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From Single- to Multi-Hazard Risk Analyses: a concept addressing emerging challenges

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ABSTRACT: Natural processes are interacting components of natural systems. Only certain characteristics possibly pose a threat to elements at risk and convert the processes into hazards. In the framework of multi-hazard risk analyses these interactions are mostly not taken into account, however mutual impacts alter the disposition and the triggering of natural hazards and negligence might lead to miss- or underestimation of the actual hazard/risk. In a case study of a medium-scale multi-hazard analysis the interactions concerning the disposition were identified with a matrix, implemented with a feedback loop and determined on a map by overlay of hazard layers. Links concerning the triggering were also identified by a matrix and determined by overlapping. In summary, multi-hazard (risk) analyses consider already multiple processes. This offers the great opportunity to add one further step and identify and integrate the interactions.

1 INTRODUCTION

1.1 Multi-hazard (risk)

The term 'multi-hazard' emerged in the political international environment associated with the aim of risk reduction and sustainable development (e.g. Agenda 21 and Johannesburg Plan). In this context the analysis of risk from multiple hazards was identified as central aspect and basis for risk management and thus for the reduction of risk and sustainable development. Given these objectives, two fundamental facets of such an analysis evolve: the analysis has to be carried out for the administrative unit in charge of risk management, i.e. for the specific administrative area and yielding the results required for this purpose. And, the hazards under consideration are all natural processes threatening humans, buildings or infrastructure, i.e. all hazards posing a relevant risk. Thus, the analysis of multi-hazard risk is, resuming the most important aspects for a definition for this article, the joint investigation of all relevant hazards in a defined area.

Although hazard and risk analysis methods are already well-established for many natural processes, their joint investigation poses a variety of challenges. Especially, the widely differing characteristics of the single processes as intensity, return period or parameters of influence on elements at risk[1] (Tyagunov et al. 2005), but also the varying procedures to estimate/model (Marzocchi et al. 2009), and units to quantify them complicate multi-hazard (risk) analyses. This leads to the need for an overarching analysis scheme to produce single-hazard (risk) results which are comparable among each other. Widespread qualitative and semi-quantitative approaches are the classification of hazards, vulnerabilities and risks according to an overall scheme adjusted to each single process (e.g. Heinimann et al. 1998, Sperling et al. 2007, Thierry et al. 2008 & Wipulanusat et al. 2009) or the development of an index scheme (e.g. Dilley et al. 2005 & Greiving 2006). For quantitative analyses of risks a clear definition of the considered timeframe and types of damage to be modeled is required to make the single-hazard risks comparable and addable to the overall multi-hazard risk (e.g. annual risk for human life in Marzocchi et al. 2009, or the annual economic risk in Bell & Glade 2004).

Such multi-hazard (risk) analysis schemes assure in first place the combinability and comparability of the single-hazard (risk) analysis results. However, the hazards are usually still considered as independent from each other, which cannot be supported by observations in the field.

1.2 Natural hazards as interrelated system components

Natural processes are components of systems (ecosystems, geosystems, etc.) and only certain characteristics which possibly pose a threat to elements at risk convert them into hazards. As components of systems these processes are not independent and se-

[1] An example is rock fall in comparison with storm hazard. Rock fall is characterized by its impact pressure while storms are mostly represented by the wind force, two measures which are not directly comparable. Furthermore they differ in extent, predictability, time of onset, duration etc.

parated from each other but are linked and connected. In the investigation and modeling of natural hazards, this aspect is still very rarely taken into account but each hazard is studied discretely.

The occurrence of natural processes/hazards depends on the disposition, i.e. the general setting which favors the specific process, and the triggering event which leads to the threshold crossing of a factor relevant for the hazard incidence (Heinimann et al. 1998).

The disposition can be subdivided into basic and variable disposition, which refers to the temporal observation scale: the basic disposition is an, over a longer time period constant or very slowly changing setting, e.g. the relief, climate or the vegetation cover. The variable disposition refers to faster alterations, e.g. seasonal or daily changes (water balance, vegetation period, etc.) which lead, in combination with the general basic disposition, to the current disposition.

In this setting, the exceeding of an internal threshold (triggering) or an external trigger may start the incidence. Processes which pose a possible threat to elements at risk are in most hazard analyses only seen as the threat. However, from a systemic point of view they are components acting within the system and shaping it. By shaping the system they may alter the general setting, i.e. the dispositions of other processes/hazards or act as trigger for other processes/hazards.

In single-hazard analyses the most important processes and parameters concerning disposure and triggering are identified and integrated in the modeling procedure. For most multi-hazard analyses a similar approach is now applied, identifying still separately the important factors to be considered for each single process. After investigating them separately only the results are brought together. However, a multi-hazard analysis would offer the possibility to create a framework containing all considered processes and taking into account additionally the relations and interconnections between them.

