ADVANCED SCENARIO-BASED HAZARD ANALYSIS IN THEORY AND PRACTICE

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ABSTRACT

Resolving a substantial part of the uncertainties underlying the hydrological cause-effect chains, like those involving sudden morphological change or clogging of critical flow sections, is doubtlessly a major challenge in hazard assessment.
On the one hand pure numerical modelling approaches fail, at least partially, to accurately and precisely mirror such a wide range of complex phenomena, on the other hand the burden of proof still remains if vaguely expressed expert knowledge complements the hazard assessment. Thus, it is advisable to mutually corroborate the results from either numerical analysis or expert knowledge through advanced scenario-based hazard analysis techniques. By outlining the theory and by presenting a case study on the Mareiterbach in South Tyrol, Italy, we demonstrate the potential of these knowledge integration techniques to enhance hazard analysis in mountain streams and to increase, as a consequence, the reliability of the subsequently delineated hazard maps.

Keywords: Natural Hazard, Scenarios, Knowledge integration

INTRODUCTION

The characterizing feature of extreme events in steep mountains streams is the multiplicity of possible tipping process patterns such as those involving sudden morphological change 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 (Mazzorana et al., 2012).
In order to have 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 flood hazard maps and flood risk maps which show the potential adverse consequences associated with different flood scenarios.
Hence, 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 and temporal patterns 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; Patè-Cornell, 1996).
With respect to uncertainties in natural hazard management, the determination of hazard scenarios for mountain streams includes (Mazzorana et al., 2009):
(1) uncertainties bout 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

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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 and temporal 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 affect 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.

Along with the objective to produce a reliable delineation of hazard zones, adopting the functional distinction between the loading and the response system (LS and RS, respectively, compare Mazzorana et al., 2011a and 2011b), i.e. between the confined part of the catchment, where water, sediment and wood fluxes are generated and the unconfined areas subject to flooding such as alluvial fans and floodplains.

We will provide an overview of the methodological steps to carry out the process routing along the stream system integrating the knowledge derived from models with expert-based judgement (Mazzorana and Fuchs, 2010) in order to derive consistent scenarios. In parallel we will discuss how to infer the spatial probability structure of the determined flood hazard scenarios (Wakker, 2010).

Since the outcomes of the loading system scenarios provide the input for the response system analysis, we will present in an analogue fashion, a synthesis of the methodological steps to analyze process propagation in the RS. Emphasis will be put on the understanding of the system behaviour regarding two main types of spatial domains, i.e. stochastic and quasi-deterministic domains, based on the predictability of their dynamics.

The practical applicability of an advanced scenario-based hazard analysis will then be demonstrated by presenting and discussing selected results of a dedicated case study conducted on the Mareiterbach in South Tyrol, Italy.

In the concluding section we will discuss the advantages of such an advanced scenario-based hazard analysis approach, despite its apparent procedural complexity.

METHODS

In this section we present a series of methodological approaches to carry out flood hazard assessment by systematically removing knowledge gaps about cause-effect chains characterizing hazard process in mountain streams.

Throughout we will employ a standard system representation scheme, which introduces with respect to a hydrologic basin, the distinction between loading and response systems (LS and RS, respectively). The former represent the spatial domains, i.e. channels, mostly confined by hillslopes where the direction of the flows is unambiguous; the latter, include alluvial/debris fans and floodplains; therein the channel can be unconfined and flows present more possible directions.

The developed methods are organized in three tables. The first table contains a summary of the main steps of hydrological analysis. The second table is deserved to the assessment steps of flood hazard analysis within the loading systems -LSs- and the third one is dedicated to the analytic steps for the response systems – RSs. Each table presents four columns, labelled respectively as “step”, “action”, “procedural aspects” and “results” to facilitate the correct tracking of the analytic efforts and the corresponding insights gained. Great efforts were undertaken to achieve a balance between formal rigor and clarity of exposition. More demanding methodological contents can be accessed via the cited references, the tables are interspersed with.

Tab. 1 Main steps of hydrological analysis.

