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ORIGINAL PAPER

A structured approach to enhance flood hazard assessment in mountain streams

B. Mazzorana · F. Comiti · S. Fuchs

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Abstract An evidence-based flood hazard analysis in mountain streams requires the identification and the quantitative characterisation of multiple possible processes. These processes result from specific triggering mechanisms on the hillslopes (i.e. landslides, debris flows), in-channel morphodynamic processes associated with sudden bed changes and stochastic processes taking place at critical stream configurations (e.g. occlusion of bridges, failure of levees). From a hazard assessment perspective, such possible processes are related to considerable uncertainties underlying the hydrological cause-effect chains. Overcoming these uncertainties still remains a major challenge in hazard and risk assessment and represents a necessary condition for a reliable spatial representation of process intensities and the associated probabilities. As a result of an accurate analysis of the conceptual flaws present in the procedures currently employed for hazard mapping in South Tyrol (Italy) and Carinthia (Austria), we propose a structured approach as a means to enhance the integration of hillslope, morphodynamic and stochastic processes into conventional flood hazard prediction for mountain basins. To this aim, a functional distinction is introduced between prevailing one-dimensional and two-dimensional process propagation domains, i.e., between confined and semi- to unconfined stream segments. The former domains are mostly responsible for the generation of water, sediment and wood fluxes, and the latter are where flooding of inactive channel areas (i.e. alluvial fans, floodplains) can occur. For the 1D process propagation domain, we discuss how to carry out a process

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B. Mazzorana (✉)
Department of Hydraulic Engineering, Autonomous Province of Bolzano South Tyrol, Bolzano, Italy
e-mail: bruno.mazzorana@provinz.bz.it

B. Mazzorana · F. Comiti
Faculty of Science and Technology, Free University of Bolzano, Bolzano, Italy

S. Fuchs
Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences, Vienna, Austria

S. Fuchs
Research Laboratory of Snow Avalanches and Debris Flows, Faculty of Geography, Lomonosov Moscow State University, Moscow, Russian Federation

routing along the stream system and how to integrate numerical models output with expert judgement in order to derive consistent event scenarios, thus providing a consistent quantification of the input variables needed for the associated 2D domains. Within these latter domains, two main types of spatial sub-domains can be identified based on the predictability of their dynamics, i.e., stochastic and quasi-deterministic. Advantages and limitations offered by this methodology are finally discussed with respect to hazard and risk assessment in mountain basins.

Keywords Natural hazards · Hazard mapping · River basin management · Mountain basins · Formative scenario analysis

1 Introduction

In recent years, at a European level increasing losses associated with natural hazards such as water floods and debris flows have demonstrated the paramount importance of management issues in order to minimise the impact of such processes on the anthroposphere (Barredo 2007). There is some scientific evidence of an increase in mean annual precipitation and extreme precipitation events, which implies that extreme flood events in general might become more frequent (Christensen and Christensen 2003; Kundzewicz et al. 2005). In parallel, exposure and vulnerability to floods have increased across Europe due to urbanisation in flood-prone areas, such that even without taking climate change into account flood-related damages are expected to increase in Europe in the future (Mitchell 2003).

These circumstances have led the EU Commission to issue the ‘Directive on the Assessment and Management of Flood Risks’ (Floods Directive, 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 the Floods Directive, flood events—defined in its broadest sense including sediment transporting flows and debris flows, and including events from the lowlands to steep mountain streams—are acknowledged to be natural phenomena which cannot be prevented. Instead, the consequences (i.e. the flood risk) have to be mitigated through an efficient and effective combination of mitigation measures (e.g. Fuchs and McAlpin 2005; Fuchs et al. 2007; Holub and Fuchs 2009). In order to have an effective tool for 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 (Commission of the European Communities 2007).

The analysis of the most recent flood events in European mountain regions (Keiler et al. 2010) highlighted considerable shortcomings in the current procedures used in 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 necessarily reliable for the prediction of process patterns since internal system dynamics, such as changing solids concentration along the flow path, are not sufficiently represented (Mazzorana et al. 2011). In particular, the effects of temporally changing channel morphology 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 scenarios and hazard assessments need to be re-established based on such issues.

Therefore, the temporal and spatial variations of process characteristics—often as a consequence of the coupling between hillslope and channel processes and their interdependencies (Kienholz et al. 1998)—need to be assessed and included in modelling approaches, namely the type of flow (e.g. debris flow, debris flood, water flood with bedload transport) occurring along the channel network; the location and magnitude of channel adjustments (e.g. bed and bank erosion, bed aggradation/incision); the volume of sediment transported; and the spatial pattern of inundation. Such assessments bring about different sources of uncertainty affecting the predictability of hazard patterns (e.g. Paté-Cornell 1996), i.e., those due to an intrinsic variability (aleatory uncertainties), and those stemming from a lack of knowledge (epistemic uncertainties; e.g., Hoffman and Hammonds 1994; Paté-Cornell 1996). By including these uncertainty issues in decision-making for natural hazard management, the nature of decision to be made will be changed. The way by which uncertainty will affect the decision, however, may depend on the context of a decision (Blazkova and Beven 2009).

