DETERMINING FLOOD HAZARD PATTERNS THROUGH A COMBINED STOCHASTIC-DETERMINISTIC APPROACH

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Abstract

A sound, evidence-based hazard mapping requires the analysis of stochastic processes taking place at critical configurations (e.g. bridges, levees) in order to reliably determine the spatial patterns of flood intensities and probabilities. Here we discuss an approach aiming to support an enhanced determination of flood hazard patterns by identifying within alluvial fans and river corridors two main types of spatial domains based on the predictability of their dynamics, i.e. stochastic and quasi-deterministic domains. The former represent critical configurations whose dynamic evolution (e.g. clogging by driftwood, failure due to breaching) cannot be realistically specified by deterministic models, whereas the latter refers to the part of the system where the flood propagation can be computed with sufficient precision and accuracy by hydrodynamic models. The applicability of the proposed approach is discussed on the basis of a case study in the Autonomous Province of Bolzano (Italy).

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1 Introduction

In the European Alps, during the last two decades considerable economic losses were caused by torrential processes and by river inundations (Barredo, 2007). An increase over time of such losses was attributed to both augmented hazards, i.e. to higher natural process magnitude (Solomon et al., 2007) and to the increase of values at risk (Fuchs, 2009). The analysis of the most recent flood events in the Alps highlighted considerable shortcomings in the current procedures used for natural hazard and risk assessment (Autonomous Province of Bolzano-Bozen, 2008). In particular, the effects of changing channel morphology during the event and the reduction of cross-sectional area due to wood clogging were found to significantly amplify process intensities (e.g., Comiti et al., 2008, Fig. 1). Furthermore, existing hazard maps turned out to be not as reliable as expected (e.g., Bezzola and Hegg, 2007). In order to improve risk analyses and to support decision making, flood event scenarios need to be re-established based on such issues, in particular to cope with the different sources of uncertainty affecting the predictability of hazard process paths (e.g., Paté-Cornell, 1996).

Figure 1. Flash flood in the Davča basin (Slovenia, September 2007). Driftwood and aggradation clogged the bridge (arrow), causing channel avulsion and thus damages to the house on the right of the picture (http://www.davca.si)

As a consequence of morphodynamic changes, driftwood obstructions and levee failures, actual flooded areas are in many cases different from those predicted by deterministic hydrodynamic models – no matter how accurate – implementing fixed channel geometries. In many cases, such discrepancies between predicted and actual flood scenarios are expected and predictable – at least in qualitative terms – by river managers, but current hazard maps do not take them into consideration because hydrodynamic 2D models have been adopted "enthusiastically" as the ultimate solution. Furthermore, in a perspective of stochastic processes occurring at nodes (i.e. bridges) along the channel network, the frequency of inundation (i.e. the return period) of many areas does not correspond to the frequency of the hydrologic event itself (i.e. the return time of a certain peak discharge).

In this paper we propose a nested scenarios approach in order to determine and map the expected flood scenarios including stochastic processes occurring at critical cross-sections, with the ultimate goal of establishing a sounder risk mapping procedure.

2 Theoretical background of flood risk assessment

The concept of risk with respect to natural hazards is defined as a function of the probability of occurrence of a process and of the related extent of damage. The latter is in turn specified by the damage potential and vulnerability of exposed objects. For an ex-ante quantification of risk (Fuchs et al., 2007) induced by a specific hazard scenario k (expressed in terms of process intensities I, e.g. flow depth, flow velocity or their combination) for a given object m, risk can be expressed as:

$$R_{k,m} = f(p_k, A_m, e_{k,m}, v_{k,m}) \quad (1)$$

Where, $R_{k,m}$ is the risk associated to the scenario k and object m; p_k is the spatial probability of occurrence of scenario k in the vicinity of the object m, A_m is the economic value of object m, $e_{m,k}$ is the probability of exposure of object m to scenario k, $v_{m,k}$ is the vulnerability of object m, depending on the local intensity of scenario k.

Working in a raster-style (i.e. grid-based) spatial environment, for each cell c of the grid, where the probability of occurrence of the hazard can be assumed to be equal, n objects can be exposed to the natural hazard, and therefore (1) becomes:

$$R_{k,c} = f(p_k, A_{k,m=1,\ldots n}, e_{k,m=1,\ldots.n}, v_{k,m=1\ldots n}) \qquad (2)$$

The overall risk for a given cell c is then determined by the sum of all the possible hazard scenarios K occurring on that spatial location, and therefore reads:

$$R_c = \sum_{k=1}^{K} R_{k,c} \qquad (3)$$

Finally, for a given area composed of C cells, the total risk is given by:

$$R = \sum_{c=1}^{C} R_c \qquad (4)$$

The most critical step to actually apply equation 2 to real cases is the evaluation of the spatial probability of process intensities (p_k).

