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Developing consistent scenarios to assess flood hazards in mountain streams

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A B S T R A C T

The characterizing feature of extreme events in steep mountain streams is the multiplicity of possible tipping process patterns such as those involving sudden morphological changes due to intense local erosion, aggradation as well as clogging of critical flow sections due to wood accumulations. Resolving a substantial part of the uncertainties underlying these hydrological cause-effect chains is a major challenge for flood risk management.

Our contribution is from a methodological perspective based on an expert-based methodology to unfold natural hazard process scenarios in mountain streams to retrace their probabilistic structure. As a first step we set up a convenient system representation for natural hazard process routing. In this setting, as a second step, we proceed deriving the possible and thus consistent natural hazard process patterns by means of Formative Scenario Analysis. In a last step, hazard assessment is refined by providing, through expert elicitation, the spatial probabilistic structure of individual scenario trajectories. As complement to the theory the applicability of the method is shown through embedded examples. To conclude we discuss the major advantages of the presented methodological approach for hazard assessment compared to traditional approaches, and with respect to the risk governance process.

1. Introduction

In recent years, increasing numbers of natural hazards and associated losses have shown to the European Commission and the Member States of the European Union the paramount importance of the natural hazards issue for the protection of the environment and the citizens (Barredo, 2007). There is some scientific evidence of an increase in mean precipitation and extreme precipitation events, which implies that extreme flood events might become more frequent (Kundzewicz et al., 2005). In parallel, exposure to floods might increase across Europe as well as flood vulnerability due to population and wealth moving into flood-prone areas. Therefore even without taking climate change into account an increase of flood disasters in Europe can be expected (Mitchell, 2003).

The *Directive on the Assessment and Management of Flood Risks* (Floods Directive) addressed to the Member States was issued in 2007 (Commission of the European Communities, 2007) as one of the three components of the *European Action Programme on Flood Risk Management* (Commission of the European Communities, 2004). Within this Directive, flood events (defined in their broadest sense comprising both water and sediment transport processes, including debris flows) have been officially acknowledged to be natural phenomena which cannot be prevented. Such events have the potential to severely compromise economic development and to undermine the economic activities of the Community due to an increase of human activities in floodplains and the reduction of the natural water retention by land use activities. As a result, an increase in the likelihood and adverse impacts of flood events is expected. Therefore, concentrated action is needed at the European level to avoid severe impacts on human life and property. In order to have an effective tool for gathering information, as well as a valuable basis for priority setting and further technical, financial and political decisions regarding flood risk mitigation and management, it is necessary to provide for the establishment of flood hazard maps and flood risk maps which show the potential adverse consequences associated with different flood scenarios.

Moreover, natural hazards, vulnerability and risk in mountain regions have become a focus of political attention since the

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implementation of the Agenda 21 (United Nations, 1993) at the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro. There, two programme areas were agreed upon: (i) generating and strengthening knowledge about the ecology and sustainable development of mountain ecosystems, and (ii) promoting integrated watershed development and alternative livelihood opportunities. Agenda 21 strengthens the case for securing the mountain environment in a sustainable way and providing the public with knowledge concerning mountain-related global change issues, including natural hazard risk management. Although the fragility of mountain ecosystems is beyond controversy, considerable research gaps still exist in terms of the relationships between individual and societal needs and environmental issues in mountain regions, and above all with respect to natural hazards influencing human livelihood.

In Europe, strategies to prevent or to reduce the effects of natural hazards in mountain areas trace back to the mediaeval times. Official authorities were first founded in the late 19th century (e.g., Länger 2003) based on first national legal regulations (e.g., Österreichisch-Ungarische Monarchie, 1884). In the second half of the 19th and in the early 20th century, protection against natural hazards was mainly organised by implementing permanent measures in the upper parts of the catchments to retain solids from erosion. These measures were supplemented by silvicultural efforts to afforest high altitudes. Since the 1950s, such conventional mitigation concepts, which aimed at decreasing both, the magnitude and the frequency of events, were increasingly complemented by other technical mitigation measures aiming at the deflection of hazard processes into areas not used for settlements. Watershed management measures, forest-biological and soil bio-engineering measures, as well as technical measures (construction material: timber and stone masonry) were implemented. Thus, conventional mitigation concepts consider technical structures within the catchment, along the channel system or channel track and in the deposition area (Holub and Fuchs, 2009). According to the approach of disposition management (reducing the probability of occurrence of natural hazards) and event management (interfering the transport process of the hazard itself), a wide range of technical measures is applicable for an active prevention (ONR, 2009). Structural mitigation inevitably has its limitations, and the analysis of the most recent flood events in European mountain regions (Keiler et al., 2010) highlighted considerable shortcomings in the current procedures used for natural hazard and risk assessment due to inherent system dynamics (e.g., Autonomous Province of Bolzano-Bozen, 2008). Conventional numerical hydrodynamic and morphodynamic river models are not always reliable in precisely predicting the process pattern since internal system dynamics, such as changing solids concentration along the flow path, are not sufficiently mirrored (Mazzorana et al., in press a). In particular, the effects of changing channel morphology over time and the reduction of cross-sectional areas due to clogging were found to significantly amplify process magnitudes and frequencies (e.g., Comiti et al., 2008). In order to improve hazard and risk analyses and to support decision making, flood event scenarios need to be re-established based on such issues.

Therefore, changing process characteristics need to be assessed and included in modelling approaches, i.e., the coupling between hillslope and channel processes, the type of flow (debris flow, debris flood, water flood with bedload transport) incurring along the channel network, the location and magnitude of channel adjustments (bed and bank erosion, aggradation), the volume of sediment transported, and the spatial pattern of inundation. Such assessments are associated with different sources of uncertainty affecting the predictability of hazard patterns, those that are rooted in the variability in known (or observable) populations and, therefore, represent randomness in samples (aleatory uncertainties), and those that are rooted in a basic lack of knowledge about fundamental phenomena (epistemic uncertainties; e.g., Hoffman and Hammonds, 1994; Paté-Cornell, 1996). By including such issues of uncertainty in decision making for natural hazard management, the nature of decision to be made will be changed. The way in which uncertainty will affect the decision, however, may depend on the context of a decision (Blazkova and Beven, 2009). With respect to uncertainties in natural hazard management, the determination of hazard scenarios for mountain streams includes:

(1) uncertainties about the main variables describing the flows, i.e. peak discharge as well as flood hydrograph shape and duration, sediment transport rate, volume and concentration (and thus type of flow), or rate of driftwood transport. Overall, this set of variables will be referred to as the system loading variables.
(2) uncertainties in the spatial patterns of hazard propagation due to obstructions at critical cross-sections, small-scale topography, abrupt morphological changes such as avulsion occurring during an event. These uncertainties determine the subsequent response system scenarios.
(3) uncertainties concerning the functionality and effectiveness of the technical protection system (e.g., related to possible failures of levees and check-dams, sediment dosing efficiency of retention basins). Uncertainties of this type may have consequences on both the loading and response system variables.

The aim of this paper is to address the uncertainties associated with the system loading variables, and to improve the hazard and risk assessment for mountain streams. In particular, the following issues will be covered: (1) identification of an adequate natural hazard system representation structure, hereafter denominated as abstracted stream system (e.g., Kienholz et al., 2010), allowing for the description of natural hazard scenarios; (2) development and refinement of expert knowledge-based techniques (Zischg et al., 2005), i.e. Formative Scenario Analysis, to derive a set of consistent scenarios for the abstracted stream system (e.g., Mazzorana and Fuchs, 2010); (3) introduction of a conceptual approach to assign subjective probabilities to identified hazard scenario trajectories (Eisenführ and Weber, 2010; Gilboa, 2009).

2. Modelling framework

With respect to the management of mountain hazards a modelling framework is required that enables a rational knowledge integration in order to foster the inherently complex and therefore often semi-structured relationships of environmental interaction, in particular since the elements of uncertainty are considerable (Funtowicz and Ravetz, 1994; Kolkman et al. 2005). The developed modelling framework is a balanced strategy of investigation based on the methodological integration of available and retrievable qualitative and quantitative knowledge of uncertainties. The guiding principle is to treat the underlying physical issues of environmental interaction as a transformed initial-boundary value problem to maintain the conceptual coherence of the mathematical-physical problem setting.