Within the EU project 'Adapt-ALP' (Work Package 5—Hazard Mapping, see http://www.adaptalp.org), a categorisation of the relevant sources of uncertainty in flood hazard assessment has been carried out. With respect to uncertainties in natural hazard management, the determination of hazard scenarios for mountain streams has to include (Mazzorana et al. 2009):

1. uncertainties about the main variables describing the flow, i.e., peak discharge as well as flood hydrograph shape and duration, sediment transport rate, volume and concentration (and thus type of flow), rate of driftwood transport. Overall, this set of variables will be referred to as the loading system variables.
2. uncertainties in the spatial pattern of hazard propagation due to obstructions at critical cross-sections, small-scale topography, and abrupt morphological changes during a flood event. These uncertainties determine the 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.

In order to address the uncertainties outlined above, the explicit use of flood event scenarios is much beneficial because it provides a clear, rationale method to recognise the inherent stochastic behaviour of natural processes. First, we consider scenarios describing the possible 'loading' conditions (in terms of water, sediment and wood material) built up in the basin by means of a process routing throughout prevailing one-dimensional process propagation domains (1D domain, hereafter 1DD). Secondly, we address scenarios arising from events taking place along stream segments potentially prone to flood adjacent areas thus with prevailing two-dimensional flow characteristics during flood events (2D process propagation domains, or 2DD). Therefore, 1DD scenarios are built for the entire drainage network but are most relevant for the valley-confined reaches (i.e. where floodplain surfaces are virtually absent and hillslope-channel processes are tightly coupled), whereas 2DD scenarios are established only for those segments where relevant inundation can occur as in semi- to unconfined reaches (i.e. where valley floor is substantially larger than the channel, as in presence of alluvial fans and floodplains). Figure 1 represents a sketch of a small mountain basin where both 1DD and 2DD are present.

It is important to remark that the distinction between these two domains is not based on the presence of objects exposed to potential damage but solely on a geomorphological analysis of the stream system, i.e., it is a hazard-based instead of a risk-based approach. In fact, we are convinced that in order to reliably define flood risks for a given area, flood hazards must be predicted first. Indeed, vulnerable objects are mostly located within 2D

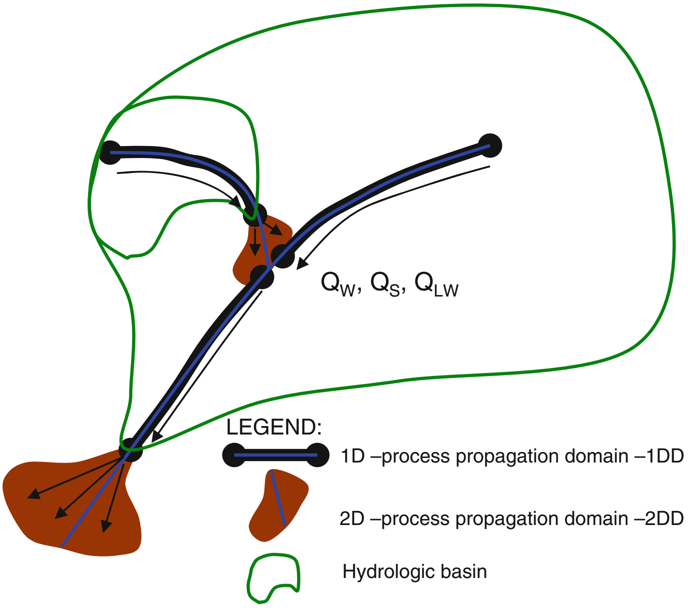

Fig. 1 Sketch representing a hydrologic basin where channels are mostly confined by hillslopes and the direction of flows (*QW* water discharge, *QS* sediment discharge, *QLW* driftwood discharge) is mostly unambiguous (1D process propagation domain *1DD*); including an alluvial/debris fan (2D process propagation domain *2DD*) where the channel is unconfined and therefore flows present more possible directions during flood events. A similar system (i.e. the sub-basin with a small fan) is nested within the main system

process propagation domains—the larger towns in mountain areas worldwide lie on fans and on floodplains—nonetheless they may be present and interact with flood flows within 1DD as well, as in the case of bridges, roads and buildings lying at low elevation with respect to channels. Even though domain types are identified irrespective of the level of potential damage, the detail at which flood scenario modelling is carrying out both in 1D and 2D domains can be adjusted depending on the value of the vulnerable objects exposed, thus increasing the effort in reaches featuring higher risk potential.

With reference to the 1D process propagation domains, in this paper, we propose a process routing along the stream system and discuss how to integrate numerical models output with expert judgement in order to derive consistent event scenarios, thus providing a consistent quantification of the input variables needed for the associated 2D domains (Scholz and Tietje 2002; Zischg et al. 2005; Mazzorana and Fuchs 2010).