3 Coupling deterministic and stochastic processes

Within an area subject to flood flows (e.g., alluvial fans, floodplains), we can identify two main types of spatial domains based on the predictability of their flood dynamics, i.e. stochastic and quasi-deterministic domains. The former represents the critical configurations whose dynamic evolution (e.g. clogging by driftwood, failure due to levee breaching) cannot be realistically specified by deterministic models, whereas the latter refers to the part of the system where the flood propagation can be computed with sufficient precision and accuracy by hydrodynamic models.

For each stochastic domain, we postulate that depending on the intensity of the hazard process, it can feature only a finite set of possible states (e.g. levee stable/breached; bridge clear/clogged). A domain undergoes a variation of its state through a finite number of transitions. Therefore, a matrix describing the possible transitions among domain states for different process intensity can be derived.

The main problem in the attempt to introduce stochastic domains in flood hazard mapping is the determination of the transition probabilities. Two distinct approaches to solve such a problem can be applied, i.e. an objective method and a subjective one. The first relies on the use of either empirical or theoretical relationships between the transition under analysis and the physical processes. When such relationships are not available, a subjective method can be applied, built upon the concept of the subjective probability theory.

Let us now consider a hypothetical area within a river corridor with well defined flood inflow conditions, either in terms of intensity and frequency (i.e. based on a purely "hydrologic" magnitude-frequency relationship). We call this region – which may consist of floodplains, alluvial fans and stream channels – the "response system", i.e. the spatial region which responds to the loading from the upstream river reach, called the "loading system". Starting from the analyzed response system, a simplified response system is derived (Fig. 2) based on an *ex ante* identification of all possible critical configurations and existing flood hazard index maps. Within the response system depicted in Figure 2, we can identify two stochastic domains, i.e. one bridge and one levee section, within the deterministic domain of the fan area. First, experts select the relevant stochastic domains for hazard scenarios.

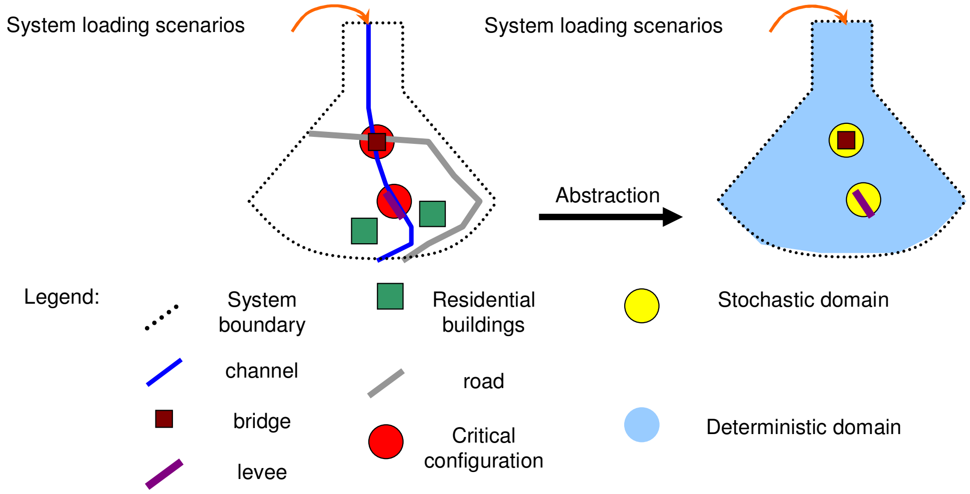

Figure 2. Example of a response system (alluvial fan). Starting from the real system (left), its simplified model (right) is derived, where the relevant stochastic domains (critical nodes) are identified within a "deterministic" area.

For each relevant stochastic domain, the experts assign for several process intensities a conditional probability to the relevant state transitions (i.e. they fill up the transition matrix mentioned above). Subsequently, several 2D hydrodynamic simulations are run implementing the relevant combinations of stochastic domains states. Finally, applying the transition probability matrix to the virtual (i.e. hydrological) event probability of each simulation will lead to derive a map of flooded areas where recurrence intervals (R.I.) actually include the possible transitions at critical sections.

It is clear that the overall flood recurrence interval map is strongly conditioned by "tipping" processes taking place at critical nodes. Neglecting or overlooking such evidences heavily increases the uncertainty associated with hazard maps, which are crucial for the subsequent risk analysis (eq. 2) and mitigation.

4 Testing the methodology: the Rienz river in Bruneck

The city of Bruneck (Aut. Prov. Bolzano) lies on the floodplain (i.e. the response system) of the Rienz river (drainage area 640 km^2), whose channel flows through the downtown with several bridges (Fig. 3). Loading systems scenarios (i.e. Rienz inflows from upstream of Bruneck for flood events > R.I. 100 yr) foresee, along with water and sediment fluxes, large driftwood transport rates, which would likely cause obstructions at the most critical bridges (i.e. those featuring the smaller free-board for the analyzed discharge). A preliminary 1D simulation helped identify two bridges (see Fig. 3) as critical nodes, and as such these were categorized as stochastic domains (see section 3) within the quasi-deterministic domain of the channel-floodplain system. Only two possible states for each stochastic domain are implemented, i.e. bridge cross-section totally clear or totally obstructed.

