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Fuzzy Formative Scenario Analysis for woody material transport related risks in mountain torrents

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ABSTRACT

Extreme torrent events in alpine regions have clearly shown a variety of process patterns involving morphological changes due to increased local erosion and deposition phenomena, and clogging of critical flow sections due to woody material accumulations. Simulation models and design procedures currently used in hazard and risk assessment are only partially able to explain these hydrological cause–effect relationships because the selection of appropriate and reliable scenarios still remains unsolved. Here we propose a scenario development technique, based on a system loading level and a system response level. By Formative Scenario Analysis we derived well-defined sets of assumptions about possible system dynamics at selected critical stream configurations that allowed us to reconstruct in a systematic manner the underlying loading mechanisms and the induced system responses. The derived system scenarios are a fundamental prerequisite to assure quality throughout the hazard assessment process and to provide a coherent problem setting for risk assessment. The proposed scenario development technique has proven to be a powerful modelling framework for the necessary qualitative and quantitative knowledge integration, and for coping with the underlying uncertainties, which are considered to be a key element in natural hazards risk assessment.

1. Introduction

Particularly since the 1990s, considerable damage occurred in the European Alps due to torrent processes (1999, 2002, 2005, and 2008) and inundation (2002, 2005, 2006). This development has been attributed to both risk-influencing factors, changes in the intensity and magnitude of processes (e.g., Houghton et al., 2001; Solomon et al., 2007) and an increase in values at risk exposed (Fuchs et al., 2005; Keiler et al., 2006; Fuchs and Keiler, 2008). As a result, society increasingly realised – also on the political level – that despite of the considerable amounts of public money spent for conventional technical mitigation and hazard mapping, a comprehensive protection of settlements and infrastructure against any loss resulting from hazard processes is not affordable and economically justifiable (Weck-Hannemann, 2006; Fuchs et al., 2007a). People and political decision makers are increasingly aware of this situation. Thus, in some Alpine countries a paradigm shift took place from hazard reduction to a risk culture (PLANAT, 2004), while dealing with natural hazard risk in other countries still remains conservative until now (Stötter and Fuchs, 2006; Fuchs et al., 2008; Holub and Fuchs, 2009).

The analysis of natural hazard risk is embedded in the circle of integral risk management, including a risk assessment from the point of view of social sciences and economics, and strategies to cope with the adverse effects of hazards. The underlying objective for risk management is the planning and implementation of protective measures in an economically efficient and societal agreeable manner. Thus, risk assessment includes both risk analysis and risk valuation within a defined system at the intersection between different disciplines (Renn, 2008a, b; Fuchs, 2009). For this reason, the scales of valuation (temporal, spatial, degree of detail) have to be well defined for a sustainable risk minimisation. To be able to compare different types of hazards and their related risks, and to design and implement adequate risk reduction measures, a consistent and systematic approach has to be established. While a hazard analysis focuses on natural processes such as debris flows and floods with related woody material transport, the method of risk analysis additionally includes the qualitative or quantitative valuation of elements exposed to these hazards, i.e. their individual values and the associated vulnerability (Fuchs et al., 2007b).

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The event documentation of recent alpine river floods and torrent processes, such as debris flows and excessive bed load transport in gravel bed streams, highlighted considerable shortcomings in the current procedures used for natural hazard and risk assessment (Berger et al., 2007; Autonome Provinz Bozen-Südtirol, 2008). In particular, the effects of changing channel morphology and cross-sectional clogging imputable to woody material transport phenomena were found to amplify process intensities significantly (e.g., Diehl, 1997; Lyn et al., 2007; Mazzorana et al., 2010). Furthermore, existing hazard maps turned out to be not as reliable as expected (e.g., Bezzola and Hegg, 2007; Holub and Fuchs, 2009). In order to improve risk analyses and to support decision making, underlying scenarios have to be re-built based on such issues (Girod and Mieg, 2008), in particular with respect to sources of uncertainty that affect the predictability of the hazard process paths (e.g., Paté-Cornell, 1996; Merz et al., 2008).

To apply the risk equation and redesign the underlying scenarios we propose a nested scenario approach composed of different levels (Fig. 1). According to the parameters of the risk equation, this nested approach is composed of (1) natural hazard scenarios; (2) exposure scenarios; (3) vulnerability scenarios; (4) analyses of values at risk; resulting in (5) risk scenarios. According to the conceptualisation of risk, these nested components have multiple functional dependencies among each other, resulting in compound intersections (Fig. 1).

In this paper we focus on the hazard part of the risk equation, i.e. the investigation of woody material transport related hazard scenarios in mountain torrents. Acknowledging the fact that the definition of robust woody material transport related risk scenarios is necessarily based on an accurate deduction of consistent and reliable hazard scenarios, the case study presented here addresses the following issues: (1) identification of an adequate natural hazard scenario level structure, hereafter denominated as system loading scenario level; and (2) identification of an appropriate scenario level for the description of possible system responses taking place at critical stream configurations (e.g. bridges), hereafter denominated as system response scenario level. In Fig. 2 possible hazard and risk scenarios along a stream configuration are shown. The importance of a robust definition of either consistent system loading scenarios (e.g. flood with high woody material transport rates) or system response scenarios (e.g. system changes such as possible bridge clogging) is indicated to reliably infer the main consequences for the exposed objects (e.g. roads and buildings) in terms of risk.

With respect to the determination of hazard scenarios for debris flows and flood processes characterised by woody material transport, a series of uncertainties have to be considered, namely:

(1) uncertainties about the possible range of rheological behaviour and the concentration of solids in the liquid–solid mixture of debris flows;
(2) uncertainties in system loading assumptions (e.g., duration-intensity related uncertainties, uncertainties related to sediment transport rates, uncertainties emerging from woody material transport);
(3) uncertainties in system response mechanisms (e.g., localised obstructions that divert the flow patterns, influence of small-scale topological features);
(4) uncertainties concerning the protection system functionality and mitigation effectiveness (e.g., failure propensities of key components within the protection system, sediment dosing behaviour of retention basins, dike failures); and

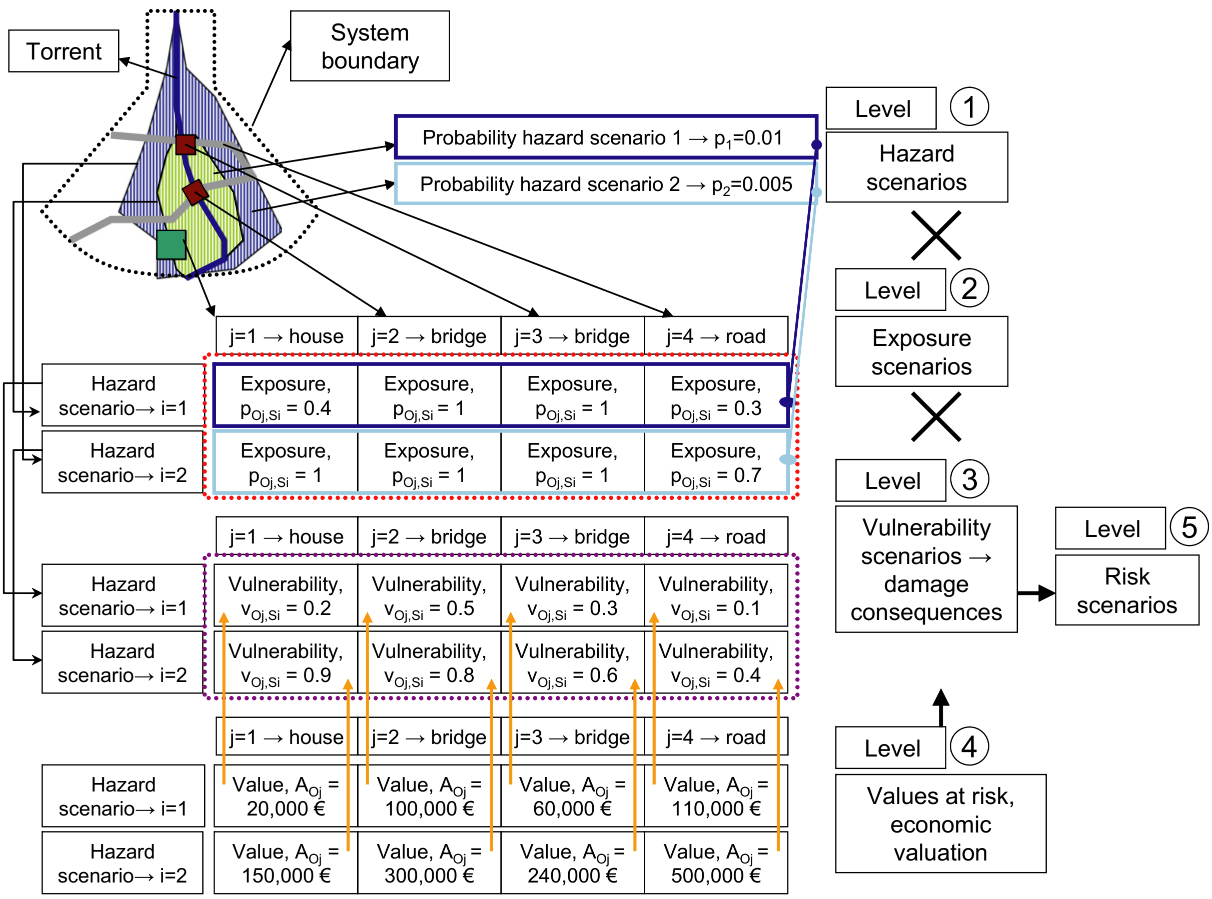

Fig. 1. Nested scenario approach referred to as level-structured risk scenario planning approach.

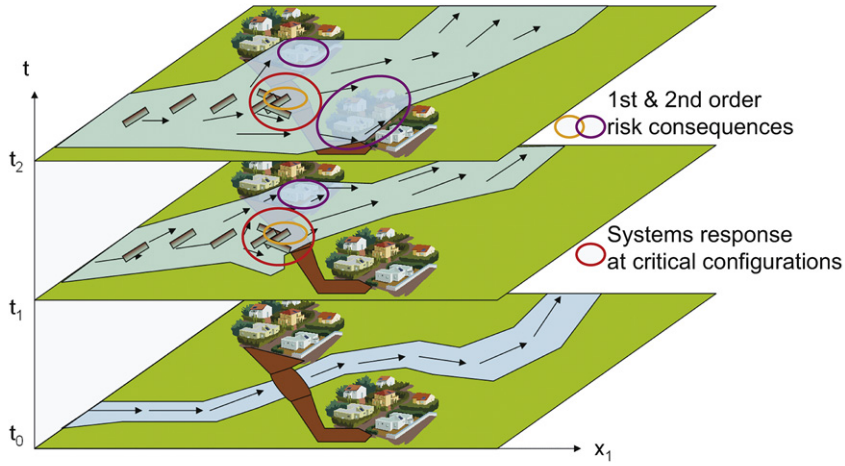

Fig. 2. Possible hazard and risk scenarios along a stream configuration.

(5) uncertainties concerning morphological changes inducing hazard processes (e.g., large erosion phenomena on alluvial fans, flow path changes in steep mountain rivers).

These uncertainties cannot yet be precisely mirrored by common 2D-hydrodynamics simulation models. We postulate here, on the basis of the comprehensive analysis of event documentations, that uncertainties regarding the statistical extrapolations of peak discharges for long return period flood events increase if the floods were accompanied by considerable sediment transport. This trend was found to be even more accentuated if woody material transport takes place (for an overview, see Montgomery and Piégay, 2003). It is a fact that the accuracy, precision and reliability of extrapolations for discharge time series with longer return periods significantly depends on the robustness of the underlying measured discharge time series. Such robust measurement series are comparatively scarce for sediment transport rates in alpine catchments and practically unavailable for woody material transport rates. Moreover, compared to liquid discharge, the currently used investigation methods and calculation procedures are less accurate if sediment dynamics and woody material transport characterise the hazard process.

In order to overcome these shortcomings related to measured data and uncertainties, we propose a concept to support a balanced strategy of investigation based on the integration of available and retrievable qualitative and quantitative knowledge of uncertainties. The approach aims at an identification of relevant impact factors and an exploration of their systemic role by determining possible system loading conditions and system response mechanisms at hydraulic weak points along mountain streams during extreme events. Hence, a comprehensive assessment of the process-response system is feasible and affordable. Therefore we extended and tested a Formative Scenario Analysis approach originally proposed by Scholz and Tietje (2002). Formative Scenario Analysis is based on qualitatively assessed impact factors and the expert-rated quantitative relations between these factors, such as impact and consistency analysis. Within this framework, "formative" indicates a generic mathematical structure behind the scenarios that is combined with quantitative and qualitative expert assessments (Tietje, 2005). Apart from the hazard assessment *sensu stricto*, all subsequently linked products, such as risk maps, intervention plans, and mitigation concepts benefit from this coherent derivation procedure for hydrological hazards involving woody material transport.

The requirement of a modelling framework that enables rational integration of qualitative and quantitative knowledge in order to analyse complex and often unstructured problems becomes essential if the elements of uncertainty are considerable on both, the system loading and the system response side (Funtowicz and Ravetz, 1994; Kolkman et al., 2005; Refsgaard et al., 2007).

