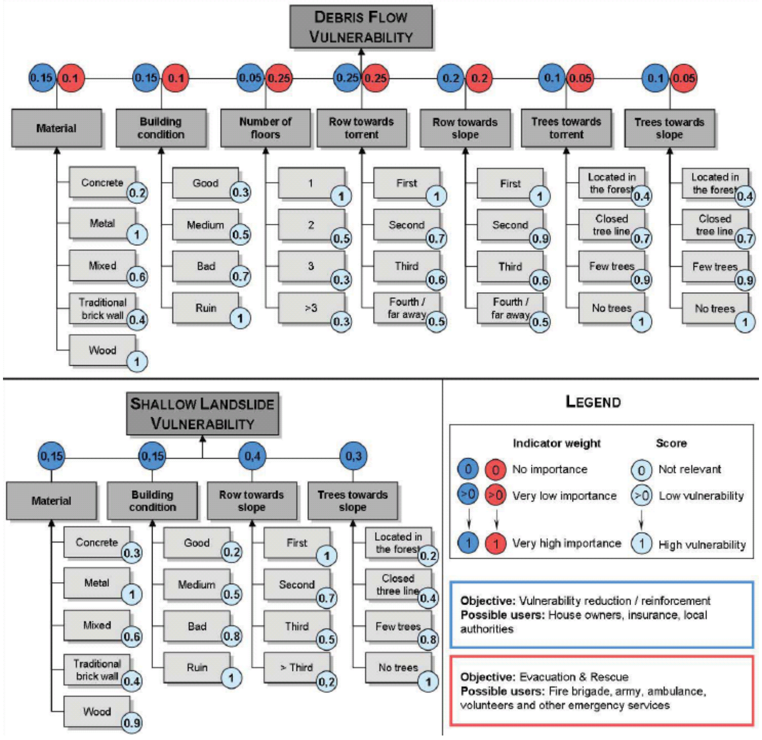


Figure 4.15 Vulnerability computation framework.



Objective: Vulnerability reduction / reinforcement
Possible users: House owners, insurance, local authorities

Objective: Evacuation & Rescue
Possible users: Fire brigade, army, ambulance, volunteers and other emergency services

Figure 4.16 : Vulnerability indicators for different processes and users.

In Figure 4.16, the indicators for each hazard on basis of expert appraisal and their weighting for different users are shown. The study area is shown in Figure 4.17. In Figure 4.18, the maps showing the spatial pattern of the physical vulnerability for debris flow (Figures 4.18a and 4.18b) and shallow landslide (Figure 4.18c) for two purposes (emergency management and building reinforcement) are demonstrated.

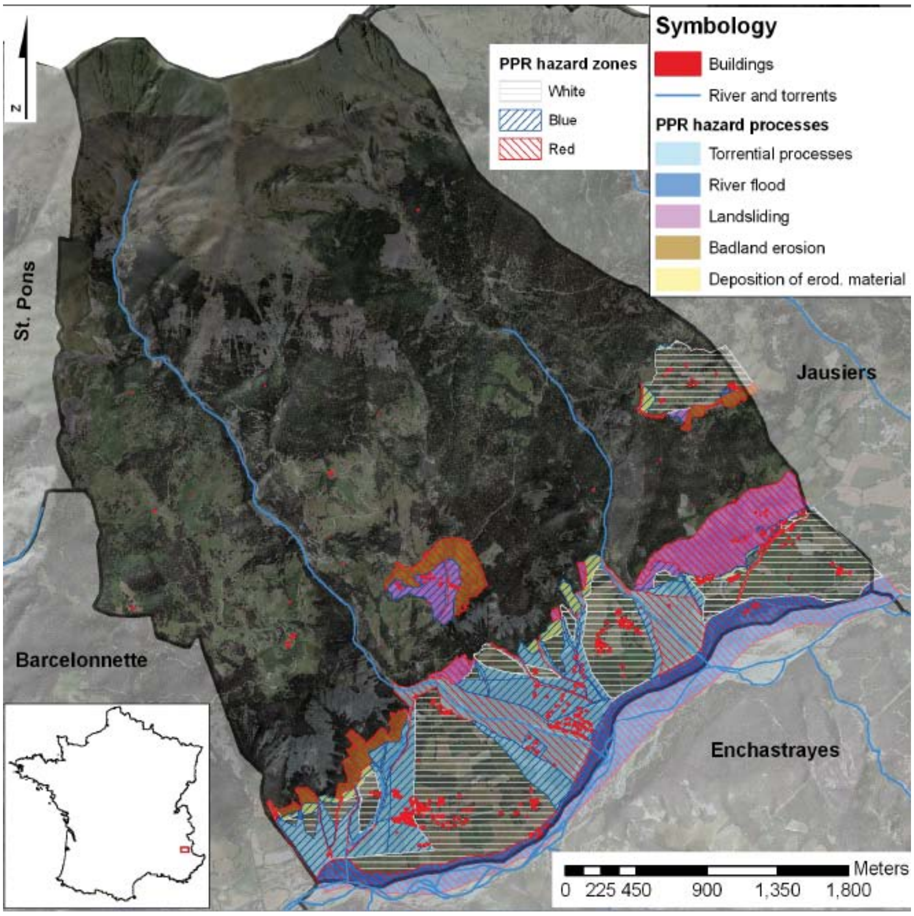


Figure 4.16: The case study area: Municipality of Faucon-de-Barcelonnette.

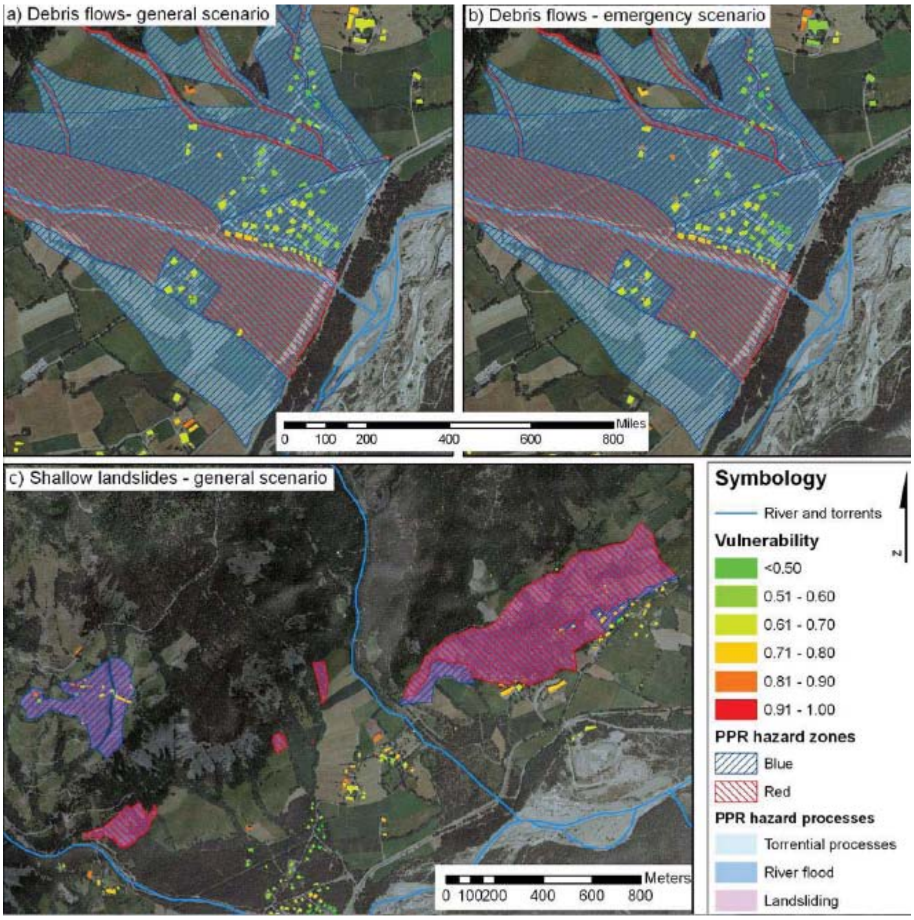


Figure 4.18: Vulnerability assessment at Faucon-de-Barcelonnette.

5 CASE STUDY AT SITE 2 – NOCERA INFERIORE

5.1 SITE DESCRIPTION – GEOGRAPHICAL INFORMATION

Monte Albino hill slopes: an area prone to hyperconcentrated flows, flowslides, landslides on open slopes

The selected test site of Monte Albino (40°43'N, 14°38'E), located in the municipality of Nocera Inferiore (southern Italy), extends over a total area of about 400 hectares, from 890 m to 90 m above sea level (Figure 5.1). Along the hill-slope, 10 catchments can be individuated as well as 10 open slopes (triangular facets), located in the lower portions of the relief (below 330 m above sea level). In March 2005, one of these open slopes was affected by a first-failure landslide (Figure 5.2) which caused 3 fatalities and the destruction of some buildings.

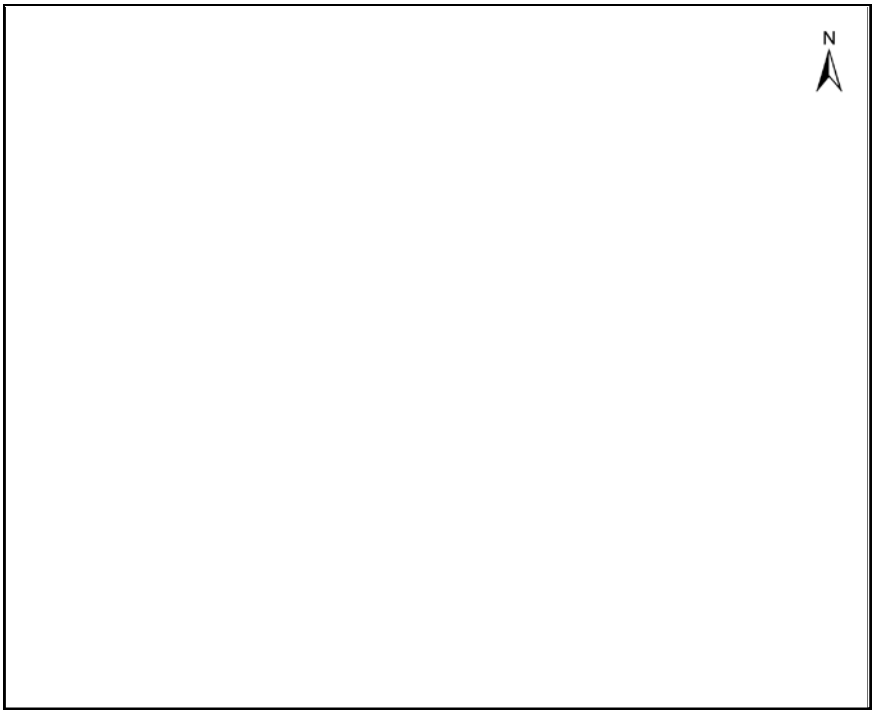


Figure 5.1 Study area.

In order to define the geological setting as well as to deepen the knowledge of the different types of phenomena which can occur on the slopes, in-situ tests, field surveys and studies were firstly carried out following a multidisciplinary approach (involving competences on historical data treatment, geology, morphology, hydrogeology, geotechnics, geomatics, geostatistics, etc.). The main results achieved during this preliminary step of the work are herein presented.

Figure 5.2 Frontal view of the debris avalanche that occurred on March 2005.

5.2 ANALYSIS OF HISTORICAL INFORMATION

5.2.1 Documentary sources

For the events preceding the 18th century the documentary sources consisted on historical-literary books (Orlando, 1884; Cimmelli, 1990; Pucci, 1995) and technical reports (Beguinot, 1957; Marciani, 1930; D'Elia, 1994).
For the 19th century, historical incident data were recovered in the documents of the "Intendenza del Regno delle Due Sicilie (Sezione Opere Pubbliche)", founded by the Bourbons in 1806, and housed in the State Archive of Salerno. These documents include the correspondence between the "Intendente" and the Mayors of the towns affected by landslides as well as appraisals for the reconstruction works following the catastrophic events.
In relation to the 20th century the main source is the report of the Operative Unit 2.38 (1998) of the University of Salerno, synthesised by Migale e Milone (1998), in which the results of a historical research on first-failure landslides occurred in Campania region in a time period spanning from the end of the 16th century up to now are summarised.

5.2.2 Results of the analyses

From a deep analysis of the contents of the recovered historical documents, it is argued that the events that occurred in the 18th and 19th centuries can be associated to the occurrence of hyperconcentrated flows (Costa, 1988). On the other hand, the incident data referring to the 20th century (also considering the landslides occurred on March 2005) can be linked to first-failure landslides on open slopes while there is lack of historical information about flowslide phenomena (Hutchinson, 1988).

5.2.2.1 Hyperconcentrated flows

With reference to the hyperconcentrated flows, information furnished by the documentary sources essentially deals with the consequences related to the occurrence of the phenomena at hand. In particular, as far as the incident data of the 18th century are concerned, the described consequences refer to some built-up areas of Nocera de' Pagani (this is the name of the Municipality at that time) and to the site called "Vescovado" (Figure 5.3); furthermore, these consequences seem to have been more severe, in terms of recorded damage, than those caused by the events occurred in the 19th century. In this regard, it can be observed that in the 18th century the described consequence are often due to adverse events originated from the Monte Albino hillslopes (i.e., the hyperconcentrated flows) as well as to flooding phenomena.

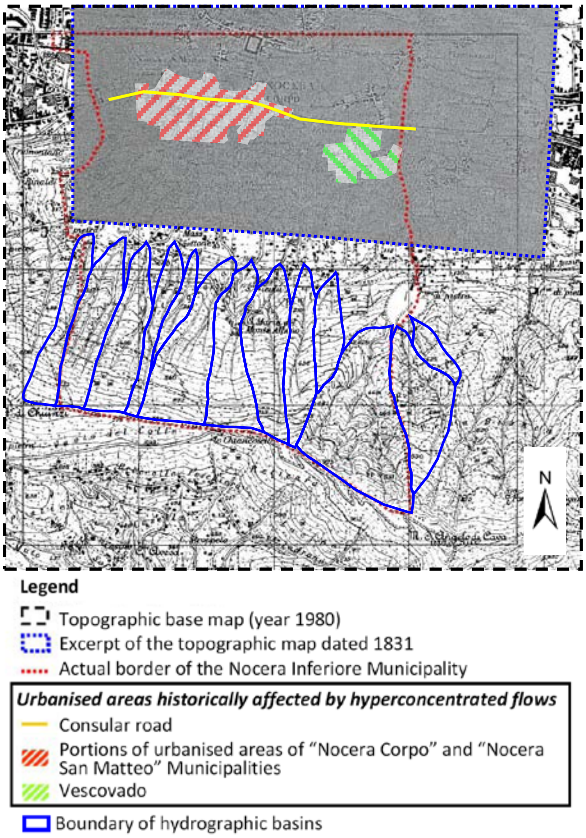


Figure 5.3 Urbanised areas affected by hyperconcentrated flows occurred during the 18th and the 19th centuries.