Hydrology			
STEP	ACTION DESCRIPTION	PROCEDURAL ASPECTS	RESULTS
1	Statistical analysis of extreme rainfall events.	Fit suitable extreme value distributions to the available time series of annual precipitation maxima for different rainfall durations. Assign to each obtained DDF curve, which is identified by the value triple (RI_j, a_j, n_j), where a_j and n_j are the parameters of the j^{th} DDF curve, the associated probability density. The probability density for the j^{th} DDF curve, is equal to $p_j = (\overline{p}_{j+1} - \overline{p}_{j-1})/2, 1 < j < M$, and $p_M = (1 - \overline{p}_M) + (\overline{p}_M - \overline{p}_{M-1})/2$ and $p_{F1} = (\overline{p}_1) + (\overline{p}_2 - \overline{p}_1)/2$, where $\overline{p}_{j+1}$ and $\overline{p}_{j-1}$ are the non-exceedance probabilities associated to the recurrence intervals RI_{j+1} and RI_{j-1}.	Depth-Duration-Frequency curves and their associated parameters corresponding to different recurrence intervals (RI). We obtain $j = 1,..., M$ tupels, (RI_j, p_j, a_j, n_j) describing the rainfall input in terms of duration-dependent magnitude and frequency.
2	Analysis of distributed catchment hydrology	Run a model for distributed catchment hydrology with the $j = 1,..., M$ tuples, derived in step 1 of the procedure, describing the rainfall input and with distributed information about the hydrologic characteristics of the catchment (i.e. land use, geology, vegetation over etc.)	For each tuple –(RI_j, p_j, a_j, n_j)- the hydrologic response in terms of runoff is obtained. Formally we derive $\left[RI_j, p_j, a_j, n_j, Q_j^W(\vec{x}, t)\right]$ where $Q_j^W(\vec{x}, t)$ identifies a water discharge hydrograph at any desired location ($\vec{x}$) along the stream network.

Tab. 2 Main process analysis steps in the loading system-LS.

Procedure for the assessment of flood hazard scenarios within the loading system - LS			
STEP	ACTION DESCRITPION	PROCEDURAL ASPECTS	RESULTS
1	Segmentation of the stream network into channel reaches in order to establish the simplified homogeneous stream system HSS.	Apply a geomorphological approach based on a combination of valley morphology, basin geology, channel confinement, hillslope processes, anthropogenic impact and intervention.	A simplified system of homogeneous stream elements, as a basis for process routing within the LS, is obtained, Formally $i = 1,..., N$ abstracted stream elements – ASE_i - are identified and described.
2	Specification of the flood hydrographs at any segmentation node of the simplified homogeneous stream system HSS for all given recurrence intervals.	Spatial Analysis of the results of distributed Hydrological Modelling (compare Table2). Specification of $Q_j^W(\vec{x}, t), \ \forall i \forall j$.	Recalling the results of distributed hydrological modelling, given as $\left[RI_j, p_j, a_j, n_j, Q_j^W(\vec{x}, t)\right]$, $\forall j$, we obtain: $S_{i,j}^H = \left[RI_j, p_j, a_j, n_j, Q_j^W(\vec{x}_i, t)\right]$, $\forall i \forall j$, where: $S_{i,j}^H$ indicates a determined hydrological scenario (i.e. flood hydrograph) with reference to the i^{th} node of the HSS, $\vec{x}_i$, and corresponding to RI_j.

3	Determination of the geomorphological channel reach variables (e.g. mean channel slope, mean channel width, mean floodway width, descriptors of initial and boundary condition, identification of adjustment descriptors).	For a complete overview of the procedural aspects compare Mazzorana et al. (2011b) for details. 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 with the mathematical-physical problem setting.	Sets of initial condition – IC -, and, upstream and downstream condition (US & DS) variables are identified. An additional set of variables, called set of ad adjustment descriptors - AD -, capturing the system dynamics, is defined. Formally we consider the following set of geomorphological channel reach variables $V_r = IC \cup US \cup DS \cup AD$. For each $v_r \in V_r$, $z_r = 1,...,Z_r$, levels of intensity are defined. We identify a generic level of intensity of a variable v_r as $v_r^{z_r}$. (Compare also Mazzorana and Fuchs, 2010, for details).
4	Determination of consistent flood scenarios at the defined nodes. Identification of the type of flow (e.g. debris flows, debris floods, fluvial sediment transport, liquid discharge); estimation of sediment and wood transport rates, identification of channel adjustments (i.e. erosion and aggradation phenomena) This action summarizes a series of detailed analytic steps discussed in Mazzorana et al. (2011b)	Application of Formative Scenario Analysis –FSA- and expert-based judgement. Step by step instructions for the application of FSA in relation to process routing problems are given, for example, in Mazzorana and Fuchs (2010). The main analytic tool is *ad hoc* constructed consistency matrix, containing expert-based consistency ratings among intensity levels of all pairs of channel reach variables. This consistency matrix supports the analyst in inferring the possible adjustments and the resulting flow type for each abstracted stream element after specifying correctly boundary and initial conditions.	Each ASE_i is now characterized by a specific set of possible process evolutions. Figure 1 shows an exemplified spectrum of possible process evolutions consistent with the underlying hydrological event for a limited number of ASE_i . As the reader may note, the application of the FSA procedure might lead to more than one consistent process scenario along one stream segment given specified initial and boundary conditions. Formally, for each hydrologic scenario chain, specified as $C_j^H = S_{(\forall 1),j}^H = \left(S_{1,j}^H,...,S_{N,j}^H\right)$, we obtain a process routing scenario tree, Γ_j^{PR} , built of a set of $q_j = 1,...,Q_j$, process routing scenario trajectories, $T_{q_j,j}^{PR}$. Within one such a trajectory, the process routing results, valid for ASE_i are logically connected to those of ASE_{i-1} (compare again Figure 1).
5	Probabilizing flood hazard scenarios in the loading system –LS.	The theory of rational decision making (compare, for example, Eisenführ et al. 2010) and its practical application to flood hazard assessment (Mazzorana et al. *in press*) suggest ways to design subjective probability measurement devices to “gauge” the experts preconceived likelihoods about specific scenario trajectories given defined sets of initial and boundary conditions.	Substantially, for each process routing scenario tree, Γ_j^{PR} , a probabilistic structure, as exemplified in Figure 1 is obtained. Put another way, each evolution scenario trajectory, $T_{q_j,j}^{PR}$, is fully probabilized. The overall probability of a evolution scenario trajectory, $\overline{P}_{q_j,j}^{PR}$, is $\overline{P}_{q_j,j}^{PR} = p_j \cdot \prod_{i=1}^{i=N} p\left[T_{q_j}^{PR} \middle\vert \left(ASE_i \leftrightarrow ASE_{i-1}\right)\right]$ where $p\left[T_{q_j}^{PR} \middle\vert \left(ASE_i \leftrightarrow ASE_{i-1}\right)\right]$ is the subjective probability assigned to a process unfolding in ASE_i given a specified unfolding in ASE_{i-1} .