Similar arguments are valid from a system response perspective. If flooding processes were not characterised by considerable sediment load and woody debris transport, currently used hydraulic simulation tools would provide reliable results. However, if sediment loads and woody material transport phenomena occur, complex system responses can be expected, particularly with respect to critical stream configurations such as constrictions at bridge cross-sections. Transported woody material might be entrapped at bridge piers leading to debris accumulation at individual piers. Moreover, if the distance between the bridge piers is smaller that the design log length of woody material (Diehl, 1997), a spanning blockage debris accumulation might occur. Such spanning blockage accumulations, occluding relevant parts of the cross-section, considerably reduce the flow discharge capacity. As a consequence, a change in the flow pattern from open channel flow conditions to orifice flow conditions is detectable. Additionally, considerable scour depths will develop at the pier toes and abutments, destabilising the entire structure of the bridge. On the upstream side of the construction, lateral overflow becomes increasingly probable as a consequence of backwater effects.

Argumentations outlined above had shown that either from the system loading, or from the system response perspective, a practical and effective solution has to be developed in order to close the existing gaps and to increase the reliability and robustness of natural hazard risk management. Therefore, within a scenario development framework (Mahmoud et al., 2009), we applied a level-based scenario approach for woody material transport in torrents and related mountain rivers. The major focus was on the explorative analysis of consequences emerging from hazards induced by woody material transport during extreme flood events at critical channel cross-sections. Therefore, we used Formative Scenario Analysis in combination with Fuzzy set theory to enhance knowledge representation. By applying Rough Set Data Analysis we validated the accuracy prediction of the selected set of consistent scenarios generated by Formative Scenario Analysis.

2. Methods

2.1. Risk concept

Risk has been a focal topic of many scientific and professional disciplines as well as practical actions. Consequently, a broad range of conceptualisations of the term exist that nevertheless show as a general basic principle, the combination of the likelihood that an undesirable state of reality may occur as a result of natural events or human activities (e.g., Fell et al., 2008). Originating from technical risk analyses, the concept of risk with respect to natural hazards is defined as a quantifying function of the probability of occurrence of a process and the related extent of damage, the latter specified by the damage potential and the vulnerability (Varnes, 1984; Fuchs, 2009):

$$R_{i,j} = f\left(p_{S_i}, A_{O_j}, p_{O_j,S_i}, v_{O_j,S_i}\right)$$

Hence, the following specifications are necessary for the ex-ante quantification of risk:

$R_{i,j}$: risk, dependent on scenario i and object j
p_{S_i}: probability of scenario i
A_{O_j}: value of object j, which is derived through economic valuation techniques (Fuchs and McAlpin, 2005)
p_{O_j,S_i}: probability of exposure of object j to scenario i
v_{O_j,S_i}: vulnerability of object j, depending on the intensity of scenario i

2.2. Formative Scenario Analysis

From a formal perspective, scenario analysis can be classified into three different types (Tietje, 2005): (1) holistic scenario analysis; (2) model scenario analysis; and (3) Formative Scenario Analysis. A holistic scenario analysis (which is analogue to the elicitation of responses from expert hearings) includes the construction of scenarios based on the opinion of specialists from the individual disciplines involved. A subjective mental integration of interdisciplinary qualitative and quantitative knowledge takes place, and intuitions and formal analyses of experts are combined (see e.g., Kahn and Wiener, 1967; van der Heijden, 2005). In doing so, mathematical methods and experimental results are commonly used to refine certain aspects of these scenarios, in particular with respect to a scale which takes into account individual (local) knowledge. Model scenario analyses are mainly based on (not always dynamical) systems modelling. By systematically varying the unknowns and assuming different values for uncertain parameters, the model is forced to create a number of trajectories, some of which are subsequently selected as scenarios by the expert pool. Following Scholz and Tietje (2002), Formative Scenario Analysis is a scientific technique to construct defined sets of assumptions to gain insight into a system and its potential development. With this procedure the study team is guided towards a differentiated and structured understanding of a system's current state and its dynamics. It is usually performed by small groups with specialised expertise about different aspects of the system, which they share with one another. Hence, Formative Scenario Analysis is based on qualitatively assessed key factors. Experts determine (by a rating procedure) quantitative relations between these factors. A Formative Scenario Analysis consists of two steps: (1) analytic modelling and decomposition of the initial state of the case studied; and (2) formative synthesis. In the first step an expert team identifies a set of key impact factors or variables that serve as perceptors. In the second step of formative synthesis, various operations are carried out on these key variables in order to generate all possible scenarios. Subsequently, a consistency analysis is performed in order to identify a number of different but internally consistent scenarios, and a scenario interpretation phase refines this procedure to iteratively identify relevant settings. This methodology was proposed by Scholz and Tietje (2002) by the application of a nine-step Formative Scenario Analysis (see Fig. 3) and it has been shown, that it could be successfully applied to natural hazard analysis (Mazzorana et al., 2009).

Here the methodology of Formative Scenario Analysis was refined, introducing methods of knowledge representation using type-1 fuzzy sets. In environmental modelling, we are dealing with imprecise and incomplete data (Brown et al., 2005; Mahmoud et al., 2009). In this context decisions made by experts are subjective and depend mainly on their individual concepts. Fuzzy set theory allows for making decisions in a fuzzy environment, which is made of fuzzy objectives, fuzzy constraints and a fuzzy decision (Rommelfanger and Eickemeier, 2001; Mouton et al., 2009). If a general system with multiple objectives and constraints is assumed, we result in $n > 1$ fuzzy objectives, $G_1,\ldots,G_n$ and $m > 1$ fuzzy constraints, $C_1, \ldots, C_n$ and defined as fuzzy sets in the set of options X_{op}. A fuzzy decision is determined as follows:

$$D = G_1 \cap G_2 \cap \cdots \cap G_n \cap C_1 \cap C_2 \cap \cdots \cap C_m$$

In order to reach agreement among different experts about their opinion on a certain event, the Fuzzy Delphi method was applied (Rutkowski, 2008). This method, which is employed in every rating procedure within this extended version of Formative Scenario Analysis consists of the following steps:

(1) The experts E_i express their opinion on a certain event in terms of triangular fuzzy numbers: $A_i = (a_s^{(i)}, a_M^{(i)}; a_l^{(i)})$, $i = 1, \ldots, n$.
(2) The average is computed as

$$A_{\text{aver}} = \left(\frac{1}{n}\sum_{i=1}^{n} a_s^{(i)}, \frac{1}{n}\sum_{i=1}^{n} a_M^{(i)}; \frac{1}{n}\sum_{i=1}^{n} a_l^{(i)}\right)$$

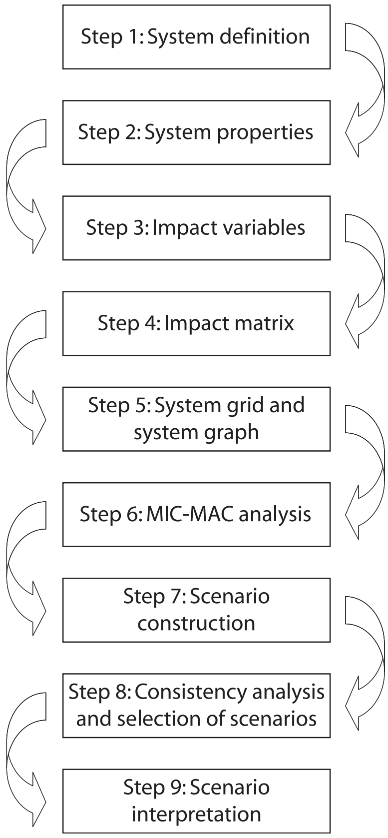

Fig. 3. The nine steps of Formative Scenario Analysis proposed by Scholz and Tietje (2002).

(3) Each expert E_i expresses his/her opinion again, taking into account the averages received from the previous round of inquiries and new fuzzy numbers and averages are created: $B_i = (b_s^{(i)}, b_M^{(i)}; b_l^{(i)})$, $i = 1, \ldots, n$ and $B_{\text{aver}} = (1/n\sum_{i=1}^{n} b_s^{(i)}, 1/n\sum_{i=1}^{n} b_M^{(i)}, 1/n\sum_{i=1}^{n} b_l^{(i)})$ respectively. The process is repeated until two sufficiently close averages $(A_{\text{aver}}, B_{\text{aver}}, C_{\text{aver}}, \ldots)$ are obtained.
(4) Subsequently, if new relevant information is obtained concerning a given problem, the procedures (1)–(3) may be repeated. In this way the effectiveness of a participative problem-solving approach is supported.

According to the Formative Scenario Approach, the specialised team of experts precisely defines the case study to be investigated (cf. Fig. 3). A conceptual sketch of this study is drawn and a concise description is carried out. In a second step, the expert team identifies the broad set of key variables that possibly determine the actual state of the studied system and the expected future developments. Importance and uncertainty of the key variables are rated by fuzzy intervals that are better able to represent the broad spectrum of the expert's case-specific knowledge than crisp values. Third, the relative importance of the key variables is estimated, and based on this rating the case study is structured by an impact matrix. This step provides activity, passivity, impact strengths and involvement measures for each variable (Scholz and Tietje, 2002). Activity quantifies the effectiveness of the impact of a variable on other variables. Passivity (or sensitivity) is correlated with the medium dependency of a variable on other variables. Impact strength is a summarising indicator of the medium impact strength of a variable on the entire case studied. Involvement indicates how strongly a certain variable is interlinked with the system. For these fundamental rating steps, fuzzy intervals were used to model the knowledge of specialised experts in an appropriate way. The above-mentioned parameters were determined by fuzzy algebraic operations. A grid of activity and passivity scores supports the expert team in selecting the core set of relevant key variables which are supposed to be the most important within the studied system. The classical Formative Scenario Analysis subsequently applies the MICMAC Analysis (Cross Impact Matrix-Multiplication Applied to Classification) that is omitted in the present version of Fuzzy Formative Scenario Analysis because the results of the impact matrix alone enable the expert team to select the relevant key variables. Instead of the MICMAC Analysis step, the following classification scheme is applied to the selected key factors: The set of key factors Q can be separated into two separate subsets, namely a set of conditional factors Co and the set of evolutional factors Ev, which are complementary to Q. Taking climate change as an example, conditional factors such as temperature and rainfall intensity changes influence evolutional factors such as peak discharges and sediment transport rates. Hence, a classification of the key variables at different levels can be introduced. Global factors (e.g., changes in rainfall intensity) are attributed to an outer level of influence, and local factors (e.g., peak discharges) to an inner level of influence. Dissecting the spatiotemporal continuum into p "spatiotemporal levels of influence", indexed by k, we obtain the following structure of the key factor set $Q^*: \; Q^* = \cup_{k=1}^{p} Q_k = \cup_{q=1}^{p} \mathrm{Co}_k \cup \mathrm{Ev}_k$. Here Q^* is used instead of Q, because some key factors can belong to more than one level. An evolution factor of an outer level can constitute a conditional factor of an inner level. Q can be structured as $Q = Q_1 \cup \bigcup_{k=2}^{p} (Q_k \setminus (Q_k \cap Q_{k-1}))$.

The subsequent consistency analysis is of crucial importance for the scenario construction phase. The expert team first identifies the levels to be assigned to each key variable and then assigns consistency ratings (fuzzy intervals) to all combinations of key factor levels belonging to each level k. Furthermore, a conjoint internal consistency measure for each scenario belonging to each level k is computed by means of fuzzy algebra. Common key factors between different levels are named connectors. The external consistency between scenarios of different levels derives from the sharing of common key factors. The key factor levels which are assumed by the common key factors along the hierarchy of levels is the outcome of the internal consistency analysis performed in the hierarchically superior level. The key factor levels of those key factors which are shared by both, the hierarchically superior and the hierarchically inferior level and which is expressed by the most consistent scenarios of the hierarchically superior level, are assumed as boundary condition for the determination of the most consistent scenarios of the hierarchically inferior level in a sort consistency cascading process. Scenario selection is performed on the basis of an overall conjoined consistency measure covering all identified levels. With respect to natural hazard risk management, two essential criteria for scenario selection were identified: (1) consistency, since inconsistent scenarios draw no realistic image of the system development; and (2) difference between scenarios, since decision makers focus on a set of principally possible system developments, while small differences between similar scenarios are of minor importance.

At the end of the procedure, the result is a series of consistent scenarios which comprise all levels that build up a case-specific scenario information system SIS.

Typically, knowledge contained in the scenario information system SIS is represented in the form of p decision tables DT_k. A decision table DT_k is the ordered 5-tuple $\mathrm{DT}_k = \langle U_k, \mathrm{Co}_k, \mathrm{Ev}_k, V_q, f_q \rangle_{q \in \mathrm{Co}_k \cup \mathrm{Ev}_k}$, where U_k denotes a set of scenarios with cardinality $|U| = h_{\max,h_{\max,k}}$, with $h_{\max,k}$ indicating the number of consistent scenarios selected for the level k, $\mathrm{Co}_k \cup \mathrm{Ev}_k$ is a finite set of key variables, V_q is the set of possible levels the key variables can assume, and f_q is the information function defined as $f_q: \; \mathrm{Co}_k \times \mathrm{Ev}_k \to V_q$. The information function defines unambiguously the set of rules included in the decision table, and is codified in the Formative Scenario Analysis procedure.