At the beginning of the 19th century, as required by the King of Bourbons Ferdinand IV who experienced the block of the consular road owing the event of 1804, some hydraulic control works were built in the flat areas (Orlando, 1884; Marciani, 1930; Beguinot, 1957). In the following, thanks also to the existence of these mitigation measures, the consequences related to the occurrence of the hyperconcentrated flows were limited to troubles in accessing some sections of the consular road, near the built-up areas.

Finally, it is worth noting that some documents also furnish information about the cost (in ducats) required for the removal of transported sediments on the road.

The cumulative curve of past hyperconcentrated flow events (Figure 5.4) is characterised by a stepped shape during the time period (from 1707 to 1846) for which historical incident data are available.

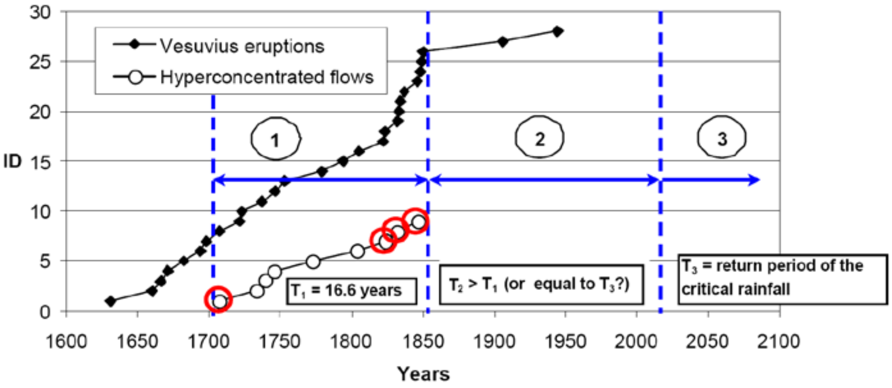


Figure 5.4 Cumulative distributions of: *i)* Vesuvius explosive eruptions occurred from 1631 up to now; ii) hyperconcentrated flow incident data (events occurred after the Vesuvius eruptions are circled in red).

Figure 5.4 also shows that the occurrence of the events may be correlated with the explosive eruptions of the Vesuvius volcano; in particular, between the 1811 and 1848, during a period of intensive strombolian activity of the volcano (Scandone et al., 2008), n. 3 hyperconcentrated flow events were recorded (Table 5.1).

With reference to the seasonal distribution of the past events, Figure 5.5 shows that the recorded incident data are concentrated between October and January, with a maximum in November. In this regard, the occurred phenomena can be ascribed to: *i)* the availability of pyroclastic soils over the hillslopes (Figure 5.6a), transported by the winds blowing toward the eastern sectors (northeast–southeast) during the Autumn-Winter periods are (Rolandi et al., 2007); *ii)* the washing operated by rainfall of short duration and high intensity.

ID	Day	Month	Year	Affected area
1	-	11	1707	All the town(*)
2	11	11	1733	All the town and the consular road
3	24	10	1739	All the town and the “Vescovado”
4	02	12	1745	All the town and the “Vescovado”
5	11	11	1773	All the town and the “Vescovado”
6		1	1804	The consular road
7	24	1	1823	The consular road
8	30	11	1832	The consular road
9	02	10	1846	The consular road

(*) The term “town” indicates the built-up area at the time when the phenomena occurred.

Table 5.1 Recorded incident data of hyperconcentrated flows from 1707 to 1846, with indication of affected areas.

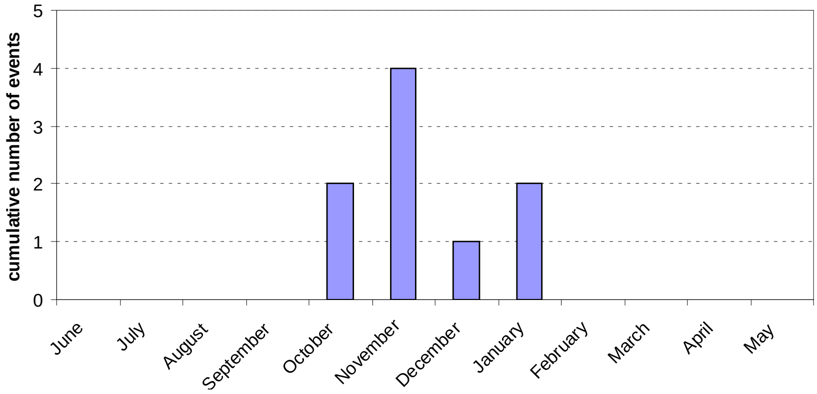


Figure 5.5 Monthly distribution of past hyperconcentrated flows in the region.

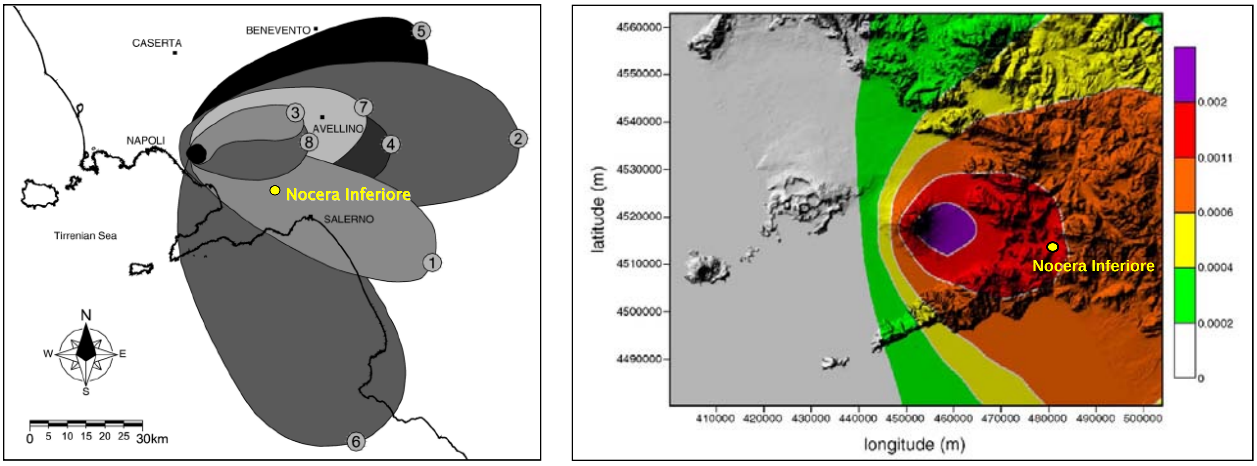


Figure 5.6 a) Distribution map of pyroclastic fall deposits of the Somma-Vesuvius deposited in the last 25 ka BP. Each lobe consists of air fall tephra 10 cm thick from a single Plinian eruption. Numbers are arranged according to the chronological sequence of the eruption. (1) 25.000 anni B.P.; (2) 18.000 anni B.P.; (3) 16020 anni B.P; (4) 8000 anni B.P.; (5) 3550 anni B.P.; (6) A.D. 79; (7) A.D. 472; (8) A.D. 1631 *(modified from Rolandi et al., 2007)*. b) Fall-out hazard map for Vesuvius eruptions. The maps are computed, by several tens thousands of computer simulations, on the basis of the observed wind velocity and direction between 0 and 35 km of height and their relative occurrence, considering all the eruption types with their statistics distributions, according to the volcanological records. The values are the yearly probabilities of a tephra load exceeding 200 kg/m^2 (producing the collapse of most roofs) *(modified from De Natale et al., 2006).*

The previous considerations allow the assumption of some hypotheses on the return period of the hyperconcentrated flow events (Figure 5.4). In particular, with reference to the time period ΔT_1 spanning from 1707 to 1846 (ΔT_1 = 140 years), it can be assumed that the average return period T_1 – in the hypothesis that the database is complete – is equal to 16.6 years (140 years/9 events). If the ΔT_2 time period (from 1846 up to now) is considered, owing to the reduced recurrence of strombolian eruptions, the average return period T_2 of the hyperconcentrated flows is greater than T_1. Moreover, since their occurrence is related to erosive phenomena rather than washing, it can be assumed that T_2 can be equal to the return period T_3 of the triggering rainfall events.

Taking into account the low annual probability that, according to De Natale et al. (2006) can be associated with the occurrence of air-fall pyroclastic deposits (Fig. 6b), future hyperconcentrated flows will be characterised by an average return period equal to T_3, being their occurrence mainly related to erosive phenomena.

5.2.2.2 Flowslides

For flowslides no incident data are available. Considerations about the frequency of this kind of phenomena may derive from the analysis of data dealing with similar events occurred in similar geo-environmental contexts nearby, such as Pizzo d'Alvano massif. This context – extending for about 60 km^2 – was affected, on May 1998, by several flowslides which hit four towns (Bracigliano, Quindici, Sarno and Siano) located in the piedmont areas (Cascini, 2004).
With reference to the portion of the Pizzo d'Alvano hillslopes threatening Sarno town, Cascini and Ferlisi (2003) showed that the available incident data – achieved from a comprehensive catalogue spanning from 1625 up to now – can be profitably managed for frequency analysis purposes by introducing an intensity index I_n. This index is defined as the ratio between the number of gullies involved in a given flowslide event to the total number of gullies (17) threatening the town.
For I_n values equal to 0.18 and 0.24, the results of the historical data reveal that events involving at one time 3 or 4 gullies are characterised by a return period of 193 years; for I_n values higher than 0.29 (more the 5 gullies involved at one time) the return period equals 386 years, namely the total length of the catalogue. Moreover, flowslide events having the above return period values (i.e., 193 and 386 years) could cause respectively 10 and 160 victims or more (Figure 5.7). This latter results is a part of a larger study (Cascini et al., 2008) carried out thanks to the availability of a database including 293 fatal landslides occurred in the Campania region from 1640 to 2006.

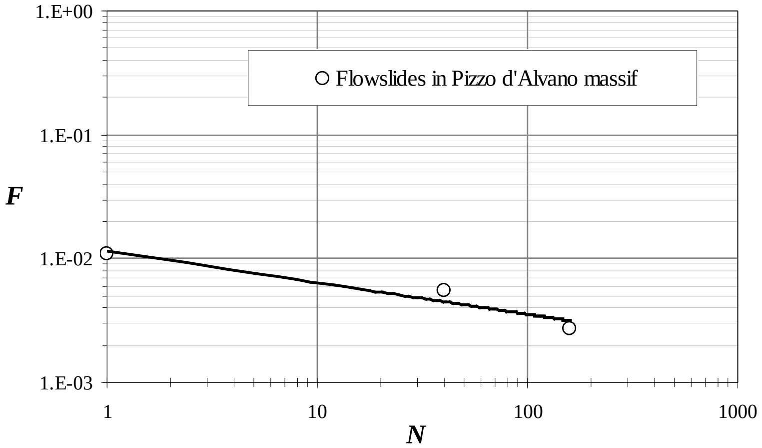


Figure 5.7 F-N curve (F represents the annual frequency of flowslides causing N or more victims) for flowslides occurred, during the period spanning from 1640 to 2006, in the Pizzo d'Alvano massif (modified from Cascini et al., 2008).

On the basis of these results, for flowslide events that could be triggered on the upper portions of the Monte Albino hillslopes, a return period of 200 years can be conveniently assumed. It is worth to stress that this assumption does not necessarily imply that, in correspondence of events characterised by this return, all existing gullies can be involved at the one time; once admitted, this further assumption can lead to the overestimation of the risk.

5.2.2.3 First-failure landslides on open slopes

With reference to the first-failure landslides on open slopes occurred from 1935 up to now, on the basis of the available data (Table 5.2), it can be observed that the average time period of recurrence equals about 19 years. This value could be unsafe, being the estimation of T carried out without considering the role played by the anthropogenic factors in predisposing this kind of instability phenomena.

ID	**Day**	**Month**	**Year**	**Fatalities/Endangered sites**
1	-	-	1935	-
2	24	10	1954	-
3	-	-	1958	-
4	4	3	2005	3 fatalities/some houses destroyed

Table 5.2 Recorded incident data of landslides on open slopes occurred from 1935 to 2005, with indication of the consequences to the exposed persons and properties.

5.3 GEOLOGICAL SETTING

On the basis of the in-situ test results and the field observations on selected areas as well as of the morphological analysis extensively carried out on both topographic maps at different scales and high-detail orthophotos, the thickness distribution of the pyroclastic deposits has been estimated and mapped in the study area. The spatial distribution of the thickness classes is controlled by the morphology of the slope. In particular, the thickness of the pyroclastic deposits reach values of 4 m in the median part of the western sector of the slope where the slope angles range between 20 and 30 degrees; on the contrary, the thickness values do not exceed 1.5 m in the eastern part of the slope where slope angles attain the highest values. Moreover, it must be observed that the main vertical discontinuities of the pyroclastic deposits correspond to: *i)* “scarps in calcareous rocks” (usually having a structural control due to the presence of fault scarps or thick strata heads) and *ii)* “erosion scarps along the gullies” (mainly originated by the erosive processes that grooved the pyroclastic covers and, in some cases, allowed the uncovering of the carbonatic bedrock often in correspondence of the buried tectonic elements).

Moving from the upper part to the toe of the slope, it is possible to recognise – in the western part of the Monte Albino hillslope – the presence of morphological concavities filled by pyroclastic soils and prone to first-failure phenomena. On the contrary, in the eastern part, streams cutting directly into the carbonatic bedrock are found. In the lateral sectors of the gullies, in the inter-rill areas and along the open slopes there is the presence of morphological elements probably related to landslide and erosive processes. The area at the toe of the slope shows a complex array of fans of different origin, on the top of which lies a part of the urbanized area of the Nocera Inferiore municipality.

Finally, it is worth to observe that the study area corresponds to the northern part of the hydrogeological Unit of the Lattari Mounts, where the groundwater regimen is conditioned by the main tectonic structures originating springs in the lower part of the slope; also ephemeral springs can be found in the upper part of the slope related to suspended groundwater.

5.4 PREVAILING FLOW-LIKE MASS MOVEMENTS

Owing to the above described geological predisposing factors and taking into account the results of the historical analysis, it can be argued that the Monte Albino hillslopes are prone to different types of rainfall-induced flow-like mass movements (Hutchinson, 2004), namely: hyperconcentrated flows, landslides on open slopes and flowslides.

The *hyperconcentrated flows*, as already outlined, essentially relate to erosion processes originated by heavy rains and affect the pyroclastic soils cover along rills as well as on the inter-rills areas.

The *landslides on open slopes* affect the triangular facets located at the base of the slope; they have similar characteristics to the phenomenon occurred on March 2005 and are classifiable as “debris avalanches” (Hungr et al., 2001).

Finally, in spite of the lack of historical incident data, *flowslides* can be triggered in some areas – e.g., in the so-called “Zero Order Basins” (Dietrich et al., 1986; Cascini et al., 2008) – located in the upper part of Monte Albino massif. The magnitude of the displaced masses could be significantly increased by the materials eventually entrained during the post-failure and propagation stages.

5.5 DECISION MAKERS AND STAKEHOLDERS

The decision makers and stakeholders include the residents of Monte Albino and the responsible public and statutory authorities at the federal, regional and municipal levels.