As outlined in Mazzorana et al. (2009), conventional physical and numerical modelling approaches are only partly capable to take into account uncertainties. It had been repeatedly stated that complimentary approaches which include participative elements can contribute to close this gap and to complement conventional modelling approaches by structured knowledge integration (Martin et al., 2009; Raymond et al., 2010). During the application of such approaches, a set of consistent scenarios is identified by a team of specialists; the identified scenarios contribute to the robustness of

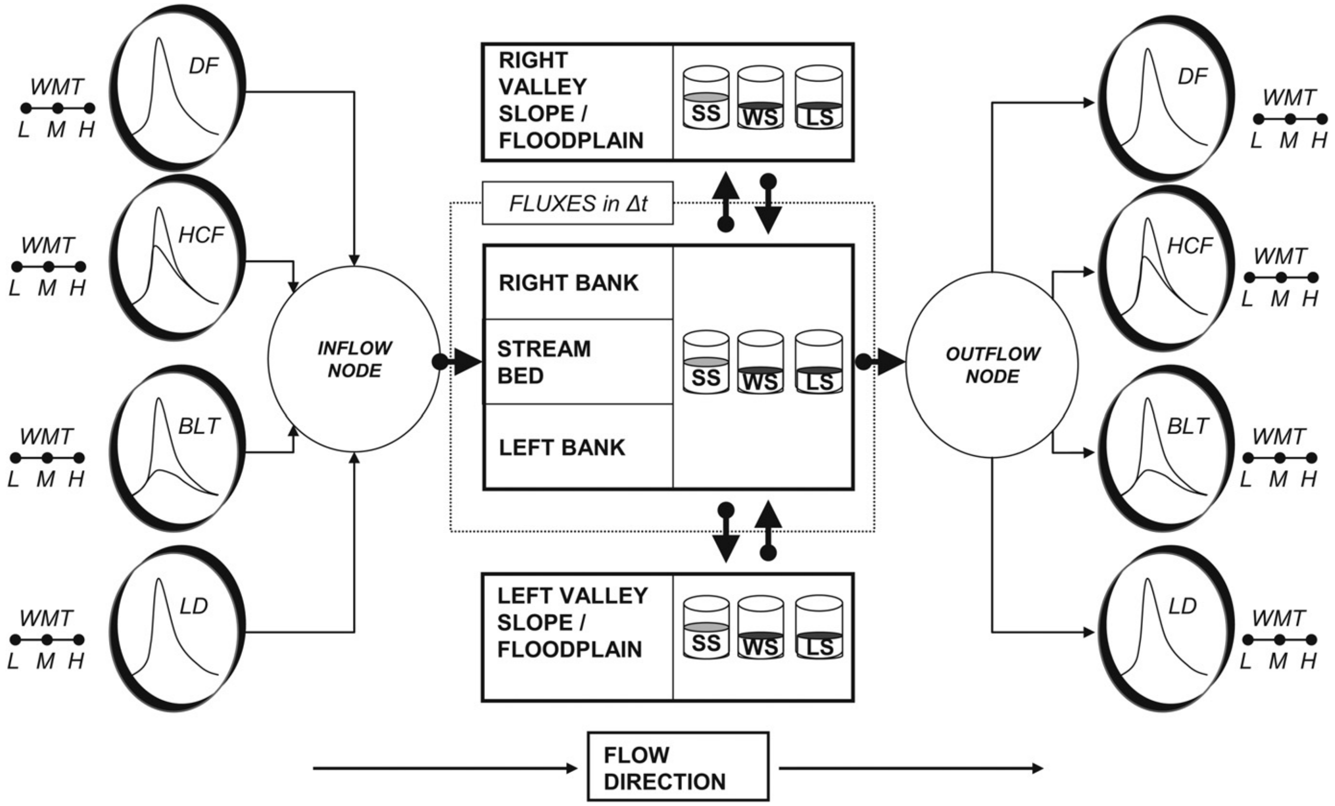

Fig. 1. A homogenous stream segment is expressed by an abstracted stream element representing the respective set of initial and boundary conditions, the induced system dynamics and the material fluxes which occur (WS = wood storage; SS = sediment storage; LS = water storage). Upstream (inflow) and downstream (outflow) boundary nodes: DF = debris flow; HCF = hyperconcentrated flow; BLT = bedload transport; LD = liquid discharge; WMT = wood material transport with low (L), middle (M) or high (H) intensity.

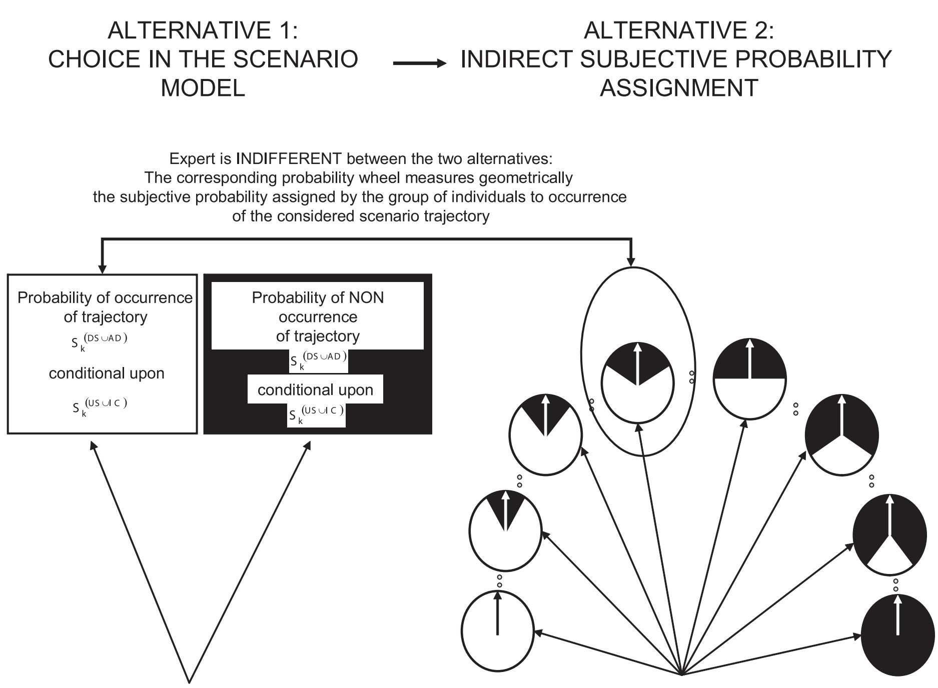

Fig. 2. Diagram for the indirect subjective probability assignment for a considered evolution trajectory.

the entire modelling procedure. In order to meet these aims, a Formative Scenario Analysis approach (Scholz and Tietje, 2002) was chosen in our study to acknowledge sources of uncertainty resulting from the conventional assessment of mountain hazards.

The following Sections mirror the structure of the methodological framework which has been set up to study natural hazard process unfolding in mountain streams which are particularly susceptible to debris flows and flash floods including fluvial sediment transport. In Section 2.1 a set of adopted hydrological system representation criteria is introduced. By these criteria typical mountain streams are represented by an abstracted stream system and individual torrent sections by abstracted stream elements. Such an abstract stream system representation allows for an unfolding of complex interactions within a mountain stream at different levels of detail and different scales, and aims at the representation of homogenous segments with defined process behaviour and corresponding system adjustments. In Section 2.2 an adapted Formative Scenario Analysis is presented that allows for the necessary knowledge representation functional to the process scenario deduction. In Section 2.3 two approaches are presented to assign, by expert elicitation, subjective probabilities to explicit process scenarios. To provide an example, in section 3, scenario building is shown for an homogeneous stream segment. The methodological steps to develop a Formative Scenario Analysis result in (1) a proposal of a complete list of impact variables responsible for the event-driven system dynamics within the homogeneous stream segment followed by (2) a knowledge synthesis in terms of a consistency matrix of the possible system behaviour spectrum and by (3) the deduction of process scenarios consistent with specific initial and boundary conditions. Moreover, through the application of the outlined subjective probability assignment approaches, the probabilistic structure of the process scenarios is deduced. This Section is completed by a paragraph related to the construction of a comprehensive spatial probability skeleton of the natural hazard process unfolding for the entire stream channel in terms of an event tree.

