A DECISION THEORETICAL APPROACH TO IDENTIFY OPTIMAL RISK MITIGATION STRATEGIES

Bruno Mazzorana[1], Sven Fuchs[2] and Margreth Keiler[3]

ABSTRACT

Communities living in mountain areas are increasingly affected by considerable damage to infrastructure and property as a consequence of flood impacts. The conception of effective flood risk mitigation strategies and their subsequent implementation is therefore essential for a continuing sustainable development in mountain areas. Effective flood risk mitigation strategies can be assessed by their expected utility, which allows the selection of optimal management strategies from a normative point of view. The objective of this paper is to present the underlying procedure, and to derive formal expressions to measure risk mitigation performance starting from the basic theorem of rational choice under risk. Moreover, an overview of existing economic valuation approaches to attach monetary values to the elements at risk is provided.

Keywords: Natural hazards, flood, flood risk management, expected utility

INTRODUCTION

Taking into account that the international community as a whole is affected by considerable damage to infrastructure and property as well as loss of lives, the United Nations General Assembly designated the 1990s as the International Decade for Natural Disaster Reduction (IDNDR, United nations General Assembly, 1989). Within the associated international framework of action, the objective of this decade was to promote concerted action in order to reduce loss of life, property damage and economic disruption caused by natural hazards, not only with a particular focus on developing countries, but also with respect to most developed countries. Based on this framework, which was continued by the International Strategy for Disaster Reduction (ISDR, United Nations General Assembly, 2000) additional emphasis was put on the necessity to consider the processes involving the physical and socio-economic dimensions of vulnerability and risk.

In coherence with these initiatives on a global level, the European Commission issued the Directive on the Assessment and Management of Flood Risk (Commission of the European Communities, 2007) as one of three components of the overarching European Action Programme on Flood Risk Management. In this Directive, the Member Countries of the European Union should provide flood risk maps on a local scale until the end of 2013, and subsequently flood risk management plans focusing on the reduction of potential adverse consequences of flooding for human health, the environment, cultural heritage and economic activity. Moreover, due to the overall scarceness of public funds, flood risk mitigation strategies should be anchored to economic criteria in order to fulfil the requirements of cost-benefit analyses (Weck-Hannemann, 2006; Perman et al., 2011). As such, in several Alpine countries efforts have been undertaken to link decisions on the implementation of flood risk mitigation strategies to methods of cost-benefit analyses (Haering et al., 2002; BMLFUW, 2005). However, risk management strategies, and in particular the need to improve cost-efficiency if measures are planned, are subject to a bundle of uncertainties; above all with respect to (1) the stochastic nature of the modelling of hazardous processes, and (2) the systems' response in terms of

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vulnerability and risk reduction (Fuchs, 2009). Additionally, (3) the estimation of the expected utility in terms of economic benefits remains crucial, since the decision makers' risk attitude is an essential element of a comprehensive planning process targeted at making explicit the factors which determine the selection of optimal risk mitigation strategies (Kruschwitz, 2008).

Based on these requirements, in this paper, we contribute to a formalised method to assess (1) the risk mitigation performance of intended mitigation strategies on a monetary basis (e.g. in terms of annual risk reduction); (2) the cost-plan for a variety of possible risk mitigation strategies, which is considered from a life-cycle perspective, and (3) the expected utility associated with each mitigation strategy. The latter is of particular importance in order to select a mitigation concept which is in line with the preference structure of the public decision maker (who, in turn, usually provides the funds necessary for the targeted mitigation alternative). This relies on the assumption that any public decision maker acts risk-averse but with an objective evaluation matrix in order to spend public money economically efficient (Fuchs and McAlpin, 2005). Subsequently, we outline from a methodological point of view the procedures necessary in order to provide a road map for an achievement of these aims. Considering the peculiarities of decisions on public investments targeted at the mitigation of natural hazard risk, the required analytic efforts need to be structured and balanced (Fig. 1). In particular long-term capital commitments necessary for mitigation expenses, and the induced interdependencies between these commitments and other important economic activities in mountain regions (e.g., tourism and trading), require such a concerted action.