5.6 QUANTITATIVE ASSESSMENT OF THE RISK OF LOSS OF LIFE

The framework for the use of QRA for landslides and engineered slopes has been recently reviewed by Fell et al. (2005). This framework includes three main components, namely: *Risk analysis; Risk assessment; Risk management*.

Focusing on *Risk analysis*, it comprises the hazard analysis and the consequence analysis. In particular, the *Hazard analysis* is “the process of identification and characterisation of existing and/or potential landslides together with estimation of their corresponding frequency of occurrence”. *Consequence analysis*, in turn, is aimed to assess the vulnerability of the elements at risk once *i)* they are identified and quantified and *ii)* their temporal spatial probabilities are assessed.

Risk estimation is the final step of the *Risk analysis* and essentially consists in the risk calculation through a probabilistic equation. For instance, referring to the risk for life loss (Fell et al., 2008), the annual probability that *a particular person* (e.g. the most exposed one to the landslide risk) may lose his/her life $P^i_{(LOL)}$ can be calculated through the formula (Fell et al., 2005):

$$P^i_{(LOL)} = P^i_{(R)} \times P^i_{(T:R)} \times P_{(S:T)} \times V^i_{(D:T)} \tag{15}$$

where $P^i_{(R)}$ is the frequency of the landslide events of a given *i*-magnitude; $P^i_{(T:R)}$ is the probability of the landslide reaching the element at risk; $P_{(S:T)}$ is the temporal spatial probability of the element at risk; $V^i_{(D:T)}$ is the vulnerability of the person with respect to the landslide event.

A similar equation can be used when the risk for property loss (Fell et al., 2008) needs to be estimated; in such a case, however, the value or the net present value of the property must also be taken into account.

Finally, it is worth noting that if the element at risk is exposed to a number of different sizes of landslides of the same classification system, the risks pertaining to each landslide size can be summed in order to obtain the total risk (Corominas et al., 2005). In such a case, the expression (15) can be rewritten as:

$$P_{(LOL)} = \sum_{i=1}^{n} \left(P^i_{(R)} \times P^i_{(T:R)} \times P_{(S:T)} \times V^i_{(D:T)} \right) \tag{16}$$

n being the number of landslide volume classes.

In the following, with reference to the different kinds of flow-like mass movements that can affect the Monte Albino hillslopes (including flooding phenomena), the adopted procedures and the main results achieved in the quantitative risk for life loss analysis (and related zoning) are briefly summarised.

5.6.1 Risk of loss of life posed by the hyperconcentrated flows

As far as the hyperconcentrated flows are concerned, the main purpose of the QRA analyses consisted on the assessment of the risk to life loss posed by the above phenomena to persons living in the urbanised area at the toe of the Monte Albino massif (Nocera Inferiore, Salerno Province). In order to pursue this goal, the methodological approach provided by Fell et al. (2005) and further deepened by SafeLand (2011c) was followed.

5.6.1.1 Hazard analysis: danger characterization

For QRA purposes hyperconcentrated flows patterns have been evaluated for each basin via the FLO-2D numerical code (O'Brien et al., 1993), referring to a rainfall event having T = 200 years (namely, the return period to be considered – in Italy – for the design of hydraulic control works) by using a DTM – of squared cells of 5 m x 5 m – obtained via the data achieved by a LIDAR survey.

A synthesis of the input data, in terms of water (V_{water}) and sediment (V_{sed}) volumes, for each of the involved basins, is reported in Table 5.3. It is worth noting that the water volumes were computed on the basis of the VAPI procedure given, for the Campania region, by Rossi and Villani (1995). As far as sediment volumes are concerned, they were estimated thanks to the erosion theory provided by Hungr (1995).

Basin	V_{sed} (m^3)	V_{water} (m^3)	V_{tot} (m^3)	V_{sed}/V_{tot}
1	2069.5	3953	6023	0.34
2	2982.5	7052	10035	0.30
3	3119.5	6890	10010	0.31
4	1689.0	3038	4727	0.36
5	705.5	1778	2484	0.28
6	4068.0	7405	11473	0.35
7	2016.0	4918	6934	0.29
8	2964.0	8237	11201	0.26
9	799.0	4586	5385	0.15
10	679.0	2775	3454	0.20

Table 5.3 Input data considered in the analyses dealing with the propagation stage of the hyperconcentrated flows.

In order to take into account the uncertainties related to rheological properties of the involved mixtures, the following combinations of the parameters τ (shear strength at the base of the propagating flow) and η (dynamic viscosity) were considered:

Scenario 1:

- $\tau = 1$ kPa
- $\eta = 1$ Pascal·sec

Scenario 2:

- $\tau = 1$ kPa
- $\eta = 0.1$ Pascal·sec

Scenario 3:

- $\tau = 0.1$ kPa
- $\eta = 0.1$ Pascal·sec

Finally, areas occupied by the buildings were assumed as “blocked” cells. Results of FLO-2D numerical code are furnished in terms of depth and velocity of hyperconcentrated flow fronts impacting the exposed houses. In particular, maximum values of both depths and velocities dealing with the cells located around each facility were considered for the analysis purposes. In particular, based on the numerical results, it was estimated that the probability $P_{(T:L)}$ of hyperconcentrated flow phenomena reaching the elements at risks (the houses and their occupants) is equal to:

- 1 if the propagating flows impacts a given house in all the considered scenarios;
- 0.66 if the propagating flows impacts a given house in two scenarios over three;
- 0.33 if the propagating flows impacts a given house in only one scenario.

5.6.1.2 Hazard analysis: frequency analysis

Complete landslide records covering a long time span may be used to perform the probabilistic analyses. According to Corominas and Moya (2008), two probability distributions can be used to assess the annual probability of occurrence of landslides: the binomial distribution and the Poisson distribution. The binomial distribution can be applied for the cases considering discrete time intervals and only one observation for interval (usually a year), as is typically made in flood frequency analysis. The annual probability of a landslide event of a given magnitude which occurs on average one time each T years is:

$$P_{(N=1;\,t=1)} = 1/T = P_{(L)} \tag{17}$$

where T is the return period of the event and $P_{(L)}$ the expected frequency for future occurrences.

Then, for the problem at hand in which 10 basins may be *potentially* involved by hyperconcentrated flow as a consequence of a rainfall event of return period T = 200 years, the following frequency value results:

$$P_{(L),200} = 1/200 \cdot 0.5 = 0.0025\ events/year \tag{18}$$

with 0.5 being the (assumed) probability that a given basin should be *really* involved by a hyperconcentrated flow during the above rainfall event.

5.6.1.3 Consequence analysis

The $P_{(S:T)}$ terms were computed on the basis of the age of the inhabitants. In particular, the adopted values are reported in Table 5.4. It is worth observing that, when information about people living in the impacted houses were lacking, it was safely assumed a $P_{(S:T)}$ value equal to 1.

Age (years)	**$P_{(S:T)}$**
0 ÷ 5	1
6 ÷ 18	0.75
19 ÷ 65	0.5
66 ÷ 75	0.75
> 75	1

Table 5.4. Temporal-spatial probability value adopted on the basis of the age of the inhabitants.

The social vulnerability factors $V_{(D:T)}$ for *persons most at risk living* within the potentially impacted buildings (i.e., having $P_{(T:L)} \neq 0$) have been assessed via a "direct approach" (Wong et al., 1997); the corresponding values are reported in Table 5.5 as a function of the output data of the FLO-2D numerical code. In particular, these values correspond to the average maximum values of both depth and velocity of hyperconcentrated flows fronts obtained with reference to the cells surrounding a given house.

Case	**flow depth h (m) / velocity v (m/s)**	**Adopted $V_{(D:T)}$ value**
1. If the building is inundated with sediment-fluid mixture and the person have a high chance to be buried	$h \geq 1$ and $v \geq 5$	0.15
	$h \geq 1$ and $1 \leq v < 5$	0.1
	$0.5 \leq h < 1$ and $v \geq 5$	0.1
2. If the building is inundated with the sediment-fluid mixture and the persons have a low chance to be buried	$h \geq 1$ and $v < 1$	0.08
	$0.5 \leq h < 1$ and $1 \leq v < 5$	0.08
	$h < 0.5$ and $v \geq 5$	0.08
	$0.5 \leq h < 1$ and $v < 1$	0.05
	$h < 0.5$ and $1 \leq v < 5$	0.05
3. If the sediment-fluid mixture strikes the building only	$h < 0.5$ and $v < 1$	0.02

Table 5.5. $V_{(D:T)}$ values adopted with reference to the vulnerability of the person most exposed at the hyperconcentrated flow risk.

5.6.1.4 Risk estimation

The obtained results, in terms of individual risk to life, were summarised in a map (Figure 5.8) showing, for each of the houses impacted by the hyperconcentrated flows, the corresponding $P_{(LOL)}$ referred to the person most at risk. It is worth noting that some of the most exposed persons have a risk higher than 10^{-4}/annum, namely the risk tolerability threshold established by the Geotechnical Engineering Office (1998b) of Hong Kong.

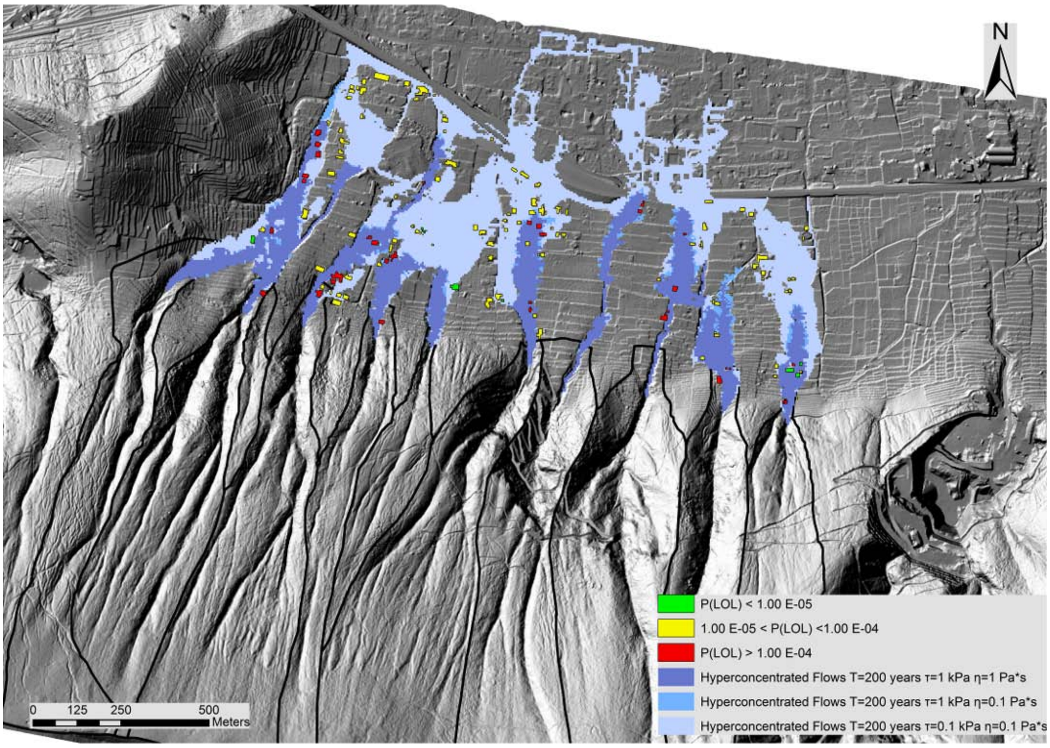


Figure 5.8 Map of the risk to life loss posed by the hyperconcentrated flows (Cascini 2011)

5.6.2 Risk of loss of life posed by the flowslides

As far as the risk to life loss posed by the flowslides, the analyses were carried out similarly to those previously described for the hyperconcentrated flows.
Anyway, for rainfall events having a return period T = 200 years, the mobilised soil volumes at the source areas were obtained by using the TRIGRS physically-based model (Baum et al., 2002) as well as the Infinite Slope Model implemented in a GIS environment (Figure 5.9).

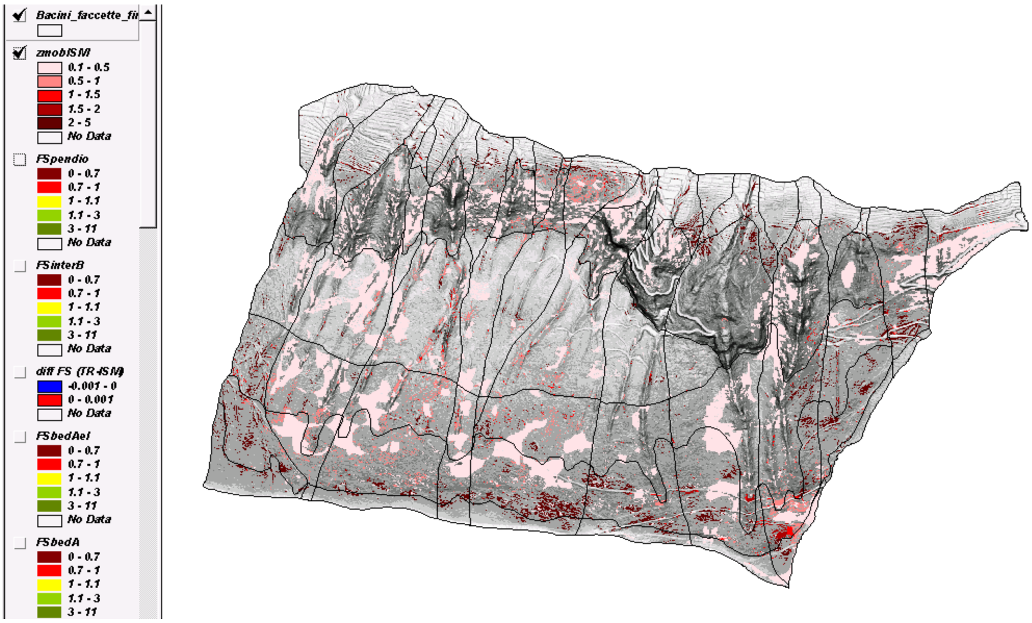


Figure 5.9 Stable (FS > 1) and unstable (FS≤ 1) areas obtained via the use of the Infinite Slope Model for a rainfall event having a return period T = 200 years.

On the other hand, only one scenario of propagation stage (via the FLO-2D numerical code, assuming $\tau = 1$ kPa and $\eta = 2$ Pascal·sec) was considered while the vulnerability values were assumed according to the information provided in Table 5.6.

Case	flow depth h (m) / velocity v (m/s)	Adopted $V_{(D:T)}$ value
1. If the building is inundated with debris and the person have a high chance to be buried	$h \geq 1$ and $v \geq 7$	1
	$h \geq 1$ and $3 \leq v < 7$	0.8
	$0.5 \leq h < 1$ and $v \geq 7$	0.8
2. If the building is inundated with debris and the persons have a low chance to be buried	$h \geq 1$ and $v < 3$	0.4
	$0.5 \leq h < 1$ and $3 \leq v < 7$	0.4
	$h < 0.5$ and $v \geq 7$	0.4
	$0.5 \leq h < 1$ and $v < 3$	0.2
	$h < 0.5$ and $3 \leq v < 7$	0.4
5. If the debris strikes the building only	$h < 0.5$ and $v < 3$	0.05

Table 5.6 $V_{(D:T)}$ values adopted with reference to the vulnerability of the person most exposed at the flowslide risk.