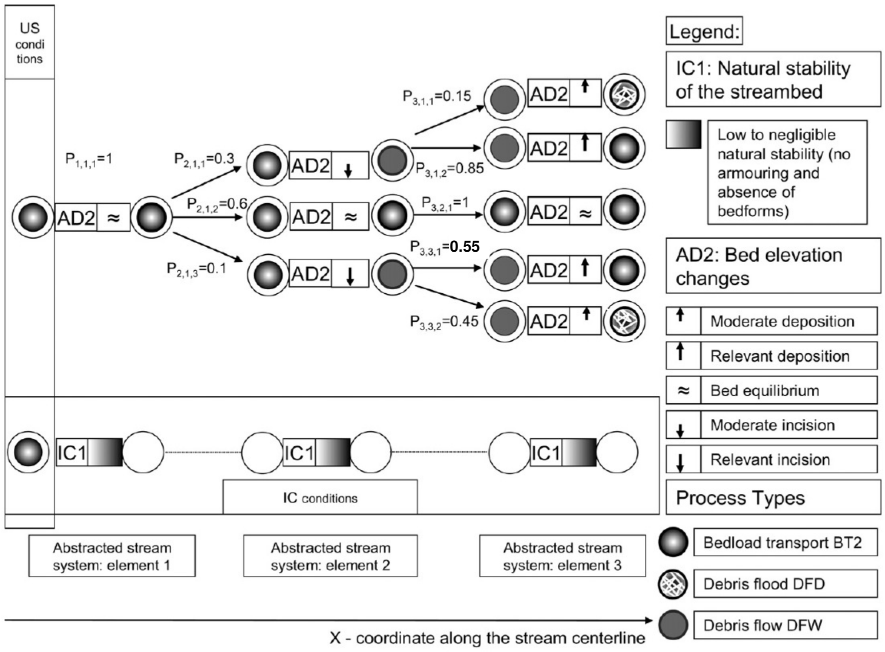

Fig. 1 Fully probabilized process routing scenario tree.

Once probabilized all single process scenario trajectories in the LS, the boundary conditions for the analysis in the RS are specified as input events in terms of liquid and solid discharges (i.e. water, sediment and wood). We use the following notation to identify a specific input event:

$$I^{PR}_{q_j,j}(\vec{x}_N,t) = \left[\overline{P}^{PR}_{q_j,j}; Q^W_j(\vec{x}_N,t); Q^S_{q_j,j}(\vec{x}_N,t); Q^{LW}_{q_j,j}(\vec{x}_N,t)\right]$$

where:

$I^{PR}_{q_j,j}(\vec{x}_N,t)$ is the input event characterized by the water, sediment and wood fluxes symbolized by $Q^W_j(\vec{x}_N,t); Q^S_{q_j,j}(\vec{x}_N,t); Q^{LW}_{q_j,j}(\vec{x}_N,t)$ respectively, entering the RS at node N with probability $\overline{P}^{PR}_{q_j,j}$ Throughout, for the input event, $I^{PR}_{q_j,j}(\vec{x}_N,t)$**,** we will use, fore simplicity only the notation $I_{q_i,j}$**.**

Tab. 3 Main process analysis steps in the response system –RS.