2.1. Stream system representation

The starting point of any comprehensive hazard assessment in mountain streams is the analysis of the underlying process chain, ranging from rainfall events of defined recurrence intervals as an input, through rainfall-runoff transformation and runoff concentration as well as sediment and wood recruitment to stream processes, to in-stream entrainment and transport processes to the basin outlet. Therefore, available hydrologic modelling scenarios, shallow landslide susceptibility computations, and indications on a hazard index level of sediment and wood transport scenarios provide background information. So far, promising results have been achieved in probabilistic analysis of watershed hydrology (e.g., Rigon et al., 2006), with respect to the initiation of shallow landslides and bank erosion (e.g., Bathurst et al., 2005; Brunetti et al., 2010), as well as with respect to wood recruitment processes (e.g., Comiti et al., 2008; Mazzorana et al., 2009) and the initiation of channelised debris flows (e.g., Simoni et al., 2007). These individual contributions have to be combined in terms of knowledge integration in order to mirror the systems behaviour accordingly. Therefore, in the first step the stream is spatially discretized by subdividing the stream into distinct stream segments. In the subsequent step, the process routing from one stream segment to its successor is described by knowledge integration through Formative Scenario Analysis.

A homogenous stream segment is expressed by an abstracted stream element characterized by the respective set of initial and boundary conditions, the induced system dynamics and material fluxes which occur (Fig. 1).

Such a generic abstracted stream element comprises at the boundaries the associated inflow and outflow nodes and the spatial domain where the dominant process interactions take place, namely the streambed and stream banks with the adjacent valley slopes or floodplains. These interactions within the stream segment include dominant in-stream transport processes and processes that occur at the bank slopes and valley slopes, or the floodplains, depending on whether the system represents a confined or an unconfined stream. In analogy to the formulation of an initial-boundary value problem (e.g., Schäfer, 2006), the definition of a consistent set of boundary conditions (e.g., flow hydrographs, sediment and wood input) at the inflow and outflow nodes as well as initial conditions describing the hydrologic and geomorphic conditions within the analysed stream segment (e.g., availability of sediment and deadwood) is required to properly deduce all possible system scenarios. Formally, the dominant process type (DF: debris flow; HCF: hyperconcentrated flow; BLT: bedload transport; LD: liquid discharge) has to be specified at the inflow node as boundary condition. In those mountain streams particularly susceptible to wood recruitment and associated transport processes, appropriated wood inflow rates at the boundary have to be specified (WMT: Wood material transport: L: low; M: medium; H: high).

Numerical models designed to solve the underlying set of partial differential equations describing the physics of movable boundary – coupled multi-phase flow processes in steep mountain streams (e.g. liquid-solid mixtures of water, sediment and wood) have been significantly improved (Rosati et al., 2008; Armanini et al., 2009). However, as indicated in Section 1, modelling uncertainties are considerable as an individual torrent event leading to above-average morphometric system shifts. These shifts can be characterised by a series of tipping process patterns along propagation paths, resulting in multiple process transitions (e.g., from debris flow to bedload transport processes and vice versa). Complementing the quantitative process analysis supported by numerical modelling through the integration of qualitative and quantitative knowledge is therefore important in order to accurately and precisely represent these transitions within the mountain stream.

2.2. Knowledge integration by Formative Scenario Analysis

Knowledge integration is used to integrate information on relevant impact variables into a system; such information is generally not yet fully represented by holistic scenario analyses or model scenario analyses (Zischg et al., 2005; Mazzorana et al., 2009). The approach aims at an identification of relevant impact factors and an exploration of their systemic role by determining

Table 1
Rating scale adapted form Saaty (1980) for a pairwise comparison between different evolution trajectories.

Point rating	Accepted meaning
1	Evolution trajectories judged to be equally probable
3	The probability of the first evolution trajectory is slightly higher than the second trajectory
5	The probability of the first evolution trajectory is higher than the second trajectory
7	The probability of the first evolution trajectory is considerably higher than the second trajectory
9	The probability of the first evolution trajectory is absolutely dominant with respect to the second trajectory
2,4,6,8	Intermediate values

Table 2
Impact variables (US_i, DS_i, IC_i, and AD_i) and the associated impact variable levels ($US_{i,j}$, $DS_{i,j}$, $IC_{i,j}$, and $AD_{i,j}$), identified by the individuals.

Impact variables				Impact variable levels	
Code	Variable	Description	References		
US_1	Relevant inflow at the upstream boundary	Flow type and intensity of sediment transport processes (i.e., based on sediment concentration) entering the reach	Pierson and Costa (1987) Slaymaker (1988) Hungr et al. (2001)	$US_{1,1}$	Debris flow (DFW)
				$US_{1,2}$	Debris flood (DFD)
				$US_{1,3}$	Bedload transport with relative high sediment transport rate compared to transport capacity (50–100%, BT1)
				$US_{1,4}$	Bedload transport with relative low sediment transport rate compared to transport capacity (0-50 %, BT2)
DS_1	Relevant outflow at the downstream boundary	Flow type and intensity of sediment transport processes (i.e., based on sediment concentration) leaving the reach	Pierson and Costa (1987) Slaymaker (1988) Hungr et al. (2001)	$DS_{1,1}$	Debris flow (DFW)
				$DS_{1,2}$	Debris flood (DFD)
				$DS_{1,3}$	Bedload transport with relative high sediment transport rate compared to transport capacity (50-100 %, BT1)
				$DS_{1,4}$	Bedload transport with relative low sediment transport rate compared to transport capacity (0-50 %, BT2)
IC_1	Natural stability of the streambed	Degree of armouring and presence of stable bedforms which are able to provide a relative stability of the channel bed up to moderate flood events	Weichert et al. (2009) Hassan et al. (2008)	$IC_{1,1}$	Bedrock, channel bed invariable
				$IC_{1,2}$	Pronounced natural stability (through armouring and stable bedforms)
				$IC_{1,3}$	Low to negligible natural stability (no armouring and absence of bedforms)
IC_2	Energy dissipation through presence of reliable grade-control structures	Degree of bed stability due to the presence of grade-control structures which are assessed to provide stability during high-magnitude events	Martín–Vide and Andreatta (2009) Conesa-Garcia and Lenzi (2010)	$IC_{2,1}$	High energy dissipation (number of reliable grade control structures >1 every 10 W length)
				$IC_{2,2}$	Medium energy dissipation (number of reliable grade control structures > 1 every 30 W length)
				$IC_{2,3}$	Low to negligible energy dissipation (number of reliable grade control structures < 1 every 30 W length)
IC_3	Available retention volume for solid material	Volumetric dimensions of natural (floodplains) or artificial (retention basins upstream of check-dams) areas representing a sediment trap during the event	D'Agostino (2010)	$IC_{3,1}$	Large compared to the upstream transport volume
				$IC_{3,2}$	Comparable to the upstream transport volume
				$IC_{3,3}$	Small compared to the upstream transport volume
IC_4	Mean channel slope	Longitudinal bed slope of the reach, which provides information on the dominant processes taking place during an event	Montgomery and Buffington, (1997) Wohl (2000)	$IC_{4,1}$	Very steep gradient (> 15 %)
				$IC_{4,2}$	Steep (3–15 %)
				$IC_{4,3}$	Moderate (0.5–3 %)
				$IC_{4,4}$	Gentle (< 0.5%)
IC_5	Variation of unit Stream Power Index	Longitudinal changes (positive = increase compared to upstream reach; negative = decrease) of the unit stream power index (approximated by a the slope-area product) drive erosion/ deposition processes	Dalla Fontana and Marchi (2003)	$IC_{5,1}$	Positive variation of Stream Power Index (Stream power increase)
				$IC_{5,2}$	Approximately no variation of Stream Power Index
				$IC_{5,3}$	Negative variation of Stream Power Index (Stream power decrease)
IC_6	Channel confinement	Lateral confinement of the reach, measured as the ratio floodway width/bankfull width, determines the possible transversal stream dynamics during the event and the degree of coupling with hillslope processes	Rosgen (1994)	$IC_{6,1}$	Highly confined (floodway/bankfull with ration < 1.5)
				$IC_{6,2}$	Moderately-confined (floodway/bankfull with ration 1.5–4)
				$IC_{6,3}$	Poorly confined (> 4)
IC_7	Relative erodibility of the banks	Degree of erodibility of the banks (i.e. lateral areas adjacent to the bankfull channel) affects sediment supply along the reach and depends on banks material and on bank protection works	Thorne (1982, 1997)	$IC_{7,1}$	Both banks highly erodible (loose sediments)
				$IC_{7,2}$	Moderate erodibility (partly cohesive sediments/vegetation pseudocohesion)
				$IC_{7,3}$	Low erodibility of both banks (bedrock or presence of reliable protection structures)