As to 2D domains, we briefly summarise an approach recently developed (Mazzorana et al. in press) to enhance the spatial delineation of flood hazard based on the identification within each 2DD of two types of spatial sub-domains according to the predictability of their dynamics, i.e., stochastic and quasi-deterministic. The integration of these two dynamics will allow predicting more consistently and reliably process characteristics along the channel network and thus process magnitudes in the inundated areas. Finally, advantages and limitations offered by the proposed integrated methodology are discussed, with a particular focus on hazard assessment in mountain streams and risk governance issues.

2 A spatial representation of the stream system in flood hazard assessment

With respect to the management of mountain hazards, a modelling framework is required that enables a rational knowledge integration in order to tackle the inherently complex environmental interactions (Refsgaard et al. 2007), particularly because 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. With reference to the concept of structural completeness of a decision-making problem (Klein and Scholl 2004), a sketch of the possible structural shortcomings in hazard assessment is shown in Fig. 2. Shortcomings in the delimitation of the system (i.e. the identification of the spatial domain of interest) are a first-order issue given the hierarchical order of structural caveats that affect hazard assessment. Adequate system delimitations and its associated representation are essential requirements for a scenario-based hazard assessment with distinct spatial reference. Consequently, as already mentioned in the previous section, we introduce two types of domains for scenario building, based on their prevailing flow geometry during flood events: (1) the one-dimensional process propagation domain (1DD) and (2) the two-dimensional process propagation domain (2DD; see Fig. 1). Following Mazzorana et al. (in press), the former could also be identified as loading systems (i.e. where flow, sediment and wood fluxes build up delivered from the basin and mostly propagate downstream along the channel network), and the latter as the response systems, whereby these fluxes can expand on alluvial fans and floodplains thus causing hydrogeomorphic responses (i.e. aggradation, inundation, bank erosion) which are likely to interact with vulnerable objects.

Hazard scenarios within the 1D domains aim to determine, for any given cross-section along the channel network and for the assigned return interval RI (e.g. 30, 100, 200, 300 year), the expected type of flow (i.e. debris flow, debris flood or bedload-water flows), the water discharge QW, the sediment transport rate QS, and wood transport rate QLW. Such values are the upstream boundary conditions for determining hazard scenarios within the 2D domains. Moreover, such scenarios allow to localise sediment and wood sources and to determine the most likely sites of morphological changes (e.g. bank erosion, bed incision) at multiple scales; thus allowing for an improved design of technical mitigation measures. An appropriate way to analyse channel networks in the 1D domains is to adopt a simplified stream system (e.g. Kienholz et al. 2010). Such a system consists of interconnected stream reaches which are homogeneous with respect of their gemorphological characteristics and therefore represent the fundamental units within a stream system (Fig. 3).

A stream reach is characterised by inflow and outflow variables at the reach boundaries, by initial conditions and by system variations during an event. The variations occurring at the stream reach scale derive from both longitudinal transport processes in the main channel and from transversal processes involving stream banks, floodplains and hillslopes. In analogy to the formulation of an initial-boundary value problem (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 reach (e.g. slope, bed structure, sediment availability) is required to properly deduce all possible system scenarios. The dominant process type (e.g. debris flow; debris flood; bedload transport) has to be specified at the inflow node as a boundary condition. In those mountain streams particularly susceptible to wood recruitment and subsequent transport (Rigon et al. 2008;