The resulting scenario information system is optimised by the means of Rough Sets Data Analysis (Pawlak, 1997; Greco et al., 2001; Tan, 2005; Olson and Delen, 2008; Rutkowski, 2008). The elimination of redundant information to provide more compact rules is achieved by identifying reducts, or subsets of key variables that still manage to preserve all the information within the decision tables DT_k and directly within the scenario information system SIS. If the results of Rough Sets Data Analysis indicate that the information content of the information system SIS is not complete and therefore fails to provide an accurate description of the case and its developments, the study team has to iteratively refine the key variable structure and re-perform the Formative Scenario Analysis procedure.

2.3. Model set-up

The framework of Formative Scenario Analysis, as proposed by Scholz and Tietje (2002), was extended by the means of Fuzzy set theory and Fuzzy algebra. This was done to meet the requirements in natural hazards and risk management, namely with respect to the problem data uncertainty and diverse experts' notion. Using fuzzy set theory (Kosko, 1992; Kruse et al., 1994; Rutkowski, 2008) is possible to formally define imprecise and ambiguous notions (e.g. "high temperature" or "average height").

The procedural steps for setting up the model are concisely summarised as follows:

(1) Formative scenario construction steps:

(a) The expert team pre-selects $q_i, \; i = 1, \ldots, N$ key variables, also referred to as system variables, impact factors or case descriptors.

(b) Next, the group of experts assigns each selected key variable to one of the following disjoined subsets of $Q: \; \mathrm{Co} \vee \mathrm{Ev}$.

(c) Following this, the group of experts organises the selected key variables $\widehat{q}_i \in \widehat{Q} \subseteq Q$ in an adequate level structure $\widehat{Q}^* = \bigcup_{k=1}^{p} \widehat{Q}_k = \bigcup_{k=1}^{p} \mathrm{Co}_k \cup \mathrm{Ev}_k$ with p levels. The apex r is introduced to describe the membership of $\widehat{q}^{\,r}_{i,k}$ to one of the above identified subsets of $\widehat{Q}^*$ as follows: $r = 1$ if $\widehat{q}^{\,r}_{i,k} \in \mathrm{Co}_k$; $r = 2$ if $\widehat{q}^{\,r}_{i,k} \in \mathrm{Ev}_k$. In $\widehat{q}^{\,r}_{i,k}$ we have: $i = 1, \ldots, \widehat{N}; \; k = 1, \ldots, p; \; r = 1, 2$.

(d) For each individual key variable the expert team assesses the relative importance, $\widetilde{I}_i$, for the case, as well as the uncertainty associated with each key variable, $\widetilde{U}_i$, in terms of fuzzy intervals of the type $\widetilde{X} = (x^{\varepsilon}_{-i} x^{1}_{-i} x^{-1}_{i} x^{-\varepsilon}_{i})^{\varepsilon}$ within the closed interval [1,10] for x. The lower bounds of acceptance are defined with fuzzy intervals of the same type (e.g., for uncertainty $\widetilde{L}_{\mathrm{U}} = (l^{\varepsilon}_{-i} l^{1}_{-i} l^{-1}_{i} l^{-\varepsilon}_{i})^{\varepsilon}$. The expert team pre-selects all key variables with a relative importance $\widetilde{I}_i$ that exceeds $\widetilde{L}_I$ and for the associated uncertainty $\widetilde{U}_i$. To account for the relative importance of each individual key variable on the entire system studied, qualitative and quantitative knowledge integration is essential. The major focus is on the detection of key variables with high importance, while associated uncertainties are considered to be small and information demand is low. These key variables are identified and included in the final set of selected impact factors. With respect to hydrologic hazards, considerable scientific evidence exists for such variables and the specific information content will directly be taken into consideration. The interaction between key variables rated with lower and higher uncertainties has to be discussed within the expert team.

(e) The expert team subsequently constructs the impact matrix, in which mutual impacts between the variables $q_{i,k}$ and $q_{j,k}$ are rated. These impacts are expressed in terms of fuzzy intervals. The impact matrix can be formally written as $\mathrm{IM} = (\tilde{A}_{i,j}), \; i,j = 1, \ldots, N$. To analyze the systemic relations among the selected indicators, an impact analysis is performed according to Formative Scenario Analysis by Scholz and Tietje (2002) or the bio-cybernetic approach of Vester (1988). The group of experts defines, for each pair of indicators, the strength of the one-directional impact or influence between them (Wiek and Binder, 2005). Activity and passivity for each variable are calculated by means of fuzzy algebra as row and column sums of $\tilde{A}_{i,j}$, respectively. Mean activity and mean passivity is obtained by the (fuzzy) arithmetic mean of the activity and passivity of each key variable. The comparison of the activity of a variable with mean activity, and of the passivity of a variable with mean passivity allows for categorising the variables into active, passive, ambivalent and buffer variables. It is important for congruity to check if the key variables $q_{i,k} \in \mathrm{Ev}$ are categorized as passive variables. Conversely, for the same congruity reasons, key variables $q_{i,k} \in \mathrm{Co}$ should not be categorized as passive.

(f) The group of experts selects, on the basis of the results of steps (d) and (e), the relevant key variables for the description of the case, namely $\widehat{q}_i \in \widehat{Q} \subseteq Q, \; i = 1, \ldots, \widehat{N}$.

(g) In a next step, the group of experts defines the levels of each individual key variable, namely $\widehat{q}^{\,r,n_i}_{i,k}$, where $n_i = 1, \ldots, \overline{N}_i$. Since the combinatorial number of scenarios is considerably influenced by the number of levels defined for each key variable, impact factors and their levels should be defined parsimoniously (Scholz and Tietje, 2002). Each key variable $\widehat{q}^{\,r}_{i,k}$ has at least two levels ($\overline{N}_i \geq 2$) which have to be discrete and denoted by $\widehat{q}^{\,r,1}_{i,k}, \widehat{q}^{\,r,2}_{i,k}, \ldots, \widehat{q}^{\,r,\overline{N}_i}_{i,k}$.

(h) Formally for each level a scenario $S_{h,k}$ can be written as a vector $S_{h,k} = (\widehat{q}^{\,1,n_1}_{1,k} \cdots \widehat{q}^{\,r,n_i}_{i,k} \cdots \widehat{q}^{\,6,n_{\widehat{N}_k}}_{\widehat{N}_k,k})$, where $\widehat{N}_k$ is the number of key variables belonging to the considered level k, and h is a scenario index.

(i) At this stage, a cascading consistency analysis procedure is proposed. A consistency matrix for the outmost level ($k = 1$) is constructed $CM_k = \tilde{C}(\widehat{q}^{\,r,n_i}_{i,k}, \widehat{q}^{\,r,n_j}_{j,k})$ which contains the consistency ratings in terms of fuzzy intervals $\tilde{C}(\bullet, \bullet)$ for all pairs of levels of all pairs of key variables $\widehat{q}^{\,r,n_i}_{i,k} \leftrightarrow \widehat{q}^{\,r,n_j}_{j,k}$, where $(i,j = 1, \ldots, \widehat{N}_k, \; i \neq j, n_i = 1, \ldots, \overline{N}_i, \; n_j = 1, \ldots, \overline{N}_j)$.

(j) For each scenario referring to the level k a consistency value is calculated as additive measure by means of fuzzy algebra as $\tilde{C}^*(S_{h,k}) = \sum \tilde{C}(\widehat{q}^{\,r,n_i}_{i,k}, \widehat{q}^{\,r,n_j}_{j,k})$ with $i,j = 1, \ldots, \widehat{N}_k; \; i \neq j; \; \widehat{q}^{\,r,n_i}_{i,k}, \widehat{q}^{\,r,n_j}_{j,k} \in S_{h,k}$.

(k) The scenario selection within the level k is based conjointly on the consistency value of the scenarios and the difference between them. As proposed by Tietje (2005) the distance measure is the number of differences between the scenarios

$$d(S_{h_1,k}, S_{h_2,k}) = \sum_{i=1}^{N_k} \left\{ 1, \text{ if the key variable level of } \widehat{q}^{\,r}_{i,k}(S_{h_1,k}) \neq \widehat{q}^{\,r}_{i,k}(S_{h_2,k}). 0, \right.$$
otherwise

The scenarios are decreasingly ranked according to consistency in an array. The scenario $S_{h_1,k}$ with the highest consistency value is selected from the array and is compared with the second scenario $S_{h_2,k}$. If $d(S_{h_1,k}, S_{h_2,k})$ is sufficiently high, e.g. $d(S_{h_1,k}, S_{h_2,k}) \geq d^*$, where d^* is a chosen threshold value, then scenario $S_{h_2,k}$ is also selected and becomes the new comparison reference for scenario three, otherwise the third scenario is compared with the first scenario etc. The selected scenarios with $\tilde{C}^*(S_{h,k}) \geq \tilde{K}(S_{h,k})$, where $\tilde{K}(S_{h,k})$ is a required minimum consistency according to the expert team, are considered. The obtained scenario structure SIS_k is now refined according to the optimisation procedure outlined under point (2).

(1) The set of the considered scenarios of the level k fixes the levels of key variables shared with the level $k+1$. This is a required condition of robustness. The procedural steps from (9) to (12) are repeated for the successive levels.

(2) Optimisation procedure:

The scenarios identified for level $k = 1$ are organised in an updatable scenario information system SIS_k with $k = 1, \ldots, p$ according to the decision table structure $\mathrm{DT}_k = \langle U_k, \mathrm{Co}_k, \mathrm{Ev}_k, V_q, f_q \rangle_{q \in \mathrm{Co}_k \cup \mathrm{Ev}_k}$ introduced in Subsection 2.1.

A set $\mathrm{Co}_k^* \subseteq \mathrm{Co}_k$ which is a minimal determining set for Ev_k is identified by means of Rough Sets Data Analysis. If no minimal determining set is found, either the key variables $\widehat{q}_{i,k}^{\,r}$ or the key variable level structure $\widehat{q}_{i,k}^{\,r,n_i}$ have to be adapted and the scenario construction procedure for this level has to be repeated.

The following definitions are needed to derive the minimal determining set $\mathrm{Co}_k^* \subseteq \mathrm{Co}_k$:

Definition 1. Equivalence class. For each $\mathrm{Co}_k \subseteq Q$ we associate an equivalence relation R_{Co_k} on U. The equivalence classes induced by R_{Co_k} are denoted by U/R_{Co_k}. If $x \in U$ holds, then $[x]_{R_{\mathrm{Co}_k}}$ is the equivalence class of R_{Co_k} containing x. Supposing that $U/R_{\mathrm{Co}_k} = \{U_1, U_2, \ldots, U_n\}$ and $\forall x, y \in U_i$, $1 \le i \le n$, we have $f_{\widehat{q}}(x) = f_{\widehat{q}}(y)$ for all $\widehat{q} \in \mathrm{Co}_k$ or $[x]_{R_{\mathrm{Co}_k}} = [y]_{R_{\mathrm{Co}_k}}$.

Definition 2. Supposing that $\mathrm{Co}_k, \mathrm{Ev}_k \subset Q$ we say that Ev_k is dependent on Co_k, written as $\mathrm{Co}_k^* \rightarrow \mathrm{Ev}_k$, if every class of U/R_{Ev_k} is a union of classes U/R_{Co_k}. In this case $\mathrm{Co}_k^* = \mathrm{Co}_k$ and is called a minimal determining set for Ev_k.

Definition 3. A set Co_k^* is a minimal determining set for Ev_k, if $\mathrm{Co}_k^* \rightarrow \mathrm{Ev}_k$ and Ev_k is not dependent on R for all $R \subset \mathrm{Co}_k^*$.

In order to measure the degree of dependence of $(\mathrm{Co}_k \rightarrow \mathrm{Ev}_k)$, a measure of the prediction or approximation quality can be written as follows:

$$\gamma(\mathrm{Co}_k \rightarrow \mathrm{Ev}_k) = \frac{\sum_{X \in U/R_{(\mathrm{Ev}_k)}} |\underline{R_{(\mathrm{Co}_k)}}X|}{|U|}$$

where $\underline{R_{(\mathrm{Co}_k)}}X$ is the lower approximation of X by Co_k ($R_{(\mathrm{Co}_k)}$-lower approximation), $0 \le \gamma(\mathrm{Co}_k \rightarrow \mathrm{Ev}_k) \le 1$, and $\underline{R_{(\mathrm{Co}_k)}}X = \{x \in U | [x]_{R_{\mathrm{Co}_k}} \subseteq X\}$. $\underline{R_{(\mathrm{Co}_k)}}X$ is the set of all elements of X that are correctly classified with respect to the attributes in Co_k, and $\gamma(\mathrm{Co}_k \rightarrow \mathrm{Ev}_k)$ is the ratio of the number of all elements of U/R_{Ev_k} that can be correctly classified based on the variables in Co_k to the total number of elements of U. Larger values $\gamma(\mathrm{Co}_k \rightarrow \mathrm{Ev}_k)$ indicate enhanced prediction quality. Note that $\mathrm{Co}_k \rightarrow \mathrm{Ev}_k$ implies $\gamma(\mathrm{Co}_k \rightarrow \mathrm{Ev}_k) = 1$ and that $\gamma(\mathrm{Co}_k \rightarrow \mathrm{Ev}_k) \neq 1$ indicates that Ev_k is not dependent on Co_k.