Table 2 (*continued*)

Impact variables				Impact variable levels	
Code	Variable	Description	References		
IC_8	Presence of structures potentially unstable (prone to failure)	Presence and size of transversal structures which are expected to be prone to failure during the event	Comiti et al. (2010)	$IC_{8,1}$	High potential drop (> 5 m) associated to these structures or critical influence for the stability of the entire reach
				$IC_{8,2}$	Moderate potential drop (< 5 m) associated to these structures
				$IC_{8,3}$	Absence of unstable structures
AD_1	Flow process transition	Estimated changes in the intensity (up- and down-ward) of sediment transport process occurring within a reach, which can drive important variations in the downstream propagation of the event as well as changes in reach geometry	Pierson and Costa (1987) Hungr et al. (2001)	$AD_{1,1}$	Sharp process intensification (from BT to DFW)
				$AD_{1,2}$	Moderate process intensification from BT1 to BT2, from BT to DFD, from DFD to DFW)
				$AD_{1,3}$	No transition
				$AD_{1,4}$	Sharp process attenuation (from DFW to BT)
				$AD_{1,5}$	Moderate process attenuation (from DFW to DFD, from DFD to BT, from BT1 to BT2)
AD_2	Bed elevation changes	Estimated changes in mean bed elevation as a consequence of erosion and deposition processes within the reach	Knighton (1998) Rickenmann and Koschni (2010)	$AD_{2,1}$	Intense incision (> 3 D90)
				$AD_{2,2}$	Moderate incision (1–3 D90)
				$AD_{2,3}$	Substantial bed equilibrium
				$AD_{2,4}$	Moderate deposition (1-3 D90)
				$AD_{2,5}$	Relevant deposition (> 3 D90)
AD_3	Bank erosion	Estimated magnitude of bank erosion (i.e., of areas adjacent to the channel, not of hillsides) along the reach during the event, caused by either strong incision or lateral instability due to aggradation	Knighton (1998)	$AD_{3,1}$	Intense erosion (> 1 W)
				$AD_{3,2}$	Moderate erosion (0.1–1 W)
				$AD_{3,3}$	No substantial erosion (< 0.1 W)
AD_4	Bed stability changes	Estimated variation in bed stability associated to breakage/burial of armour layer or bedforms	Weichert et al. (2009) Hassan et al. (2008) Zimmermann et al. (2010)	$AD_{4,1}$	Armouring removed or bedforms disrupted
				$AD_{4,2}$	Armouring and bedforms stable
				$AD_{4,3}$	Absence of armouring or bedforms (as prior to the flood)
				$AD_{4,4}$	Armouring created
AD_5	Variation in grade-control structure density (due to failure)	Estimated changes in the spatial density of consolidation structures along the reach as a response to their failure		$AD_{5,1}$	Substantial decrease (> 20 %)
				$AD_{5,2}$	Small decrease (0-20 %)
				$AD_{5,3}$	No variation
AD_6	Variation in bank protections	Estimated changes in the longitudinal extent of bank protection along the reach as a response to their failure		$AD_{6,1}$	Substantial decrease in length (>20 %)
				$AD_{6,2}$	Small decrease in length (0-20 %)
				$AD_{6,3}$	No variation
AD_7	Lateral sediment input and associated channel response	Estimated magnitude of sediment input delivered to the reach by mass movements (i.e. landslides, debris flows) and by tributaries, evaluated in terms of channel size and transport capacity	Jacob and Jordan (2001) Hancox et al. (2005) Marchi and Cavalli (2007) O'Connor et al. (2010)	$AD_{7,1}$	A temporary obstruction is expected to be formed with subsequent dam-break flows
				$AD_{7,2}$	Large sediment input but no obstructions expected
				$AD_{7,3}$	Low sediment input

possible systems' behaviour. Within this study, a Formative Scenario Analysis approach originally proposed by Scholz and Tietje (2002) was adapted and applied to the analysis of system dynamics in mountain streams. This approach aims at the construction of a defined set of information and the encrypting of scenario structures on the basis of participative elements. With this procedure a sufficiently large study team is guided towards a differentiated and structured understanding of the current state of the system to be analysed. Hence, Formative Scenario Analysis is based on qualitatively assessed key factors. Individuals determine by a rating procedure quantitative relations between these key factors. Subsequently, a consistency analysis is performed based on these key factors in order to identify a number of different but internally consistent scenarios. A scenario interpretation phase refines this procedure to iteratively identify relevant settings.

This methodology was recently applied to natural hazard analysis (Mazzorana et al., 2009), and is subsequently presented in a modified version suitable to mirror the requirements of natural hazard process unfolding in mountain streams. A detailed description of the individual steps to be applied to the sequence of abstracted stream elements includes

a) A team of individuals familiar with the problem setting lists $v_i, i = 1, \ldots, N$ impact variables relevant for the setting, also referred to as system variables, impact factors or case descriptors. The individuals assign every selected impact variable to one of the following categories:

- □ *Variables describing the inflow characteristics at the homogenous stream segment upstream boundary (US)*;
- □ *Variables describing the outflow characteristics at the homogenous stream segment downstream boundary (DS)*;

- *Variables describing the homogenous stream segment initial conditions (IC);*
- *Variables describing the homogenous stream segment adjustment descriptors (AD).*

The union of the above listed categories represents the entire set of impact variables $D = US \cup DS \cup IC \cup AD$.

b) In a next step, the individuals define the impact levels for each individual impact variable. Since the combinatorial number of scenarios is considerably influenced by the number of levels defined for each impact variable, impact variables and their levels should be defined parsimoniously. Each impact variable v_i requires the definition of at least two discrete levels$(N_i \geq 2)$ which are denoted by $v_i^1, v_i^2, \ldots, v_i^{N_i}$.
c) Formally a scenario is a vector $S_k = (v_1^{n_1}, .., v_i^{n_i}, .., v_N^{n_N})$ with $k = 1, \ldots, k_0$; the number of scenarios is $k_0 = \prod_{i=1}^{N} N_i$.
d) In this step the consistency matrix is constructed as $C = [c(v_i^{n_i}, v_j^{n_j})]$ containing the consistency ratings, $c(\bullet, \bullet)$, for all pairs of impact variables at all levels c,$(i, j = 1, \ldots, N, i \neq j, n_i = 1, \ldots, N_i, n_j = 1, \ldots, N_j)$.
e) For each scenario a consistency value is calculated respectively as additive measure as $c^*(S_k) = \sum c(v_i^{n_i}, v_j^{n_j})$ or as multiplicative measure as $c^*(S_k) = \prod c(v_i^{n_i}, v_j^{n_j})$ with $i, j = 1, \ldots, N, i \neq j$, $v_i^{n_i}, v_j^{n_j} \in S_k$.
f) The scenario selection is based conjointly on the consistency value of the scenarios and the difference between them. As proposed by Tietje (2005) the distance measure Δ corresponds to the number of differences between the scenarios $\Delta(S_k, S_l) = \sum_{i=1}^{n} \begin{cases} 1 & \text{if } v_i(S_k) \neq v_i(S_l) \\ 0 & \textit{otherwise} \end{cases}$. The scenarios are ranked in decreasing order according to consistency in an array. The scenario with the highest consistency value S_k is selected from the array and compared with the second scenario S_l. If $\Delta(S_k, S_l)$ is sufficiently large, e.g. $\Delta(S_k, S_l) \geq \Delta^*$, where Δ^* was a chosen threshold value, then scenario S_l is also selected and becomes the new comparison reference for scenario three, otherwise the third scenario is compared with the first scenario, etc.
g) Scenario interpretation completes the adapted steps of Formative Scenario Analysis (Mazzorana and Fuchs, 2010).

2.3. Probability assignment to the selected system scenarios

Within this study, the assumption that the set of system scenarios selected for each abstracted stream element on the basis of consistency within the Formative Scenario Analysis sufficiently mirrors the range of possible system dynamics was introduced. Conversely, the complementary set of unselected scenarios was therefore neglected.