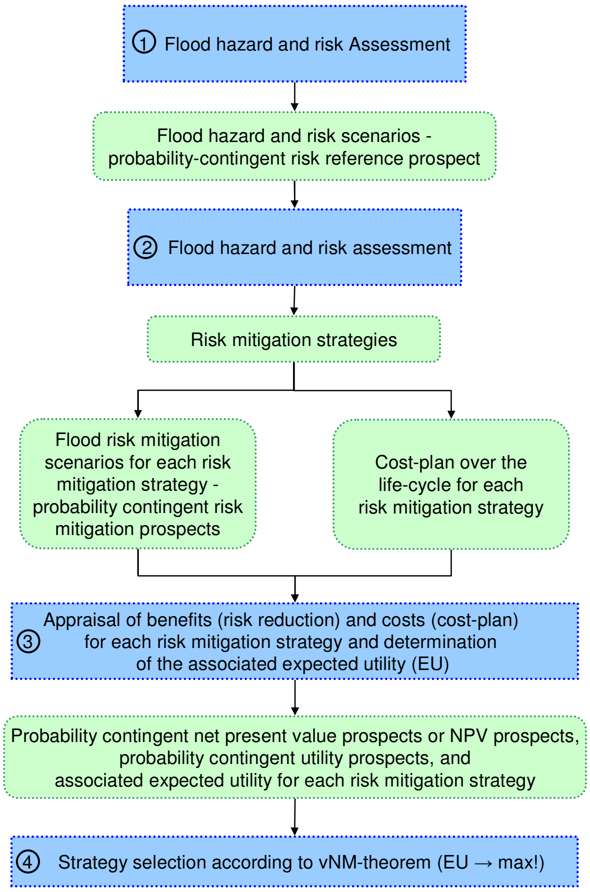

Fig. 1 Procedural roadmap for a comprehensive risk mitigation approach based on the concept of expected utility (EU).

With reference to Fig. 1, the first step (sub-procedure 1) of the proposed procedural roadmap consists of determining consistent flood hazard and risk scenarios. The specific aims include a spatially explicit representation of frequency and magnitude (intensity) for each of the underlying flood hazard scenarios, and a quantification of the associated consequences in terms of risk. The main result is the so-called risk reference prospect, which serves as a basis for performance comparison of possible risk mitigation options. In this paper, emphasis is put on the computational aspects of risk whereas the peculiarities related to the determination of the underlying flood hazard scenarios are discussed in more detail elsewhere (Mazzorana et al., 2011).

The second step (sub-procedure 2) entails the generation of risk mitigation strategies targeted at maximising the reduction of flood risk in accordance to the system. From a methodological perspective, substantial effort has been undertaken to systematise the design of risk mitigation strategies and to formulate heuristics for the practitioners (compare for an overview Mazzorana and Fuchs, 2010). For each planned risk mitigation strategy, the system under consideration has to be re-analysed from a flood hazard and risk assessment perspective. Thus, the analytic steps of sub-procedure 1 have to be repeated in order to explicitly modify the systems' behaviour either concerning flood hazard process unfolding or concerning the determination of expected consequences on vulnerability and elements at risk exposed.

An essential requisite for the economic assessment of risk mitigation strategies (sub-procedure 3) is the assessment of the benefit and cost flows over the life-cycle of the planned mitigation strategy. Concerning the benefits, in this paper, we limit our discussion to the annual flood risk reduction with respect to the risk reference prospect for property, infrastructure and human lives. At this stage, a probability contingent net present value (NPV) prospect can be determined for each strategy.

The range of NPVs obtainable by the entire set of mitigation strategies can be transformed into corresponding utility values reflecting the decision makers' attitude. This attitude is influenced by a certain degree of risk aversion, but also by other factors such as the distribution of properties and real estates (more general, by so-called endowment effects). As such, the NPVs are transferred into corresponding utility values according to expected utility theory (compare Eisenführ et al., 2010; Wakker, 2010). At this stage, probability-contingent utility prospects can be derived for each individual mitigation strategy.

The optimal flood risk mitigation strategy is finally selected according to the von Neumann-Morgenstern's Theorem (von Neumann and Morgenstern, 1953; Kreps, 1988) as the strategy which maximises the expected utility (EU). The theoretical underpinnings of EU Theory are introduced in the following section. Then, in a subsequent section, the core concept of risk prospect, used to determine the risk mitigation performance of the available risk mitigation strategies, is explained. Moreover, an overview of existing valuation methods to determine the economic value of elements at risk is provided. Finally, the description of recently developed approaches for the quantification of vulnerability is provided, which links the intensity of the process to the relative extent of the losses for each element at risk.

EXPECTED UTILITY THEORY: A CONCISE EXPOSITION

Following the procedure outlined by Wakker (2010), firstly, we outline the essential structural assumptions for decision under uncertainty and risk, respectively. Subsequently, we introduce expected utility (EU) and provide the basic theorem for rational choice under risk.

Structural Assumption 1 [decision under uncertainty]: S is a, finite or infinite, state space, and $\breve{R}$ is the outcome set. Prospects map states into outcomes, taking only a finite set of values. The domain of preference is the set of all prospects, i.e., of all such maps; $\geq$ is a preference relation in the set of prospects; and non-degeneracy holds.

Structural Assumption 2 [decision under risk]: $\geq$ is a preference relation over all (probability contingent) prospects, i.e., over all finite probability distributions over the outcome set $\breve{R}$.