We investigated the relationships between potentially hazardous processes and their relevance for the overall risk and risk management, subdivided into relations concerning disposition and triggering.

We will in the first section explain what a system approach in combination with the disposition-triggering model for multi-hazard analyses means and give examples of studies in which hazard relationships are already taken into account.

Furthermore, we will make the transfer to explain why the relations are relevant and to be considered for risk management and reduction and how they could be taken into account. In a second section we will give an example for a medium-scale multi-hazard analysis and the implementation of hazard relations in this framework.

2 MULTI-HAZARD INTERACTIONS IN THE FRAMEWORK OF DISPOSITION AND TRIGGERING

2.1 *Alteration of the disposition*

Each natural process acts in a specific subarea of the system area and exhibits its specific footprint, i.e. the zone in which it operates. Where process footprints (process activity areas) overlap, the processes will influence each other more or less strongly. As long as no direct triggering of one hazard by another or temporally simultaneous occurrence exists, an influence will entail alterations of the basic and variable disposition. One process changes the general setting of another one and thus its disposition towards a possibly occurring trigger event.

Examples: De Graff et al. (2007) mention the "fire-flood cycle" which describes the relation of forest fires and subsequent floods and debris flows due to the loss of vegetation, rapid runoff and increased sediment washout. Detailed investigations suggest a significant increase of debris flow frequency after forest fires (Cannon & de Graff 2009). Wichmann et al. (2009) examine the sediment cascade consisting of several mass moving processes which fall into the category of natural hazards. They model several mass moving processes (e.g. rock fall, full depth avalanches and debris flows) and subdivide each one into the erosion, transport and deposition area. Where the deposition zone of one and the erosion area of another process coincide direct influence of the first process on the disposition of the second one and a coupled material transport can be assumed. Garcin et al. (2008) include the sea level rise into the modeling of storm surges and tsunami hazard for the next 100 years.

Transfer: The consideration of this aspect is of great importance to prevent underestimation of slowly or rapidly evolving hazards. The first step is the identification of influences and links between natural processes/hazards. If these links are determined, the occurrence of one process (A) indicates directly the possible alteration of the disposition of another process (B) and the need for reassessment of the second process' current hazard level. A very good example is given by de Graff et al. (2007) with the "Burned Area Emergency Response (BAER)". For the BAER post-wildfire threat (including debris-flow hazard) shall be assessed within seven days after a wildfire to ensure that counter-measures can be organized before the first storm event strikes. I.e. the general relation between fire and debris flows is identified, its severity determined and the necessary reaction defined. To make the second part, the reassessment, more user-friendly, the direct implementation of the links into the modeling framework by relating the models "so that the results of one model could feed into another" was proposed by Bovolo et al. (2009, p. 925). Such an application offers the possibility to test management or model hazard scenarios taking into account the wide-ranging implications they will have.

2.2 *Triggering*

One hazard inducing one or more other threats which may again provoke further ones is an aspect of multi-hazard studies gaining recently more and more attention. The terminology and definition differs from author to author slightly: Delmonaco et al. (2006, p.10) refer to this phenomenon as domino effect or cascading failure which is a "failure in a system of interconnected parts, where the service provided depends on the operation of a preceding part, and the failure of a preceding part can trigger the failure of successive parts". Marzocchi et al. (2009, pp. 3 & 9) define them as "coupled events" where "an adverse event triggers one or more sequential events (synergistic event)". A difficulty with this definition is that the triggering event has to be a hazard. Processes with low magnitudes might act as triggers but not cause damages and other triggers might not be hazards but cause several threats. Thus it seems reasonable to include in general all chains in which two or more hazards are involved, i.e. two or more hazards causally linked by triggering. This would also incorporate two hazards triggered by the same non-hazard event as floods and debris flows due to heavy rainfall, although heavy rainfall itself is not a hazard.

Examples: A prominent event chain is the triggering of mass movements due to earthquakes (e.g. Meyenfeld 2008 & Miles & Keefer 2009). Another frequently occurring cascade starts with a landslide which dams a river or torrent, this dam breaks and the runoff of a mixture of water and debris causes considerable damage (Carrasco et al. 2003, Costa & Schuster 1988 & Dai et al. 2005). Huggel et al. (2003) investigated lake outbursts and the formation of a debris flow due to triggering by ice avalanches or debris flows.