In order to assign probabilities to the selected system scenarios a grouping according to specific initial and boundary conditions is undertaken. For every specific combination of initial and boundary conditions, one or more evolution trajectory can be associated. Thus, well-defined subjective probabilities of occurrence conditional upon specific combinations of levels, $S_k^{(US \cup IC)}$, describing both the initial (IC) and boundary conditions (US) to the possible (and consistent) evolution trajectories, and captured by the corresponding set adjustment descriptor levels (AD) and downstream boundary outflow levels (DS), $S_k^{(DS \cup AD)}$, have to be assigned. The subjective probability assignments have to fulfil both, the axioms of probability theory and the comparative probability axioms (compare Fishburn, 1986).

Based on these principles two alternative indirect probability assignment procedures were elaborated:

a) An indirect subjective probability elicitation method was introduced to enhance the subjective probability assignment procedure (Fig. 2).
   1. The group of individuals considers a given specific combination of levels, $S_k^{(US \cup IC)}$, describing both the initial (IC) and upstream boundary conditions (US) and all consistent evolution trajectories $S_k^{(DS \cup AD)}$.
   2. Starting with the evolution trajectory belonging to the most consistent scenario $(S_k)_{\max}$ with $C^*(S_{h,k}) = \max!$, the subjective probability of occurrence of $(S_k^{(DS \cup AD)})^*$ conditional upon $S_k^{(DS \cup AD)}$ is judged indirectly following the probability assignment scheme shown in Fig. 2. Each probability wheel represents a defined geometrical probability measure. If the group of individuals is indifferent between betting on the outcome of the considered evolution trajectory and the outcome of the determined probability wheel (compare Fig. 2), the probability structure of the probability wheel can be used to infer the probability of the outcome of the considered evolution trajectory $w((S_k)_{\max})$ (Fishburn, 1986).
   3. The procedure is repeated for the other selected consistent scenarios S_k, and is refined as long as $\sum w(S_k) = 1$. These methodological steps have to be applied for all abstracted stream elements representing the stream system in a hydrological consistent and therefore logical sequence.
b) As a valid alternative, an indirect subjective probability elicitation method, based on a pairwise comparison between all different scenario evolution trajectories, can be used. This method is an analogue to the Analytic Hierarchic Process (AHP, Saaty, 1980; Saaty and Sodenkamp, 2008), which provides a comprehensive and rational framework for structuring a complex decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions.
   1. The group of individuals considers a given specific combination of levels,$S_k^{(US \cup IC)}$, describing both the initial (IC) and upstream boundary conditions (US) and all consistent evolution trajectories $S_k^{(DS \cup AD)}$.
   2. All evolution trajectories $S_k^{(DS \cup AD)}$ are compared among each other using a nine-point scale shown in Table 1 (modified from Saaty, 1980).
   3. Once the pairwise comparison matrix is constructed, in a next step a weight vector corresponding to the principal eigenvector of the pair wise comparison matrix is determined. The elements of this vector can be interpreted as the subjective probabilities to be assigned to the corresponding evolution trajectory. For the computation of the principal eigenvector we refer to the method proposed by Meixner and Haas (2002), in which, in a first step, the pairwise comparison matrix is multiplied by itself. Then, in a second step, the normalized row sums of the obtained matrix are calculated obtaining a vector of probability estimates. The procedure is repeated until the difference between the new and the old vector of probability estimates becomes sufficiently small, which is generally the case after a few iterations.

After having processed all abstracted stream elements in a cascade with the outlined analysis procedure, the retrieved knowledge about the systems' behaviour is used to construct an event tree. This event tree contains the probability assignments on process unfolding for individual trajectory evolution. As a result, the spatial probability skeleton is set up.

3. Scenario building for a homogeneous stream segment

In this section, the model being set up is implemented for the management of hazard processes in mountain streams, and the associated scenario-building procedure is exemplified for one theoretical homogenous stream segment. 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.

The impact variables necessary for an accurate and precise assessment of possible system scenarios were defined and categorised according to (1) variables describing the inflow characteristics (US); (2) variables describing the outflow characteristics (DS); (3) variables describing the homogenous stream segment initial conditions (IC); and (4) variables describing the homogenous stream segment adjustment descriptors (AD), see Table 2. The associated impact variable levels were chosen according to information in the available literature and as a result from geomorphologic evidence in the studied catchment.

The group of individuals assigned a consistency rating for each individual combination of possible impact levels for all pairs of different impact variables as follows:

$c(\bullet,\bullet) = 3 \rightarrow$ Complete consistency
$c(\bullet,\bullet) = 1 \rightarrow$ Partial or weak inconsistency
$c(\bullet,\bullet) = -1 \rightarrow$ Inconsistency

In Table 3, an excerpt of the consistency matrix, containing the consistency ratings assigned to each pair of impact levels of different impact variables, is presented.

Formally the consistency matrix (compare Table 3, the entire matrix is available at link (Electronic Supplementary Material) represents the final result of the first five steps of the adopted Formative Scenario Analysis procedure. Within this matrix, the determined process knowledge for the considered abstracted stream element is concisely described. Within the matrix shown in Table 3, the cells containing the rating value "−1" represent the inconsistent combinations of possible impact levels for all pairs of different impact variables. Similarly the cells containing the rating value "3" represent the combinations with complete consistency. The cells containing the rating value "1" indicate combinations with partial or week consistency.

As shown in Table 4 we defined specific initial and boundary conditions for the studied stream segment in order to undertake an analysis of possible scenario evolution trajectories.

By suppressing those rows and columns that correspond to the unselected impact factor levels the original consistency matrix was significantly reduced. The resulting reduced consistency matrix is shown in Table 5.

Taking the reduced consistency matrix (compare Table 5) as basis of departure the full set of possible evolution scenario trajectories can be unfolded; first, by calculating the multiplicative consistency measure for each scenario (compare step "e" of the FSA procedure outlined in section 2.2); second, by applying the scenario selection criteria foreseen by the FSA procedure (compare steps "f" and "g").

In Table 6 the ten most consistent evolution scenario trajectories resulting from the analysis of the reduced consistency matrix are reported. In the last column of Table 6 the multiplicative consistency measure − MCM − corresponding to each selected scenario is shown.

Once defined the possibility space, defined as the set of consistent evolution scenario trajectories (compare Table 6), the probability of occurrence for each of them has to be determined. Applying the second of the two proposed indirect methods for the

Table 3
Excerpt of the consistency matrix, containing the consistency ratings assigned to each pair of impact levels of different impact variables

		US1,1	US1,2	US1,3	US1,4	DS1,1	DS1,2	DS1,3	DS1,4	IC1,1	IC1,2	IC1,3
		US1,1 DFW – debris flow	US1,2 DFD – debris flood	US1,3 BT – bedload transport with relative high sediment transport rate compared to transport capacity (50–100%)	US1,4 BT – bedload transport with relative sediment transport rate compared to transport capacity (0–50%)	DS1,1 DFW – debris flow	DS1,2 DFD – debris flood	DS1,3 BT – bedload transport with relative high sediment transport rate compared to transport capacity (50–100%)	DS1,4 BT – bedload transport with relative sediment transport rate compared to transport capacity (0–50%)	IC1,1 – bedrock – inalterable	IC1,2 - pronounced natural stability (through armouring and stable bedforms)	IC1,3– low to negligible natural stability (no armouring and absence of bedforms)
AD1,1 – sharp process intensification (from BT to HF or DF)	AD1,1	*−1*	*−1*	1	1	1	1	1	*−1*	1	**3**	1
AD1,2 – moderate process intensification (increase in BT saturation or from HF to DF)	AD1,2	*−1*	1	1	1	1	1	1	1	1	1	1
AD1,3 –no transition	AD1,3	1	1	1	1	1	1	1	1	1	1	1
AD1,4 – sharp process attenuation (from DF to BT)	AD1,4	1	1	1	*−1*	*−1*	*−1*	1	1	*−1*	1	1
AD1,5 – moderate process attenuation (from DF to HF, from HF to BT, from high to low BT)	AD1,5	1	1	1	1	*−1*	1	1	1	1	1	1