Definition 1: Under structural assumption 2; expected utility (EU) holds if there exists a strictly increasing utility function (U) from the outcome set $\breve{R}$ to the real numbers $\widehat{R}$, such that the next evaluation represents preferences: $(p_1 x_1 \ldots . p_m x_m) \rightarrow p_1 U(x_1) + \ldots . + p_m U(x_m)$.

Endorsed with these structural assumptions and the EU definition we state the following theorem:

Theorem [EU for risk]. Under structural assumption 2, the following two statements are equivalent:

(i) Expected Utility holds

(ii) $\geq$ satisfies: weak ordering, standard gamble solvability, dominance and consistency.

A formal proof of this theorem can be found in Gilboa (2009). The conditions listed above to be satisfied by the preference relation are explained in Wakker (2010) and can be intuitively understood as precise consistency requirements for the decision maker. We introduce now a general method for the measurement of utility, enabling the decision maker to express, for example, NPVs in terms of perceived utility.

In general, assume two fixed outcomes, $\mathrm{Max} > \mathrm{Min}$, and assume that we have normalised utility, $U(\mathrm{Min}) = 0$ and $U(\mathrm{Max}) = 1$. For each outcome α, such that $\mathrm{Max} \geq \alpha \geq \mathrm{Min}$, we can elicit the standard gamble (SG) probability with respect to Min and Max, being the probability p such that the equivalence in Figure 2 holds.

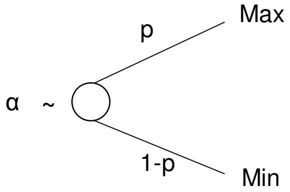

Fig. 2 The SG probability p of α.

Applying EU gives the SG equation, $U(\alpha) = pU(\mathrm{Max}) + (1-p)U(\mathrm{Min}) = p$. Expressed another way, $U(\alpha)$ is the SG probability p. The probability-contingent risk prospect is a core concept necessary for the procedural workflow outlined in Figure 1, and is, formally introduced in the subsequent section.

RISK PROSPECTS

According to the conceptualisation of natural hazard risk (Fuchs, 2009; Mazzorana and Fuchs, 2010), risk for objects exposed to the impacts of flood hazard processes (e.g. debris flows) is quantified on an annual basis as follows:

$$R = \sum_{j=1}^{j=M} p_{F_j} \cdot \sum_{h=1}^{h=H} \left\{ p_{E_h} \cdot \sum_{i=1}^{i=N} \left[ED_{i,j,h}\left(I_{F_j}\left(\vec{x}_{i,h}\right), s \right) \right] \right\} \qquad (1)$$

In equation (1) R is the annual risk in terms of expected losses for the elements at risk ($i = 1,\ldots,N$) induced by the flood hazard scenarios ($j = 1,\ldots,M$) under the assumed exposure configurations ($h = 1,\ldots,H$).

The probability associated to a specific flood scenario is denoted by p_{F_j} and the probability of a given exposure configuration, namely a defined set of locations – $\vec{x}_{i,h} \forall i$ – of the considered elements at risk, is denoted by p_{E_h}. $ED_{i,j,h}\left(I_{F_j}\left(\vec{x}_{i,h}\right), s\right)$ is the expected damage (or loss) to an element at risk, given a process intensity I_{F_j} in $\vec{x}_{i,h}$ resulting from the considered flood hazard scenario. In the adopted static notion of risk (for a theoretical treatment of dynamic risk, compare Mazzorana et al., 2012), I_{F_j} corresponds to the maximum intensity in terms of flow depths or flow velocities. Finally, s is a Boolean variable aiming at identifying situations where mobile objects are sheltered by enveloping objects (e.g., people within buildings, cars in vehicle halls).

Particular attention has to be given to accurately identify the probability p_{F_j} to be associated to each flood scenario. It is assumed that a statistical analysis of extreme events delivered a probability distribution fitted to the available annual discharge maxima at a relevant flow section. In this case for each recurrence interval, RI_{F_j}, or each non-exceedance probability $\overline{p}_{F_j}$ (or exceedance probability as its complement to 1), the corresponding peak discharge value Q_{F_j} is known. p_{F_j} is calculated as

$$p_{F_j} = \frac{\left(\overline{p}_{F_{j+1}} - \overline{p}_{F_{j-1}}\right)}{2},\ 1 < j < M,\ \text{and}\ p_{F_M} = \left(1 - \overline{p}_{F_M}\right) + \left(\overline{p}_{F_M} - \overline{p}_{F_{M-1}}\right)/2\ \text{and}$$

$$p_{F_1} = \left(\overline{p}_{F_1}\right) + \left(\overline{p}_{F_2} - \overline{p}_{F_1}\right)/2.$$