The obtained results, in terms of individual risk to life, were summarised in a map (Figure 5.10) showing, for each of the houses impacted by the flowslides, the corresponding $P_{(LOL)}$ referred to the person most at risk. Obviously, passing from the hyperconcentrated flow to flowslide phenomena, the number of the most exposed persons having a risk higher than 10^{-4}/annum strongly increases as $V_{(D:T)}$ values increase.

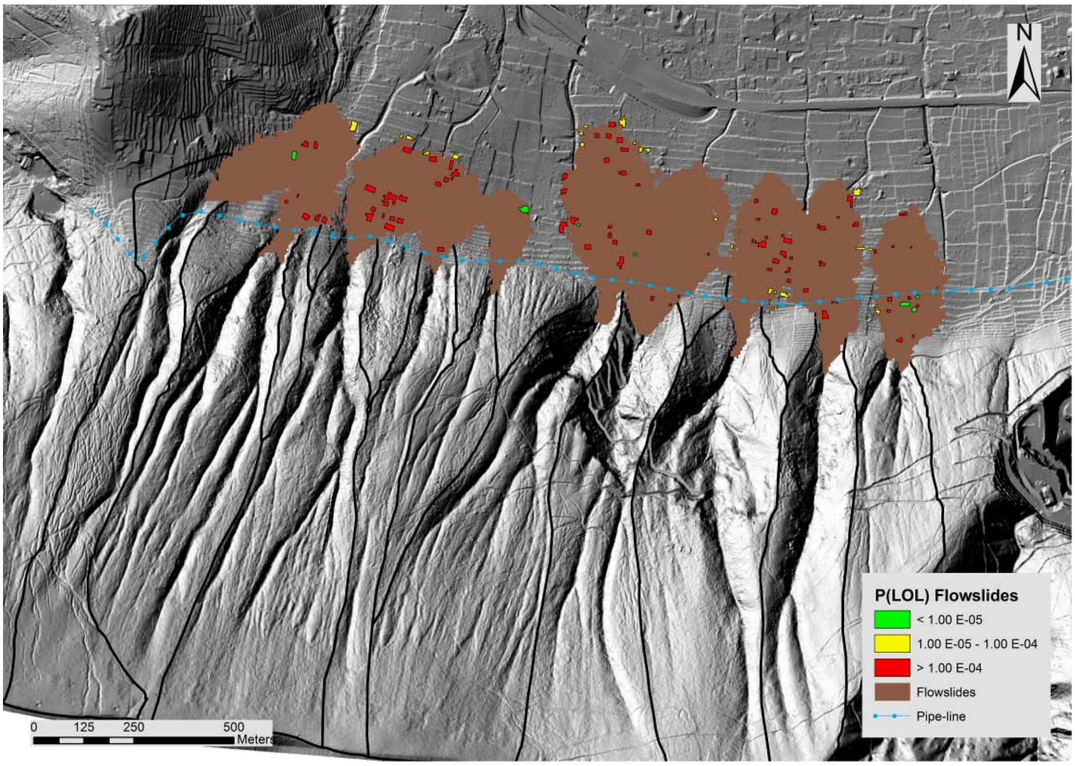


Figure 5.10 Map of the risk to life loss posed by the flowslides (Cascini 2011).

5.6.3 Risk to life loss posed by the landslides on open slopes

Referring the risk to life loss posed by the landslides on open slopes, the run-out distance was computed by adopting a heuristic criterion, taking into account the shape of the ancient alluvial fans.

The landslide frequency $P_{(L)}$ was computed considering that, on the basis of historical information, 4 events occurred, over a period of 80 years, in a total of 10 open slopes. As a consequence:

$$P_{(L)} = \left(4/80\right)\cdot\left(1/10\right) = 0.005/\mathit{annum} \tag{19}$$

The vulnerability $V_{(D:T)}$ was, in turn, estimated considering the criterion explained in Figure 5.11, similar to that proposed by Wong (2005). The obtained results, in terms of individual risk to life, were summarised in a map (Figure 5.12) showing, for each of the houses impacted by the flowslides, the corresponding $P_{(LOL)}$ referred to the person most at risk. It is worth to observe that the most exposed persons have, in the case of landslides on open slopes, the highest risk among those obtained for the different kind of flow-like mass movements that could originate from Monte Albino hillslopes.

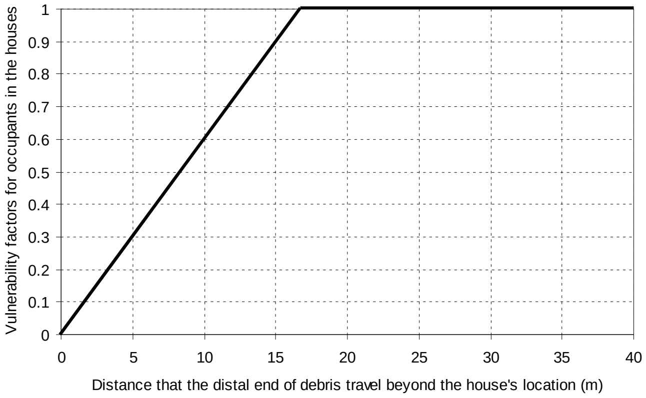


Figure 5.11 Vulnerability factors.

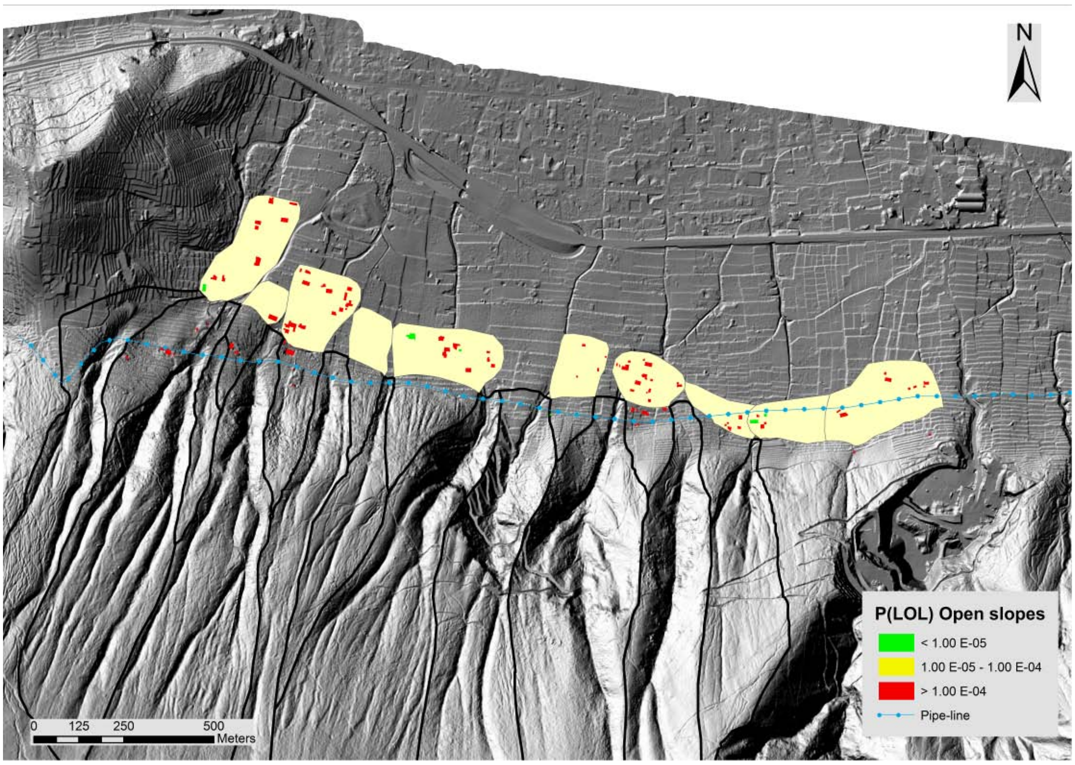


Figure 5.12 Map of the risk to life loss posed by the landslides on open slopes (Cascini 2011).

5.6.4 Risk posed by the flooding phenomena

As far as the risk to life loss posed by the flooding phenomena is concerned, a rainfall event having a return period T = 100 years was considered for the analysis purposes. On the basis of the results obtained via the FLO-2D numerical code, the vulnerability values were assumed according to the information provided by Table 5.7.

The obtained results, in terms of individual risk to life, were summarised in a map (Figure 5.13) showing, for each of the houses impacted by the flooding phenomena, the corresponding $P_{(LOL)}$ referred to the person most at risk. It is worth noting that the obtained risk values are tolerable for all persons most at risk.

Case	flow depth h (m) / velocity v (m/s)	Adopted $V_{(D:T)}$ value
1. If the building is inundated with the water and the person have a high chance to be buried	$h \geq 1$ and $v \geq 5$	0.1
	$h \geq 1$ and $1 \leq v < 5$	0.05
	$0.5 \leq h < 1$ and $v \geq 5$	0.05
2. If the building is inundated with the water and the persons have a low chance to be buried	$h \geq 1$ and $v < 1$	0.025
	$0.5 \leq h < 1$ and $1 \leq v < 5$	0.025
	$h < 0.5$ and $v \geq 5$	0.025
	$0.5 \leq h < 1$ and $v < 1$	0.01
	$h < 0.5$ and $1 \leq v < 5$	0.01
3. If the water strikes the building only	$h < 0.5$ and $v < 1$	0.005

Table 5.7 $V_{(D:T)}$ values adopted with reference to the vulnerability of the person most exposed at the flooding risk.

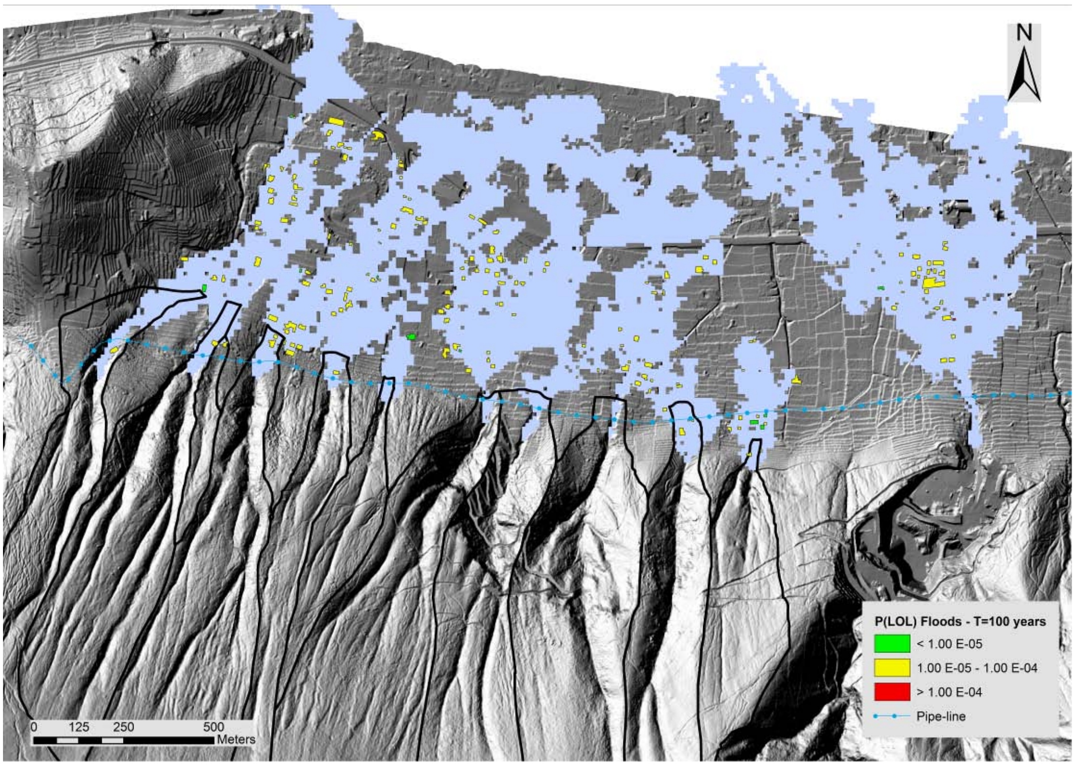


Figure 5.13 Map of the risk to life loss posed by the flooding phenomena (Cascini 2011).

5.6.5 Societal risk

The results obtained from QRA analyses can be used also to determine the so-called “societal risk”, i.e. *the risk of widespread or large scale detriment from the realization of a defined risk, the implications being that the consequence would be on such a scale as to provoke socio/political response* (Leroi et al., 2005). The estimation of the societal risk allows the achievement of different purposes, among which the ranking of the portions of a given urbanised territory at landslide risk and, thus, the prioritization of the areas needing mitigation measures.

In order to pursue this aim for the problem at hand, the urbanised area at the toe of the Monte Albino massif was previously subdivided in 6 sectors whose shape and size were established on the basis of the run-out distance results accomplished via the analyses explained in the previous paragraphs. Then, on the basis of the QRA results obtained – for all the considered flow-like mass movement risk (excluding floods) scenarios – in terms of annual probability of loss of live for the persons living within the exposed houses, the maximum number of equivalent victims (Wong et al., 1997) to be expected for each of the considered sectors was finally assessed. This allowed the ranking of the sectors at risk, as shown in Figure 5.14. It is worth noting that the most exposed sectors are those labelled with symbols S2, S5 and S4 where an equivalent number of victims equal to 149, 106 and 78 can be respectively expected.