Table 4
Assigned initial and boundary conditions for the studied stream segment

Condition type	Impact factor	Token	Impact factor level	Symbol
Upstream boundary condition	US_1 Relevant inflow at the upstream boundary	$US_{1,2}$	$US_{1,2}$ – DFD – Debris flood	$v_{1,2}$
Initial condition	IC_1 –Natural stability of the streambed – armouring and stable bedforms	$IC_{1,3}$	$IC_{1,3}$ – Low to negligible natural stability (no armouring and absence of bedforms)	$v_{3,4}$
Initial condition	IC_2 – Energy dissipation through presence of reliable grade-control structures	$IC_{2,1}$	$IC_{2,1}$ – High energy dissipation (number of reliable grade control structures > 1 every 10W length)	$v_{4,1}$
Initial condition	IC_3 – Available retention volume for solid material	$IC_{3,1}$	$IC_{3,1}$ –Large compared to the upstream transport volume	$v_{5,1}$
Initial condition	IC4 – Mean channel slope	$IC_{4,3}$	$IC_{4,3}$ – Moderate (0.5 – 3%)	$v_{6,3}$
Initial condition	IC_5 – Variation of Stream Power Index	$IC_{5,3}$	$IC_{5,3}$ – Negative variation of Stream Power I ndex (Stream Power Decrease)	$v_{7,3}$
Initial condition	IC_6 – Channel confinement ratio (floodway width/bankfull width)	$IC_{6,2}$	$IC_{6,2}$ – Moderately-confined (1.5 – 4)	$v_{8,2}$
Initial condition	IC_7 – Relative erodibility of the banks	$IC_{7,2}$	$IC_{7,2}$ – Moderate relative erodibility	$v_{9,2}$
Initial condition	IC_8 – Presence of structures potentially unstable (prone to failure)	$IC_{8,3}$	$IC_{8,3}$ – Absence of unstable structures	$v_{10,3}$

Table 5
Resulting reduced consistency matrix corresponding to a defined set of initial and boundary conditions ($US_{i,j}, IC_{i,j}$; dark gray colored cells in the first row and first column respectively). Within the matrix the dark gray colored cells with the rating value "-1" indicate inconsistent key variable level combinations, light gray colored cells with the rating value "3" indicate consistent key variable level combinations and the white cells with rating value "1" indicate key variable level combinations characterized by partial or week consistency.

	US1,2	DS1,1	DS1,2	DS1,3	DS1,4	IC1,3	IC2,1	IC3,1	IC4,3	IC5,3	IC6,2	IC7,2	IC8,3	AD1,1	AD1,2	AD1,3	AD1,4	AD1,5	AD2,1	AD2,2	AD2,3	AD2,4	AD2,5	AD3,1	AD3,2	AD3,3	AD4,1	AD4,2	AD4,3	AD4,4	AD5,1	AD5,2	AD5,3	AD6,1	AD6,2	AD6,3
US1,2																																				
DS1,1	1																																			
DS1,2	1																																			
DS1,3	1																																			
DS1,4	1																																			
IC1,3	1	1	1	1	1																															
IC2,1	1	1	1	1	1	1																														
IC3,1	1	-1	-1	-1	1	1	1																													
IC4,3	1	-1	1	1	1	1	1	1																												
IC5,3	1	-1	1	1	1	1	1	1	1																											
IC6,2	1	1	1	1	1	1	1	1	1	1																										
IC7,2	1	1	1	1	1	1	1	1	1	1	1																									
IC8,3	1	1	1	1	1	1	1	1	1	1	1	1																								
AD1,1	-1	1	1	1	-1	1	1	-1	-1	1	1	1	1																							
AD1,2	1	1	1	1	1	1	1	-1	-1	1	1	1	1																							
AD1,3	1	1	1	1	1	1	1	1	1	1	1	1	1																							
AD1,4	1	-1	-1	1	1	1	1	3	1	3	1	1	1																							
AD1,5	1	-1	1	1	1	1	1	1	3	3	3	1	1																							
AD2,1	1	3	1	1	1	1	-1	1	-1	-1	1	1	1	3	1	1	-1	-1																		
AD2,2	1	1	1	1	1	1	1	1	1	-1	1	1	1	1	3	1	-1	-1																		
AD2,3	1	-1	1	1	1	1	1	1	3	1	1	1	1	-1	-1	3	-1	-1																		
AD2,4	1	1	1	1	1	1	1	1	1	3	1	1	1	-1	-1	1	1	3																		
AD2,5	1	-1	1	1	1	1	1	1	1	3	1	1	1	-1	-1	1	3	1																		
AD3,1	1	1	1	1	1	1	-1	1	1	1	1	-1	1	3	1	-1	-1	-1	3	1	-1	1	3													
AD3,2	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	3	1	3	1													
AD3,3	1	1	1	1	1	1	1	1	1	1	1	1	1	-1	-1	1	-1	-1	-1	-1	3	1	1													
AD4,1	3	3	1	1	1	-1	1	1	1	1	1	1	1	3	1	-1	3	1	3	1	-1	1	3	3	1	-1										
AD4,2	-1	-1	-1	1	1	-1	1	1	1	1	1	1	1	-1	-1	1	1	1	-1	-1	1	-1	-1	-1	-1	1										
AD4,3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1										
AD4,4	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	-1	-1	1	-1	1	1	1	1	-1	-1	-1	-1	3										
AD5,1	1	1	1	1	-1	1	1	1	1	-1	1	1	-1	1	1	1	1	1	3	1	1	1	1	3	1	-1	3	-1	1	1						
AD5,2	1	1	1	1	1	1	1	1	1	1	1	1	-1	1	1	1	1	1	3	1	1	1	1	1	3	-1	1	1	1	1						
AD5,3	1	-1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1	-1	1	1	3	1	-1	1	3	1	1	1	1						
AD6,1	1	1	1	1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1	3	1	-1	3	1	1	1	3	1	-1			
AD6,2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1	3	-1	1	1	1	1	1	3	1			
AD6,3	1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	-1	-1	3	1	1	1	1	-1	1	3			
AD7,1	1	3	3	1	-1	1	1	1	1	1	1	1	1	3	1	-1	-1	-1	3	-1	-1	1	3	3	1	1	3	-1	1	-1	3	1	1	3	1	1
AD7,2	1	1	3	3	1	1	1	1	1	1	3	3	1	1	3	-1	-1	-1	1	1	-1	3	1	1	1	-1	1	-1	1	-1	1	1	1	1	1	1
AD7,3	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 6
Evolution scenario trajectories ranked in descending consistency order (MCM = multiplicative consistency measure), resulting from the expansion of the reduced consistency matrix. The first column contains the indicative number of the selected scenario. Columns 2 to 18 contain the key variable levels for each key variable describing completely a scenario (compare also Table 2). The last column contains the MCM values corresponding to each selected scenario.