Formally, from an ex-post perspective, the height of loss for a given object impacted by a flood event can be assumed to be equal to the depreciated value of the part of the object to be reinstated, hence:

$$D_i = C_i \delta_i - RV_i - SE_i \tag{2}$$

where: D_i is the monetary value of the losses attributable to flood impacts; C_i are the reinstatement costs, namely the costs to substitute the damaged parts of the object by the corresponding new components; δ_i is a depreciation coefficient reflecting the depreciation of the object (compare Gallerani et al., 2011); RV_i is the residual value of the damaged portion; SE_i are the post-event expenditures for damage reduction.
To perform an ex-ante estimation of the expected damage – $ED_{i,j,h}$ – we re-write the last equation, introducing proper vulnerability functions, $\upsilon_{i,j,h} = \upsilon_i\left(I_{F_j}\left(\vec{x}_{i,h}\right), s\right)$, reflecting for a given intensity $-I_{F_j}$ – of the considered flood hazard scenario (at the location of the object) the ratio between C_i and the new construction costs of the entire object NV_i. Due to the ex-ante perspective the expected values of RV_i and SE_i will be neglected and the expected damage $-ED_{i,j,h}$ – can be expressed as:

$$ED_{i,j,h} = \upsilon_i\left(I_{F_j}\left(\vec{x}_{i,h}\right), s\right) \cdot NV_i \cdot \delta_i \tag{3}$$

Now equation (1) can be rewritten as:

$$R = \sum_{j=1}^{j=M} p_{F_j} \cdot \sum_{h=1}^{h=H} \left\{ p_{E_h} \cdot \sum_{i=1}^{i=N} \left[\upsilon_i\left(I_{F_j}\left(\vec{x}_{i,h}\right), s\right) \cdot NV_i \cdot \delta_i \right] \right\} \tag{4}$$

Equation (4) can conveniently be represented as a probability-contingent risk prospect – RP – (Table 1).

Tab. 1 Probability-contingent risk prospect – RP.

<table>
<tr><td colspan="5">$s_1 \rightarrow p_{F_1}$</td><td>..</td><td colspan="5">$s_j \rightarrow p_{F_j}$</td><td>..</td><td colspan="5">$s_M \rightarrow p_{F_M}$</td></tr>
<tr><td>$p_{F_1} p_{E_1}$</td><td></td><td>$p_{F_1} p_{E_h}$</td><td></td><td>$p_{F_1} p_{E_H}$</td><td></td><td>$p_{F_j} p_{E_1}$</td><td></td><td>$p_{F_j} p_{E_h}$</td><td></td><td>$p_{F_j} p_{E_H}$</td><td></td><td>$p_{F_M} p_{E_1}$</td><td></td><td>$p_{F_M} p_{E_h}$</td><td></td><td>$p_{F_M} p_{E_H}$</td></tr>
<tr><td>$\sum_{i=1}^{i=N} ED_{i,1,1}$</td><td>..</td><td>$\sum_{i=1}^{i=N} ED_{i,1,h}$</td><td>..</td><td>$\sum_{i=1}^{i=N} ED_{i,1,H}$</td><td>..</td><td>$\sum_{i=1}^{i=N} ED_{i,j,1}$</td><td>..</td><td>$\sum_{i=1}^{i=N} ED_{i,j,h}$</td><td>..</td><td>$\sum_{i=1}^{i=N} ED_{i,j,H}$</td><td>..</td><td>$\sum_{i=1}^{i=N} ED_{i,M,1}$</td><td>..</td><td>$\sum_{i=1}^{i=N} ED_{i,M,h}$</td><td>..</td><td>$\sum_{i=1}^{i=N} ED_{i,M,H}$</td></tr>
<tr><td colspan="5">$\sum_{h=1}^{H} \sum_{i=1}^{N} ED_{i,1,h} = R_{s_1}$</td><td>..</td><td colspan="5">$\sum_{h=1}^{H} \sum_{i=1}^{N} ED_{i,j,h} = R_{s_j}$</td><td>..</td><td colspan="5">$\sum_{h=1}^{H} \sum_{i=1}^{N} ED_{i,M,h} = R_{s_M}$</td></tr>
</table>

For convenience we denote the probability-contingent risk reference prospect with RP^R and the risk prospects corresponding to the, $z = 1,\ldots,Z$, risk management strategies with RP^z.
Throughout, we assume that the decision maker does not have any influence on the truth of the events (Machina, 1987). However, as outlined in Gilboa (2009), the distinction between acts over which the decision maker has control and states over which the decision maker has no control is one of the pillars of rational choice. Hence, we assume that the flood hazard scenarios (with their associated probabilities) are the only relevant states to be considered. Mazzorana et al. (in press) introduce the distinction between a process loading and process response system according to the principle of rational choice, thus, hazard processes unfolding in the loading system characterise the state space.
The probability-contingent risk mitigation prospect, $\Delta RP^{Rz} = RP^R - RP^z$, is shown in Table 2.