Transfer: An important aspect of hazard chains is the possible amplification of the overall hazard and risk of such causally linked processes in comparison to the aggregation of assumedly independent hazards (Marzocchi et al. 2009). For example, a debris flow resulting from the dam break of a landslide dam might be of a higher magnitude than expected channel or slope debris flows. This possible amplification effect does not only refer to direct chaining of hazards but also to threats induced by one common trigger which results in temporal coincidence and increases the probability of spatial overlapping. Tarvainen et al. (2006, p. 84) state that an "additional hazard potential [… may arise due to] a possible coincidence of different hazards in space and time". They mention the example of a coincidence of a river flood and a storm surge in the Rhine estuary which would have simultaneously a much higher impact than the pure sum of both. Thus the amplification effect can either be the result of the chaining - one hazard triggering and increasing the next - or a consequence of the spatial and temporal coincidence of both.

Besides the amplification, a second aspect is that the impact of two processes simultaneously or one shortly after the other (a landslide triggered by an earthquake) exhibit a higher impact on humans, buildings or infrastructure than the simple sum of both and alter thereby the risk. An earthquake damaged structure is surely much more vulnerable to the following landslide than it was in the original state. A community under stress due to a flood is already in an altered state when the debris flow occurs.

The third important aspect is the challenge for early warnings and emergency management in a situation of more than one threat. Several events and impacts have to be managed simultaneously, often in a multi-agency cooperation as shown in the case of the Shanghai Multi-Hazard Early Warning System (Tang 2009) which poses a high challenge.

3 CONSIDERATION OF HAZARD RELATIONS IN MEDIUM-SCALE MULTI-HAZARD MODELING

Multi-hazard (risk) analyses aim, in accordance with the description given in the introduction, at the consideration of all natural hazards in a specified administrative unit. Since the data requirements are very high for multiple processes and the occurrence and spatial distribution of several processes is much less clear as in the case of one single process, it seems reasonable to adapt a top-down approach. Starting with a relatively coarse and low data intensive analysis for an overview and the identification of potential risk areas the regions in need for more detailed, local studies can be determined. A coherent analysis scheme is the fundamental precondition for the consideration of multi-hazard relationships. The scheme applied in this study will be mentioned only shortly since the focus is on the consideration of the hazard relations.

The case study is carried out in the Barcelonnette Basin, a valley in the southern French Alps between 1100 m and 3000 m a.s.l. drained by the Ubaye River (for detailed information on the area refer to Flageollet et al. 1999, Maquaire et al. 2003, Remaître 2006, Remaître et al. 2008). The processes considered in the analysis are snow avalanches, rock fall, shallow landslides, debris flows and river floods. Further hazards threatening the valley include flash floods and earthquakes which are at this point not included into the analysis due to the unavailability of models fitting in the set of the other five.

For each process the area affected by a high-magnitude low-frequency event (worst-case scenario) is modeled by means of relatively simple models: the mass movement analyses are split in two parts, the source identification with empirical/heuristic criteria (debris flow sources following Horton et al. 2008; avalanche sources after Maggioni 2004; rock fall sources based on Corominas et al. 2003, and shallow landslide sources referring to Montgomery & Dietrich 1994) and the run out computation primarily with the angle of reach concept (Heim 1932) by means of the model Flow-R (Horton et al. 2008). The flood modeling is carried out with the model FloodArea (Geomer 2008) on basis of hydrograph information. Details about the processes, models and parameter choices for the case study will be published later, thus we will not describe these aspects in the article at hand because of the different focus of this contribution.

The outputs are, as already mentioned, the zones possibly affected in a high-magnitude event by each one of the hazards.

In the following we will outline, how the relations between hazard concerning disposition and triggering are taken into account.

3.1 *Disposition*

A general procedure of two steps is suggested: 1) identification of the influences and links between the different hazards, and 2) the establishment of the links between the hazard models adjusted to the modeling scale and methods used. For a medium-scale multi-hazard analysis the following realization of the two steps was carried out:

1) The links between hazards were identified by means of a matrix opposing all hazards to each other after de Pippo et al. (2008). In the interjacent cells the respective effect is shortly explained (Tab. 1).

Table 1. Matrix for the identification of influences of one process on the disposition of another one. The process in the line is the causing one, the column indicates the affected one.

Avalanche	Influence on vegetation cover (Removal of forest)	Influence on vegetation cover (Removal of forest)	Influence on vegetation cover	-
-	Debris flows	-	-	Change of river bed morphology (acc. & erosion)
Increased slope roughness	Supply of material	Rock falls	Increase of load	Material accumulation in river bed
Alteration of surface roughness	Supply of material	-	Landslides	Change of river course
-	Remobilisation of material	-	Erosion/ saturation of landslide deposits	Floods

2) For the linkage of models (the output of one model used as input for the next model) a practical approach is the listing of all model inputs and the identification which model outcomes can be used to update the input layers and parameters. E.g. the avalanche run out zone can be used to roughly estimate the area of potential forest destruction and thus to update the land cover information (Figure 1).