																		MCM
1	$US_{1,2}$	$DS_{1,4}$	$IC_{1,3}$	$IC_{2,1}$	$IC_{3,1}$	$IC_{4,3}$	$IC_{5,3}$	$IC_{6,2}$	$IC_{7,2}$	$IC_{8,3}$	$AD_{1,5}$	$AD_{2,4}$	$AD_{3,2}$	$AD_{4,3}$	$AD_{5,3}$	$AD_{6,2}$	$AD_{7,3}$	177147
2	$US_{1,2}$	$DS_{1,4}$	$IC_{1,3}$	$IC_{2,1}$	$IC_{3,1}$	$IC_{4,3}$	$IC_{5,3}$	$IC_{6,2}$	$IC_{7,2}$	$IC_{8,3}$	$AD_{1,3}$	$AD_{2,3}$	$AD_{3,3}$	$AD_{4,3}$	$AD_{5,3}$	$AD_{6,3}$	$AD_{7,3}$	59049
3	$US_{1,2}$	$DS_{1,4}$	$IC_{1,3}$	$IC_{2,1}$	$IC_{3,1}$	$IC_{4,3}$	$IC_{5,3}$	$IC_{6,2}$	$IC_{7,2}$	$IC_{8,3}$	$AD_{1,4}$	$AD_{2,4}$	$AD_{3,2}$	$AD_{4,3}$	$AD_{5,3}$	$AD_{6,2}$	$AD_{7,3}$	19683
4	$US_{1,2}$	$DS_{1,4}$	$IC_{1,3}$	$IC_{2,1}$	$IC_{3,1}$	$IC_{4,3}$	$IC_{5,3}$	$IC_{6,2}$	$IC_{7,2}$	$IC_{8,3}$	$AD_{1,3}$	$AD_{2,4}$	$AD_{3,2}$	$AD_{4,3}$	$AD_{5,3}$	$AD_{6,2}$	$AD_{7,3}$	6561
5	$US_{1,2}$	$DS_{1,4}$	$IC_{1,3}$	$IC_{2,1}$	$IC_{3,1}$	$IC_{4,3}$	$IC_{5,3}$	$IC_{6,2}$	$IC_{7,2}$	$IC_{8,3}$	$AD_{1,3}$	$AD_{2,4}$	$AD_{3,3}$	$AD_{4,3}$	$AD_{5,3}$	$AD_{6,3}$	$AD_{7,3}$	6561
6	$US_{1,2}$	$DS_{1,4}$	$IC_{1,3}$	$IC_{2,1}$	$IC_{3,1}$	$IC_{4,3}$	$IC_{5,3}$	$IC_{6,2}$	$IC_{7,2}$	$IC_{8,3}$	$AD_{1,5}$	$AD_{2,5}$	$AD_{3,2}$	$AD_{4,3}$	$AD_{5,3}$	$AD_{6,2}$	$AD_{7,3}$	6561
7	$US_{1,2}$	$DS_{1,4}$	$IC_{1,3}$	$IC_{2,1}$	$IC_{3,1}$	$IC_{4,3}$	$IC_{5,3}$	$IC_{6,2}$	$IC_{7,2}$	$IC_{8,3}$	$AD_{1,4}$	$AD_{2,5}$	$AD_{3,2}$	$AD_{4,3}$	$AD_{5,3}$	$AD_{6,2}$	$AD_{7,3}$	6561
8	$US_{1,2}$	$DS_{1,4}$	$IC_{1,3}$	$IC_{2,1}$	$IC_{3,1}$	$IC_{4,3}$	$IC_{5,3}$	$IC_{6,2}$	$IC_{7,2}$	$IC_{8,3}$	$AD_{1,3}$	$AD_{2,3}$	$AD_{3,2}$	$AD_{4,3}$	$AD_{5,3}$	$AD_{6,2}$	$AD_{7,3}$	2187
9	$US_{1,2}$	$DS_{1,4}$	$IC_{1,3}$	$IC_{2,1}$	$IC_{3,1}$	$IC_{4,3}$	$IC_{5,3}$	$IC_{6,2}$	$IC_{7,2}$	$IC_{8,3}$	$AD_{1,3}$	$AD_{2,5}$	$AD_{3,3}$	$AD_{4,3}$	$AD_{5,3}$	$AD_{6,3}$	$AD_{7,3}$	2187
10	$US_{1,2}$	$DS_{1,4}$	$IC_{1,3}$	$IC_{2,1}$	$IC_{3,1}$	$IC_{4,3}$	$IC_{5,3}$	$IC_{6,2}$	$IC_{7,2}$	$IC_{8,3}$	$AD_{1,3}$	$AD_{2,5}$	$AD_{3,2}$	$AD_{4,3}$	$AD_{5,3}$	$AD_{6,2}$	$AD_{7,3}$	729

probability assignments the pair wise comparison matrix is constructed (compare Table 7). This matrix contains the comparison of all pairs of consistent evolution scenario trajectories applying the point scale (compare Table 1) introduced in section 2.3. For the computation of the principal eigenvector the method proposed by Meixner and Haas (2002) is applied and the probability associated to each evolution scenario trajectory is reported in the last column of Table 7.

Once identified the possible evolution scenario trajectories for the first abstracted stream element, which is part of a more complex abstracted stream system, and once estimated the probability of occurrence associated to each possible evolution scenario trajectory, the entire procedure has to be repeated proceeding from one abstracted stream to the next until the process routing within the abstracted stream system is completed. When cascading the process chain throughout the abstracted stream system it has to be considered that the relevant processes characterizing the outflow at the downstream node of an abstracted stream element fix the upstream boundary condition for the subsequent abstracted stream element.

Here we report as an exemplification of the application of the process routing throughout a simple hypothetical stream. For simplicity we consider the associated abstracted stream system built of a sequence of three abstracted stream elements. In Fig. 3 the hypothetical spectrum of evolution scenario trajectories and the associated spatial probability spectrum are shown. Graphical constrains admit representing only a small set of impact factors. As shown in Fig. 3 we selected IC_1 "Natural stability of the streambed" as a representative key variable describing the initial conditions and AD2 "bed elevation changes" as a characterizing adjustment descriptor. Though the key variables US1 and DS1 we kept track of the process type at the boundary nodes of the abstracted stream elements. To graphically identify the key variable levels we used a specific hachure for $US_{1,j}$, $DS_{1,j}$, $IC_{1,j}$ and specific symbols for $AD_{2,j}$ as specified in the legend of Fig. 3. Moreover we associated to each connection line between a specific scenario trajectory evolving along one abstracted stream element and the possible scenario trajectories capturing the dynamics in the successive abstracted stream element the corresponding probability of occurrence (compare elicitation methods outlined in section 2.3). By repeating this procedure for each abstracted stream element composing the abstracted stream system the complete spatial probability skeleton is constructed.

To appropriately apply the above outlined procedures, the interdisciplinary expert team should consider a minimum number of necessary framework conditions. It is crucial to identify unstable hillslopes and their potential slide volumes, as well as to interpret past and present channel forms (e.g. terraces, floodplains, bedforms) in order to understand the location of preferential deposition/erosion during extreme events.

The segmentation of the drainage network has to be undertaken with particular care in order to establish reaches with uniform processes (i.e. debris flow vs. bedload transport, erosion/equilibrium/deposition), of sufficient size (excessive fragmentation).

An extensive survey of the natural stream system is absolutely necessary to correctly map the actual geomorphologic characteristics of the stream into a coherent set of initial conditions as required by the adopted FSA procedure. For particular geomorphologic/geologic settings a specific need for the construction of an *ad hoc* consistency matrix with additional impact factors could emerge. In these cases individuals with a specific expertise relevant for the specific problem setting could be required.

Table 7
Pair wise comparison matrix containing the comparison of all pairs of consistent evolution scenario trajectories and the associated probabilities. The first row and the first column contain the indicative number of the selected scenarios. The cells with row index >1 and column index comprised between 2 and m-1 contain the ratings for a pairwise comparison among the selected scenarios. The last column reports the calculated subjective probabilities to be associated to each selected scenario resulting form the pairwise comparisons.

	1	2	3	4	5	6	7	8	9	10	Probabilities of the scenario trajectories
1	1.00	3.00	5.00	7.00	7.00	7.00	8.00	8.00	8.00	9.00	0.35
2	0.33	1.00	3.00	5.00	5.00	5.00	7.00	7.00	7.00	8.00	0.22
3	0.20	0.33	1.00	5.00	5.00	5.00	7.00	7.00	7.00	8.00	0.17
4	0.14	0.20	0.20	1.00	1.00	1.00	3.00	3.00	3.00	5.00	0.06
5	0.14	0.20	0.20	1.00	1.00	1.00	3.00	3.00	3.00	5.00	0.06
6	0.14	0.20	0.20	1.00	1.00	1.00	3.00	3.00	3.00	5.00	0.06
7	0.13	0.14	0.14	0.33	0.33	0.33	1.00	1.00	1.00	3.00	0.03
8	0.13	0.14	0.14	0.33	0.33	0.33	1.00	1.00	1.00	3.00	0.03
9	0.13	0.14	0.14	0.33	0.33	0.33	1.00	1.00	1.00	3.00	0.03
10	0.11	0.13	0.13	0.20	0.20	0.20	0.33	0.33	0.33	1.00	0.02
											1.00