3. Model implementation

In this section, the model being set up is implemented based on the case study on selected woody material transport induced hazard scenarios at hydraulic weak points. In order to implement this model, ten individuals were selected from different stakeholder groups, all of which have at least ten years professional experience in applied natural hazard management. Three of these experts were related to the category of academic university research, three to the category of administrative bodies in charge of torrent control, and four to the category of practitioners concerned with ex-post event documentation.

Fig. 4 shows the mental system map ideated by this expert team for the case study being analysed. The group of experts identified two levels suitable for describing the hazard mechanisms related to woody material transport phenomena: (1) the system loading scenario level ($k = 1$); and (2) the system response scenario level ($k = 2$). The group of specialised experts identified five perceptors that explain the hazard potential due to woody material transport to be considered in structuring the system loading scenario level: (a) recruitment volumes from hill slopes; (b) in-stream recruitment volumes; (c) reachability of the considered critical stream configuration; (d) severity of woody material transport conditions at the considered configuration; and (e) woody material system loading severity at the considered configuration.

In a next step, in addition to (e) being identified as a common perceptor, the group of experts identified three receptors necessary to describe the interaction of the transported woody material at hydraulic weak points and the possible consequences (system response scenario level): (f) geometrical inappropriateness of the

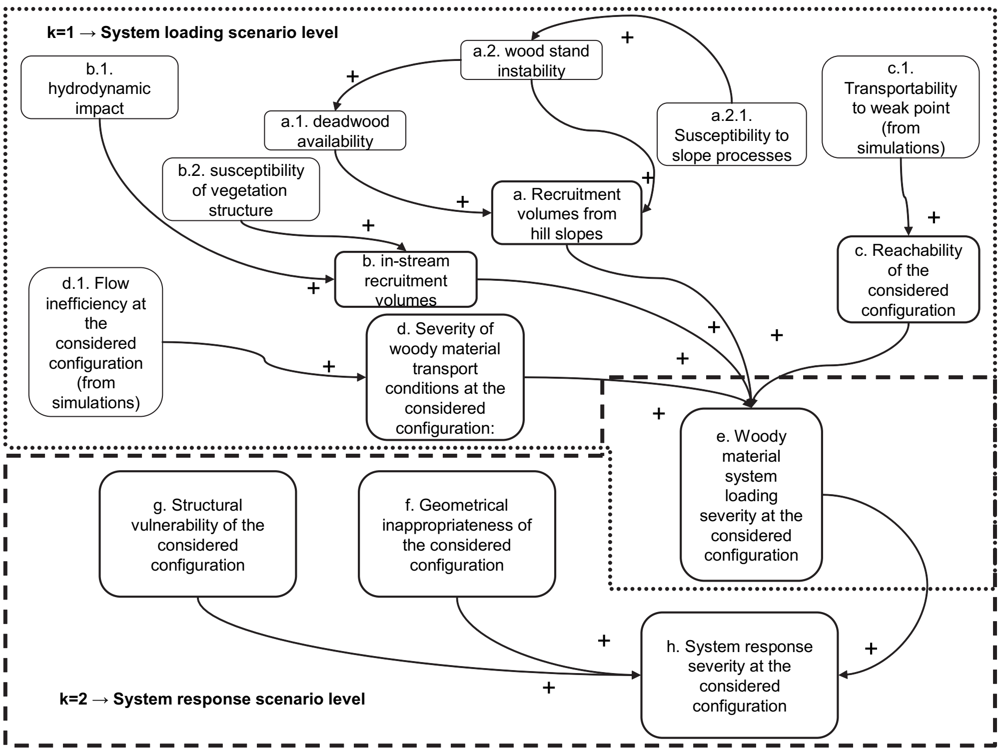

Fig. 4. Mental system map for the case study on woody material transport hazards. Please note that woody material system loading severity (WSL) is part of both system loading and system response scenario levels.

considered configuration; (g) structural vulnerability of the considered configuration; and (h) system response severity at the considered configuration.

As can be seen from the following description of the system loading and the system response scenario levels, this woody material hazard assessment framework is both multi-instrumental and multi-expert based, involving computational modelling steps and expert knowledge elicitation phases.

In the following paragraph, a detailed description of the perceptors of the system loading scenario level is given (upper part of Fig. 4).

As shown by Fig. 4, the experts subdivided the recruitment process in (a) recruitment from hill slopes and (b) in-stream recruitment. In accordance to the findings of Rickli and Bucher (2006), woody material recruitment volumes from hill slopes were judged to depend mainly on deadwood availability (a.1) and on wood stand stability (a.2). The susceptibility to slope processes (a.2.1) (e.g. landslides) was judged to exert an influence either on deadwood availability or on wood stand stability. In the expert opinion in-stream recruitment (b) could be estimated according to a conceptual framework proposed by Mazzorana et al. (in press). The in-stream recruitment volumes depend on the hydrodynamic impact forces (b.1) on in-stream vegetation and (b.2) on the resistance of vegetation exposed to those impacts. Flow conditions which assure a sufficient hydraulic connectivity between the woody material recruitment areas and the hydraulic weak point are required to satisfy the reachability condition (c). Calculations of the transportability (c.1) of woody material based on a computational procedure (Mazzorana et al., 2010) were judged to be an important prerequisite. The flow conditions at the weak point (liquid and woody material transport) contribute substantially in determining the system loading at the considered configuration (hydraulic loading). The severity of these flow conditions (d) can be estimated by detecting flow inefficiencies (d.1). Woody material transport induced system loading severity (e) was identified as a suitable descriptor of possible consequences of woody material transport dynamics at the considered configuration.

In the following paragraph, a detailed description of the perceptors of the system response scenario level is given (lower part of Fig. 4).

The group of experts agreed on assigning to woody material transport induced system loading severity (e) a relevant role as perceptor also for the system response scenario level. The geometrical inappropriateness (f) is another important perceptor identified by the pool of experts and indicates the propensity of woody material entrapment and subsequent decrease of the available flow section for conveyance and the closely related accentuation of hydrostatic and hydrodynamic pressures. These accentuated pressure loads are particularly severe if spanning blockage phenomena induced by cross-section wide woody material accumulations occur. Moreover the expert pool underlined the importance of properly assessing the structural vulnerability (g) of the in-stream structures at the critical configuration in order to draw a complete spectrum of conclusions about system response severity (h).

3.1. Initial set of key variables

According to the first procedural step of Formative Scenario Analysis, and as a result of the mental system map for the case study, possible relevant key variables $q^r_{i,k},\ i = 1,\dots,N,\ r = 1,2,\ k = 1,2$ significantly influencing the current state of the system and the system dynamics were identified (see Table 1).

3.2. Rating of key variables

O'Brien and Dyson (2007) pointed out criteria for selecting the key factors that will form the structure of the scenarios, i.e. the level of uncertainty in quantifying key variables, and the associated level of importance of the variable for the system. The group of specialised experts assessed the relative importance $\widetilde{I}$ for each key variable on the system, the uncertainty associated with each key variable $\widetilde{U}$ and the lower bounds of acceptance $\widetilde{L}_{\mathrm{I}}$ and $\widetilde{L}_{\mathrm{U}}$ (cf. Table 2).

3.2.1. Uncertainty versus importance matrices

The experts constructed two distinct uncertainty versus importance matrices, one for the key variables of the system loading scenario level (Table 2) and one for the key variables of the system response scenario level (Table 3). While on the system loading side the relevance of the key variables RPH, IRP, WTC and WSL were fixed, the relevance of variable PWD has been acknowledged after a reconsideration step. On the system response side, the relevance of variable WEP has been extensively discussed. Some experts argued that the variable BR indirectly depends on WEP. The final decision was to not discard the variable WEP.

3.2.2. Construction of impact matrices

The next step involved the construction of the impact matrix for the pre-selected variables of the system loading and the system response level in accordance to the following matrix structure:

$$
\begin{array}{cccccc}
 & 1 & \dots & N & \widetilde{A}_{i,\bullet} & \widetilde{A}_{i,\bullet}/\widetilde{A}_{\bullet,i} \\
1 & \widetilde{A}_{1,1} & \dots & \widetilde{A}_{i,N} & \sum_{j=1}^{N}\widetilde{A}_{1,j} & \widetilde{A}_{1,\bullet}/\widetilde{A}_{\bullet,1} \\
\vdots & \vdots & \dots & \vdots & \vdots & \vdots \\
N & \widetilde{A}_{N,1} & \dots & \widetilde{A}_{N,N} & \sum_{j=1}^{N}\widetilde{A}_{N,j} & \widetilde{A}_{N,\bullet}/\widetilde{A}_{\bullet,N} \\
\widetilde{A}_{\bullet,j} & \sum_{i=1}^{N}\widetilde{A}_{i,1} & \dots & \sum_{i=1}^{N}\widetilde{A}_{i,1} & \widetilde{A}_{\bullet,\bullet} = \sum_{i=1}^{N}\sum_{j=1}^{N}\widetilde{A}_{i,j} & \\
\widetilde{A}_{\bullet,j}*\widetilde{A}_{j,\bullet} & \widetilde{A}_{\bullet,1}*\widetilde{A}_{1,\bullet} & \dots & \widetilde{A}_{\bullet,N}*\widetilde{A}_{N,\bullet} & &
\end{array}
$$

where the symbols $\sum_{j=1}^{N}$ and $\sum_{i=1}^{N}$ represent the fuzzy algebraic sum operation $\oplus$ of two or more fuzzy intervals, $\widetilde{A}_{\bullet,j}*\widetilde{A}_{j,\bullet}$ represent the fuzzy algebraic multiplication operation $\otimes$ and $\widetilde{A}_{i,\bullet}/\widetilde{A}_{\bullet,i}$ represent the fuzzy division operation $\div$. The mutual impacts between the variables d_i and d_j were rated according to three fuzzy impact levels $(\widetilde{L}_{\mathrm{IMPACT}};\widetilde{M}_{\mathrm{IMPACT}};\widetilde{H}_{\mathrm{IMPACT}})$ as shown in Fig. 5. Taking Medium impact as an example, the fuzzy interval is written as

Table 1
Possible key variables for the case study on woody debris transport hazards.

Key variable	Level	Perceptor	Name	Description
$q^1_{1,1}$	System loading level	(a) Recruitment volumes from hill slopes	RPH	**R**ecruitment **p**ropensity from **h**ill slopes. Estimates are externally provided through computational modelling (Mazzorana et al., 2009). The computational procedure takes into consideration the following parameters: wood stand instability, susceptibility to slope processes and deadwood availability
$q^1_{2,1}$	System loading level	(b) In-stream recruitment volumes	IRP	**I**n-stream **r**ecruitment **p**ropensity. Estimates are externally provided through computational modelling (Mazzorana et al., 2009). The computational procedure takes into consideration the intensity of the flood processes and the resistance of the vegetation structures within the wetted perimeter of the flood
$q^1_{3,1}$	System loading level	(c) Reachability of the critical configuration	WTC	**W**oody material **t**ransport **c**ost (transportability) to reach the critical configuration. Estimates are externally provided through computational modelling (Mazzorana et al. in press). The transportability depends primarily on existing hydrodynamic conditions, given considered stream geometry, and on the woody material characteristics, which can be suitably described through the parameters design log length (Diehl, 1997) and design log diameter.
$q^1_{4,1}$	System loading level	(d) Severity of woody material transport conditions at the considered configuration	PWD	**P**otential **w**oody material **d**istribution at the considered configuration. Diehl (1997) proposes a structured expert based procedure to assess this parameter. Knowing the design log characteristics and characteristics of the flow, the experts suggest hypotheses about the spatial distribution of the woody material volumes potentially approaching the critical configuration
$q^2_{5,1} \vee q^1_{1,2}$	System loading level and system response level	(e) Woody material system loading severity	WSL	**W**oody material **s**ystem **l**oading severity. On the basis of the overall picture of the system loading conditions, the level of the system loading severity is deduced
$q^1_{2,2}$	System response level	(f) Geometrical inappropriateness of the considered configuration	WEP	**W**oody material **e**ntra**p**ment propensity. Here the experts judge the propensity of woody material being entrapped as a consequence of the interaction with certain geometrical features and components of in-stream structures. Practical indications have been provided by Diehl (1997) and Lange and Bezzola (2006)
$q^1_{3,2}$	System response level	(f) Geometrical inappropriateness of the considered configuration	BR	**B**lockage **r**atio. Here the experts judge possible cross-sectional blockage configurations on the basis of its geometry and the woody material characteristics (i.e. design log length)
$q^1_{3,2}$	System response level	(g) Structural vulnerability of the considered configuration	SCP	**S**ystem **c**hange **p**ropensity. The experts assess this parameter on the basis of the vulnerability of the structural components of the in-stream structures and the possible erosion of the streambed and banks. Stable channel design computations (USACE, 2008) are of great advantage.
$q^2_{4,2}$	System response level	(h) System response severity at the considered configuration	SRS	**S**ystem **r**esponse **s**everity. On the basis of the overall picture of the system loading and response conditions, the level of the system response severity is deduced

$\widetilde{M}_{\mathrm{IMPACT}} = (0.5, 1.0, 1.5, 2.0)^{\varepsilon}$. The underlying impact matrix of the system loading level is shown in Table 4 and the impact matrix of the system response level is shown in Table 5.