Tab. 2 Probability-contingent risk mitigation prospect, $\Delta RP^{Rz} = RP^R - RP^z$, of the strategy z. The superscripts R and z are related to the risk reference prospect, RP^R, and the risk prospect corresponding to the strategy z, respectively.

$s_1 \rightarrow p_{F_1}$	$\cdots$	$s_j \rightarrow p_{F_j}$	$\cdots$	$s_M \rightarrow p_{F_M}$
$\Delta RP^{Rz}_{s_1} = RP^{R}_{s_1} - RP^{z}_{s_1}$	$\cdots$	$\Delta RP^{Rz}_{s_j} = RP^{R}_{s_j} - RP^{z}_{s_j}$	$\cdots$	$\Delta RP^{Rz}_{s_M} = RP^{R}_{s_M} - RP^{z}_{s_M}$

In Table 2 the results achievable by strategy z with respect to the risk reference prospect for all states of the state space, $s \in S$, are outlined. Expressed in another way, Table 2 represents a finite probability distribution over the outcome set $\breve{R}$, namely the annual risk reduction, which corresponds to the benefits associated with the implementation of strategy z.

The implementation of such a strategy z includes a series of costs over the planned life cycle. For analytic purposes it is convenient to specify the expenditure flows – $C(LC)^{z}_{t}$ – over the life cycle duration T in form of a cost plan. According to the workflow presented in Figure 1 we build the probability-contingent net present value $-NPV-$ prospect (compare Table 3) for all strategies, $z = 1,...,Z$, following the general principles of project appraisal (compare Perman et al. 2011).

Tab. 3 Probability-contingent NPV prospects and their expected values – EVs – for all strategies, $z = 1,...,Z$.

N	$s_1 \rightarrow p_{F_1}$	$s_j \rightarrow p_{F_j}$	$s_M \rightarrow p_{F_M}$	EV^{Rz}
1	$NPV^{R1}_{s_1} = \sum_{t=0}^{t=T} \frac{\Delta R^{R1}_{s_1} - C(LC)^{1}_{t}}{(1+r)^{t}}$	$NPV^{R1}_{s_j} = \sum_{t=0}^{t=T} \frac{\Delta R^{R1}_{s_j} - C(LC)^{1}_{t}}{(1+r)^{t}}$	$NPV^{R1}_{s_M} = \sum_{t=0}^{t=T} \frac{\Delta R^{R1}_{s_M} - C(LC)^{1}_{t}}{(1+r)^{t}}$	$EV^{R1} = \sum_{j=1}^{j=M} p_{F_j} \cdot NPV^{R1}_{s_j}$
..	$\cdots$	$\cdots$	$\cdots$	$\cdots$
z	$NPV^{Rz}_{s_1} = \sum_{t=0}^{t=T} \frac{\Delta R^{Rz}_{s_1} - C(LC)^{z}_{t}}{(1+r)^{t}}$	$NPV^{Rz}_{s_j} = \sum_{t=0}^{t=T} \frac{\Delta R^{Rz}_{s_j} - C(LC)^{z}_{t}}{(1+r)^{t}}$	$NPV^{Rz}_{s_M} = \sum_{t=0}^{t=T} \frac{\Delta R^{Rz}_{s_M} - C(LC)^{z}_{t}}{(1+r)^{t}}$	$EV^{Rz} = \sum_{j=1}^{j=M} p_{F_j} \cdot NPV^{Rz}_{s_j}$
..	$\cdots$	$\cdots$	$\cdots$	$\cdots$
Z	$NPV^{RZ}_{s_1} = \sum_{t=0}^{t=T} \frac{\Delta R^{RZ}_{s_1} - C(LC)^{Z}_{t}}{(1+r)^{t}}$	$NPV^{RZ}_{s_j} = \sum_{t=0}^{t=T} \frac{\Delta R^{RZ}_{s_j} - C(LC)^{Z}_{t}}{(1+r)^{t}}$	$NPV^{RZ}_{s_M} = \sum_{t=0}^{t=T} \frac{\Delta R^{RZ}_{s_M} - C(LC)^{Z}_{t}}{(1+r)^{t}}$	$EV^{RZ} = \sum_{j=1}^{j=M} p_{F_j} \cdot NPV^{RZ}_{sj}$

For a risk-neutral decision maker it would be important to select the optimal flood risk mitigation strategy on the basis of Tab. 3. As such, the expected values – EVs – of the probability-contingent NPV prospects accurately represent the preferences of the decision maker, hence, the strategy with the highest EV should be selected from a normative point of view. However, in case that a decision maker does not act according to these premises, and therefore acts risk-avers, we will explicitly make use of the theorem [EU for risk], introduced above along with the key concepts of expected utility theory. The entire outcome set, namely the set of all probability-contingent $NPV^{Rz}_{s_j}$, $\forall j, z$, is assumed to be known.