ANALYTIC STEPS TO DEDUCE THE INUNDATION PATTERNS IN THE RS			
STEP	ACTION DESCRITPION	PROCEDURAL ASPECTS	RESULTS
1	Delineation of the RS domains (areas adjacent to channels subject to inundation / erosion) and exact identification of the vulnerable RS domains, containing the relevant assets at risk.	Analysis of the valley (fan) morphology, channel confinement, valley (fan) substrate. Analysis of present and use maps, exploratory investigation to anticipate future land demands and land use change. Retrieval of documentation of past floods events, scrutiny to corroborate the delineation of the vulnerable RS domains, Ω^{RS} .	Datasets (i.e. digital terrain model landuse, values at risk, input and validation data for hydrodynamic flood modelling) clipped according to the perimeter of the RS domains.

2	Identification of the relevant stochastic nodes (or domains) within the vulnerable RSs.	Identification of bridges, culverts, unreliable hydraulic structures (e.g. old levees and check dams) interacting with the flow and possibly causing severe consequences in terms of risk. The analysis entails the scrutiny of past events and the collection of site specific expert knowledge.	Spatially identified stochastic nodes (or domains) – SN_k - $k = 1,...,K$ within the Ω^{RS}. Construction of the abstracted response system, ARS, corresponding to an area partition of Ω^{RS} in SN_k and the surrounding quasi-deterministic domain DD (for a complete treatment of the method and its logical aspects, compare Mazzorana et. al. 2011b)
3	Determination of the possible states for each stochastic node (e.g. states, clogged and unclogged, in case of bridge) and estimation of "process-intensity-contingent" state-transition probabilities	Analysis based on the type and dimension of each SN_k. Hypothesize possible ranges of loading conditions in terms of flood intensities and define parsimoniously a limited number of relevant states, $\sigma_{h_1},...,\sigma_{H_k}$, for each stochastic node SN_k. Expert-based judgement is central for the estimation of state- transition probability, $p(\sigma_{h_i} \| (\sigma_{h_j} \wedge I_l))$, representing the probability of a transition from σ_{h_j} to σ_{h_i} a process intensity level I_l.	For each SN_k a matrix of "process-intensity-contingent" state- transition probabilities, A_{SN_k}, is constructed, containing al possible state-transition probabilities, $p(\sigma_{h_i} \| (\sigma_{h_j} \wedge I_l)) \forall h_i, h_j \wedge \forall$ Examples of such state-transition probability matrices can found in Mazzorana et al. (2011b).
4	Determination through hydrodynamic simulations of the stochastic "space-time" evolution of flood inundation, corresponding to each single input event (compare also Table 2).	"Interfacing" the results of the hydrodynamic simulations (intensity maps corresponding to different time steps) with the matrices of state-transition probabilities, is the first essential step. Marching forward in time, different stochastic nodes may exhibit one or more possible state transitions, $\sigma_{h_j} \rightarrow \sigma_{h_i}$, with well defined state-transition probabilities according to the local intensity of the process - I_l. For each concerned stochastic node - SN_k an updating from the old to new states follows, determining distinct constellation of states (with defined probabilities). The construction of $E_{RS} \| I_{q_j,j}$ proceeds by running different simulations, each one corresponding to a specific constellation, staring from the state- transition time step.	For each input event $I_{q_j,j}$ we obtain a stochastic "space-time" evolution scheme of flood inundation, $E_{RS} \| I_{q_j,j}$, i.e. a graph specifying through time the probabilistic structure of the constellation changes in the RS. Each constellation change carries along different flood intensity maps. What results is a complete representation both in a space and time of the flood hazard in the RS.
4*	Simplified version of step 4 for practical purposes. Determination through hydrodynamic simulations of the reduced and approximated stochastic structure of flood inundation, corresponding to each single input event.	Unlike in step 4, we introduce an *ex ante* assumption by fixing the relevant states (which can be more than one) for the entire event duration for each SN_k reducing significantly the computational complexity. A reduced number of possible system constellations results, each one of which with a defined probability. Expert-based judgement is essential to adjust the level of simplification according to the scope of the study (e.g. conventional hazard mapping)	For each input event $I_{q_j,j}$ we obtain a simplified stochastic structure of flood inundation $\overline{E}_{RS} \| I_{q_j,j}$.

In the following section we present and discuss selected results of a dedicated case study conducted on the Mareiterbach, South Tyrol, Italy. The study was supported by the EU- co-financed project IREK, an international project with Italian and Austrian project-partners. The full set of elaborations based on the methods outlined in Tables 1, 2 and 3 can found in Scherer et al. (2011).