The results of the impact analyses led to the conclusion that the congruity of the choice of the key variables is satisfactory. As expected in the system loading cell RPH, IRP and WTC are clearly active variables, while WSL is passive. As assumed, the role of WSL in the system response level turns out to be active. SRS logically is passive. A crucial role is expected to be played by the ambivalent key variables, namely WEP, BR and SCP. Hence, the expert team decided to retain both the current level structure and the pre-selected key variables.

3.3. Definition of the level of each key variable

The subsequent step consisted in defining the impact levels $\widehat{q}^{\,r,1}_{i,k}, \widehat{q}^{\,r,2}_{i,k}, \ldots, \widehat{q}^{\,r,N_i}_{i,k}$ for each key variable $q^r_{i,k}$ (see Table 6).

3.4. Consistency matrix, scenario construction and selection for the system loading level

In order to construct the consistency matrix, the expert team started the cascading consistency analysis procedure for the outmost level ($k = 1$). The consistency ratings $CM_k = \widetilde{C}(\widehat{q}^{\,r,n_i}_{i,k}, \widehat{q}^{\,r,n_j}_{j,k})$ for each

Table 2
Importance and uncertainty levels for each variable of the system loading level in relation to the acceptance levels.

Fuzzy evaluation: Uncertainty vs. importance										
Key variable	$\widetilde{L}_U$				$\widetilde{L}_I$					
	Uncertainty margins of acceptance				Importance margin of acceptance				Acceptance evaluation	
	3	3.5	4.5	5	3	3.5	4.5	5		
	$\widetilde{U}$				$\widetilde{I}$				$\widetilde{U} \geq \widetilde{L}_U \rightarrow ok$	$\widetilde{I} \geq \widetilde{L}_U \rightarrow ok$
	Uncertainty evaluation				Importance evaluation				Uncertainty constraints	Importance constraints
RPH	5	6	7	8	8.5	9	9.5	10	OK	OK
IRP	6	6.5	7	9	4	5	6	7	OK	OK
WTC	5	5.5	6	7	8	8.5	9	9.5	OK	OK
PWD	3	3.5	4.5	5	7	7.5	8	8.5	Re-discussion → OK	OK
WSL	8	9	9	9	6	7	8	9	OK	OK

Table 3
Importance and uncertainty levels for each variable of the system response level in relation to the acceptance levels.

Fuzzy evaluation: Uncertainty vs. importance										
Key Variable	$\tilde{L}_U$				$\tilde{L}_I$					
	Uncertainty margins of acceptance				Importance margin of acceptance				Acceptance evaluation	
	3	3.5	4.5	5	3	3.5	4.5	5		
	$\tilde{U}$				$\tilde{I}$				$\tilde{U} \geq \tilde{L}_U \rightarrow ok$	$\tilde{I} \geq \tilde{I}_U \rightarrow ok$
	Uncertainty evaluation				Importance evaluation				Uncertainty constraints	Importance constraints
WSL	5	6	7	8	8.5	9	9.5	10	OK	OK
WEP	6	6.5	7	9	3	4	4.5	5	OK	Re-discussion → OK
BR	5	5.5	6	7	8	8.5	9	9.5	OK	OK
SCP	3	3.5	4.5	5	7	7.5	8	8.5	OK	OK
SRS	8	9	9	9	6	7	8	9	OK	OK

The applied rating values are expressed as ϵ-type Fuzzy intervals. The trapezoidal membership function of these intervals is therefore described by four values.

pair of impact levels (cf. Table 6) of different key variables $\widehat{q}\,^{r,n_i}_{i,k} \leftrightarrow \widehat{q}\,^{r,n_j}_{j,k}$ were assigned with $(i,j = 1,\ldots,\widehat{N}_k,\ i \neq j,\ n_i = 1,\ldots,\overline{N}_i,\ n_j = 1,\ldots,\overline{N}_j)$, in terms of fuzzy intervals $\tilde{C}(\bullet,\bullet)$, see Fig. 6.

Taking $(\widehat{q}\,^{1,3}_{1,1}, \widehat{q}\,^{1,2}_{4,1})$ as an example, rated consistency between pairs of impact levels of different key variables $(\widehat{q}\,^{r,n_i}_{i,1}, \widehat{q}\,^{r,n_j}_{j,1})$ was identified by the fuzzy interval $\tilde{P}_{\mathrm{CONSISTENCY}} = (0.0, 1.0, 1.25, 3.0)^{\varepsilon}$.

The result was the consistency matrix $CM_1 = \tilde{C}(\widehat{q}\,^{r,n_i}_{i,1}, \widehat{q}\,^{r,n_j}_{j,1})$ containing all consistency ratings between pairs of impact levels of different key variables, as shown in Table 7.

At this stage for each scenario referring to the level $k = 1$, a consistency value was calculated as additive value by means of fuzzy algebra as $\tilde{C}^*(S_{h,1}) = \sum \tilde{C}(\widehat{q}\,^{r,n_i}_{i,1}, \widehat{q}\,^{r,n_j}_{j,1})$ with $i,j = 1,\ldots,\widehat{N}_1;\ i \neq j;\ \widehat{q}\,^{r,n_i}_{i,1}, \widehat{q}\,^{r,n_j}_{j,1} \in S_{h,1}$. Taking as an example the scenario $q^{1,1}_{1,1} \wedge q^{1,1}_{2,1} \wedge q^{1,1}_{3,1} \wedge q^{1,2}_{4,1} \wedge (q^{2,1}_{5,1} \vee q^{1,1}_{1,2})$, the additive consistency value is calculated as follows:

$$\begin{aligned}\tilde{C}^*(S_{1,1}) &= \tilde{C}\left(\widehat{q}\,^{1,1}_{1,1}, \widehat{q}\,^{1,1}_{2,1}\right) \oplus \tilde{C}\left(\widehat{q}\,^{1,1}_{2,1}, \widehat{q}\,^{1,1}_{3,1}\right) \oplus \tilde{C}\left(\widehat{q}\,^{1,1}_{3,1}, \widehat{q}\,^{1,1}_{4,1}\right) \oplus \tilde{C}\left(\widehat{q}\,^{1,1}_{4,1}, \widehat{q}\,^{1,1}_{5,1}\right) \oplus \tilde{C}\left(\widehat{q}\,^{1,1}_{1,1}, \widehat{q}\,^{1,1}_{3,1}\right) \oplus \tilde{C}\left(\widehat{q}\,^{1,1}_{1,1}, \widehat{q}\,^{1,1}_{4,1}\right) \\ &\oplus \tilde{C}\left(\widehat{q}\,^{1,1}_{1,1}, \widehat{q}\,^{1,1}_{5,1}\right) \oplus \tilde{C}\left(\widehat{q}\,^{1,1}_{2,1}, \widehat{q}\,^{1,1}_{4,1}\right) \oplus \tilde{C}\left(\widehat{q}\,^{1,1}_{2,1}, \widehat{q}\,^{1,1}_{5,1}\right) \oplus \tilde{C}\left(\widehat{q}\,^{1,1}_{3,1}, \widehat{q}\,^{1,1}_{5,1}\right) = \tilde{P} \oplus \tilde{H} \oplus \tilde{H} \oplus \tilde{H} \oplus \tilde{P} \oplus \tilde{H} \oplus \tilde{H} \oplus \tilde{H} \oplus \tilde{H} \oplus \tilde{H} \\ &= (16.0, 20.0, 26.5, 30.0)^{\varepsilon}\end{aligned}$$

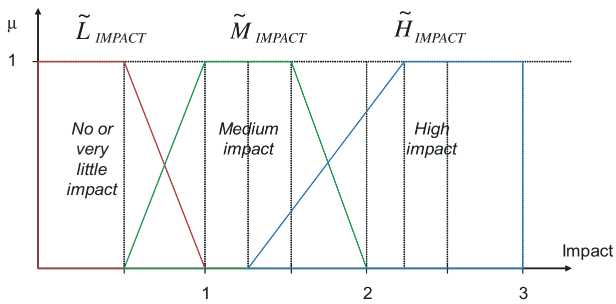

Fig. 5. Impact levels between variables.

The respective summands are highlighted in yellow in Table 7.

The consistency of, and distance criteria between scenarios allowed for a selection of tweleve scenarios, with $\tilde{C}^*(S_{h,k}) \geq \tilde{K}(S_{h,k})$, as shown (and highlighted) in Table 8.

In a subsequent step, the scenarios identified for level $k = 1$ were organised in a scenario information system SIS_k with $k = 1$ according to the decision table structure $DT_k = \langle U_k, \mathrm{Co}_k, \mathrm{Ev}_k, V_q, f_q \rangle_{q \in \mathrm{Co}_k \cup \mathrm{Ev}_k}$ (Table 9).

Definition of equivalence classes U/R_{Co_1}:

$$U/R_{\mathrm{RPH}} = \{\{x_1, x_2, x_3, x_6\}, \{x_4, x_5\}, \{x_8, x_9\}, \{x_7, x_{10}, x_{11}, x_{12}\}\}$$

$$U/R_{\mathrm{IRP}} = \{\{x_1, x_2, x_3, x_4, x_5\}, \{x_6, x_7\}, \{x_8, x_9, x_{10}, x_{11}, x_{12}\}\}$$

$$U/R_{\mathrm{WTC}} = \{\{x_1, x_2, x_4, x_6\}, \{x_3, x_5, x_8, x_{10}\}, \{x_7, x_9, x_{11}, x_{12}\}\}$$

$$U/R_{\mathrm{PWD}} = \{\{x_1, x_3, x_4, x_5, x_6\}, \{x_2, x_{11}\}, \{x_7, x_8, x_9, x_{10}, x_{12}\}\}$$

$$U/R_{\mathrm{WSL}} = \{\{x_1, x_2, x_4, x_5, x_6\}, \{x_3\}, \{x_7, x_8, x_9, x_{10}, x_{11}, x_{12}\}\}$$

$\mathrm{Co}_k \rightarrow \mathrm{Ev}_k$

$$\begin{aligned}U/R_{\mathrm{Co}_1} &= \{\{x_1\}, \{x_2\}, \{x_3\}, \{x_4\}, \{x_5\}, \{x_6\}, \{x_7\}, \{x_8\}, \{x_9\}, \\ &\quad \{x_{10}\}, \{x_{11}\}, \{x_{12}\}\}\end{aligned}$$

Definition of the lower approximations:

$$\begin{aligned}\underline{R_{\mathrm{Co}_1}}X_1 &= \{x_1, x_2, x_4, x_5, x_6\},\ \underline{R_{\mathrm{Co}_1}}X_2 = \{x_3\},\ \underline{R_{\mathrm{Co}_1}}X_3 \\ &= \{x_7, x_8, x_9, x_{10}, x_{11}, x_{12}\}\end{aligned}$$

Calculation of the approximation quality:

$$\gamma(\mathrm{Co}_k \rightarrow \mathrm{Ev}_k) = \frac{\sum_{X \in U/R_{(\mathrm{Ev}_k)}} |\underline{R_{(\mathrm{Co}_k)}}X|}{|U|} = 1$$

Table 4
Impact matrix for the key variables belonging to the system loading level and characterisation of the key variables either as active, passive, buffer or ambivalent variables.

	RPH				IRP				WTC				PWD				WSL				Activity				Mean activity			
RPH	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	0.50	1.00	1.50	2.00	0.00	0.00	0.50	1.00	1.25	2.25	3.00	3.00	1.75	3.25	5.50	7.00	1.45	2.75	4.90	6.60
IRP	0.00	0.00	0.50	1.00	0.00	0.00	0.00	0.00	0.50	1.00	1.50	2.00	0.50	1.00	1.50	2.00	1.25	2.25	3.00	3.00	2.25	4.25	6.50	8.00				
WTC	0.00	0.00	0.50	1.00	0.50	1.00	1.50	2.00	0.00	0.00	0.00	0.00	0.50	1.00	1.50	2.00	1.25	2.25	3.00	3.00	2.25	4.25	6.50	8.00				
PWD	0.00	0.00	0.50	1.00	0.50	1.00	1.50	2.00	0.00	0.00	0.50	1.00	0.00	0.00	0.00	0.00	0.50	1.00	1.50	2.00	1.00	2.00	4.00	6.00				
WSL	0.00	0.00	0.50	1.00	0.00	0.00	0.50	1.00	0.00	0.00	0.50	1.00	0.00	0.00	0.50	1.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	4.00				
Passivity	0.00	0.00	2.00	4.00	1.00	2.00	4.00	6.00	1.00	2.00	4.00	6.00	1.00	2.00	4.00	6.00	4.25	7.75	10.50	11.00								
Mean passivity																												
1.45 2.75 4.90 6.60																												
RPH	1.00	0.00	active																									
IRP	1.00	0.00	active																									
WTC	1.00	0.00	active																									
PWD	0.00	0.00	buffer																									
WSL	0.00	1.00	passive																									

Table 5
Impact matrix for the key variables belonging to the system response level and characterisation of the key variables either as active, passive, buffer or ambivalent variables.