We introduce the following conventions:

1. $NPV^{Rz}_{s_j} = 0 \rightarrow U\left(NPV^{Rz}_{s_j}\right) = U^{Rz}_{s_j} = 0$
2. $NPV^{Rz}_{s_j} = Max \rightarrow U\left(NPV^{Rz}_{s_j}\right) = U^{Rz}_{s_j} = 1$

We assume, moreover, for a negative $NPV^{Rz}_{s_j}$ the corresponding disutility is determined by inverting the sign of the utility of $\left|NPV^{Rz}_{s_j}\right|$. Endorsed with this setting we construct the positive part of the utility function, whereas the negative part is obtained by point reflection. Eliciting the standard gamble (SG) probability $p_{NPV^{Rz}_{s_j}}$ with respect to $NPV^{Rz}_{s_j} = 0$ and $NPV^{Rz}_{s_j} = Max$ of all positive probability-contingent $NPV^{Rz}_{s_j}$ of Tab. 3, we obtain the corresponding utilities as $U^{Rz}_{s_j} = p_{NPV^{Rz}_{s_j}}$. Endowed with these nodes the positive part of the utility function is constructed by piecewise linear interpolation between the nodes. At this stage Tab. 3 can be rewritten by substituting the $NPV_{s_j}^{Rz}$ by the corresponding $U_{s_j}^{Rz}$ (compare Table 4).

Tab. 4 Probability-contingent utility – U – prospects and their expected utilities – EUs – for all strategies, $z = 1,...,Z$.

Nr	$s_1 \rightarrow p_{F_1}$	..	$s_j \rightarrow p_{F_j}$	…	$s_M \rightarrow p_{F_M}$	EU^{Rz}
1	$U_{s_1}^{R1}$		$U_{s_j}^{R1}$		$U_{s_M}^{R1}$	$EU^{R1} = \sum_{j=1}^{j=M} p_{F_j} \cdot U_{s_j}^{R1}$
…	…	..	…	…	…	…
z	$U_{s_1}^{Rz}$		$U_{s_j}^{Rz}$		$U_{s_M}^{Rz}$	$EU^{Rz} = \sum_{j=1}^{j=M} p_{F_j} \cdot U_{s_j}^{Rz}$
…	…	..	…	…	…	…
Z	$U_{s_1}^{RZ}$		$U_{s_j}^{RZ}$		$U_{s_M}^{RZ}$	$EU^{RZ} = \sum_{j=1}^{j=M} p_{F_j} \cdot U_{s_j}^{RZ}$

As a consequence of the theorem [EU for risk], from a normative point of view the rational choice is the selection of the risk mitigation strategy which maximises expected utility – EU^{Rz}.

ECONOMIC VALUATION OF ELEMENTS AT RISK

In the adopted conceptualisation of flood hazard risk (compare equations 1 and 4) the expected losses are expressed monetarily, which entails an economic valuation. Flood damages can be classified into direct and indirect losses. While the former occur due to the physical contact (impact) of flood water with properties, people at risk, or any other object (Merz et al., 2010), the latter – although triggered by the direct impacts – are not spatially restricted to the flooded areas. Furthermore, indirect losses may extend well beyond the duration of the flood event. Depending on whether or not flood losses can be assessed in monetary values, a further distinction into tangible and intangible damages seems appropriate (Parker et al., 1987; Smith et al., 1998). More precisely, tangible damage is damage to capital stocks or resource flows which can be specified in monetary terms, whereas intangible damage is damage to assets which are not traded in a market and are therefore difficult to transfer into monetary values (Fuchs et al. 2007a). Although the terminology of this classification is commonplace, interpretations and delineations differ. Different valuation principles are employed to attach values to distinct object categories (Drees and Paul, 2011, Perman et al., 2011).

In order to provide the optimal supply of protection against flood hazards, the public sector will need, among other information, evaluation of costs and benefits (Fuchs and McAlpin, 2005). Costs are evaluated in terms of the present value of the previous investment so that the opportunity costs can be compared to the utility that would have resulted from an alternative appropriation of the resources. Here, we put the distinction between tangibles and intangibles into a dynamic perspective. Environmental valuation is a rapidly expanding field. Refined valuation techniques, based on first principles such as willingness to pay (WTP) or willingness to accept (WTA) are in perpetual development. An ever widening spectrum of non-market commodities and services are made accessible to economic valuation (Pommerehne et al., 1992; Perman et al., 2011). Different valuation principles are employed to attach values to distinct object categories (Fuchs, 2009; Gallerani et al., 2011). Operationally we distinguish between object categories valued through economic approaches using market values (e.g., reinstatement value for structures) and the category of statistical life – SL – of people at risk, where contingent valuation (CV) methods are applied (Viscusi, 2008). With reference to the former we introduce a general scheme to structurally dissect complex objects and make them accessible to economic valuation in risk assessment, while the latter is treated separately. Hence, in dissecting a complex object (e.g., a production plant) we distinguish between:

1. vertically extending fixed structures (e.g., walls of the buildings) impacted directly by the flood process;

2. particular superstructures (e.g., roofs, decks) impacted rarely and therefore indirectly by the flood process; and
3. installations and/or mobile objects (e.g., machines and cars) impacted directly by the flood process.