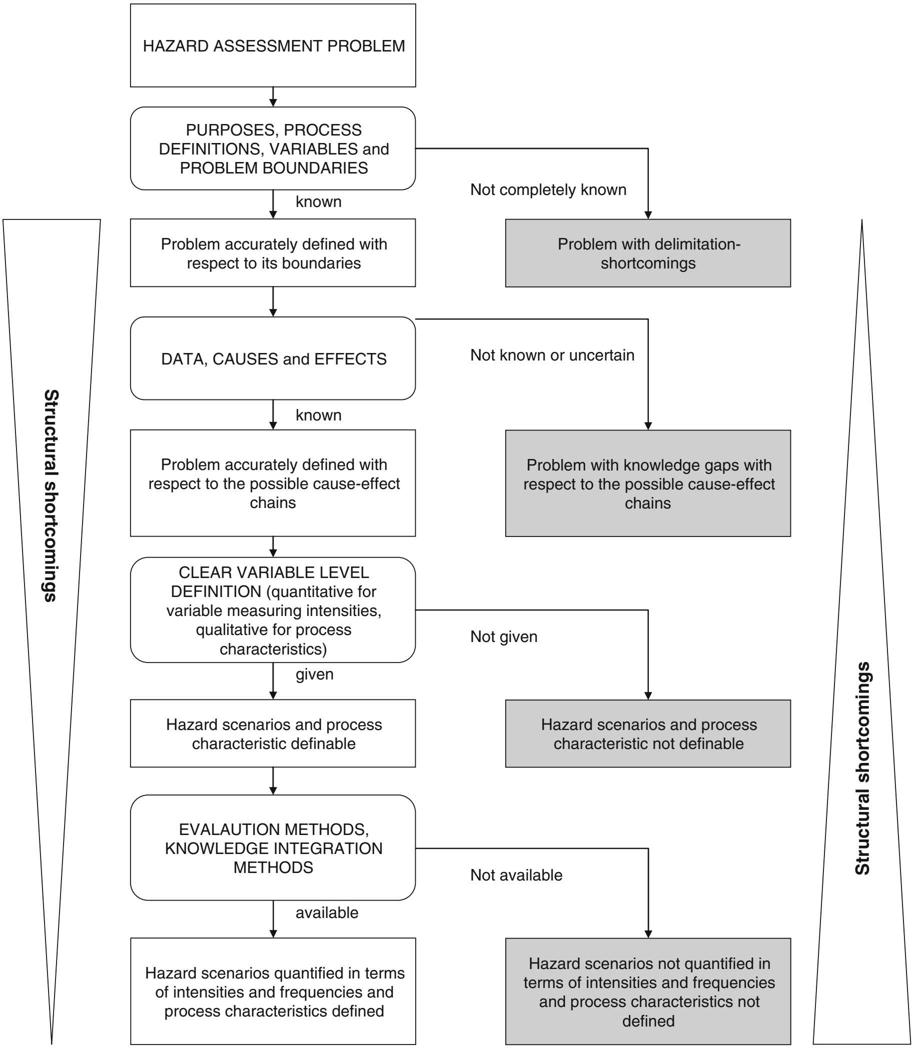

Fig. 2 Chain of possible structural shortcomings during the hazard assessment for a mountain stream (*right hand side* of the figure). The workflow on the *left hand side* of the figure indicates knowledge integration steps to obtain a progressive refinement of hazard assessment

Mazzorana et al. 2011), wood inflow rates at the boundary should also be specified. Although a retraceable process routing is the main result of hazard analysis within the 1DD, hazard intensities (i.e. flow velocities and flow depths) can be locally derived by 1D numerical simulations if areas at risk are present (e.g. roads, buildings, see Sect. 1).

Hazard scenarios within the 2DD aim to draw, starting from the 1DD output, reliable hazard maps on floodplains, alluvial and debris fans by means of a spatial analysis of the inundation patterns. It is worth noting that more than one 2D domain can be present in a basin, and the larger the basin, the more (and more extended) 2DD are likely to be identified. As already mentioned, two main types of spatial sub-domains, i.e., stochastic and quasi-deterministic, are to be identified in each 2DD (Fig. 4). The former represents

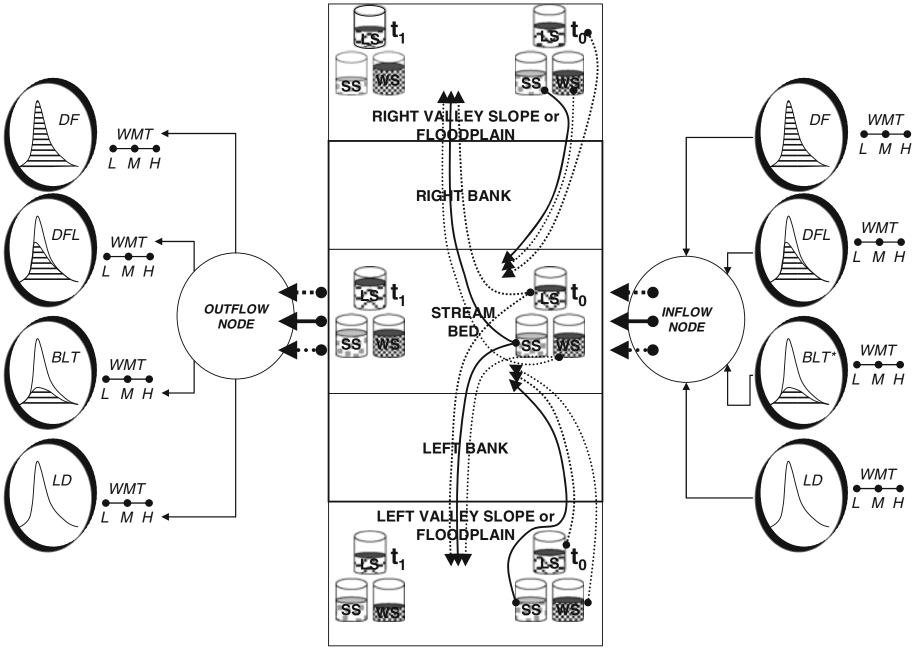

Fig. 3 A homogenous stream segment is expressed by an abstracted stream element representing the respective set of initial and boundary conditions, the induced system dynamics and occurring material fluxes within the stream element (*WS* wood storage, *SS* sediment storage, *LS* water storage). Upstream (inflow) and downstream (outflow) boundary nodes: *DF* debris flow, *DFL* debris flood, *BLT* bedload transport, *LD* liquid discharge, *WMT* wood material transport with low (*L*), middle (*M*) or high (*H*) intensity

stream sections/nodes, hereafter referred to as critical sections, whose dynamic evolution cannot be realistically specified by deterministic models (e.g. a bridge which may become clogged by floating wood, or any critical sections where avulsion is likely), whereas the latter refers to the part of the system where the flow propagation and the morphological dynamics can be computed with sufficient precision and accuracy by hydrodynamic models. For more details and for a case study, see Mazzorana et al. (in press).