	WSL				WEP				BR				SCP				SRS				Activity				Mean activity			
WSL	0.00	0.00	0.00	0.00	0.50	1.00	1.50	2.00	0.50	1.00	1.50	2.00	0.50	1.00	1.50	2.00	0.50	1.00	1.50	2.00	2.00	4.00	6.00	8.00	2.00	3.88	6.00	7.60
WEP	0.00	0.10	0.50	1.00	0.00	0.00	0.00	0.00	1.25	2.25	3.00	3.00	0.50	1.00	1.50	2.00	1.25	2.25	3.00	3.00	3.00	5.60	8.00	9.00				
BR	0.00	0.10	0.50	1.00	0.50	1.00	1.50	2.00	0.00	0.00	0.00	0.00	1.25	2.25	3.00	3.00	0.50	1.00	1.50	2.00	2.25	4.35	6.50	8.00				
SCP	0.00	0.10	0.50	1.00	0.50	1.00	1.50	2.00	0.50	1.00	1.50	2.00	0.00	0.00	0.00	0.00	1.25	2.25	3.00	3.00	2.25	4.35	6.50	8.00				
SRS	0.00	0.10	0.50	1.00	0.50	1.00	1.50	2.00	0.00	0.00	0.50	1.00	0.00	0.00	0.50	1.00	0.00	0.00	0.00	0.00	0.50	1.10	3.00	5.00				
Passivity	0.00	0.40	2.00	4.00	2.00	4.00	6.00	8.00	2.25	4.25	6.50	8.00	2.25	4.25	6.50	8.00	3.50	6.50	9.00	10.00								
Mean passivity																												
2.00 3.88 6.00 7.60																												
WSL	1.00	0.00	active																									
WEP	1.00	1.00	ambivalent																									
BR	1.00	1.00	ambivalent																									
SCP	1.00	1.00	ambivalent																									
SRS	0.00	1.00	passive																									

Table 6
Impact level definition for each key variable.

Name	Description	Impact levels defined	
RPH	**R**ecruitment **p**ropensity from **h**ill slopes	$q_{1,1}^{1,1}$	Low or negligible recruitment propensity from hill slopes. Fragmentary wood buffer along the stream positioned far away from the critical configuration.
		$q_{1,1}^{1,2}$	Medium recruitment propensity from hill slopes. Continuous wood buffer along the stream, relatively stable wood structure.
		$q_{1,1}^{1,3}$	High recruitment propensity from hill slopes. Continuous wood buffer along the stream, relatively unstable due to lateral erosion processes; and isolated and rather infrequent hill slope processes.
		$q_{1,1}^{1,4}$	Very high recruitment propensity from hill slopes. Continuous wood buffer along the stream, unstable due to lateral erosion and extended and frequent hill slope processes.
IRP	**I**n-stream **r**ecruitment **p**ropensity	$q_{2,1}^{1,1}$	Low in-stream recruitment propensity. Small in-stream woody vegetation volumes, rather flexible structure.
		$q_{2,1}^{1,2}$	Medium in-stream recruitment propensity. Larger in-stream woody vegetation volumes, structures rather inflexible; movable streambed during high floods.
		$q_{2,1}^{1,3}$	High in-stream recruitment propensity. Large in-stream woody vegetation volumes; inflexible, movable streambed and high erosion rates during high floods.
WTC	**W**oody material **t**ransport **c**ost (transportability) to reach the critical configuration	$q_{3,1}^{1,1}$	Low transportability or high woody debris roughness. Highly curved stream, small water depths with respect to the design wood log diameters, narrow channel widths with respect to the design wood log lengths.
		$q_{3,1}^{1,2}$	Medium transportability or medium woody debris roughness. Rather straight-lined stream, occasionally narrow water depths with respect to the design wood log diameters, occasionally narrow channel widths with respect to the design wood log lengths.
		$q_{3,1}^{1,3}$	High transportability or low woody debris roughness. Straight-lined stream. Large water depths with respect to the design wood log diameters, large channel widths with respect to the design wood log lengths.
PWD	**P**otential **w**oody material **d**istribution at the considered configuration	$q_{4,1}^{1,1}$	Rather favourable potential distribution. Woody material is presumed to be transported in a small part of the flow section and the orientations of the woody material logs is supposed parallel to the flow direction.
		$q_{4,1}^{1,2}$	Rather unfavourable potential distribution. Woody material is presumed not to be restricted to a small part of the flow section and the orientations of the woody material logs are randomly distributed with respect to the flow direction.
		$q_{4,1}^{1,3}$	Extremely unfavourable potential distribution. Woody material is presumed to be transported throughout the flow section and the orientations of the woody material logs are randomly distributed with respect to the flow direction.
WSL	**W**oody material **s**ystem **l**oading severity	$q_{5,1}^{2,1} \vee q_{1,2}^{1,1}$	Low or negligible woody material system loading severity. This is an impact level of a key variable classified as an evolutional factor (level $k = 1$).
		$q_{5,1}^{2,2} \vee q_{1,2}^{1,2}$	Medium woody material system loading severity. This is an impact level of a key variable classified as an evolutional factor (level $k = 1$).
		$q_{5,1}^{2,3} \vee q_{1,2}^{1,3}$	High woody material system loading severity. This is an impact level of a key variable classified as an evolutional factor (level $k = 1$).
WEP	**W**oody material **e**ntra**p**ment **p**ropensity	$q_{2,2}^{1,1}$	Low or negligible woody material entrapment propensity. Interference between the potentially transported woody material and the geometrical features is unlikely (no piers, no protruding abutments, sufficient flow section).
		$q_{2,2}^{1,2}$	Medium woody material entrapment propensity. Interference between the potentially transported woody material and the geometrical features is likely but large accumulations of woody material are unlikely (max. single pier accumulations, sufficient flow section).
		$q_{2,2}^{1,3}$	High woody material entrapment propensity. Interference between the potentially transported woody material and the geometrical features is likely. Large accumulations of woody material are possible (single pier and spanning blockage accumulations, insufficient flow section).
BR	**B**lockage **r**atio	$q_{3,2}^{1,1}$	Low or negligible blockage ratio.
		$q_{3,2}^{1,2}$	Medium blockage ratio.
		$q_{3,2}^{1,3}$	High blockage ratio.
SCP	**S**ystem **c**hange **p**ropensity	$q_{4,2}^{1,1}$	Low or negligible system change propensity. The vulnerability of the components of the critical configuration is low: Either the in-stream structures (e.g. piers, abutments) or the flow confining structures (e.g. embankments, levees) are structurally reliable.
		$q_{4,2}^{1,2}$	Medium system change propensity. The vulnerability of the components of the critical configuration is medium: The reliability of either the in-stream structures (e.g. piers, abutments) or the flow confining structures (e.g. embankments, levees) is medium. Increasing damage with increasing system loading conditions is likely.
		$q_{4,2}^{1,3}$	High system change propensity. The vulnerability of the components of the critical configuration is low: The reliability of either the in-stream structures (e.g. piers, abutments) or the flow confining structures (e.g. embankments, levees) is low. Sudden collapses cannot be excluded.
SRS	**S**ystem **r**esponse **s**everity	$q_{5,2}^{2,1}$	Low or negligible system response severity. Low or negligible structural damage. Floodplain inundation processes not induced by system responses at the critical configuration.
		$q_{5,2}^{2,2}$	Medium system response severity. Increasing damages with increasing system loading conditions are likely.
		$q_{5,2}^{2,3}$	High system response severity either in terms of damage to the in-stream structures or to the flow confining structures. Significant damage with medium system loading severity is possible. Consequences also in terms of subsequent floodplain inundation processes.

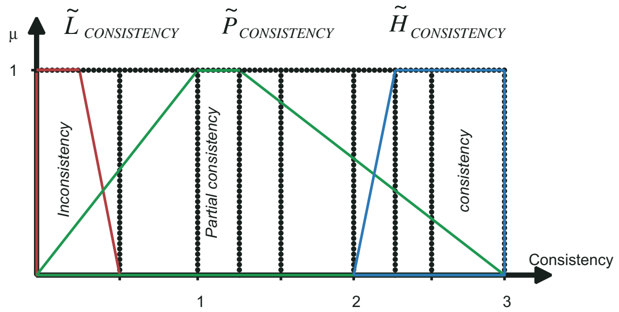

Fig. 6. Fuzzy intervals for consistency rating.

3.5. *Consistency matrix, scenario construction and selection for the system response level*

In analogy to the estimations and computations carried out for level $k=1$, the expert team constructed a consistency matrix for the innermost level ($k=2$) assigning the consistency ratings $\text{CM}_k = \tilde{C}(\widehat{q}^{\,r,n_i}_{i,k}, \widehat{q}^{\,r,n_j}_{j,k})$ for each pair of impact levels (Table 10) of different key variables $\widehat{q}^{\,r,n_i}_{i,k} \leftrightarrow \widehat{q}^{\,r,n_j}_{j,k}$, with $(i,j = 1,\ldots,\widehat{N}_k,$ $i \neq j,$ $n_i = 1,\ldots,\overline{N}_i,$ $n_j = 1,\ldots,\overline{N}_j)$, in terms of fuzzy intervals $\widetilde{C}(\cdot,\cdot)$ (see Fig. 6).

The respective consistency ratings in terms of additive consistency values are reported in Table 11. The consistency of and distance criteria between scenarios allowed to select nine scenarios, with $\widetilde{C}^*(S_{h,k}) \geq \widetilde{K}^*(S_{h,k})$, as shown and highlighted in Table 11 by numbers.

In a subsequent step, the scenarios identified for level $k=2$ were organised in a scenario information system SIS_k with $k=2$ according to the decision table structure $\text{DT}_k = \langle U_k, \text{Co}_k, \text{Ev}_k, V_q, f_q \rangle_{q \in \text{Co}_k \cup \text{Ev}_k}$ (Table 12).

Definition of equivalence classes U/R_{Co_2}:

$$U/R_{\text{WSL}} = \{\{x_1,x_2,x_3\},\{x_4,x_5,x_7\},\{x_6,x_8,x_9\}\}$$

$$U/R_{\text{WEP}} = \{\{x_1,x_2,x_3,x_4\},\{x_5,x_6\},\{x_7,x_8,x_9\}\}$$

$$U/R_{\text{BR}} = \{\{x_1,x_3,x_4\},\{x_2,x_5,x_6,x_8\},\{x_7,x_9\}\}$$

$$U/R_{\text{SCP}} = \{\{x_1,x_2,x_4\},\{x_3,x_5,x_6\},\{x_7,x_8,x_9\}\}$$

$$U/R_{\text{SRS}} = \{\{x_1,x_2,x_3,x_4\},\{x_5,x_6\},\{x_7,x_8,x_9\}\}$$

$$(\text{Co}_k \rightarrow \text{Ev}_k)$$

$$U/R_{\text{Co}_2} = \{\{x_1\},\{x_2\},\{x_3\},\{x_4\},\{x_5\},\{x_6\},\{x_7\},\{x_8\},\{x_9\}\}$$

Definition of the lower approximations:

$$\underline{R_{\text{Co}_2}}X_1 = \{x_1,x_2,x_3,x_4\}, \quad \underline{R_{\text{Co}_2}}X_2 = \{x_5,x_6\}, \quad \underline{R_{\text{Co}_2}}X_3 = \{x_7,x_8,x_9\}$$

Calculation of the approximation quality:

$$\gamma(\text{Co}_k \rightarrow \text{Ev}_k) = \frac{\sum_{X \in U/R_{(\text{Ev}_k)}} |\underline{R_{(\text{Co}_k)}}X|}{|U|} = 1$$

Tables 9 and 12 contain the knowledge structure and the specific contents about the case study on woody material transport, as elicited from the expert team. The conceptual validity of the mental system map shown in Fig. 3 was supported by the results. Thus a coherent step-by-step interpretation of the woody material transport related hazard processes and the severity of the induced consequences are provided.

Table 7
Consistency matrix for the scenario level $k=1$.