For completeness two supplementary categories are introduced that are affected by flooding as well as sediment and wood deposition processes:

4. surfaces (areas) for different land use purposes (e.g., agricultural land, but also parking lots and roads); and
5. biotic systems (e.g. wood, but also orchards).

The direct economic reference for a valuation of object parts belonging to the categories (1) and (2) is the determination of the reinstatement value. As suggested by Gallerani et al. (2011), the reinstatement value can be calculated as construction value – NV – by:

$$NV = \sum_{i=1}^{n} \sum_{j=1}^{m} q_{ij} \cdot p_i \qquad (5)$$

where NV is the reinstatement value of the considered object; q_{ij} is the required quantity of input j to perform the construction workflow unit i; and p_i is the unitary price of the construction workflow unit i.

For the category (3) the estimation of the market value – MV – of the components of equipment is calculated as follows:

$$MV = C_h \cdot \left(1 + \frac{M}{100}\right) \cdot \frac{D_r}{D} \qquad (6)$$

Where MV is the most probable market value of the considered equipment component; C_h is the purchase prize; M is the cost increment from the year of purchase to the year of valuation; D_r is the residual economic life (in years); and D is the economic life span (in years);

For category (4) it is relevant to determine the costs of clearing-up operations and the necessary reinstatements to re-establish the original functionality.

In case of object category (5) the economic valuation is carried out by determining the capital value of the considered biotic system through suitable capitalisation formulas.

The economic valuation of the category statistical life – SL – needs a separate consideration. In fact the estimation of the value of a statistical life as a typical non-market value is defined as the rate at which people are willing to exchange income for the reduction in mortality risk. It is calculated by dividing the annual mean or median willingness to pay – WTP – through the corresponding risk variation. Several studies aiming at determining the VSL have been conducted in different contexts (Viscusi and Aldy, 2003), such as snow avalanches, where the influence of implicit information associated with the occurrence of avalanches on WTP-values for risk prevention was quantified with a range between € 1.8 and 5.2 million (Leitner and Pruckner, 2005). These results are consistent with other studies (e.g. Alberini et al., 2005).

VULNERABILITY OF ELEMENTS AT RISK

The shift from hazard to risk obviously requires a completely different approach with respect to necessary management issues (Fuchs, 2009). Despite the comprehensive experiences that have been made by applying the concept of risk to mountain hazard management, in particular in Switzerland (Kienholz 1994; Hollenstein 1995; Heinimann 1998; Kienholz et al. 2004), considerable questions with respect to the methods developed for an operational implementation of the concept of vulnerability still remain open (Fuchs et al., 2012).

The assessment of vulnerability requires an ability to both identify and understand the susceptibility of elements at risk and – in a broader sense – of the society to these hazards (Fuchs, 2009). Studies related to vulnerability of human and natural systems to mountain hazards, and of the ability of these systems to adapt to changes in the functional chain of hazards, are a relatively recent field of research that brings together experts from a wide range of disciplines, including natural science, social science, disaster management, policy development and economics, to name only a few. Researchers from these fields bring their own conceptual models to study vulnerability and adaptation, models which often address similar problems and processes using different languages (Brooks, 2003). However, apart from the overall discussion on linguistic placements and semantic dimensions of the term (Cutter, 1996; 2003), vulnerability in the context of flood hazards in European mountain regions is, from a practitioner's side such as the Austrian Torrent and Avalanche Control Service, usually defined as the physical impact of hazardous events on elements at risk. Accordingly, if quantitatively assessed, vulnerability is defined as the expected degree of loss for an element at risk due to the impact of a defined hazardous event within a defined period of time and a defined location. These events are themselves conditioned by a certain intensity, frequency and duration, all of which affect vulnerability. From this technical point of view, as a general rule, vulnerability assessment is based on the evaluation of parameters and factors such as building categories or types, construction materials and techniques, state of maintenance, presence of protection structures, and presence of warning systems (Fell et al., 2008). For this reason, vulnerability values describe the susceptibility of elements at risk to damage, facing different process types with different spatial and temporal distributions of process intensities (e.g., flow depths, accumulation heights, flow velocities and pressures).

The review of the concept of risk for Alpine countries resulted in gaps concerning appropriate tools for the assessment of vulnerability of elements at risk and of communities exposed. To overcome these shortcomings, studies on vulnerability have been undertaken aiming at (1) the methodological development of loss functions with respect to buildings located in the run-out areas of torrent processes (Fuchs et al., 2007b) and with respect to fluvial sediment transport (Totschnig et al., 2011); and (2) the conceptualisation of an overarching vulnerability model including structural, economic, social and institutional vulnerability (Fuchs, 2009) as well as the spatial characteristics of vulnerability (Fuchs et al., 2012).