APPLIED SCENARIO-BASED HAZARD ANALYSIS

Functional to the application of scenario-based hazard analysis was a general assessment of the salient climatological, geological, and geomorphological and land-use related characteristics, which are omitted without loosing anything essential, of the catchment of the Mareiterbach, (90 km² with reference to the village Mareit, the relevant area at rise perspective).

The ca. 10,5 km long stream reach upstream of Mareit was interested by frequent and destructive debris flood and fluvial sediment transport events (i.e. causing relevant channel adjustments, erosions/ aggradations), which in the river-corridor area at risk perspective resulted in major disruptions (channel outburst, flooding, local aggradations and incisions on the floodplain) including relevant economic losses. As a consequence, a series of consolidation check dams, a (now partially replenished) sediment retention basin right upstream of Mareit, and a water retention basin in the upper chatchment were built.

A dedicated analysis of the reliability of the single elements of the existing protection system (Scherer et al.2011) evidenced (i) that the consolidation check dams are expected to function properly in case of extreme events, except a limited number of them, located along a steep stream segment with hillslopes prone to landslides, and (ii) that the water retention basin is only of minor importance for the overall hazard mitigation effect with respect to the area at risk perspective.

Hence, the important aims of the scenario based hazard analysis were, first, to conduct a process routing in the loading system -LS- to highlight the possible effects of debris flood and fluvial sediment transport process in the current situation (i.e. with the above outlined protection system performance) and, second, to represent the flood inundation patterns in the RS, necessary for the delineation of hazard zone maps and for subsequent risk analysis (compare Figure 2 for a system representation).

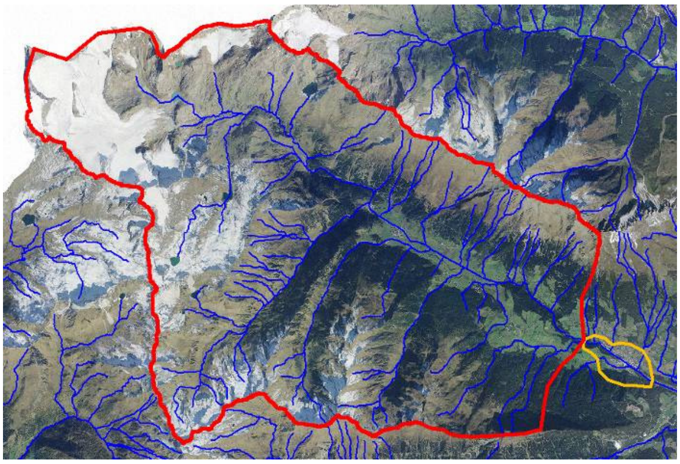

Fig. 2 System representation with loading system, LS, - (red-contoured) - and with response system, RS, - (orange-contoured)

Skipping for brevity the presentation of the standard hydrological analysis (compare Table 1 for methodological overview and Scherer et al., 2011 for details) we prefer to put emphasis on the application of the concepts presented in Tables 2 and 3.

Following step 1 of the procedure for the assessment of flood hazard within the loading system –LS- we segmented the stream system into abstracted stream elements - , whose connectivity determines the HSS (compare Figure 3).

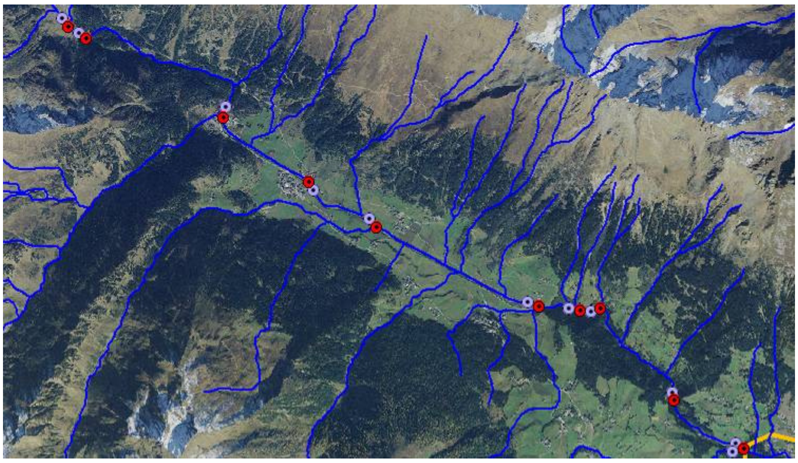

Fig. 3 Homogeneous Stream System, HSS, and Abstracted Stream Elements, ASE_i , delimited by purple (upstream) and red (downstream) nodes.