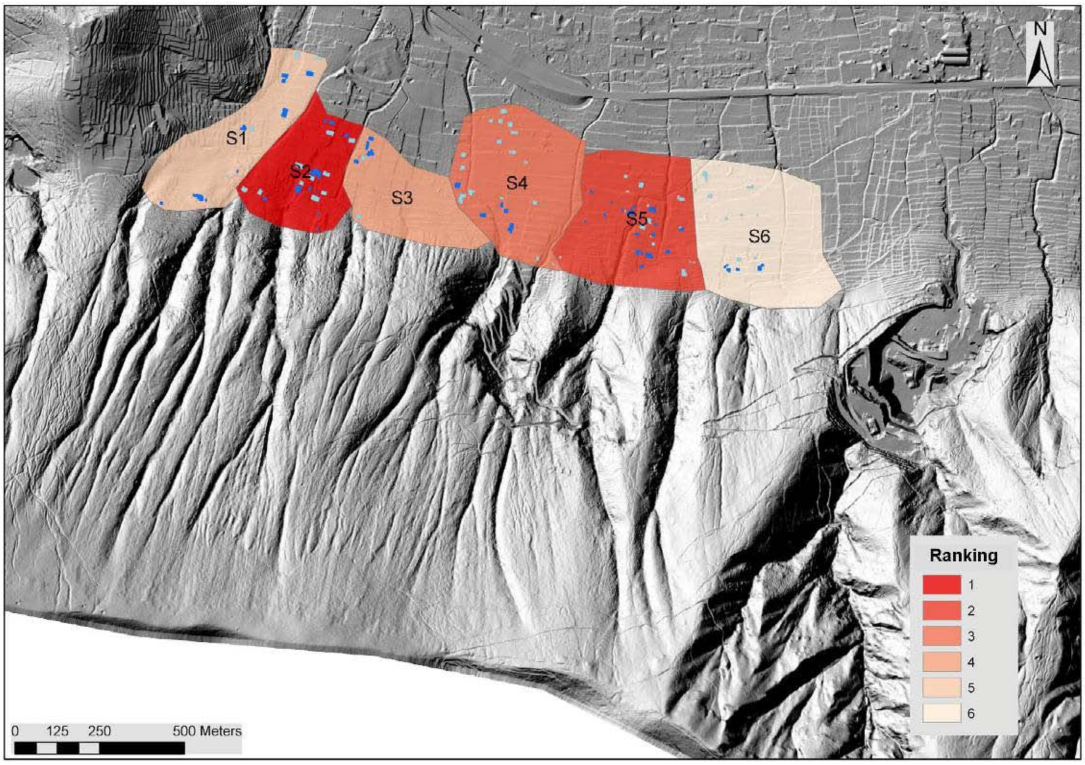


Figure 5.14 Ranking of the sectors at flow-like mass movement risk established for the urbanised area at the toe of the Monte Albino massif. The houses highlighted in blue are those for which the risk to life loss for the person most at risk living inside is the highest.

5.7 PROPOSAL PACKAGES FOR RISK MITIGATION MEASURES

On the basis of the acquired knowledge of the phenomena to which the Monte Albino hillslopes are prone as well as the results achieved by the QRA analyses described above and also information provided from the interviews and work of the different focus groups as part of the ongoing participatory stakeholder process in Nocera Inferiore (WP5.2 of the SafeLand

Project), three packages of risk mitigation measures and a compromise package have been conceived. The three packages are based, in part, on the three policy narratives that have been established for risk management in the region as part of the work of WP 5.2 (Stakeholder process for choosing an appropriate set of mitigation and prevention measures) of the SafeLand project; extracts of these policy narratives are provided below. Hazard and risk maps and risk-cost-benefit analyses are useful in guiding the necessary investments into these packages.

The studies carried out highlighted that the Monte Albino hillslopes are prone to flow-like mass movements characterised by own triggering mechanism, propagation stage and return period. By neglecting the role played by the alarm systems, it can be argued that persons living at the toe of the Monte Albino are exposed to a very high landslide risk. Taking into account social and technical aspects, in order to mitigate the risk it is possible to establish – among the different solutions – three options whose cost ranges between 23 and 30 million Euros. Bearing in mind that the available funds are limited, the above options must be re-conceived so that their cost does not exceed 7 million Euros.

The mitigation measures are conceived with the aim to protect both persons and properties. If the available funds are limited, the safeguard of the inhabitants becomes the priority. In this regard, the alarm systems may play a relevant role in the reduction of the people exposure with reference to the phenomena characterised by a high return period (namely, hyperconcentrated flows and flowslides). On the contrary, for the phenomena characterised by a low return period (namely, landslides on open slopes and flooding phenomena), the alarm systems could not be adequate for the people safeguarding and control works would be realised. On the basis of these considerations, the “excerpts” of the risk mitigation packages or options were established and provided along with the description of the entire risk mitigation package (all the excerpts include an efficient alarm system and a territorial survey).

5.7.1 Option 1 – Mixed control works (active and passive)

The first risk mitigation option is titled “Mixed control works (active and passive)” and is based on the policy narrative titled “Protect lives and properties”. The focus here is on spending the available public resources to assure the greatest protection possible, recognising that protection before lives and property are lost than would possibly cost less compared to the amount incurred in compensating victims and other losses after the disaster. A careful mix of active measures such as cleaning drains and properly managing forests and limited passive measures including decanting structures and storage basins is envisaged. With sufficient investments, risks can be reduced to acceptable levels but there will still remain some residual risks. Existing buildings in high risk areas should be safeguarded and only under very exceptional cases should homes be relocated. Local public authorities should have more responsibility for preventing future construction in designated high-risk areas. Early warning systems combined with emergency plans are important and the existing system needs to be improved and further developed. Since the local population may not have adequate information on the risks, it is important that to inform the local population on the working of the warning system works, e.g., what to do in the case of a warning and whom to rely upon.

Based on the above policy narrative and other site specific analyses and considerations, this risk mitigation package option titled "Mixed control works (active and passive)" (Figure 5.15) consists of:

- active control works *i)* in the flowslide source areas (e.g., via steel paling), *ii)* along the river banks (e.g., via their reshaping), *iii)* over the open slopes (e.g., via the use of naturalistic engineering works);
- passive control works corresponding to storage basins, located at the toe of the catchments, to be designed for hyperconcentrated flows having a return period T = 200 years.

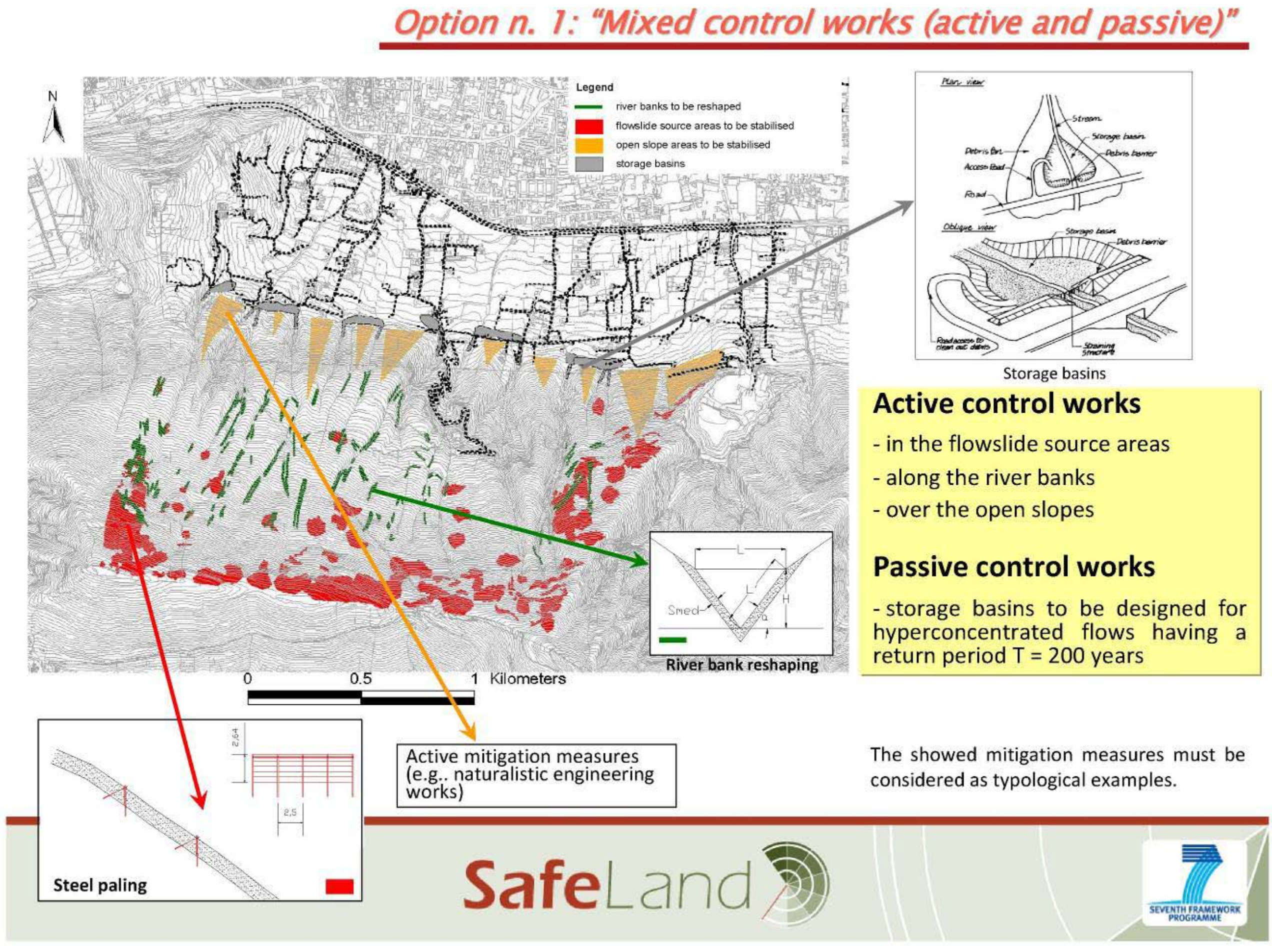


Figure 5.15 Risk mitigation measures – Option 1 (Cascini 2011).

The excerpt of this option consisting of active control works over the open slopes and passive control works corresponding to storage basins, located at the toe of the catchments, to be designed for hyperconcentrated flows having a return period T = 200 years is shown in Figure 5.16. The cost breakdown for this risk mitigation option is shown in Table 5.8.

Category	**Typology**	**Cost [€] per typology**	**Cost [€] per category**	**Total cost [€]**
Active mitigation measures	Anchored sheet piling (to stabilize a total area of about 3 ha)	1,354,087	1,354,087	***6,950,842***
Passive mitigation measures	n. 6 storage basins (including n. 2 of 16,200 m^3, n. 5 of 12,200 m^3, n. 3 of 6,000 m^3 in capacity)	5,296,755	5,296,755	
Non-structural mitigation measures	Warning system	300,000	300,000	

Table 5.8 Cost breakdown of excerpt for risk mitigation option 1

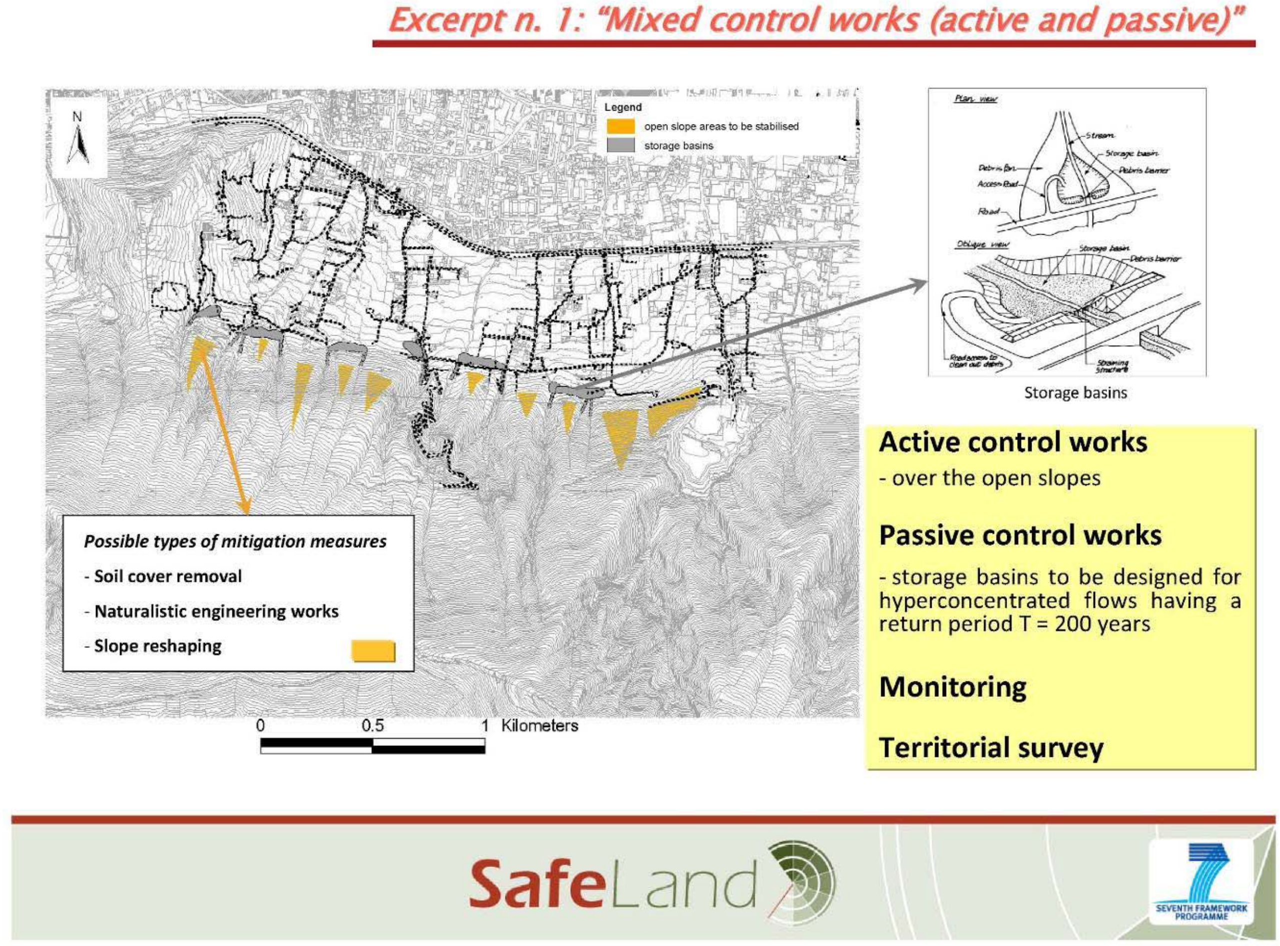


Figure 5.16 Risk mitigation measures – Excerpt of option 1 (Cascini 2011).

5.7.2 Option 2 – Active control works, forestation and natural park

The title of the second risk mitigation option is "Active control works, forestation and natural park" and this is based on the policy narrative titled "***Careful stewardship of the mountain***". Because of anthropogenic activities including environmentally detrimental practices (such as building roads, industrial activities and even cattle grazing), the region has become less stable and subject to dangerous landslides, with climate change possibly worsening the situation. While some immediate measures will be needed to reduce the acute risks to residents of Monte Albino, the critical long-term issue is dealing with the multitude of factors contributing to the instability of the slopes. Not only must the residents be protected, but also the natural cycles and the evolving mountain terrain should be respected. This will mean taking a more holistic and ecological view of the mountain and its maintenance – this is the focus of this policy narrative.

The risk mitigation measures conceived in this narrative are active measures including naturalistic engineering works (e.g. hydroseeding, turfing, trees/brushes, fascines, geosynthetics). One of the interventions is the creation of a natural park at the toe of the slope to reduce the urbanization in the area. Also a network of naturalistic paths is planned to give the opportunity to local residents to appreciate the mountain areas and to "control" the territory at the same time. In addition to the park and the paths, small scale organic farming on the mountain and a better management of the forest (including both public and private properties) could be encouraged. Activities that promote a sustainable future for the area will likely need support through public-private partnerships. It is also seen necessary to investigate industrial activities in the area and more forcibly prohibit and/or restrict construction in some areas. In some exceptional cases, however, it may be necessary to relocate homes. The use of early warning systems combined with emergency plans is important and such systems should be improved and further developed. It is very important that the residents are involved in the design and implementation of these systems.