3 A knowledge integration structure for flood hazard assessment

In accordance to the spatial system representation presented above, in this section, the procedures for conducting the process routing within the 1DD and for establishing the hazard propagation scenarios within the 2DD are presented. Both procedures consist of a series of distinct steps. For each step, specific analysis actions are specified and necessary data requirements and tools applicable are indicated.

With reference to Fig. 2, the objective is to progressively reduce through a rational and structured approach the structural shortcomings that occur during the hazard assessment for mountain streams. This is carried out by removing as far as possible the knowledge gaps about cause-effect chains characterising hazard processes in mountain streams, by refining the description of natural hazard process, by integrating knowledge derived from model scenarios as well as form expert judgement, by addressing hazard intensities and spatial

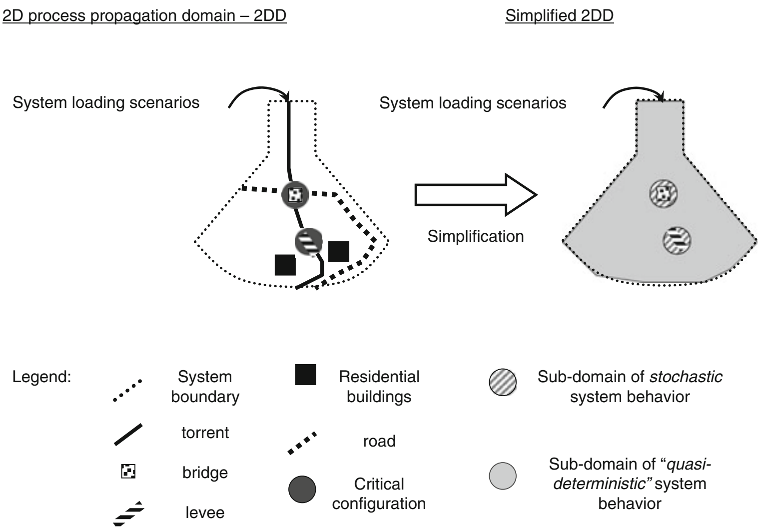

Fig. 4 Representation of the 2D process domain, 2DD, and its abstraction by means of identification of stochastic and deterministic sub-domains

probabilities both for 1DDs and for 2DDs and finally by adjusting the computational effort and accuracy according to available information and to the estimated complexity of system dynamics.

3.1 Procedure for assessing flood hazard scenarios within 1D process propagation domains (1DD)

Step 1:

Action: segmentation of the basin channel network into channel reaches in order to establish the simplified homogenous stream system

Spatial extent: entire drainage basin up to 1st order channels

How: based on a combination of valley morphology, basin geology, channel confinement (i.e. valley width/channel width), hillslope processes, landslide inventories, anthropogenic elements (dams, check-dams)

Data and tools: hillshade DTM, aerial photos, historical flood reports, geological/geomorphological maps, longitudinal stream profiles

Step 2:

Action: determination of geomorphological channel reach variables (compare Table 1). 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 (compare also Fig. 2).

Spatial extent: reach

How: GIS analysis, field measurements

Data and tools: DTM, field surveys

Table 1 Channel reach variables to be determined at step 2 for 1DD scenarios

Variable	Description and reason
Mean channel slope	Longitudinal bed slope of the reach, which informs about the dominant processes taking place during an event
Mean channel width	Average bankfull width, determining wood mobility, unit stream power index and channel confinement
Mean floodway width	Average width of flood corridor, determining channel confinement, wood/sediment recruitment and storage potential
Channel morphological patterns	Channel type (colluvial, alluvial, bedrock), bedforms (cascade, step-pool, plane-bed, pool-riffle, dune-ripple) and planimetric configuration, i.e., single channel (straight, alternate bars, sinuous, meandering) or multiple channels (i.e. braided, wandering)
Sediment grain size	Estimation of surface and subsurface grain size for hydraulic modelling and degree of armouring

Step 3:

Action: determination of flood hydrograph (for any given RI)

Spatial extent: drainage basin at each reach

How: hydrological modelling

Data and tools: DTM, land use maps, soil maps, rainfall and discharge data, distributed hydrological modelling

Step 4:

Action: determination of consistent flood scenarios at the analysed cross-section

Spatial extent: entire segmented channel network

How: application of Formative Scenario Analysis methods, expert-based judgment. Step by step instructions for the application of Formative Scenario Analysis to process routing problems are given in Annex 1. For a complete overview of the most recent advances see Mazzorana and Fuchs (2010).

Data and tools: list of variables for boundary and initial conditions, as well as for event-driven variations (compare Table 2) at the reach scale, consistency matrices, historical reports, morphological evidences. An excerpt of the consistency matrix, containing the consistency ratings assigned to each pair of impact levels of different impact variables, is provided in Table 3.

Step 5:

Action: Determination of sediment and wood input (for any given RI)

Spatial extent: reach and adjacent hillslopes

How: estimation of mass wasting volumes, bank erosion volumes, wood volumes. The latter can be estimated based on forested areas subject to fluvial erosion and landsliding multiplied by the estimated/measured forest stand volume in m^3 per unit of surface area (Rigon et al. 2008).