Performing stepwise the remaining actions of Table 2, we obtained for the identified HSS:
(i) a specification of the flood hydrographs at any segmentation node, (ii) the determination of the channel reach variables and (iii) the subsequent deduction of a consistent process routing scenario trees with (iv) the associated assignment of subjective probabilities to each process routing scenario trajectory for the underlying hydrological events of recurrence interval $-RI$ of 30, 100 and 300 years, respectively.

In Figure 4 we show the process routing scenario tree corresponding to a hydrological event of $RI = 100$ years. For each ASE_i within the HSS, the process routing scenario tree evidences, for specified initial conditions (for example streambed stabilization) and given upstream boundary conditions (flow type-compare legend in Figure 4), the possible system evolution captured by defined adjustment descriptors –AD- (for example bed elevation change). The reader is referred for a full list of system variables, their levels and for the application of Formative Scenario Analysis to Mazzorana el al. (in press).

Table 4 gives a succinct description of the most relevant process routing scenario trajectory (worst case) out of all trajectories spanning the process routing scenario tree (i.e., the corresponding trajectory is highlighted by the dashed line in Figure 4).

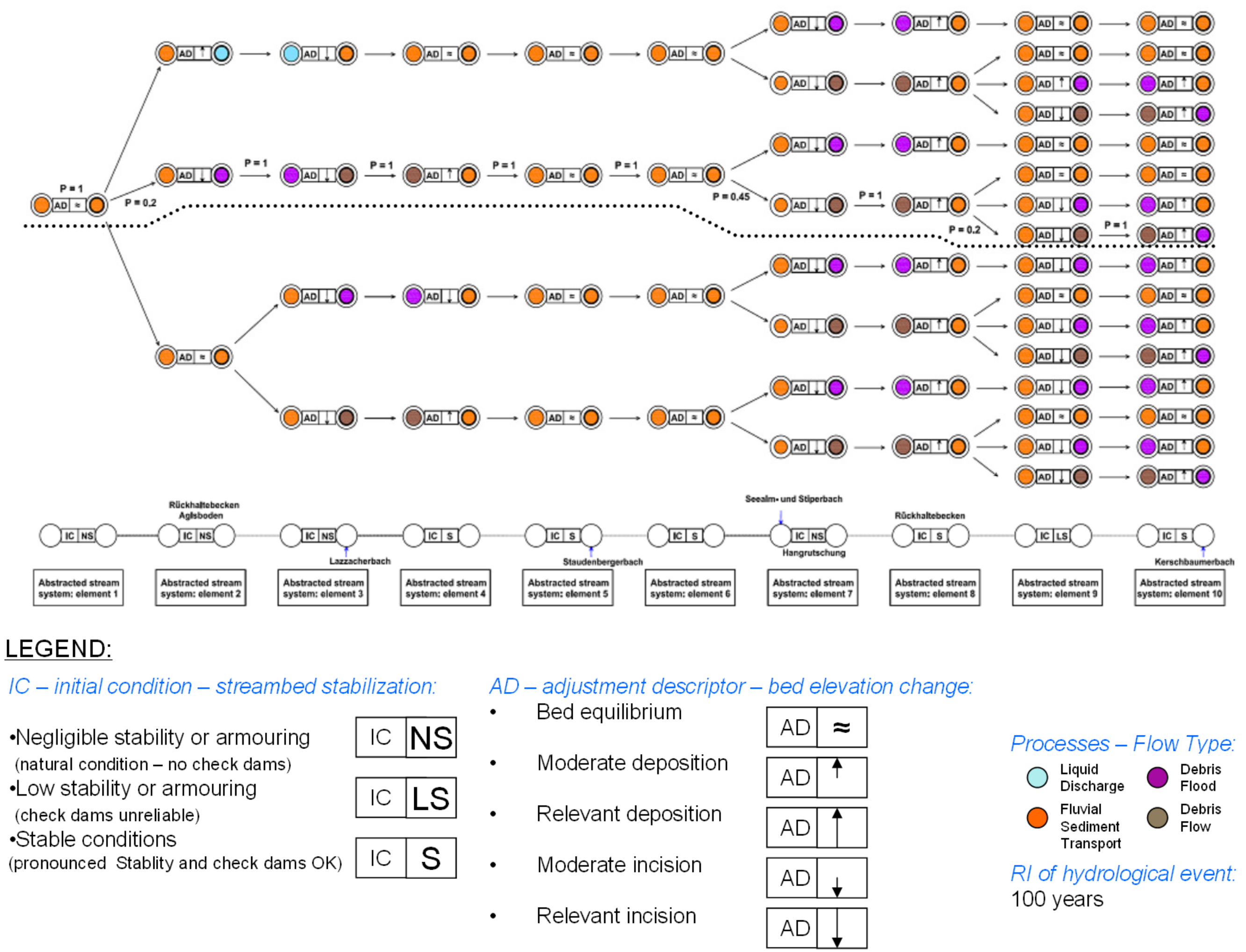

Fig. 4 Probabilized process routing scenario tree in the loading system –LS with the single process routing scenario trajectories.