The second risk mitigation package option titled "Active control works, forestation and natural park" and based on the above policy narrative and other site specific analyses and considerations consists of (Figure 5.17):

- active control works *i)* in the flowslide source areas (e.g., via steel paling), *ii)* along the river banks (e.g., via their reshaping), *iii)* along the rills (e.g., via the use of gabions), iv) over the open slopes (e.g., via the use of naturalistic engineering works);
- passive control works corresponding to water tanks to be localised in the urbanised area at toe of the Monte Albino;
- forestation, with oak threes located at the of the Monte Albino hillslopes;
- creation of a natural park in correspondence of the urbanised area at toe of the Monte Albino massif.

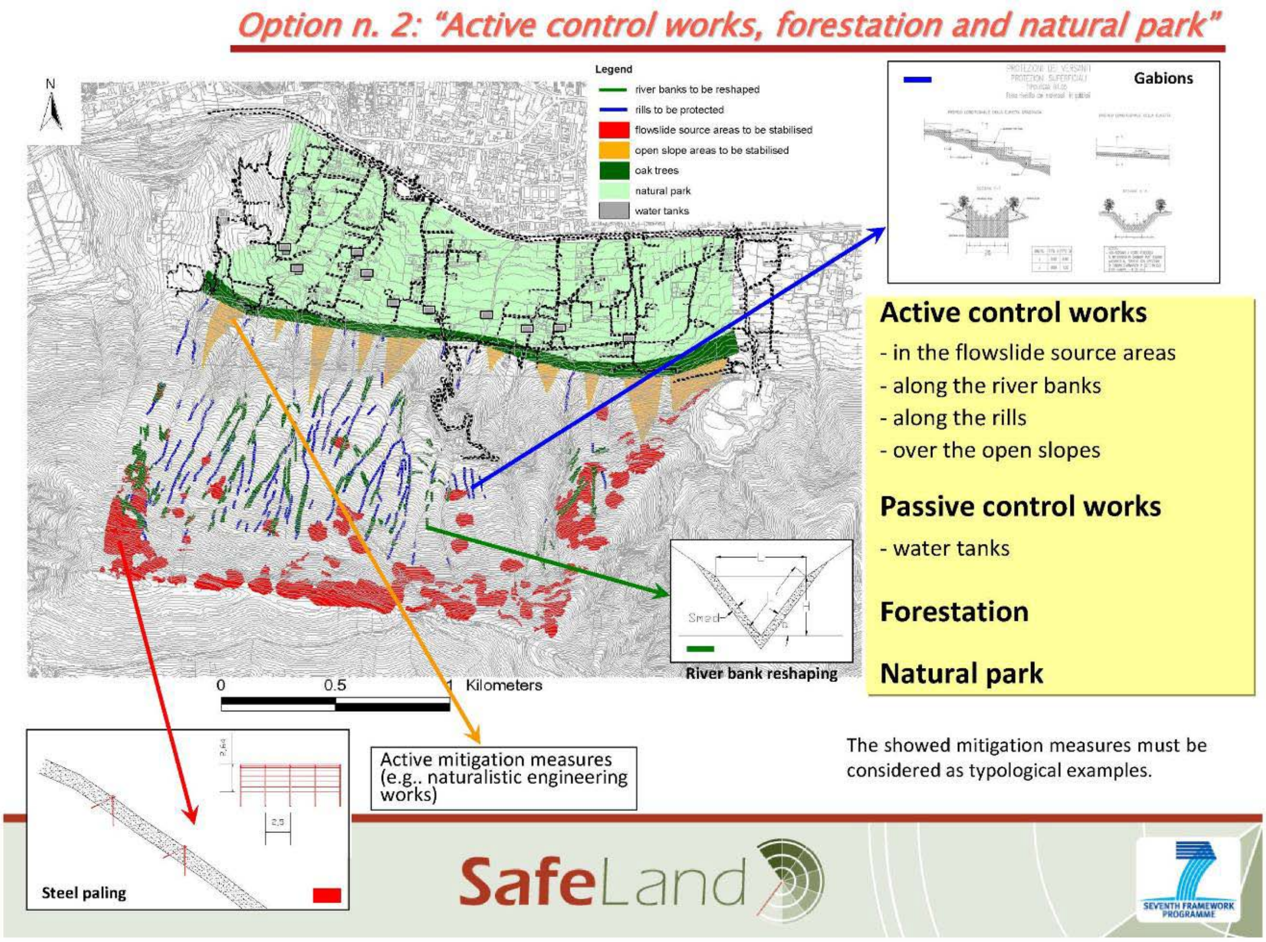


Figure 5.17 Risk mitigation measures – Option 2 (Cascini 2011).

The excerpt of this option consisting of active control works over the open slopes and along the rills, passive control works corresponding to water tanks to be localised in the urbanised area at toe of the Monte Albino and forestation, with oak trees located at the of the Monte Albino hillslopes is shown in Figure 5.18. The cost breakdown for this risk mitigation option is shown in Table 5.9.

Category	Typology	Cost [€] per typology	Cost [€] per category	Total cost [€]
Active mitigation measures	Anchored sheet piling (to stabilize a total area of about 3 ha)	1,354,087	3,061,372	***6,930,397***
	Gabions (to mitigate the erosion in correspondence of rills developing for a total length of about 10,700 m)	1,707,285		
Passive mitigation measures	Water tanks	2,000,000	2,000,000	
	Forestation	1,569,025	1,569,025	
Non-structural mitigation measures	Warning system	300,000	300,000	

Table 5.9 Cost breakdown of excerpt for risk mitigation option 2

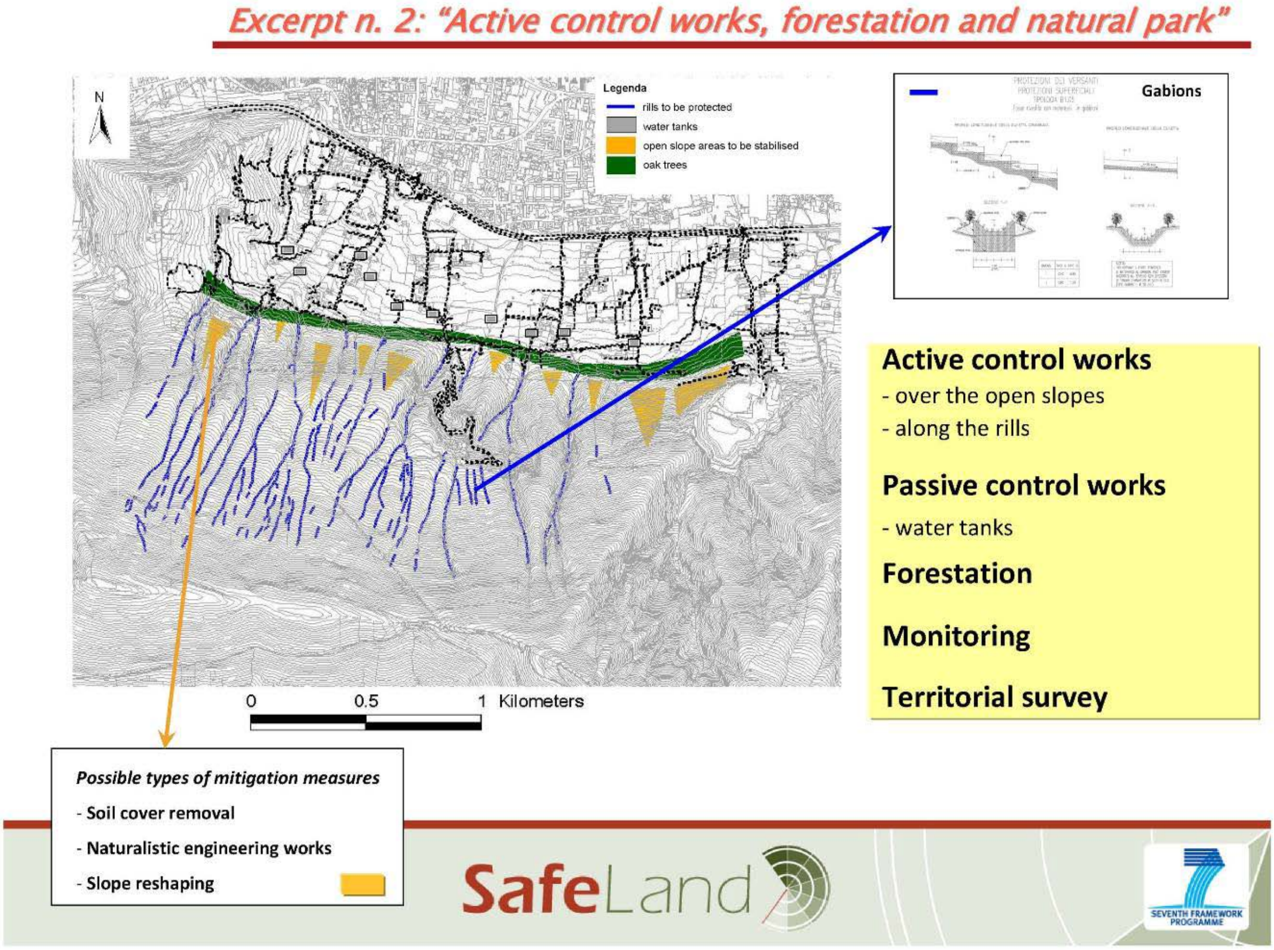


Figure 5.18 Risk mitigation measures – Excerpt of option 2 (Cascini 2011).

5.7.3 Option 3 – Relocation

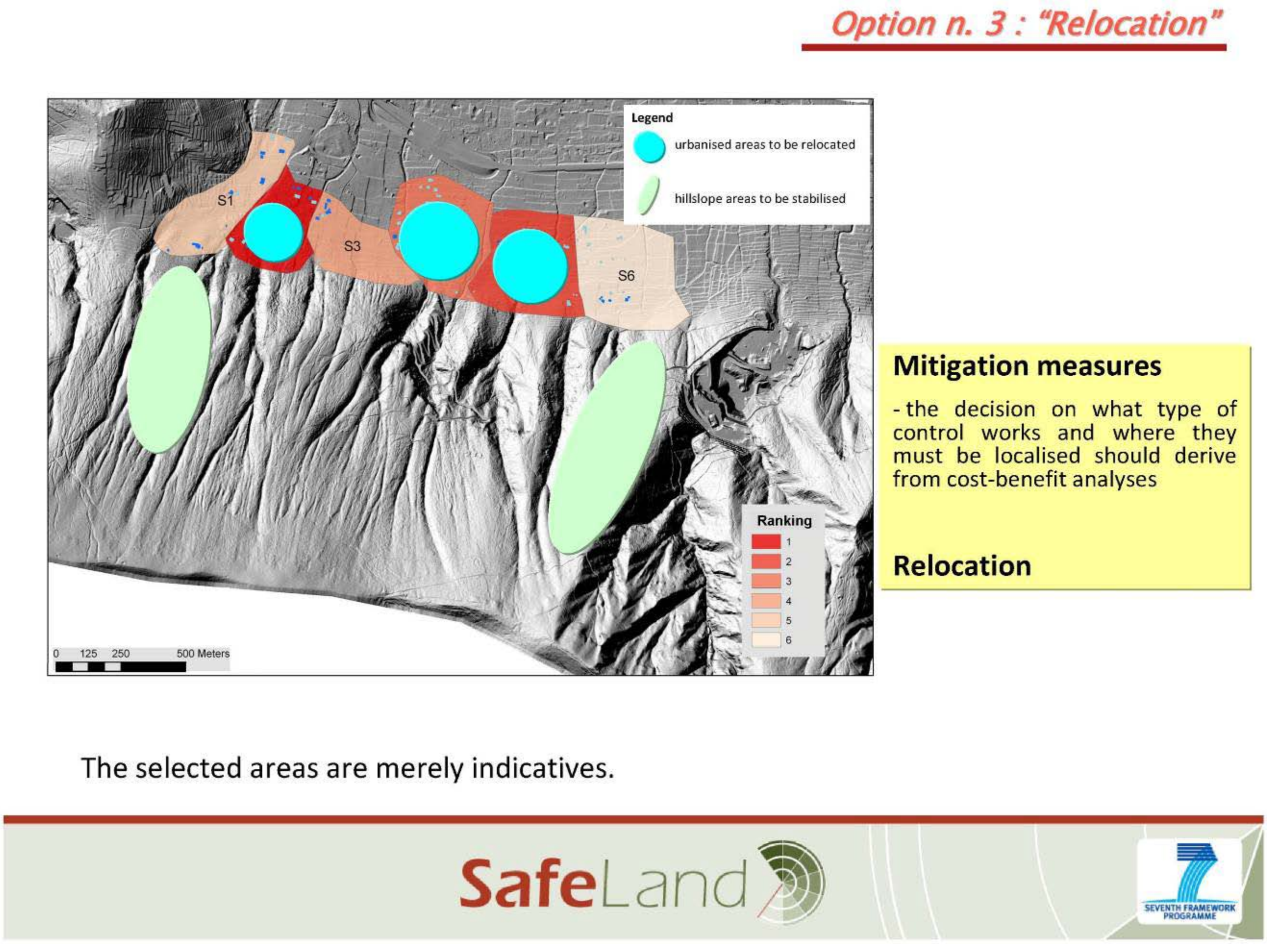
The third risk mitigation option is titled “Relocation” and is based on the policy narrative is titled “***rational individual choice***”. This narrative takes a broader view, appreciating the fact that the risk due to landslide is not the only (and probably not the main one) concern of the residents of the affected areas, with unemployment, environmental pollution, waste management being among other worries. Moreover, many residents also face a risk of flooding, and it may be more cost effective to invest in flood prevention. It is very important to allocate scarce public resources taking account of all the priorities of the municipalities, and for this reason it is important to evaluate the use of public funds if “no action” for landslides is taken.

If, however, the landslide risk is shown to be high and unacceptable, then investments for the mitigation of these risks need to be carefully considered. It is hence important to calculate the costs and the benefits of the mitigation measures and communicating them to the stakeholders. This will eventually determine the nature of investment, whether into *active* (eg. cleaning drains, reforestation) measures, *passive* (eg., embedded walls or reinforced fills) measures *or more holistic* (creating a park or subsidies for organic farming) measures. What is of utmost importance here is that residents are aware of the risks they are facing. If the residents are adequately informed and aware of the underlying risks, the decision on relocation is left to them. While public compensation is justified for those wishing to relocate, it should not be applied to anyone consciously deciding to build in a dangerous area after information is available. There remains a residual risk, however, even in some unrestricted areas, and to protect residents against the economic risk, insurance should be more readily available. As before, early warning systems combined with emergency plans are important and existing systems should be improved.