Table 2 Boundary/initial conditions and variations expected during the event to be analysed at step 4 for 1DD scenarios

Variable	Description
Reach boundary conditions	
Relevant inflow at the upstream boundary	Flow type and intensity of sediment transport processes (i.e. based on sediment concentration) and driftwood rates entering the reach
Relevant outflow at the downstream boundary	Flow type and intensity of sediment transport processes (i.e. based on sediment concentration) and driftwood rate leaving the reach
Reach initial conditions	
Natural stability of the streambed	Degree of armouring and presence of stable bedforms which are able to impart a relative stability to the bed
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 stable during high-magnitude events
Available retention volume for solid/wood material	Volumetric dimensions of natural (floodplains) or artificial (retention basins upstream of check-dams) areas functioning as sediment/wood traps during the event
Mean channel slope	Longitudinal bed slope of the reach, which informs about the dominant processes taking place during an event
Variation of unit Stream Power Index	Longitudinal changes (positive = increase compared with upstream reach; negative = decrease) of the unit stream power index (SPI = qS) drive to erosion/deposition processes
Channel confinement	The 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
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
Presence of structures potentially unstable (prone to failure)	Presence and size of transversal structures which are thought to be prone to failure during the event
Variations occurring during the event	
Flow process transition	Estimated changes in the intensity (up- and down-ward) of sediment transport process occurred within the reach, which drive important variations in the downstream propagation of the event as well as changes in reach geometry
Bed elevation changes	Estimated changes in mean bed elevation taking place as a consequence of erosion and deposition processes within the reach
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
Bed stability changes	Estimated variation in bed stability associated to breakage/burial of armour layer or bedforms
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
Variation in bank protections	Estimated changes in the longitudinal extent of bank protection along the reach as a response to their failure
Lateral sediment/wood input and associated channel response	Estimated magnitude of sediment/wood 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

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

	Relevant inflow at the upstream boundary				Relevant Inflow at the downstream boundary				Natural stability of the streambed		
	Debris flow	Debris flood	Bedload transport with relative high sediment transport rate compared to transport capacity (50–100%)	Bedload transport with relative sediment transport rate compared to transport capacity (0–50%)	DFW—debris flow	DFD—Debris flood	BT—bedload transport with relative high sediment transport rate compared to transport capacity (50–100%)	BT—bedload transport with relative sediment transport rate compared to transport capacity (0–50%)	Bedrock—inalterable	Pronounced natural stability (through armouring and stable bedforms)	Low to negligible natural stability (no armouring and absence of bedforms)
Flow process transition											
Sharp process intensification (from BT to DFD or DFW)	−1	−1	1	1	1	1	1	−1	1	3	1
Moderate process intensification (increase in BT saturation or from DFD to DFW)	−1	1	1	1	1	1	1	1	1	1	1
No transition	1	1	1	1	1	1	1	1	1	1	1
Sharp process attenuation (from DFW to BT	1	1	1	−1	−1	−1	1	1	−1	1	1

Table 3 continued

	Relevant inflow at the upstream boundary				Relevant Inflow at the downstream boundary				Natural stability of the streambed		
	Debris flow	Debris flood	Bedload transport with relative high sediment transport rate compared to transport capacity (50–100%)	Bedload transport with relative sediment transport rate compared to transport capacity (0–50%)	DFW—debris flow	DFD—Debris flood	BT—bedload transport with relative high sediment transport rate compared to transport capacity (50–100%)	BT—bedload transport with relative sediment transport rate compared to transport capacity (0–50%)	Bedrock—inalterable	Pronounced natural stability (through armouring and stable bedforms)	Low to negligible natural stability (no armouring and absence of bedforms)
Moderate process attenuation (from DFW to DFD, from DFD to BT, from high to low BT)	1	1	1	1	−1	1	1	1	1	1	1

The cells containing the value ‘−1’ represent the inconsistent combinations of possible impact levels for all pairs of different impact variables. Similarly, the cells containing the value ‘3’ represent the combinations with complete consistency, whereas the cells containing the value ‘1’ indicate combinations with partial or week consistency. The consistency of a distinct scenario is obtained through an additive or multiplicative consistency measure involving the consistency ratings assigned to each pair of impact levels of different impact variables specifying the considered scenario

Data and tools: land use/forest plan maps, aerial photos, forest management plans.

Step 6:

Action: estimation of wood transfer efficiency (%) along the reach

Spatial extent: reach

How: based on channel morphology, channel roughness, channel width, structures

Data and tools: literature studies (based on relative log size, channel curvature and obstacles density, see Rigon et al. 2008), historical records, expert-based judgement, numerical wood transport modelling (e.g. Mazzorana et al. 2011)

Step 7:

Spatial extent: reach (only for bedload/debris flood reaches)

How: based on channel morphology, channel slope, peak discharge, channel width, sediment size

Data and tools: literature equations suitable for the reach characteristics, applied to a discretised hydrograph

Step 8:

Action: calculation of actual sediment transport capacity (volumes) transferred downstream of each reach for the analysed hydrograph

Spatial extent: reach

How: for bedload/debris flood, based on the comparison (i.e. determination of the minimum) between potential sediment transport (step 7) and the sediment input coming into the reach from lateral sources (step 5) and from upstream reaches (step 8 performed on upstream reaches). For debris flows, all eroded sediment can be assumed to be transferred downstream, unless evident depositional sites (natural or anthropic) are present.