In general, the damage ratio is quantified using an economic approach by establishing a ratio between the loss and the reconstruction value of every individual element at risk exposed (Fuchs et al., 2007b). In a second set of calculations, this ratio obtained for every individual element at risk is attributed to the respective process intensities. The relation between damage ratio and process intensity is defined as vulnerability. Therefore, information on the elements at risk exposed on the individual torrent fans is necessary, as well as data on the process intensities of the particular hazardous events. As a result, scatterplots can be developed linking process intensities to object vulnerability values. These data are further analysed using regression approaches in order to develop vulnerability functions which serve as a proxy for the structural resistance of buildings with respect to flood processes on torrent fans (Fuchs et al., 2007b; Totschnig and Fuchs, 2012).

Hence, the assessment of physical vulnerability is an essential requirement to quantify the expected damage in monetary terms. Functional vulnerability approaches have been proposed only for a limited number of object categories (e.g. residential buildings), however, in particular vulnerability functions for buildings impacted by debris flows (Fuchs et al., 2007b) and fluvial sediment transport are limited (Totschnig et al. 2011). According to the debris flow hazards, the relationship between debris flow intensity in terms of deposit heights, $I_{DF}(\vec{x}_i) \equiv h_d(\vec{x}_i)$, at the location of the object, $\vec{x}_i$, and vulnerability, $\upsilon_i = \upsilon_i\left(h_d\left(\vec{x}_i\right)\right)$, was found to fit best to the data by a second-order polynomial function for all intensities $h_d\left(\vec{x}_i\right) \leq 2.5\text{m}$, namely:

$$\upsilon_i = \upsilon_i\left(h_d\left(\vec{x}_i\right)\right) = 0.11 \cdot h_d^2\left(\vec{x}_i\right) - 0.01 \cdot h_d\left(\vec{x}_i\right)$$

According to the fluvial sediment transport phenomena, the best-fitting function was expressed as

$$\upsilon_i = \upsilon_i\left(I_{R_{ST}}\left(\vec{x}_i\right)\right) = e^{-0.466\left(\frac{\tan\left(\frac{\left(I_{R_{ST}}\left(\vec{x}_i\right)\right)\pi}{2}\right)+0.395}{0.395}-1\right)^{-2.091}}$$

where $I_{R_{ST}}\left(\vec{x}_i\right)$ is the relative intensity of the fluvial sediment transport process at the location of the object, $\vec{x}_i$, expressed as ratio between the deposit height $h_d\left(\vec{x}_i\right)$and the height of the considered building H_i.

DISCUSSION AND OUTLOOK

In this paper we presented a computational framework for the economic assessment of flood risk mitigation strategies pillared on the expected utility theory. In a fist step methods for the quantification of flood risk were discussed. Subsequently, related concepts of probability-contingent risk reference prospects and the risk mitigation prospect of potential mitigation strategies were introduced. In parallel, the necessity to specify the cost plan for each mitigation option was highlighted. By a monetary quantification of the expected benefits, expressed in terms of annual risk reduction, and of the incurring associated costs, formal representations of the corresponding probability-contingent net present value – NPV – prospects were derived. For a risk-neural decision maker, the calculation of the expected value – EV – of these prospects is sufficient to select an optimal mitigation strategy. To overcome the constraint of a decision maker with a possibly different risk attitude, and to establish a normative basis for rational decision making, elements of the expected utility theory were introduced. Successively the previously determined formal representations of – NPV – prospects were converted into the corresponding utility – U – prospects. Recalling the essence of the vNM-Theorem [EU for risk], the rational choice is given by the selection of this risk mitigation strategy which maximises expected utility – EU . In this paper we addressed two supplementary topics, which are closely related to the overarching umbrella of risk assessment, (1) the economic valuation of the objects at risk and (2) the assessment of their vulnerability. Contextually, we presented respective quantification approaches and identified research gaps to be closed in the near future.

The conceptual structure for a risk-based project assessment presented in this paper allows to incorporate further aspects from the field of risk analyses or the field of rational decision making, such as dynamic risk analyses (i.e. tracking the vulnerability of the endangered objects throughout the duration of the flood event). The theoretical setup provided in this paper is valid for the determination of each available flood risk mitigation strategy, and of the corresponding expected utility with known probabilities of the underlying flood hazard events. This is, strictly speaking, the special case of a more general problem of determining the expected utility with both, unknown probabilities and unknown utilities. The treatment of this task becomes relevant in the context of imperfect information, and requires the adoption of the Subjective Expected Utility Theory (compare Savage, 1954; Wakker, 2010).

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