Based on the above policy narrative and other site specific analyses and considerations, the third risk mitigation package option titled “Relocation” implies (Figure 5.19):

- the relocation of some houses located in the most at risk areas at the toe of the Monte Albino massif;
- the realisation of active control works along chosen catchments.

It is worth noting that the decision on what type of control works and where they must be localised may be derived from cost-benefit analyses.



Option n. 3 : “Relocation”

Mitigation measures

- the decision on what type of control works and where they must be localised should derive from cost-benefit analyses

Relocation

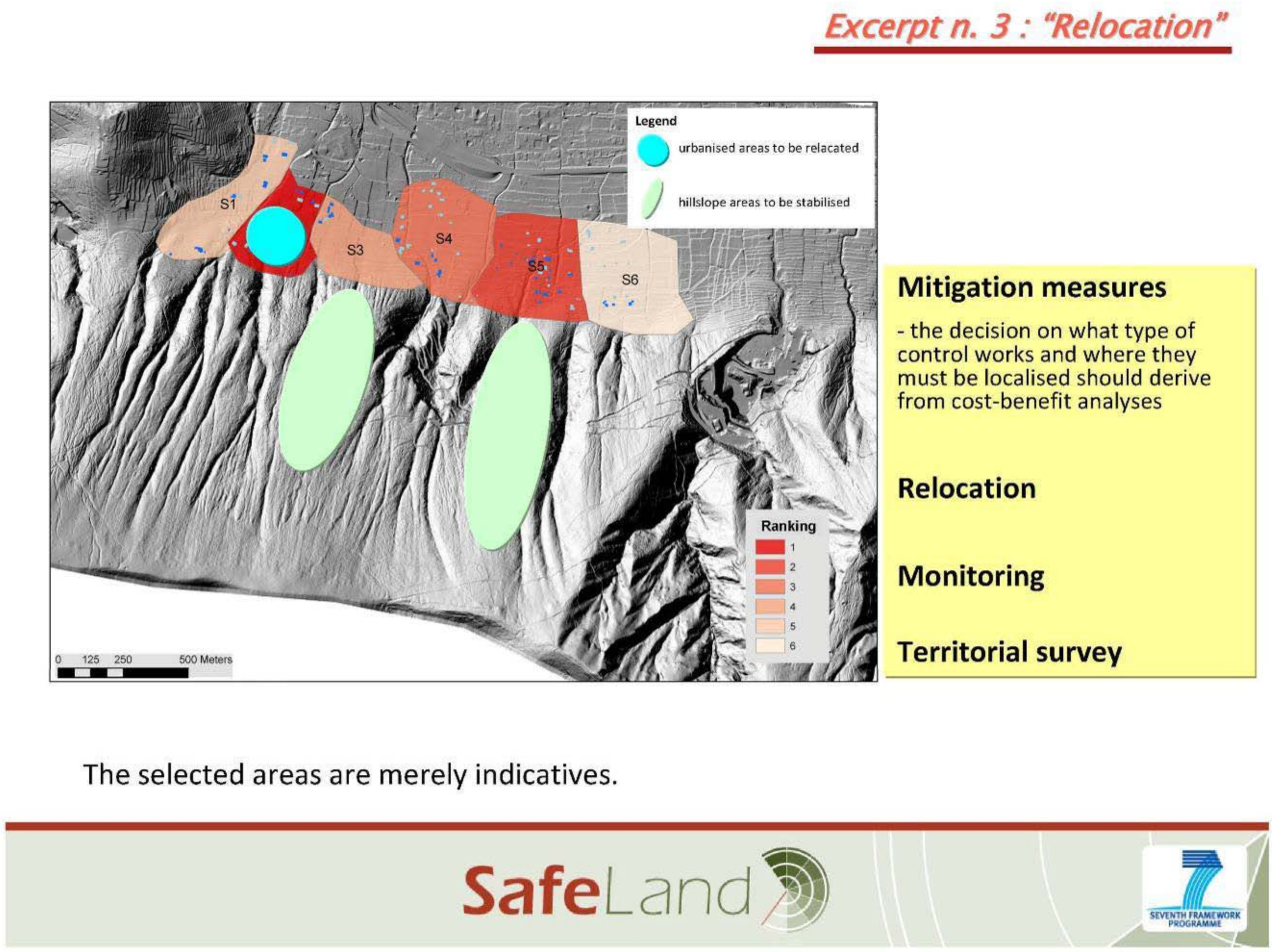
The selected areas are merely indicatives.

Figure 5.19 Risk mitigation measures – Option 3 (Cascini 2011).

The excerpt of option 3 entitled “Relocation” consisting of the relocation of some houses located in the most at risk areas at the toe of the Monte Albino massif and the realisation of active control works along chosen catchments is shown in Figure 5.20. The cost breakdown for this risk mitigation option is shown in Table 5.10.

Category	**Typology**	**Cost [€] per typology**
Active mitigation measures	To be established on the basis of CBA results	-
Passive mitigation measures	To be established on the basis of CBA results	-
Non-structural mitigation measures	Relocation (of n. 29 households, for instance)	3,480,000
	Warning system	300,000

Table 5.10 Cost breakdown of excerpt for risk mitigation option 3



Excerpt n. 3 : "Relocation"

Mitigation measures

- the decision on what type of control works and where they must be localised should derive from cost-benefit analyses

Relocation

Monitoring

Territorial survey

The selected areas are merely indicatives.

Figure 5.20 Risk mitigation measures – Excerpt of option 3 (Cascini 2011).

5.7.4 Compromise solution

Finally, a compromise solution has been proposed considering elements from the three risk mitigation measures described above.

In particular, the solution includes the implementation of an integrated system of monitoring and territorial survey as well as the:

1. stabilization of all the open slopes via naturalistic engineering works and - if this is reasonable, possible and acceptable by the participants - relocation of maximum 2 ÷ 4 households at the toe of 1 ÷ 2 open slopes (this last option necessarily calls for the agreement of the homes-candidates for relocation);
2. realization of a storage basin at the mouth of each catchment to capture the water volumes associated to flooding having a return period of T = 200 years;
3. erosion control works along the rills over the hillslopes via "km zero" (i.e. using directly the material provided by the forest) naturalistic engineering works;
4. knowledge deepening all over the massif to identify the most appropriate active measures to be developed in the next future to stabilize the flowslides' source areas.

The cost breakdown for this compromise risk mitigation option is shown in Table 5.11.

Category	Typology	Cost [€] per typology	Cost [€] per category	Total cost [€]
Active mitigation measures	Naturalistic engineering works (to stabilize a total area of about 3 ha)	1,354,087	3,061,372	***6,931,938***
	"km 0" naturalistic engineering works (to mitigate the erosion in correspondence of rills developing for a total length of about 10,700 m)	1,707,285		
Passive mitigation measures	n. 6 storage basins	3,090,566	3,090,566	
Non-structural mitigation measures	Relocation of n. 4 households	480,000	480,000	
	Warning system	300,000	300,000	

Table 5.11 Cost breakdown of excerpt for compromise risk mitigation option

5.8 EVALUATION OF BENEFITS FROM RISK MITIGATION MEASURES

5.8.1 Evaluation of reduction in risk of loss of life

The results obtained from the estimation of societal risk and presented in section 5.6.5 were used as the basis for the estimation of benefits (in the form of reduction in the risk of loss of life) due to the implementation of the risk mitigation options. Basing on the result of the societal risk estimation, the residual risk of loss of life – for each of the three "excerpts" of mitigation packages and the proposed compromise solution – was estimated as the ratio between the number of equivalent victims related to the occurrence of a given phenomenon (flowslide, landslide on open slope, hyperconcentrated flow) having a return period T = 200 years and the maximum number of equivalent victims computed in the absence of mitigation measures (both structural and non-structural).

The obtained results are reported in Tables 5.12, 5.13, 5.14 and 5.15. It is worth noting that, in the Tables, the residual risk (1) values related the execution of the structural (active and passive) mitigation measures was differentiated from the "tolerable" residual risk (2) value to be achieved by considering also the existence of an warning system. In this latter case, the tolerability criterion (in terms of F-N curve) provided by the Geotechnical Engineering Office (1998b) of Hong Kong was adopted for the analysis purposes (Figure 5.21). Of course, the value (in percentage) of the difference Δ = residual risk (1) – residual risk (2) can be considered as an indirect measure of the efficiency to be pursed, for each of the urbanised sector, in designing the warning system.

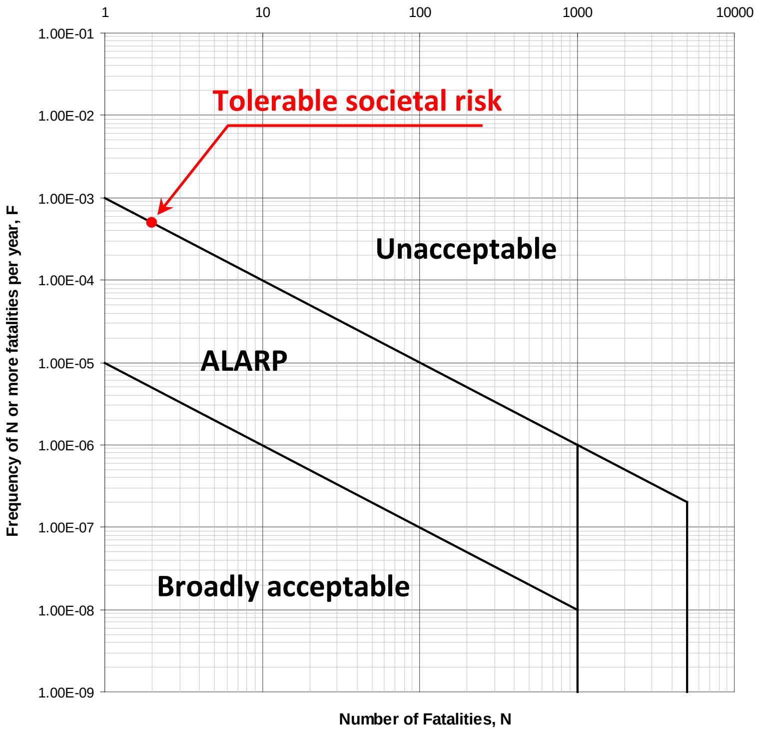


Figure 5.21 Interim societal risk tolerance criterion (Geotechnical Engineering Office, 1998b).

	RESIDUAL RISK [%]					
	Flowslides (a)	**Landslides on open slopes (b)**	**Hyperconcentrated flows (c)**	**Residual risk (1) (d = a + b + c)**	**Residual risk (2) (e)**	**Δ [%] (f = d – e)**
SECTOR 1	13.3	6.7	0.0	20.0	4.4	15.6
SECTOR 2	7.5	0.0	0.0	7.5	1.3	6.2
SECTOR 3	0	9.8	0.0	9.8	3.9	5.9
SECTOR 4	34.6	0.0	0.0	34.6	2.6	32.0
SECTOR 5	20.8	0.0	0.0	20.8	1.9	18.9
SECTOR 6	30.8	0.0	0.0	30.8	5.1	25.7

Table 5.12 Residual risk values associated with the excerpt of risk mitigation option 1

(1) Residual risk to loss of life related to the execution of the structural (active and passive) mitigation measures.
(2) Tolerable residual risk to loss of life to be achieved also considering the existence of a warning system.

	RESIDUAL RISK [%]					
	Flowslides (a)	**Landslides on open slopes (b)**	**Hyperconcentrated flows (c)**	**Residual risk (1) (d = a + b + c)**	**Residual risk (2) (e)**	**Δ [%] (f = d – e)**
SECTOR 1	15.6	8.9	0.0	24	4.4	19.7
SECTOR 2	32.9	19.5	0.0	52	1.3	50.4
SECTOR 3	21.6	15.7	0.0	37	3.9	32.9
SECTOR 4	41.0	2.6	0.0	44	2.6	41.4
SECTOR 5	26.4	3.8	0.0	30	1.9	28.2
SECTOR 6	35.9	2.6	0.0	38	5.1	32.7

Table 5.13 Residual risk values associated with the excerpt of risk mitigation option 2

(1) Residual risk to loss of life related to the execution of the structural (active and passive) mitigation measures and the forestation.
(2) Tolerable residual risk to loss of live to be achieved also considering the existence of an warning system.

	RESIDUAL RISK [%]					
	Flowslides (a)	**Landslides on open slopes (b)**	**Hyperconcentrated flows (c)**	**Residual risk (1) (d = a + b + c)**	**Residual risk (2) (e)**	**Δ [%] (f = d – e)**
SECTOR 1	13.3	8.9	0.0	22	4.4	17.6
SECTOR 2	0.0	0.0	0.0	0.0	0.0	0.0
SECTOR 3	29.0	67.0	4.0	100	3.9	96.1
SECTOR 4	58.0	38.0	4.0	100	2.6	97.4
SECTOR 5	23.6	5.7	0.0	29	1.9	27.1
SECTOR 6	49.0	46.0	5.0	100	5.1	94.9

Table 5.14 Residual risk values associated with the excerpt of risk mitigation option 3

(*) In the excerpt for risk mitigation option 3, as a work hypothesis, it was considered: 1) the relocation of the at risk households in the sector n. 2; the stabilisation of the portions of the hillslope threatening the sectors n. 1 and n. 5

(1) Residual risk to loss of life related to the execution of the of the structural (active and passive) mitigation measures.
(2) Tolerable residual risk to loss of live to be achieved also considering the existence of a warning system.

	RESIDUAL RISK [%]					
	Flowslides (a)	**Landslides on open slopes (b)**	**Hyperconcentrated flows (c)**	**Residual risk (1) (d = a + b + c)**	**Residual risk (2) (e)**	**Δ [%] (f = d – e)**
SECTOR 1	15.6	11.1	0.0	26.7	4.4	22.3
SECTOR 2	17.8	3.4	0.0	21.2	1.3	19.9
SECTOR 3	0.0	15.7	0.0	15.7	3.9	11.8
SECTOR 4	44.9	0.0	0.0	44.9	2.6	42.3
SECTOR 5	29.2	0.0	0.0	29.2	1.9	27.3
SECTOR 6	41.0	0.0	0.0	41.0	5.1	35.9

Table 5.15 Residual risk values associated with the excerpt of the compromise risk mitigation option

(1) Residual risk to loss of life related to the execution of the of the structural (active and passive) mitigation measures.
(2) Tolerable residual risk to loss of live to be achieved also considering the existence of a warning system.

5.8.2 Evaluation of reduction in economic losses

On the basis of the available data, the economic losses (in terms of cost of repair) were estimated with reference to buildings potentially impacted by only flowslides triggered by rainfalls having a return period T = 200 years. In this regard, the damage index (DI) for each exposed building was assessed based on results obtained by the analysis of the propagation stage via the numerical code FLO-2D; the relative cost of repair (RCC) was then estimated on the basis of the curve reported in Figure 5.22. The initial cost of each building at risk was obtained considering a unitary cost equal to 800 €/m^2. The obtained results are reported in Table 5.16.