Data and tools: iterative applications of Step 8 moving downstream

Step 9:

Action: estimation of sediment and wood *volume* at the analysed cross-section

Spatial extent: entire segmented channel network

How: budgeting input and transferred sediment/wood from each reach of the network

Data and tools: as proposed for the previous steps

Step 10:

Action: estimation of sediment and wood transport *rate* at the analysed cross-section

Spatial extent: entire segmented channel network

How: based on hydrograph shape and length, estimation of average/peak rates for sediment and wood, for bedload transport the maximum rate is set by transport capacity equations, for wood by geometrical considerations (surface flow area times velocity are the limiting factor for congested transport)

Data and tools: hydraulic modelling, estimation of flow velocity based on literature equations

3.2 Procedure for assessing flood hazard scenarios within 2D process propagation domains (2DD)

Step 1:

Action: identification of 2D domains (areas adjacent to channels subject to inundation/erosion)

Spatial extent: entire drainage basin

How: based on valley morphology, channel confinement, valley substrate.

Data and tools: hillshade DTM, geological maps (quaternary fluvial and colluvial deposits), hydraulic models, aerial photos, historical flood reports. Suitable river corridor limits (for flood purposes) may already be available.

Step 2:

Action: identification and delineation of vulnerable 2D domains.

Spatial extent: entire drainage basin

How: within all 2D domains, extract those featuring a present/future vulnerable land use

Data and tools: output from step 1, present land use maps, land planning maps

Step 3:

Action: identification of all potential stochastic nodes within vulnerable 2DDs

Spatial extent: vulnerable 2DDs

How: identification of all bridges, culverts, unreliable hydraulic structures (e.g. old levees and check-dams)

Data and tools: hydraulic structures inventories, aerial photos

Step 4:

Action: identification of stochastic domains (SD)

Spatial extent: vulnerable 2DDs

How: identification of only those stochastic nodes which are likely to interact with flood flows (for the analysed RI) causing relevant consequences

Data and tools: historical reports, hydraulic models, expert-based evaluation, DTM

Step 5:

Action: determination of possible states for each SD

Spatial extent: stochastic domains

How: based on the type and dimension of SD, but only few states (2–3) are desirable

Data and tools: expert-based judgement (see also Mazzorana et al. in press)

Step 6:

Action: estimation of state transition probabilities for each SD for any analysed RI and representation of these probabilities in form of a matrix describing the possible transitions among domain states for different process intensities.

Spatial extent: stochastic domains

How: empirical and analytical methods (if available), subjective probability estimation

Data and tools: fragility curves for levees (Apel et al. 2009), literature equations for bridge clogging (Mazzorana et al. in press), historical flood reports and subjective probability methods (compare Eisenführ and Weber 2010; Gilboa 2009)

Step 7:

Action: determination of probabilities for the all SD states combination (2DD scenarios) for any analysed RI

Spatial extent: vulnerable 2DDs

How: application of the law of compound probability (i.e. multiplication of SD states probabilities)

Data and tools:

Step 8:

Action: simulation of flood propagation for different 2DD scenarios

Spatial extent: vulnerable 2DDs

How: numerical models runs for 2DD scenario having relevant probabilities ($p > 0.05$)

Data and tools: 2D hydrodynamic (morphodynamic only if suitable for the case) models, 2D simplified morphological models (e.g. for debris flows see Huggel et al. 2003)

Step 9:

Action: Determination of relative spatial probability of process intensity (Mazzorana et al. in press) for any RI

Data and tools: vulnerable 2DDs

How: overlapping scenario results, i.e., summing scenario probabilities for each cell

Data and tools: GIS analysis

Step 10:

Action: Determination of actual spatial probability of process intensity for any RI

Spatial extent: vulnerable 2DDs

How: application of the law of compound probability (i.e. 1/RI multiplied by relative spatial probability at each cell as from step 9)

Data and tools: GIS analysis

3.3 Remarks on the application of the presented procedure

In order to appropriately apply the above outlined procedures, the interdisciplinary expert team should consider a minimum number of necessary framework conditions, which are briefly presented in this subsection.

First, 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. Also, the segmentation of the drainage network has to be undertaken with particular care (Step 1 of 1DD procedure) in order to establish reaches with uniform processes (i.e. debris flow vs. bedload transport, erosion/equilibrium/deposition), of sufficient size (i.e. to avoid excessive fragmentation).

In order to simplify the process routing within the 1DDs, these portions of the channel network that evidently do not affect the segments located further downstream can be neglected during the segmentation and analysis procedure. Instead, these segments could be treated as lumped systems, i.e., one reach covers the entire channel in terms of a 1st order channel. Confluences with major tributaries or with steep sediment-rich channels, as well as locations prone to clogging are focal points since process intensities change considerably. The availability of recent and detailed geological/geomorphological maps (i.e. with a detailed description of quaternary deposits) should be checked and viewed as a precious tool for the procedure. Important land use changes that may have occurred since the previous event have to be taken into account. Such changes are predominantly used to adjust the physical behaviour of hillslope/channel dynamics (e.g. sediment and wood input).