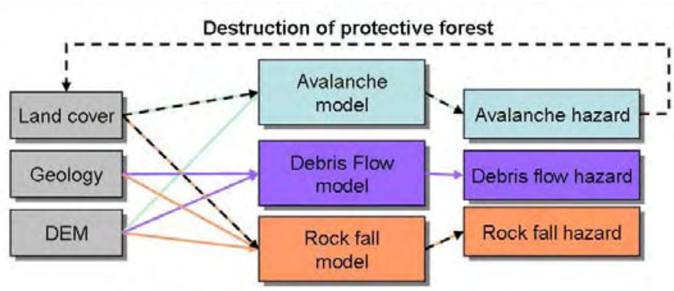

Figure 1. Implementation of the effect of one hazard, in this case avalanche, on the disposition of other processes, in this case rock fall and avalanche hazard itself, due to the effect on an input parameter (land cover). Feedback loop shown with black dashed lines.

This updated information can again be integrated in all models using land cover as input (in this case only the rock fall and the avalanche model itself since e.g. debris flows under forest can, according to our opinion, not be excluded completely) and the new hazard level assessed. However, at such a small scale and with the relatively coarse models and little input data used, most of the relations as e.g. change of river bed morphology (modeling is done on basis of a 10m DEM and volumes are not taken into account) or material provision (volumes are not taken into account) cannot be considered. Such feedback loops allow the consideration of the consequences of a certain event (scenario modeling)

3.2 *Triggering*

As well as for the relations concerning the disposition also in the case of triggering a two-step procedure is convenient consisting of the 1) identification and 2) establishment of links between hazards.

Table 2. Matrix opposing all considered hazards towards the range of identified triggers and hazards taken into account to identify triggering relations.

	AV	DF	RF	LS	FL
Avalanches (AV)					x
Debris flows (DF)					x
Rock falls (RF)					x
Landslides (LS)					x
Floods (FL)				x	
Heavy rainfall	x	x		x	x
Earthquake	x		x	x	

(1) We propose a matrix based on de Pippo et al. (2008) as in the previous section, now for the determination possible triggering effects and complemented by the list of all possible non-hazard triggers (Tab. 2).

(2) While for detailed local studies event trees (e.g. Egli 1996 or Marzocchi et al. 2009) are a useful method to describe the complete chain with the respective probabilities, its application on a small scale is not possible since a huge amount of data and information would be necessary. However, these event trees have to be designed for areas prone to the occurrence of hazard chains and this information can be gained in a medium-scale study by overlaying the modeled hazard areas of possibly linked hazards. In case of floods, landslides might be triggered by undercutting of slopes. The flooded zone can be overlaid with landside prone regions and where both hazards overlap or occur in a distance lower as the range of influence of the flood (due to rising ground water table etc.) a possible cascading can be assumed. For the case of one non-hazard trigger inducing two or more hazards likewise the hazard zones can be overlaid (e.g. for the case of heavy rainfall the process areas of debris flow, shallow landslide and flood). First, the overall area possibly threatened during/shortly after heavy rainfall can be identified and secondly the regions perhaps affected by more than one hazard simultaneously or sequentially with potentially amplifying effect can be determined for further detailed studies by means of event trees.

4 CONCLUSIONS

Natural systems are not just the sum of its components but are a net of interacting parts and we are not able to understand and even less to model them entirely. The natural processes we perceive as hazards form part of these systems. In single-hazard analyses we create subsystems we can handle to model the threat “satisfactorily” and according to the data availability. The same procedure is applied for multi-hazard analyses - still creating for each single process one subsystem and only the results are combined and compared. However, hazards are, as natural processes, part of the same overall system, influence each other and interact. Thus, multi-hazard risk contains emergent properties: It is not just the sum of single-hazard risks since their relations would not be considered and this would lead to unexpected effects. The relations can, for analysis purposes, be subdivided in alteration of the disposition and triggering (cascades and related triggering).

Multi-hazard (risk) analyses offer the great advantage to consider a slightly larger part of the overall system than regarded in merged single-hazard analyses. The major step herein is to identify the relations and establish the respective links. This can be done in a very simple way by merely identifying which hazards could be interlinked or happening at the same time but can also include sophisticated event trees and probabilistic what-if scenarios. However, the beginning is the decision to include the relationships and starts with their identification. In the future, amplification towards the perspective of complex system research would be desirable since also the system theory has its short-comings. Complex systems imply two fundamental conditions: (1) The system consists of multiple interactive components and (2) these interactions give rise to emergent forms and properties which are not reducible to the sum of the individual components of observed system (Bründl et al. 2010, Keiler in press). Both conditions were highlighted in this study for multi-hazard and a new perspective of complex systems research will offer new concepts and methodologies to deal with multi-hazard and multi-risk.

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