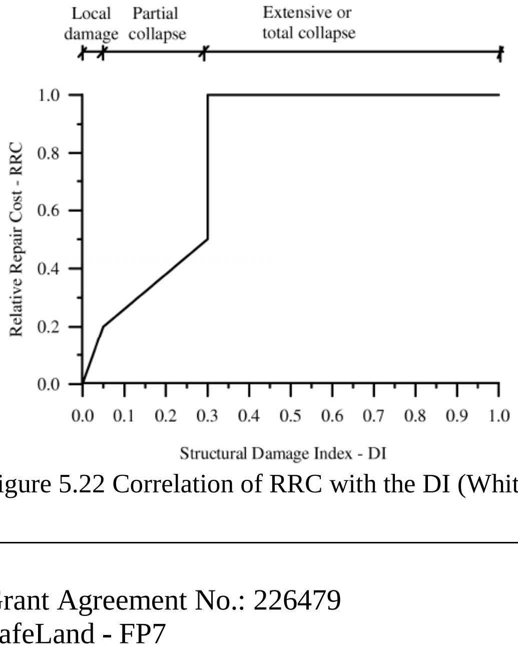


Figure 5.22 Correlation of RRC with the DI (Whitman et al., 1973).

LOCATION	Number of houses at risk	Total economic value of the houses [€]	Total cost of repair [€]			
			Excerpt I	**Excerpt II**	**Excerpt III**	**Compromise**
SECTOR 1	5	1,120,016	481,360	526,487	481,360	706,997
SECTOR 2	18	4,745,088	1,205,519	2,812,878	4,018,397	3,455,821
SECTOR 3	8	1,885,384	183,901	990,237	1,414,624	1,273,162
SECTOR 4	30	5,024,200	1,977,436	2,065,978	2,951,397	2,774,313
SECTOR 5	34	4,572,488	2,174,306	2,454,862	2,174,306	3,296,529
SECTOR 6	22	2,698,072	1,155,429	1,207,165	1,724,522	1,638,296

Table 5.16 Cost of buildings' repair related to the occurrence of flowslide phenomena (T = 200 years)

5.9 RISK-COST-BENEFIT ANALYSIS OF RISK MITIGATION OPTIONS

The evaluation of acceptance of risks and the determination of the optimal risk mitigation are carried out based on the Life Quality Index (LQI) criteria discussed in section 3.3.5. For convenience and continuity in discussion, the key points and equations of the LQI criteria are repeated here together with the presentation of the results in this section.

5.9.1 Assumptions and methodology

The risk-cost-benefit analysis is carried out based on the consideration of the occurrence of a design event identified as one landslide event having a return period of 200 years. This assumption is used here because the input information for this analysis used the same assumption and basis – the input information includes the evaluation of the probability of loss of life, societal risk (section 5.6.5) and residual risk with regard to risk mitigation measures (section 5.8.1). The results of the cost-benefit analysis are therefore conditional on this considered design event. This assumption and its implications must be carefully understood and borne in mind while considering and using the results of this risk-cost-benefit analysis.

The risk-cost-benefit analysis of the risk mitigation options is carried out on the basis of an evaluation of the benefits associated with investments into life safety and non-life-safety associated benefits (which could be economic, environmental, political or psychological). Based on availability of information, the non-life-safety benefits considered here include the reduced/avoided cost of repair of buildings; the reduction (avoidance) in the repair costs is due to the application of the risk mitigation measures.

First, an evaluation of the acceptance of the risk mitigation measures with regard to investments into life safety is carried using the Life Quality Index (LQI). As discussed in section 3.3.5, the underlying idea of the LQI is to model the preferences of a society quantitatively as a scalar valued social indicator, comprised by a relationship between the GDP per capita *g*, the life expectancy at birth *e* and the proportion of life spent for earning a living *w*. Details regarding the LQI principle and approach can be found in Nathwani et al. (2009), Nathwani et al. (1998) and others.

Based on the theory of socio-economics, the Life Quality Index can be expressed in the following principal form:

$$L = g^q e \tag{20}$$

Here the parameter *q* is a measure of the trade-off between the resources available for consumption and the value of the time of healthy life. It depends on the fraction of life allocated for economic activity and furthermore accounts for the fact that a part of the *GDP* is realised through work and the other part through returns of investments. The parameter *q* is assessed as:

$$q = \frac{1}{\beta} \frac{w}{1-w} \tag{21}$$

In the above quation, β is a constant taking into account that only part of the GDP is based on human labour, the other part is due to investments and other activities. Every risk mitigation measure influences the value of the LQI. The consideration that any investment into life risk mitigation should lead to an increase of the LQI leads to the following risk acceptance criteria that could be used to assess the net life safety benefit from decision alternatives concerning risk mitigation options for the system:

$$dL = \frac{\partial L}{\partial g} dg + \frac{\partial L}{\partial e} de \geq 0 \tag{22}$$

$$\frac{dg}{g} + \frac{1}{q}\frac{de}{e} \geq 0 \tag{23}$$

$$-dg \geq \frac{g}{q}\frac{de}{e} \approx \frac{g}{q} C_x dm \tag{24}$$

5.9.2 Evaluation of acceptance of risk mitigation options

The societal acceptance criterion for life safety requires that investments into the risk mitigation measures associated with life safety must be undertaken as long as the corresponding marginal risk mitigation exceeds the marginal costs of risk mitigation. Investments below the threshold in Equation (24) are therefore not acceptable. For technical problems, only the marginal mortality reduction (or the expected number of lives saved) *dm* is generally quantified. This reduction in mortality or the expected number of lives saved is transformed into a corresponding increase in life expectancy through a demographic constant C_x that can be estimated from population life tables.

Using the above criterion, all the risk mitigation options are evaluated for their acceptance. The results are presented in Table 5.17; the analysis has been performed for two cases for each risk mitigation option – i) application of active and passive structural measures and relocation wherever relevant and ii) application of all measures (including warning system).
(*Note*: In this analysis, the total cost for active and passive structural measures for option 3 has been assumed to be 3,000,000 Euros. It is possible to determine the optimal investment into the active and passive structural measures for option 3 by considering different investment amounts if the corresponding information on the benefits (reduction in risk of loss of life and cost of repair of buildings) for the different investment possibilities in this option is available.)

Application of active and passive structural measures and relocation wherever relevant			
Risk mitigation option	**Cost of risk reduction (Euros)**	**Expected number of lives saved**	**Measure of risk reduction achieved ($= \frac{g}{q} C_x dm$)**
1	6,650,842	1.895	5,149,946
2	6,630,397	1.390	3,777,533
3	6,480,000	1.295	3,519,356
COMPROMISE	6,631,938	1.655	4,497,710
Application of all measures (including warning system)			
Risk mitigation option	**Cost of risk reduction (Euros)**	**Expected number of lives saved**	**Measure of risk reduction achieved ($= \frac{g}{q} C_x dm$)**
1	6,950,842	2.270	6,169,064
2	6,930,397	2.270	6,169,064
3	6,780,000	2.280	6,196,241
COMPROMISE	6,931,938	2.270	6,169,064

Table 5.17 Evaluation of acceptance of risk mitigation options

All the risk mitigation options are seen to satisfy the acceptance criterion defined in Equation (24) and hence can be deemed to be acceptable based on the acceptance criterion derived using the Life Quality Index.

5.9.3 Identification of the optimal risk mitigation option from benefit-cost analysis

The evaluation of the benefits and costs for each risk mitigation option is made with reference to the ‘do nothing’ option (the option when no risk mitigation measures are applied). Ideally, such an evaluation needs to be performed through a joint consideration of the benefits associated with investments into life safety and the non-life-safety associated benefits which could be economic, environmental, political or psychological in nature. In this case study, the analyses aimed to assess the life safety benefits were carried out considering the consequences to exposed persons due to all flow phenomena that could be triggered over the Monte Albino hillslopes – these included hyperconcentrated flows, flowslides and first-failure landslides on open slopes. However, the results of analyses aimed to assess the non-life-safety benefits were obtained with reference to buildings potentially impacted by only flowslides. The non-life-safety benefits are expressed in the form of reduced/avoided cost of repair of buildings; the reduction (avoidance) in the repair costs is due to the application of the risk mitigation measures.

Due to the above mentioned differences in the benefits estimation analyses, the evaluation of the net benefits and the benefits to costs ratio is carried out separately for the life safety benefits and the non-life-safety benefits for reasons of consistency. For each risk mitigation option, the evaluation of the benefits and costs is carried out as described below:

i) *Life safety benefits* – These benefits are expressed as a product of the expected number of lives saved due to the application of the risk mitigation measures in the event of the occurrence of the considered design event and the Societal Value of a Statistical Life (SVSL) which is assessed through (Faber, 2010):

$$SVSL = \frac{g}{q}E \tag{25}$$

Here E is the age averaged discounted life expectancy life expectancy taking into account average life expectancies over all ages and discounting / rate of time preference. The quantities g and q are as defined previously.

ii) *Non-life-safety benefits* – These benefits are evaluated as the reductions in the cost of repair of buildings due to the application of the risk mitigation measures.

iii) *Costs* – The costs for the risk mitigation options and their breakdown are given in Tables 5.8 to 5.11.

The results of the benefit-cost analysis are shown in Tables 5.18 (for life safety benefits) and 5.19 (for non-life-safety benefits). The analysis has been performed for two cases for each risk mitigation option – i) active and passive structural measures and relocation wherever relevant and ii) all measures (including warning system).
(*Note*: In this analysis, the total cost for active and passive structural measures for option 3 has been assumed to be 3,000,000 Euros. It is possible to determine the optimal investment into the active and passive structural measures for option 3 by considering different investment amounts if the corresponding information on the benefits (reduction in risk of loss

of life and cost of repair of buildings) for the different investment possibilities in this option is available.)

Risk mitigation option	Costs of risk reduction (Euros)	Life safety benefits (Euros)	Net benefits (Benefits – Costs) (Euros)	Benefits to Costs ratio
Application of active and passive structural measures and relocation wherever relevant				
DO NOTHING	0	0	0	-
1	6,650,842	7,645,949	995,107	1.15
2	6,630,397	5,608,374	-1,022,023	0.85
3	6,480,000	5,225,068	-1,254,932	0.81
COMPROMISE	6,631,938	6,677,597	45,659	1.01
Application of all measures (including warning system)				
DO NOTHING	0	0	0	-
1	6,950,842	9,159,000	2,208,158	1.32
2	6,930,397	9,159,000	2,228,603	1.32
3	6,780,000	9,199,348	2,419,348	1.36
COMPROMISE	6,931,938	9,159,000	2,227,062	1.32

Table 5.18 Benefit-cost analysis of risk mitigation options, considering life safety benefits

Risk mitigation option	Costs of risk reduction (Euros)	Non-life-safety Benefits (Euros)	Net benefits (Benefits – Costs) (Euros)	Benefits to Costs ratio
Application of active and passive structural measures and relocation wherever relevant				
DO NOTHING	0	0	0	-
1	6,650,842	12,867,297	6,216,455	1.93
2	6,630,397	9,987,641	3,357,244	1.51
3	6,480,000	7,280,642	800,642	1.12
COMPROMISE	6,631,938	6,900,130	268,192	1.04
Application of all measures (including warning system)				
DO NOTHING	0	0	0	-
1	6,950,842	12,867,297	5,916,455	1.85
2	6,930,397	9,987,641	3,057,244	1.44
3	6,780,000	7,280,642	500,642	1.07
COMPROMISE	6,931,938	6,900,130	-31,808	0.99

Table 5.19 Benefit-cost analysis of risk mitigation options, considering non-life-safety benefits

The results of the evaluation when considering the life safety benefits related to the different options and to the compromise solution are given in Table 5.18. For the case where active and passive structural measures and relocation (wherever relevant) are considered and the warning system is not considered, option 1 is seen to be the most optimal package of risk mitigation measures in terms of the benefits to costs ratio criterion, immediately followed by the compromise solution. For the case where the application of all measures including the warning system is considered for analysis, the life safety benefits are seen to be almost equal for all the options. While using the results from this case, the effectiveness of the warning system needs to be considered (see Section 5.8.1).

The results in Table 5.19 – where the non-life-safety benefits related to the different options and to the compromise solution have been considered – highlight a ranking of the packages of risk mitigation measures which is different to the one obtained for life-safety benefits (Table 5.18). In particular, the compromise solution is characterised by the lowest values of the benefit to cost ratio. This result is not surprising considering that the compromise solution was conceived during the participatory stakeholder process in Nocera Inferiore (WP5.2 of the SafeLand Project) with the main aim to guarantee – in the short term – the safeguarding of the human life, even in the absence of a warning system. Furthermore, as underlined in Section 5.7.4, it must be observed that the compromise solution includes the development of knowledge about the Monte Albino hill slopes that is to be obtained via territorial survey. The objective here is to then identify the most appropriate active and sustainable measures from technical and economic points of view that need to be developed – in the medium/long term – to stabilize the source areas of the flowslides. In short, the compromise solution pursues the maximum safeguarding of the human life from the beginning and from this perspective can be considered to be the best solution to optimize the economic resources in the future for risk to property mitigation.

As mentioned in this section earlier, a holistic benefit-cost analysis involves a joint consideration and evaluation of the benefits associated with investments into life safety and the non-life-safety associated benefits which could be economic, environmental, political or psychological in nature. In this analysis, the evaluation of the net benefits and the benefits to costs ratio is carried out separately for the life safety benefits and the non-life-safety benefits for reasons of consistency. This nature of the analysis needs to be borne in mind while understanding and interpreting the values of the benefits to costs ratios obtained in this analysis and possibly comparing these values to those obtained for other applications.

6 CONCLUSIONS AND RECOMMENDATIONS

Risk assessment and risk management can be seen as essential and integral aspects and inputs to the decision planning, decision support and decision making processes. The importance of risk is brought out in the following quotation of Henry Ford : “The best we can do is size up the chances, calculate the risks involved, estimate our ability to deal with them, and then make our plans with confidence.” Decision problems in general and especially in natural hazards management are generally subject to a combination of inherent, modelling and statistical uncertainties. If all aspects of a decision problem would be known with certainty, the identification of optimal decisions would be straightforward by means of traditional cost-benefit analysis. Due to the existing uncertainties, it is not possible to assess the results of decisions in certain terms. There is hence no way to assess with certainty the consequences resulting from the decisions we make. However, what can be assessed is the risk associated with the different decision alternatives. Based on risk assessments, decision alternatives may then be consistently ranked on the basis of their associated utilities (which may be more useful for engineering decision problems) and cost-benefit analyses (which may be relevant for life safety and overall risk management problems), thereby providing a rational basis for societal decision making.

A general framework for the purpose of carrying out a risk-cost-benefit analysis that could be utilised for decision making has been described in Chapter 3 of this deliverable. In Chapter 4, a case study in Barcelonnette (France) involving the analysis and management of risks arising from debris flow phenomenon has been described. Another case study concerned with the risk analysis and risk management for risks posed by different flow-like phenomena in Nocera Inferiore (Italy) has been reported in Chapter 5. The use of the Life Quality Index (LQI) approach has been demonstrated for the evaluation of the acceptance of the mitigation options with regard to investments into life safety and the evaluation of the optimal risk mitigation alternative.

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