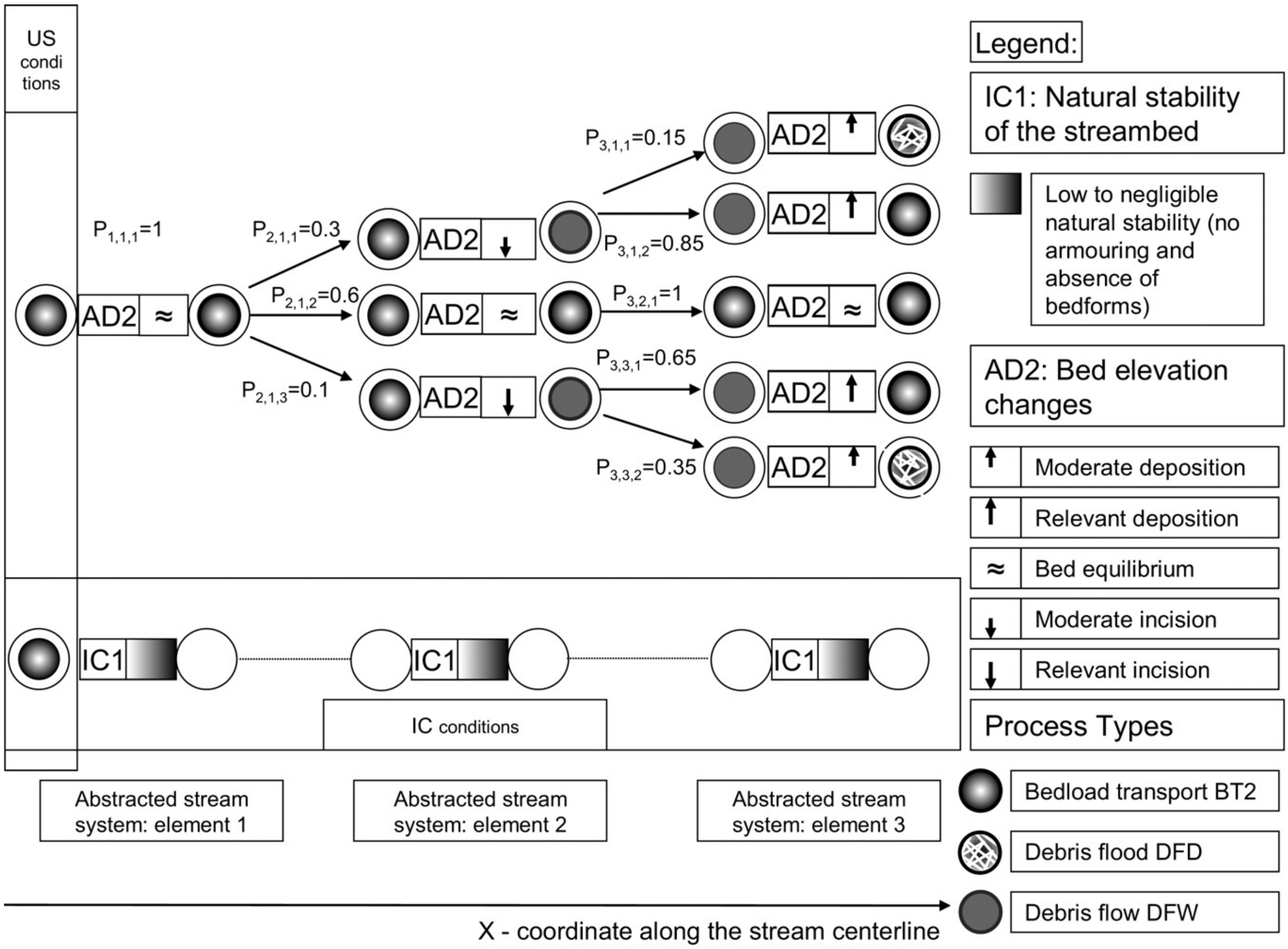

Fig. 3. Exemplified spectrum of evolution scenario trajectories and the associated spatial probability spectrum.

4. Discussion and conclusion

In this paper we presented a methodology to derive a set of consistent scenarios for flooding in mountain basins by performing a process routing following a structured knowledge integration approach. Starting from the basic level, a mountain stream is interpreted in a geomorphologic perspective, resulting in a simplified stream system composed of interconnected stream reaches ideally featuring quasi-homogenous behaviour in terms of hydraulics and sediment transport. These reaches represent the basic spatial unit at which the mountain stream dynamics are captured. In order to perform the process routing and to infer possible process dynamics, an adapted Formative Scenario Analysis procedure – including an *ad hoc* categorisation scheme for the relevant impact factors driving the system evolution – was proposed. In analogy to a classic initial/boundary conditions formulation in physics, we introduced the distinction between impact factors describing the initial/boundary conditions and adjustment descriptors predicting the system evolution during a flood event. Expert knowledge and expert judgement play a major role throughout the entire set of procedural steps. Moreover, a participative approach is another distinctive feature of such methodological framework. The application of the adopted FSA procedure resulted in the deployment of a general consistency matrix which represents the elicited knowledge about the process dynamics during the event at the reach scale (second level of knowledge generation). We further introduced two indirect probability assignment methods built on the expert-based evaluation, aiming at the determination of the probability of occurrence of individual evolution scenarios (third level of knowledge generation). By extending the analysis to the entire simplified channel system (upscaling), the entire spectrum of possible stream evolution (fourth level of knowledge generation) and the associated spatial probability structure (fifth level of knowledge generation) are obtained.

Even though such an approach may appear rather complex to be actually carried out by local agencies, the above mentioned advantages are multi-fold especially for locations where a considerable amount of values at risk is exposed, i.e. in mountain settlements and cities.

From the perspective of an integrated river management, the spatially explicit representation of flood dynamics and stream evolution scenarios along with their associated spatial probability brings about a series of advantages which complement the traditional use of numerical hydrodynamics models.

1. With respect to hazard management, the reduction of epistemic uncertainties (rooted in a basic lack of knowledge of fundamental phenomena) is made possible by following the conceptual model outlined above. This is of particular relevance with respect to the inherent modelling uncertainties, the natural variability within a system (e.g., mountain streams), and

a limited amount of information available during conventional hazard assessment. Therefore, the nature of decision making will be changed, since information necessary to select between different management options will be provided.

2. The selection between different management options, in turn, increases the reliability of risk analyses, and can be expanded to the system response scenarios, i.e., with respect to elements at risk exposed and their vulnerability (Fuchs et al., 2007a; Fuchs, 2009). In particular, a deeper insight into vulnerability resulting from mountain hazards can be achieved, aiming at a more precise evaluation with respect to different scales and multiple spatio-temporal resolutions. Hence, by improving the scenario-building process for mountain streams, more effective mitigation strategies will become possible (Holub and Fuchs, 2009). Simultaneously, the acknowledgement of the considerable uncertainties inherent in flood processes in mountain basins will promote a sustainable development of mountain environments including sociological aspects, i.e. through a participative approach of all stakeholders following a more widespread education towards natural hazards and risk.
3. With reference to river management, intervention options can be evaluated either by modifying the initial conditions for the stream reach (e.g., by changing the number of reliable grade-control structures) or by varying the upstream boundary conditions (e.g., bedload transport instead of debris flow as a consequence of a planned check-dam). Therefore, the expected effects of existing or planned mitigation structures can be assessed though a formal procedure including necessary cost-benefit analyses (Fuchs et al., 2007b).

Such a procedure for planning structural (as well as non-structural) interventions will result in a balanced strategy between flood hazard mitigation and environmental conservation/amelioration (Fuchs, 2009) since the most relevant source of environmental degradation in mountain channels originates from their physical alteration with a notable impact on lowland rivers (Giller and Malmqvist, 1998). Most of the mountain channels in the European Alps suffer from heavy modifications of their bed morphology and sediment transport regime associated with the presence of grade-control structures and retention check-dams, built to stabilize the river morphology and thus preventing sudden changes during flood events. The physical instability of channel beds has been recognized to be the most important driver of fluvial ecosystems in the Alps (Petts et al., 2000), such that a real river ecological restoration (e.g. Kondolf, 1995; Palmer et al., 2005) would imply the reestablishment of destabilizing transport processes which are not acceptable from a social perspective (i.e. river stakeholders). In contrast, check-dams cause severe disruption of the longitudinal river continuum (sediments, organic matter, biotic communities; Füreder et al., 2002; Monaghan et al., 2005), local alteration of macroinvertebrates and diatom populations (Bona et al., 2008; Comiti et al., 2009) as well as a strong visual impairment of the mountain landscape due to such human action.

As a consequence, the requirements to conserve or ameliorate the river ecological quality following the European Water Framework Directive prescriptions, as well as to mitigate flood risk in accordance to the Floods Directive, imply that only those structural measures that are really needed and effective under the most likely flood scenarios should be maintained and/or built in the river network. The procedure presented in this paper specifically dedicated to mountain basins has the potential to support river managers in this respect.

The procedure described in this paper was developed and initially formulated in the framework of the EU project 'Adapt-ALP' (http://www.adaptalp.org Mazzorana et al., in press b), where it was evaluated as being relevant for an application by both, river basin agencies and professionals in the process of establishing and/or revising flood hazard maps. Furthermore, the need to take into account different flood scenarios in flood risk mapping is set by the EU Floods Directive and thus, this methodology may be functional after further tests and developments to meet such requirements. In particular, the adoption of different flood scenarios for flood risk mapping has been recently fostered by the "Working Group F" of the European Commission (Common Implementation Strategy WGF, 2011).

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