Tab. 4 Most relevant process routing scenario trajectory (worst case) out of all trajectories spanning the process routing scenario tree.

Evolution path i,j,k with Probability $P_{i,j,k}$	DESCRIPTION
$P_{1,1,1}$=1	The input flow type from upstream is bedload transport, which intensifies throughout this stream segment due to solid material inputs from side erosion.
$P_{2,1,2}$=0.2	Only a part of the solid volumes is retained in the retention basin. Moreover localized erosion immediately downstream of the retention basin triggers a change in flow type resulting in a debris flood.
$P_{3,2,1}$=1	The debris flood evolves towards a intense debris flow due streambed incision over the whole length of this steep segment. Debris flow inputs from a tributary are possible
$P_{4,2,1}$=1	In this segment large parts of the solid materials transported from upstream are deposited resulting in aggradation of the stream and a local bridge clogging. A flow type towards bedload transport is the consequence.
$P_{5,2,1}$=1	In this stream segment a substantial equilibrium between erosion and aggradation is to be expected and therefore no flow type change takes place.
$P_{6,2,1}$=1	Due to the mild slopes of this stream segment, the equilibrium is altered. The result is a net deposition. Although "unsaturated" bedload transport continues at low rates.
$P_{7,2,1}$=0.45	This preponderantly natural stream segment is particularly steep and a series of tributaries may deliver solid inputs to the main stream due to debris flow activity. These circumstances corroborate the argument of a flow type change inducing a debris flood as a result.
$P_{8,4,1}$=1	Deposition processes in the retention basin cause a rapid flow type transition towards bedload transport.
$P_{9,4,3}$=0.2	Lateral erosion and intense channel incision cause a flow type transition. Initially a debris flood evolves, but, approaching the downstream boundary the conditions for a further evolution into a debris flow are given.
$P_{10,8,1}$=1	Within this stream segment pronounced depositions are only partially balanced by local side erosion. A transition towards a debris flood results.

The subsequent analytic steps to deduce the inundation patterns in the RS (compare Table 3) entailed the delimitation of the vulnerable RS (i.e. the locality of Mareit and its surroundings) and, within it, the identification of the stochastic nodes (2 bridges and 2 key locations along the levees, compare Figure 5 for an overview).

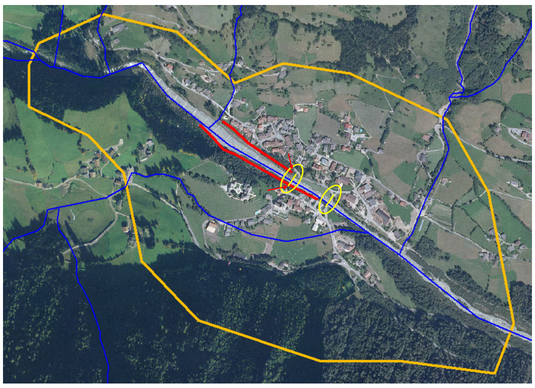

Fig. 5 Response system with the identified stochastic nodes: two bridges (yellow) and two key locations (red arrows) along the levees (red).

For this set of stochastic nodes the corresponding matrices of "process-intensity-contingent" state-transition probabilities were defined. For inferring the probability of clogging of the two bridges crossing the Mareiterbach within the RS, an existing matrix proposed by Mazzorana et al.(2011b) was adopted, whereas for the levee failure problem we developed a simplified matrix, based on the results in terms of fragility curves, obtained by Vorogushyn et al. (2009).
With respect to the most relevant process routing scenario trajectory (compare Figure 4) and the associated debris flood input event, judged compatible with the underlying hydrologic event

(RI=100years), 1D hydrodynamic simulations were conducted in the RS to assess the possible system responses at the stochastic nodes, which are summarized in Table 5.

Tab. 5 Matrix of possible system states in the RS with associated probabilities for the specified input event.