Name	Description	Name	RPH				IRP			WTC			PWD		
		Impact levels	$q^{1,1}_{1,1}$	$q^{1,2}_{1,1}$	$q^{1,3}_{1,1}$	$q^{1,4}_{1,1}$	$q^{1,2}_{2,1}$	$q^{1,2}_{2,1}$	$q^{1,3}_{2,1}$	$q^{1,1}_{3,1}$	$q^{1,2}_{3,1}$	$q^{1,3}_{3,1}$	$q^{1,1}_{4,1}$	$q^{1,2}_{4,1}$	$q^{1,3}_{4,1}$
RPH	Recruitment propensity from hill slopes	$q^{1,1}_{1,1}$													
		$q^{1,2}_{1,1}$													
		$q^{1,3}_{1,1}$													
		$q^{1,4}_{1,1}$													
IRP	In-stream recruitment propensity	$q^{1,1}_{2,1}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{L}$									
		$q^{1,2}_{2,1}$	$\widetilde{P}$	$\widetilde{L}$	$\widetilde{L}$	$\widetilde{P}$									
		$q^{1,3}_{2,1}$	$\widetilde{L}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$									
WTC	Woody material transport cost to reach the critical configuration	$q^{1,1}_{3,1}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{L}$	$\widetilde{H}$	$\widetilde{H}$	$\widetilde{L}$						
		$q^{1,2}_{3,1}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{H}$	$\widetilde{P}$	$\widetilde{H}$						
		$q^{1,3}_{3,1}$	$\widetilde{L}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{L}$	$\widetilde{H}$	$\widetilde{H}$						
PWD	Potential woody material distribution at the considered configuration	$q^{1,1}_{4,1}$	$\widetilde{H}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{L}$	$\widetilde{H}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{H}$	$\widetilde{P}$	$\widetilde{P}$			
		$q^{1,2}_{4,1}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$			
		$q^{1,3}_{4,1}$	$\widetilde{L}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{H}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{H}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{H}$			
WSL	Woody material system loading severity	$q^{2,1}_{5,1} \vee q^{1,1}_{1,2}$	$\widetilde{H}$	$\widetilde{P}$	$\widetilde{L}$	$\widetilde{L}$	$\widetilde{H}$	$\widetilde{P}$	$\widetilde{L}$	$\widetilde{H}$	$\widetilde{P}$	$\widetilde{L}$	$\widetilde{H}$	$\widetilde{P}$	$\widetilde{L}$
		$q^{2,2}_{5,1} \vee q^{1,2}_{1,2}$	$\widetilde{P}$	$\widetilde{L}$	$\widetilde{L}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$	$\widetilde{P}$
		$q^{2,3}_{5,1} \vee q^{1,3}_{1,2}$	$\widetilde{L}$	$\widetilde{L}$	$\widetilde{P}$	$\widetilde{H}$	$\widetilde{L}$	$\widetilde{P}$	$\widetilde{H}$	$\widetilde{L}$	$\widetilde{P}$	$\widetilde{H}$	$\widetilde{L}$	$\widetilde{P}$	$\widetilde{H}$

$\widetilde{L}$, inconsistency; $\widetilde{P}$, partial consistency; $\widetilde{H}$, high consistency.

Table 8
Possible scenarios with corresponding additive consistency values.

		$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,1}$	$q_{5,1}^{2,2}$	$q_{5,1}^{2,2}$	$q_{5,1}^{2,2}$	$q_{5,1}^{2,2}$
		$q_{4,1}^{1,1}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,2}$	$q_{4,1}^{1,2}$	$q_{4,1}^{1,2}$	$q_{4,1}^{1,2}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,1}$
		$q_{3,1}^{1,1}$	$q_{3,1}^{1,1}$	$q_{3,1}^{1,1}$	$q_{3,1}^{1,1}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,1}$	$q_{3,1}^{1,1}$	$q_{3,1}^{1,1}$	$q_{3,1}^{1,1}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,2}$
$q_{1,1}^{1,1}$	$q_{2,1}^{1,1}$	16.0	20.0	26.5	30.0					8.0	15.0	19.5	30.0	6.0	13.8	17.8	30.0
$q_{1,1}^{1,2}$	$q_{2,1}^{1,1}$	12.0	17.5	23.0	30.0	8.0	15.0	19.5	30.0								
$q_{1,1}^{1,1}$	$q_{2,1}^{1,2}$	12.0	17.5	23.0	30.0												
		$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$	$q_{5,1}^{2,3}$				
		$q_{4,1}^{1,3}$	$q_{4,1}^{1,3}$	$q_{4,1}^{1,3}$	$q_{4,1}^{1,3}$	$q_{4,1}^{1,2}$	$q_{4,1}^{1,2}$	$q_{4,1}^{1,2}$	$q_{4,1}^{1,2}$	$q_{4,1}^{1,3}$	$q_{4,1}^{1,3}$	$q_{4,1}^{1,3}$	$q_{4,1}^{1,3}$				
		$q_{3,1}^{1,2}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,3}$	$q_{3,1}^{1,3}$	$q_{3,1}^{1,3}$	$q_{3,1}^{1,3}$	$q_{3,1}^{1,3}$	$q_{3,1}^{1,3}$	$q_{3,1}^{1,3}$	$q_{3,1}^{1,3}$				
$q_{1,1}^{1,4}$	$q_{2,1}^{1,2}$									12.0	17.5	23.0	30.0				
$q_{1,1}^{1,3}$	$q_{2,1}^{1,3}$	8.0	15.0	19.5	30.0					12.0	17.5	23.0	30.0				
$q_{1,1}^{1,4}$	$q_{2,1}^{1,3}$	12.0	17.5	23.0	30.0	8.0	15.0	19.5	30.0	16	20	26.5	30				

4. Results

By the application of the Formative Scenario Analysis procedure, it was both possible to assess and validate the expert knowledge contained in the mental system map (Fig. 4), as well as to specify and weight the relevant system components in the system loading and system response level. Based on a reasonable identification and robust selection of the relevant key variables, followed by an accurate characterisation of each key variable in terms of activity and passivity ratings, the multiple facets of system dynamics induced by woody material transport related hazard processes were detected. As a result, specific key variables with major influence on the system were defined and rated. Subsequently, by the definition of appropriate impact levels for each specific key variable the description of possible changes in the system behaviour was possible. The most consistent and representative system loading and system response scenarios were systematically derived which added quality to the cause–effect relationships outlined in Fig. 4.

The results of the application of the Formative Scenario Analysis are represented by the twelve system loading scenarios and nine system response scenarios, respectively, as shown in Tables 9 and 12 in terms of a Scenario Information System. These results were based on the selection of consistent scenarios derived from Tables 8 and 11.

For the scenarios given in Table 9 it is shown that the individual impact level of the key variable WSL results from a concisely defined combination of different levels for each conditional key variable belonging to the conditional factor subset.

The scenarios reported in Table 9 show that the different impact levels of the key variable WSL (evolution factor of the level $k=1$) are a consequence of different system loading conditions, expressed in terms of specific level combinations of different key variables belonging to the conditional factor subset. Taking as an example the six consistent scenarios of WSL = 3, characterised by a high system loading severity, six different explanations in terms of different level combinations can be adduced. The most consistent among these six scenarios can be deduced from Table 8 as follows:

Recruitment propensity from hill slopes – very high ($q_{1,1}^{1,4}$), in-stream recruitment propensity – medium ($q_{2,1}^{1,3}$), woody material transport costs – low ($q_{3,1}^{1,3}$), potential woody material transport distribution extremely unfavourable ($q_{4,1}^{1,3}$), and woody material system loading severity – high ($q_{5,1}^{2,3}$).

The additive consistency value for this scenario is given by

Table 9
Scenario information system SIS_k with $k=1$ represented as a decision table.

NR	RPH				IRP			WTC			PWD			WSL
	$q_{1,1}^{1,1}$	$q_{1,1}^{1,2}$	$q_{1,1}^{1,3}$	$q_{1,1}^{1,4}$	$q_{2,1}^{1,1}$	$q_{2,1}^{1,2}$	$q_{2,1}^{1,3}$	$q_{3,1}^{1,1}$	$q_{3,1}^{1,2}$	$q_{3,1}^{1,3}$	$q_{4,1}^{1,1}$	$q_{4,1}^{1,2}$	$q_{4,1}^{1,3}$	$q_{5,1}^{2,1} \vee q_{5,1}^{2,2} \vee q_{5,1}^{2,3}$
1	1	0	0	0	1	0	0	1	0	0	1	0	0	1
2	1	0	0	0	1	0	0	1	0	0	0	1	0	1
3	1	0	0	0	1	0	0	0	1	0	1	0	0	2
4	0	1	0	0	1	0	0	1	0	0	1	0	0	1
5	0	1	0	0	1	0	0	0	1	0	1	0	0	1
6	1	0	0	0	0	1	0	1	0	0	1	0	0	1
7	0	0	0	1	0	1	0	0	0	1	0	0	1	3
8	0	0	1	0	0	0	1	0	1	0	0	0	1	3
9	0	0	1	0	0	0	1	0	0	1	0	0	1	3
10	0	0	0	1	0	0	1	0	1	0	0	0	1	3
11	0	0	0	1	0	0	1	0	0	1	0	1	0	3
12	0	0	0	1	0	0	1	0	0	1	0	0	1	3

Table 10
Consistency matrix for the scenario level $k = 2$.

	Name	Impact levels	WSL $q_{5,1}^{2,1} \vee q_{1,2}^{1,1}$	WSL $q_{5,1}^{2,2} \vee q_{1,2}^{1,2}$	WSL $q_{5,1}^{2,3} \vee q_{1,2}^{1,3}$	WEP $q_{2,2}^{1,1}$	WEP $q_{2,2}^{1,2}$	WEP $q_{2,2}^{1,3}$	BR $q_{3,2}^{1,1}$	BR $q_{3,2}^{1,2}$	BR $q_{3,2}^{1,3}$	SCP $q_{4,2}^{1,1}$	SCP $q_{4,2}^{1,2}$	SCP $q_{4,2}^{1,3}$
WSL	Woody material system loading severity	$q_{5,1}^{2,1} \vee q_{1,2}^{1,1}$												
		$q_{5,1}^{2,2} \vee q_{1,2}^{1,2}$												
		$q_{5,1}^{2,3} \vee q_{1,2}^{1,3}$												
WEP	Woody material entrapment propensity	$q_{2,2}^{1,1}$	$\tilde{H}$	$\tilde{P}$	$\tilde{L}$									
		$q_{2,2}^{1,2}$	$\tilde{P}$	$\tilde{P}$	$\tilde{P}$									
		$q_{2,2}^{1,3}$	$\tilde{L}$	$\tilde{P}$	$\tilde{H}$									
BR	Blockage ratio	$q_{3,2}^{1,1}$	$\tilde{P}$	$\tilde{P}$	$\tilde{L}$	$\tilde{H}$	$\tilde{P}$	$\tilde{L}$						
		$q_{3,2}^{1,2}$	$\tilde{P}$	$\tilde{P}$	$\tilde{P}$	$\tilde{P}$	$\tilde{H}$	$\tilde{P}$						
		$q_{3,2}^{1,3}$	$\tilde{L}$	$\tilde{P}$	$\tilde{P}$	$\tilde{L}$	$\tilde{P}$	$\tilde{H}$						
SCP	System change propensity	$q_{4,2}^{1,1}$	$\tilde{H}$	$\tilde{P}$	$\tilde{L}$	$\tilde{H}$	$\tilde{L}$	$\tilde{L}$	$\tilde{H}$	$\tilde{P}$	$\tilde{L}$			
		$q_{4,2}^{1,2}$	$\tilde{P}$	$\tilde{P}$	$\tilde{P}$	$\tilde{L}$	$\tilde{P}$	$\tilde{L}$	$\tilde{P}$	$\tilde{H}$	$\tilde{P}$			
		$q_{4,2}^{1,3}$	$\tilde{L}$	$\tilde{P}$	$\tilde{H}$	$\tilde{L}$	$\tilde{L}$	$\tilde{H}$	$\tilde{L}$	$\tilde{P}$	$\tilde{H}$			
SRS	System response severity	$q_{5,2}^{2,1}$	$\tilde{P}$	$\tilde{L}$	$\tilde{L}$	$\tilde{H}$	$\tilde{L}$	$\tilde{L}$	$\tilde{H}$	$\tilde{P}$	$\tilde{L}$	$\tilde{H}$	$\tilde{P}$	$\tilde{L}$
		$q_{5,2}^{2,2}$	$\tilde{L}$	$\tilde{P}$	$\tilde{L}$	$\tilde{L}$	$\tilde{H}$	$\tilde{L}$	$\tilde{P}$	$\tilde{H}$	$\tilde{P}$	$\tilde{P}$	$\tilde{H}$	$\tilde{P}$
		$q_{5,2}^{2,3}$	$\tilde{L}$	$\tilde{P}$	$\tilde{P}$	$\tilde{L}$	$\tilde{L}$	$\tilde{H}$	$\tilde{L}$	$\tilde{P}$	$\tilde{H}$	$\tilde{L}$	$\tilde{P}$	$\tilde{H}$

$\tilde{L}$, inconsistency; $\tilde{P}$, partial consistency; $\tilde{H}$, high consistency.

Table 11
Possible scenarios with corresponding additive consistency value.