The procedure for determining hazard propagation within the 2D domains has to account for a multi-scenario approach (i.e. from possible levee failures, bridge clogging and natural channel avulsion) that is reckoned indispensable when elements at risk are or will be present. However, most of the scenario-based modelling efforts should be primarily concentrated on those strategic 2DDs (within the vulnerable 2D domains as in Sect. 3.2) that include densely urbanised areas, whereas in the other 2DDs a single-scenario, traditional approach may be sufficient if modelling resources are limited. Nevertheless, if the application of 1DD process routing inform about likely high sediment and/or wood load, an appropriate inclusion of avulsion and cross-section clogging in the modelling procedure is recommended whenever feasible. Finally, the selection of appropriate 2D numerical models for determining hazard propagation scenarios within the 2DDs is of considerable importance. If the test site is characterised by steep debris fans or if reliable modelling parameters are not accessible, simpler morphological and empirical models are preferable.

4 Conclusions

The methodological structure presented above may assist to derive a reliable set of consistent flood scenarios in prevailingly confined channel segments (1D domains) and to delineate flood process patterns on semi- to unconfined segments (alluvial fans and floodplains, 2D domains). Such a distinction stems from both process-specific and computational reasons, and the methodology follows a structured, multi-level knowledge integration approach. The channel network of mountain basins is interpreted as a series of homogenous stream segments, and the resulting simplified stream system is composed of

1D and 2D domains, the latter then further subdivided into deterministic and stochastic sub-domains.

Distinct procedures for hazard assessment in 1DDs and 2DDs were proposed to progressively reduce the structural shortcomings affecting the procedures currently adopted in most of Alpine regions. Expert knowledge and expert judgement play a considerable role throughout the entire method, but they complement the use of modern tools such as GIS analysis and hydrodynamic numerical modelling. References to specific techniques (e.g. Formative Scenario Analysis) were provided to carry out process-specific knowledge generation through a balanced synthesis of different sources. Moreover, the use of indirect subjective probability assignment methods was advocated for partly relying on judgemental contributions of the experts involved.

Several relevant remarks on the application of the entire procedure were provided, and we highlighted those steps requiring a markedly interdisciplinary approach to improve the traditional engineering perspective embraced during hazard assessment, as well as in the planning of mitigation measures. Strategies to reduce the complexity of the hazard assessment procedure were also suggested because public agencies dealing with hazard management often operate with limited resources and thus strategic areas must be addressed at a higher detail than less vulnerable ones. However, the hazard assessment procedure should always be performed based not only on the elements at risk present at a certain time, but in the view of the future land changes in order to avoid ill-advised land planning leading to increase flood risk. Therefore, the contribution of this work is directed towards a proposal of a coherent structure as a means to effectively convey knowledge acquisition, generation and integration throughout the entire hazard assessment process, and to provide reliability for an enhanced dealing with natural hazard risk targeted at a sustainable use of mountain areas for settlement, economic purpose and recreation activities.

Annex 1: Formative Scenario Analysis procedure:

1. A team of individuals familiar with the problem setting lists v_1, $i = 1, \ldots, N$ 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 $D = US \cup DS \cup IC \cup AD$

2. 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 $v_i^1, v_i^2, \ldots, v_i^{N_i}$.

3. Formally, a scenario is a vector $S_k = \left(v_1^{n_1}, \ldots, v_i^{n_i}, \ldots, v_N^{n_N}\right)$ with $k = 1, \ldots, k_0$; the number of scenarios is $k_0 = \prod_{i=1}^{N} N_i$.
4. In this step, the consistency matrix is constructed as $C = \left[c\left(v_i^{n_i}, v_j^{n_j}\right)\right]$ containing the consistency ratings, c(.,.), for all pairs of impact variables at all levels c, $\left(i,j = 1,\ldots,N, i \neq j, n_i = 1,\ldots,N_i, n_j = 1,\ldots,N_j\right)$.
5. For each scenario a consistency value is calculated respectively as additive measure as $c^*(S_k) = \sum c\left(v_i^{n_i}, v_j^{n_j}\right)$ or as multiplicative measure as $c^*(S_k) = \prod c\left(v_i^{n_i}, v_j^{n_j}\right)$ with $i,j = 1,\ldots,N, i \neq j, v_i^{n_i}, v_j^{n_j} \in S_k$.
6. The scenario selection is based conjointly on the consistency value of the scenarios and the difference between them. The distance measure Δ corresponds to the number of differences between the scenarios $\Delta(S_k, S_l) = \sum_{i=1}^{n} \begin{cases} 1 & \text{if } v_i(S_k) \neq v_i(S_l) \\ 0 & \text{otherwise} \end{cases}$. 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.
7. Scenario interpretation completes the adapted steps of Formative Scenario Analysis

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