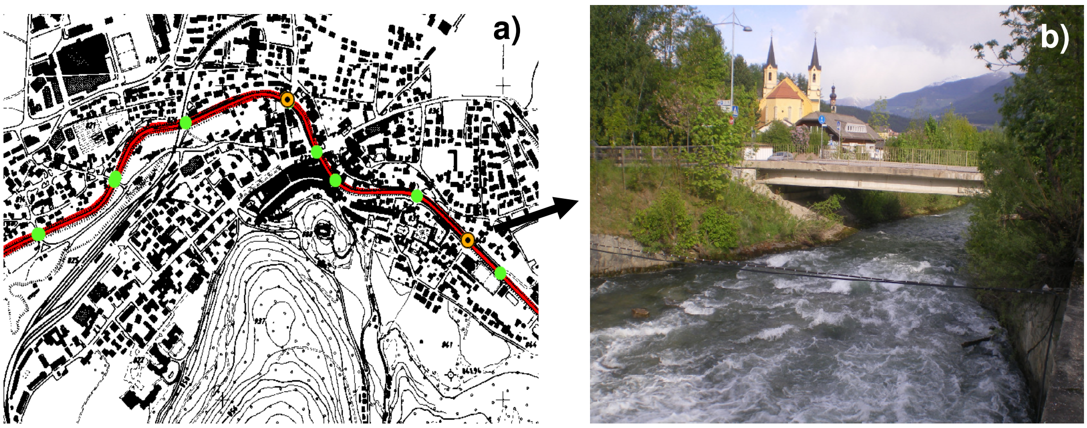

Figure 3. The Rienz in Bruneck: a) the two "critical" bridges (stochastic domains) are the orange dots, those assumed to be negligible for flood propagation are in green. Flow is right to left; b) photo of the first critical bridge.

Four flood propagation scenarios (i.e. no obstructions at all, obstruction of the 2 bridges, obstruction of only one of the two bridges) were simulated by the 2D hydrodynamic model "Sobek-River" for the same inflow hydrograph (re100 yr). As depicted in Fig. 4, significant differences in terms of flood intensity (i.e. water depth) would stem from bridge clogging. Flooding temporal evolution (i.e. onset and duration) is also heavily affected (figure not shown).

The final step to actually calculate the spatial probability for each process intensity (p_k in eq. 1-2) is to assign the probability of clogging for the each bridge under different inflow discharges - just 2 flow ranges can be used - based on the expected driftwood rate and size. Recent experimental works (e.g. Imhof, 2008) can provide guidance for such evaluation, which nevertheless could be also solely expert-based, i.e. adopting a subjective probability approach (see Gilboa, 2009).

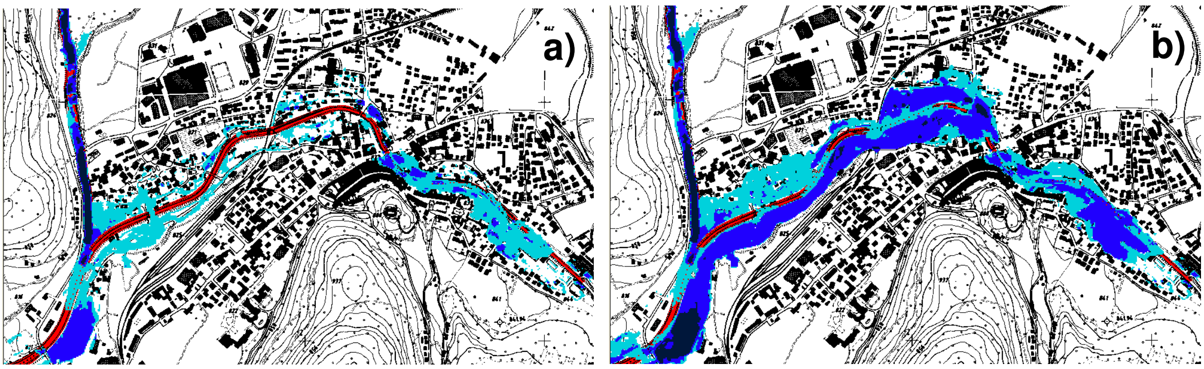

Figure 4. Inundation maps at the flood peak (inflow hydrograph R.I. 100 yr) for a subset of the possible propagation scenarios for the Rienz in Bruneck: a) bridges not clogged; b) both critical bridges clogged (see Fig. 3). Note the larger flooded areas and the deeper water depths (darker blue) for case b.

5 Conclusions

The present paper has illustrated how flood hazard mapping procedures carried out without taking into account different scenarios – arising from stochastic processes at critical cross-sections (e.g. bridges) – can result in highly erroneous evaluations, especially in forested basins whose channels naturally transport high wood loads. A nested approach entailing deterministic simulations as well as stochastic evaluation is thus advocated for in order to achieve a more reliable determination of flood risks.

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