		$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$	$q_{5,2}^{2,1}$
		$q_{4,2}^{1,1}$	$q_{4,2}^{1,1}$	$q_{4,2}^{1,1}$	$q_{4,2}^{1,1}$	$q_{4,2}^{1,1}$	$q_{4,2}^{1,1}$	$q_{4,2}^{1,1}$	$q_{4,2}^{1,1}$	$q_{4,2}^{1,2}$	$q_{4,2}^{1,2}$	$q_{4,2}^{1,2}$	$q_{4,2}^{1,2}$
		$q_{3,2}^{1,1}$	$q_{3,2}^{1,1}$	$q_{3,2}^{1,1}$	$q_{3,2}^{1,1}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,1}$	$q_{3,2}^{1,1}$	$q_{3,2}^{1,1}$	$q_{3,2}^{1,1}$
$q_{1,2}^{1,1}$	$q_{2,2}^{1,1}$	16	20	26,5	30	10	16,3	21,3	30	8	14	18,5	27.5
$q_{1,2}^{1,2}$	$q_{2,2}^{1,1}$	12	16,5	22	27,5								
		$q_{5,2}^{2,2}$	$q_{5,2}^{2,2}$	$q_{5,2}^{2,2}$	$q_{5,2}^{2,2}$	$q_{5,2}^{2,3}$	$q_{5,2}^{2,3}$	$q_{5,2}^{2,3}$	$q_{5,2}^{2,3}$	$q_{5,2}^{2,3}$	$q_{5,2}^{2,3}$	$q_{5,2}^{2,3}$	$q_{5,2}^{2,3}$
		$q_{4,2}^{1,2}$	$q_{4,2}^{1,2}$	$q_{4,2}^{1,2}$	$q_{4,2}^{1,2}$	$q_{4,2}^{1,3}$	$q_{4,2}^{1,3}$	$q_{4,2}^{1,3}$	$q_{4,2}^{1,3}$	$q_{4,2}^{1,3}$	$q_{4,2}^{1,3}$	$q_{4,2}^{1,3}$	$q_{4,2}^{1,3}$
		$q_{3,2}^{1,2}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,2}$	$q_{3,2}^{1,3}$	$q_{3,2}^{1,3}$	$q_{3,2}^{1,3}$	$q_{3,2}^{1,3}$
$q_{1,2}^{1,2}$	$q_{2,2}^{1,2}$	10	16,3	21,3	30								
$q_{1,2}^{1,3}$	$q_{2,2}^{1,2}$	10	15,3	20,3	27,5								
$q_{1,2}^{1,2}$	$q_{2,2}^{1,3}$									12	17,5	23	30
$q_{1,2}^{1,3}$	$q_{2,2}^{1,3}$					10	16,3	21,3	30	16	20	26,5	30

Table 12
Scenario information system SIS_k with $k = 2$ represented as a decision table.

NR	WSL $q_{1,2}^{1,1}$	WSL $q_{1,2}^{1,2}$	WSL $q_{1,2}^{1,3}$	WEP $q_{2,2}^{1,1}$	WEP $q_{2,2}^{1,2}$	WEP $q_{2,2}^{1,3}$	BR $q_{3,2}^{1,1}$	BR $q_{3,2}^{1,2}$	BR $q_{3,2}^{1,3}$	SCP $q_{4,2}^{1,1}$	SCP $q_{4,2}^{1,2}$	SCP $q_{4,2}^{1,3}$	SRS $q_{5,2}^{2,1} \vee q_{5,2}^{2,2} \vee q_{5,2}^{2,3}$
1	1	0	0	1	0	0	1	0	0	1	0	0	1
2	1	0	0	1	0	0	0	1	0	1	0	0	1
3	1	0	0	1	0	0	1	0	0	0	1	0	1
4	0	1	0	1	0	0	1	0	0	1	0	0	1
5	0	1	0	0	1	0	0	1	0	0	1	0	2
6	0	0	1	0	1	0	0	1	0	0	1	0	2
7	0	1	0	0	0	1	0	0	1	0	0	1	3
8	0	0	1	0	0	1	0	1	0	0	0	1	3
9	0	0	1	0	0	1	0	0	1	0	0	1	3

$$\begin{aligned}\tilde{C}^*(S_{324,1}) &= \tilde{C}\left(\widehat{q}^{\,1,4}_{1,1},\widehat{q}^{\,1,3}_{2,1}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{2,1},\widehat{q}^{\,1,3}_{3,1}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{3,1},\widehat{q}^{\,1,3}_{4,1}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{4,1},\widehat{q}^{\,2,3}_{5,1}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,4}_{1,1},\widehat{q}^{\,1,3}_{3,1}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,4}_{1,1},\widehat{q}^{\,1,3}_{4,1}\right)\\ &\oplus\tilde{C}\left(\widehat{q}^{\,1,4}_{1,1},\widehat{q}^{\,2,3}_{5,1}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{2,1},\widehat{q}^{\,1,3}_{4,1}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{2,1},\widehat{q}^{\,2,3}_{5,1}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{3,1},\widehat{q}^{\,2,3}_{5,1}\right) = \widetilde{P}\oplus\widetilde{H}\oplus\widetilde{H}\oplus\widetilde{H}\oplus\widetilde{P}\oplus\widetilde{H}\oplus\widetilde{H}\oplus\widetilde{H}\oplus\widetilde{H}\oplus\widetilde{H}\\ &= (16.0, 20.0, 26.5, 30.0)^{\varepsilon}\end{aligned}$$

A similar result can be drawn for the system response scenario level. Taking a high system loading severity (WSL = high), the most consistent corresponding scenario of the system response scenario level can be deduced from Table 11 as follows:

Woody material system loading severity – high ($q^{1,3}_{1,2}$), woody material entrapment propensity – high ($q^{1,3}_{2,2}$), blockage ratio – high ($q^{1,3}_{3,2}$), system change propensity – high ($q^{1,3}_{4,2}$), and system response severity – high ($q^{2,3}_{5,2}$).

The additive consistency value for this scenario is given by

$$\begin{aligned}\tilde{C}^*(S_{243,2}) &= \tilde{C}\left(\widehat{q}^{\,1,3}_{1,2},\widehat{q}^{\,1,3}_{2,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{2,2},\widehat{q}^{\,1,3}_{3,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{3,2},\widehat{q}^{\,1,3}_{4,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{4,2},\widehat{q}^{\,2,3}_{5,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{1,2},\widehat{q}^{\,1,3}_{3,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{1,2},\widehat{q}^{\,1,3}_{4,2}\right)\\ &\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{1,2},\widehat{q}^{\,2,3}_{5,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{2,2},\widehat{q}^{\,1,3}_{4,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{2,2},\widehat{q}^{\,2,3}_{5,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{3,2},\widehat{q}^{\,2,3}_{5,2}\right) = \widetilde{H}\oplus\widetilde{H}\oplus\widetilde{H}\oplus\widetilde{H}\oplus\widetilde{P}\oplus\widetilde{H}\oplus\widetilde{P}\oplus\widetilde{H}\oplus\widetilde{H}\oplus\widetilde{H}\\ &= (16.0, 20.0, 26.5, 30.0)^{\varepsilon}\end{aligned}$$

The same degree of system response severity being equal to the system loading scenario can also be deduced from another scenario (Table 11):

Woody material system loading severity – high ($q^{1,3}_{1,2}$), woody material entrapment propensity – high ($q^{1,3}_{2,2}$), blockage ratio – medium ($q^{1,2}_{3,2}$), system change propensity – high ($q^{1,3}_{4,2}$), and system response severity – high ($q^{2,3}_{5,2}$).

The additive consistency value for this scenario is given by

$$\begin{aligned}\tilde{C}^*(S_{243,2}) &= \tilde{C}\left(\widehat{q}^{\,1,3}_{1,2},\widehat{q}^{\,1,3}_{2,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{2,2},\widehat{q}^{\,1,3}_{3,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,2}_{3,2},\widehat{q}^{\,1,3}_{4,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{4,2},\widehat{q}^{\,2,3}_{5,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{1,2},\widehat{q}^{\,1,2}_{3,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{1,2},\widehat{q}^{\,1,3}_{4,2}\right)\\ &\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{1,2},\widehat{q}^{\,2,3}_{5,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{2,2},\widehat{q}^{\,1,3}_{4,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,3}_{2,2},\widehat{q}^{\,2,3}_{5,2}\right)\oplus\tilde{C}\left(\widehat{q}^{\,1,2}_{3,2},\widehat{q}^{\,2,3}_{5,2}\right) = \widetilde{H}\oplus\widetilde{P}\oplus\widetilde{P}\oplus\widetilde{H}\oplus\widetilde{P}\oplus\widetilde{H}\oplus\widetilde{P}\oplus\widetilde{H}\oplus\widetilde{H}\oplus\widetilde{P}\\ &= (10.0, 16.3, 21.3, 30.0)^{\varepsilon}\end{aligned}$$

The results obtained in terms of the scenario information systems of the two levels have considerable implications for natural hazard risk management in general and particularly for risk due to woody material transport. Problem-solving strategies aiming at minimising the system response severity – SRS – can be directly deduced from the scenario information systems. In the specific case under investigation, partial risk mitigation strategies which only take into consideration a strong reduction of woody material system loading severity, turn out to be less promising. This is because small amounts of woody material are judged to be sufficient to clog the available flow section and to produce severe consequences. Instead, interpreting Table 12 in terms of a proposed strategy to mitigate system severity induced by woody material transport, woody material system loading severity should be reduced ($\widehat{q}^{\,1,3}_{1,2}\rightarrow\widehat{q}^{\,1,2}_{1,2}$) and in parallel, the reliability ($\widehat{q}^{\,1,3}_{4,2}\rightarrow\widehat{q}^{\,1,1}_{4,2}$) and functionality of the critical stream configuration ($\widehat{q}^{\,1,3}_{3,2}\rightarrow\widehat{q}^{\,1,1}_{3,2}\wedge\widehat{q}^{\,1,3}_{2,2}\rightarrow\widehat{q}^{\,1,1}_{2,2}$) should be enhanced. Such an approach mirrors the idea in integral risk management that a combination of mitigation measures often turns out to be more effective in hazard and risk reduction than only one single countermeasure (e.g., Holub and Fuchs, 2008). Moreover, by implementing systematic redundancies in both the system loading and system response level, enhanced system resilience is achieved.

5. Conclusion

Current methods of risk analyses for natural hazards are, from an engineering point of view, based on quantitative methods of impact assessment to a given environmental setting, and require the assessment of processes as well as values exposed. With respect to torrent processes, these quantitative methods usually include process-based numerical analysis, which necessitates precise data on input parameters. Therefore, some limitations occur by applying such approaches. Above all, complex flow mechanisms which are important for small-scale analyses such as woody material transport dynamics at critical stream configurations cannot satisfyingly be mirrored. Moreover, the missing connectivity between causes and effects, such as precipitation input, liquid and solid discharge and woody material transport rates as output, results in simplifications and does not represent either flow mechanisms nor deposition characteristics in sufficient detail. In particular, morphological changes that induce hazard processes are of virtual importance for a reliable assessment of hazard paths, and thus, system configuration. As a result, system response mechanisms are only partly understood so far, leading to uncertainties in protection system functionality and mitigation efficacy.

In order to overcome these shortcomings, a nested scenario approach referred to as scenario level structure was proposed, taking into account causes (system loading level) and effects (system response level) within a torrent system. By applying

Formative Scenario Analysis, this level structure was used to derive qualitative and quantitative (expert and local, respectively) knowledge that can be integrated into scenario definition within the framework of natural hazard risk management. From a conceptual point of view, the extension of Formative Scenario Analysis by introducing elements of fuzzy modelling resulted in an enhancement:

(1) of the representation of impacts by an impact matrix through fuzzy intervals, resulting in an integration of the broad expert knowledge spectrum;
(2) in characterisation of the impacts by relevant key variables influencing the processes studied;
(3) in modelling of importance and uncertainties assessed by the expert team;
(4) in modelling of conjoined consistency values for pairs of different key variables impact levels;
(5) in selecting the most consistent scenarios with respect to efficient mitigation strategies.

By Rough Set Data theory it was possible to organise the knowledge content in scenario information systems for each level. Hence, the robustness of the hazard assessment procedure was increased by using such an approach, and the management of hydrological hazards was supplemented by an integration of expert knowledge into the framework of calculation. With respect to basic and operational principles (Shepard, 2005), formative analysis can provide crucial insights into the entire process of hazard assessment and mapping. Consequently, consistent assumptions either concerning system loading or system response mechanisms will be integrated into the decision process, and bounding uncertainties can be considered where possible. Thereby, the presented method has to be used complementary to hydrological and hydraulic simulation models in order to produce consistent, intelligible and retraceable results. As a result, available resources can be utilised more efficiently to meet the requirements of integral risk management strategies.

It is of fundamental importance to capture at least qualitatively the different aspects of multi-hazard situations and nonlinearity in cause–effect relationships in order to design resilient protection systems by minimising conceptual susceptibilities and by providing robustness over the entire life cycle of a protection system. The case study performed in this work had proven that a small set of consistent and reliable exploratory scenarios is suitable to identify effects given a specific set of causes, if the overall objective is to obtain a broad spectrum of possible system responses.

One of the challenges of integral risk management is to be prepared for unexpected system behaviour. If weak signals of such unexpected system behaviour are not discerned and represented by deterministic models, and probabilistic models neglect important impact factors, the possibility-based approach of Formative Scenario Analysis provides clear problem-solving advantages. A further development step will foster a widening of possible applications of Formative Scenario Analyses to sets of cases with a high degree of similarity, e.g. similar protection system configurations in different torrent basins or similar depositional zone characteristics of different alluvial fans. These issues can be addressed introducing the fuzzy logic paradigm, without any loss of significance and rigor. The flexibility of the proposed knowledge modelling and integration framework seems to be particularly suitable for providing in-depth insights into coping strategies emerging from interdisciplinary expert workshops and participatory planning processes.

Consequently, if risk management processes were adjusted to these findings, risk communication could be enhanced, and awareness-building of the public will be increased. Particularly concerning the European Flood Risk Directive, but also with respect to the overall aim of building hazard-resilient communities, future studies might include the applicability of Formative Scenario Analysis and its extension by fuzzy modelling within flood risk management planning.

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