Bridge clogging	Levee failure			
	(rl, f; ll, f)	(rl, nf; ll, f)	(rl, f; ll, nf)	(rl, nf) (ll, nf)
(b1,c; b2,c)	0,0649	0,1113	0,0928	0,1160
(b1,u; b2,c)	0,0317	0,0544	0,0453	0,0566
(b1,c; b2,u)	0,0398	0,0683	0,0569	0,0711
(b1,u; b2,u)	0,0317	0,0544	0,0453	0,0566

Objects:	Objects:
rl: right levee	b1: first bridge
ll: left levee	b2: second bridge
States:	States:
f: failure	c: clogged
nf: no failure	u: unclogged

The results of Table 5 highlight, that in the specific case, the most probable system configuration (red cell in Table 5) is given by a clogging of both bridges, whereas the levees resist. This configuration is closely followed in terms of probability by a system configuration featuring in addition to the bridge clogging also a failure of the left levee (orange cell in Table 5). One may recognize, that a system configuration entailing no unfavourable states is, in the given case, relatively unlikely if compared to the most configurations characterized by at least one unfavourable state. Instead of the rigorous, but computationally demanding, fourth analytic step of Table 3, we identified the flood hazard inundation patterns following the simplified procedure (compare step 4*, Table 3). Therefore, the obtained results don't mirror the full stochastic "space-time" evolution scheme of flood inundation, but reflect a reduced and approximated stochastic structure of flood hazard. The approximated structure is obtained by modelling flood hazard propagation separately for each specified system configuration and each corresponding inundation map is "weighted" according to the probability of the underlying configuration (compare Table 5). Repeating for the response system analysis the same procedure for all input events resulting from the detailed loading system analysis, the preliminary hazard map shown in Figure 6 could be drawn.

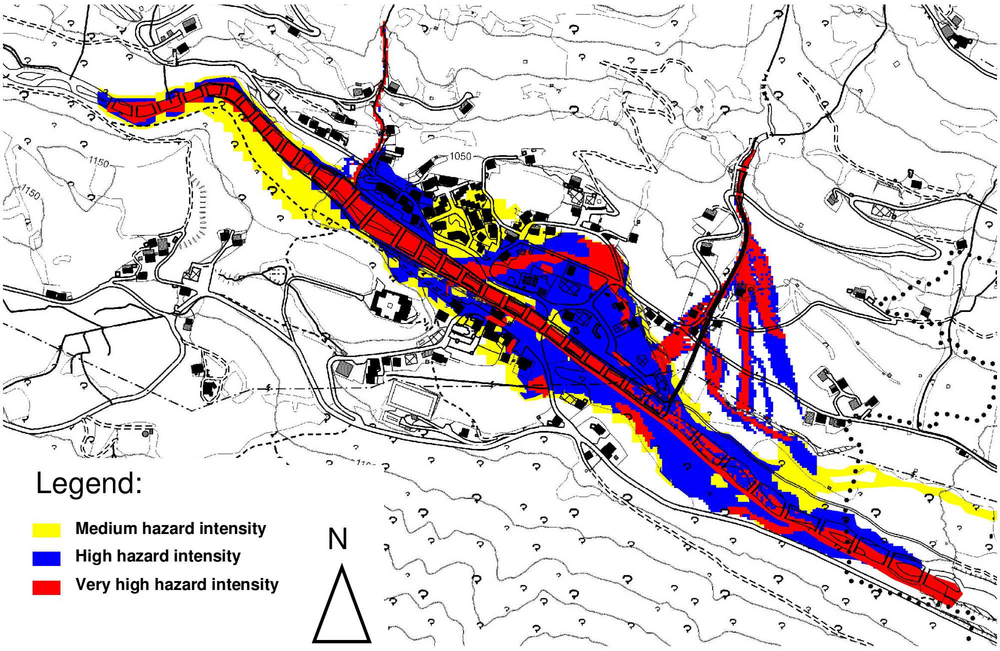

Fig. 6 Preliminary hazard map resulting from a scenario-based hazard analysis.

In comparison to flood hazard representations obtained by conventional analysis, these results highlight a more pronounced variability of the range of possible hazard inundation patterns, due to the richness of the underlying set of system scenarios.

CONCLUSIONS

From the perspective of integrated river management, the spatially explicit representation of flood dynamics and steam evolutions along with their associated spatial probabilities brings about a series of advantages which complement more traditional approaches to flood hazard analysis.

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

Moreover, despite its apparent procedural complexity, the advantages of such a scenario-based hazard analysis are multi-fold especially where the values at risk are relevant.

First, the evaluation of how inundated areas could change depending on bridge clogging or levee failure allows for estimates of economical net benefits of hazard mitigation measures (e.g. structures to trap wood, modification of bridge type and geometry) and, thus, supports cost-benefit analysis of such interventions.

Secondly, the identification of the most critical sites can inform the Civil Protection agencies on where and how it would be more efficient to concentrate efforts during a flood event. Finally, the need to take into account different flood scenarios in flood risk mapping is set by the EU Floods Directive (2007), and the methodology presented could be functional, after further tests and developments, to meet such requirements for the European countries.

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