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Landslides in a Multi-Hazard context

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Abstract

Landslides and other hazards are components of natural systems and thus often related to each other. Since these relationships may result in unexpected effects, an approach to account for these relationships in a regional multi-hazard study is proposed. Subdivided into relations concerning disposition alteration and hazard chains in which one process triggers another process, the hazard links are identified and studied by means of GIS-based methods. Two techniques are used for the implementation of relations into the analysis procedure, the establishment of feedback loops and the overlay of hazard areas to determine overlaps. Such a regional analysis enables in first place the definition of those areas possibly affected by unexpected effects due to hazard relations and indicates the spots to be studied in detail by local and detailed methods to quantify the potential consequences.

Keywords multi-hazard, interaction, hazard chains, disposition and triggering.

Introduction

Already for many years the system theory attempts to account for the continuous nature of the world and the complex relations between components (Chorley and Kennedy 1971). One prime example of the implementation of a system approach in geomorphology is the concept of debris or sediment cascades (Chorley and Kennedy 1971). In these cascading systems “the output of one subsystem forms the input of another” (Schneevoigt and Schrott 2006, p. 182). Processes as rock falls, debris flows or shallow landslides form part of these systems. Due to “certain characteristics which possibly pose a threat to elements at risk” these, primarily natural, processes convert to natural hazards (Kappes et al. 2010, p. 351). Although this does not change anything concerning their affiliation to geomorphic systems, natural hazards and among them also the previously mentioned processes are still commonly regarded, analyzed and managed separately. However, interactions cause consequences, lead to modifications of e.g. hazard levels and result in unexpected incidences. Thus, a reductionist approach is not able to account for such effects and thus not advisable. An example for hazard relations is the Jubaguerra event: a debris slide blocked the Arroyo de Jubaguerra gorge resulting in a damming of the stream. As consequence of the subsequent dam break a flood wave rushed down the river and reached the mouth of the watershed (Carrasco et al. 2003). Costa and Schuster (1988) present a whole range of formation and dam failure events of which several resulted in unexpected incidences with high numbers of fatalities.

The consideration of multiple hazards jointly and the inclusion of cascade and interaction effects is still an emerging research field. One pioneer project which addressed the topic from a geomorphic and system theoretic approach rather than from a hazard approach is SEDAG (SEDiment cascades in Alpine Geosystems). One main objective of SEDAG was to better understand the sediment pathways (Wichmann et al. 2009). However, Wichmann and Becht (2003) mentioned that the applied models might also be used for hazard assessments. By investigating source, transport and deposition areas of each process and the identification where these zones overlap the sediment routing can be determined (e.g. rock fall deposition in locations of debris flow erosion leads to cascading propagation of the sediment).

A practical approach coming from a hazard assessment background is proposed by Kappes et al. (2010). According to this concept, two types of influences between hazards can be distinguished: (1) the alteration of hazard dispositions by a hazardous event, e.g. the accumulation of material by rock falls and the subsequent availability of this material for debris flows or an increase of the load on a slope which destabilizes the slope and the disposition to a failure, and (2) the triggering of one or more hazards by another hazard, e.g. the triggering of rock falls by an earthquake or of lahars by a volcanic eruption hitting a glacier. Likewise, the triggering of at least two hazards by a process which does not classify as hazard, e.g. the triggering of debris flows and landslides by heavy rainfall, falls into this category.

In this study the practical consideration and implementation of interactions in a regional study are presented, subdivided into disposition alteration and triggering (according to Kappes et al. 2010). For the performance of the hazard modelling, the multi-hazard risk analysis tool MultiRISK Kappes et al. (in prep) was used and the case study is carried out in the Barcelonnette valley, located in the South-eastern French Alps.

Consideration of interactions in a regional context

Multi-hazard analyses suffer several limitations. The extended requirements of soil, infiltration, geology, precipitation, discharge data and further information are often a limiting factor. Especially inventories of past events are of particular relevance for the calibration and validation of hazard models. However, high quality multi-hazard inventories are extremely scarce. A second challenge in a multi-hazard setting is the multi-disciplinarity of the topic. In seldom cases, one expert is proficient with all processes. Thus a first evaluation of the multi-hazard situation, including areas of potential overlay and the occurrence of relations and interactions between them is much more difficult than the determination in a single-hazard environment. Both issues call for a top-down approach in multi-hazard investigations. In a first step an overview of the patterns is obtained. This is done by simple methods with low data requirements to ensure its applicability as first overview and avoid extensive and time-consuming data acquisition. On this basis, the resources can then be applied specifically to detailed local analyses in the areas identified as potentially prone to hazard interactions and risk.

The medium-scale analysis scheme

Kappes et al. (in prep) present a simple, GIS-based analysis scheme on basis of low data requirements (Fig. 1). It is designed as first step of a top-down approach for multi-hazard exposure analyses. From a digital elevation model (DEM), land use/cover and lithological information (dark grey boxes at the left side of Fig. 1) multiple derivatives are deduced (medium grey boxes). These serve as input for the models and GIS operations (light grey boxes with rounded edges). With this input the areas of potential rock fall, shallow landslide, debris flow and avalanche sources and areas affected by the run out as well as the zone susceptible to river flooding are modelled. The analysis scheme has been automated in the software tool MultiRISK. Herein, the intermediate steps such as the computation of derivatives, required format changes etc. are automatically computed. The software interface guides the user through the modelling process and guarantees user-friendly, faster, less error-prone and reproducible multi-hazard modelling (for further details concerning the analysis scheme and MultiRISK refer to Kappes et al. in prep). The consideration of hazard relations is still not automated in MultiRISK. However, the joint analysis of multiple hazards and the option of a fast re-calculation form a solid basis for *external* examinations of hazard cascades, feedback loops and other effects.

To illustrate the application of the concept of dealing with hazard interactions, a case study has been carried out in the Barcelonnette basin. This high mountain valley is prone to a multitude of landslide types and other natural hazards. In Kappes et al. (in prep) a worst-case analysis of shallow landslides, rock falls, debris flows, snow avalanches and river floods has been carried out and the obtained susceptibility zones form the basis for the hazard relation analysis which is presented in this study.

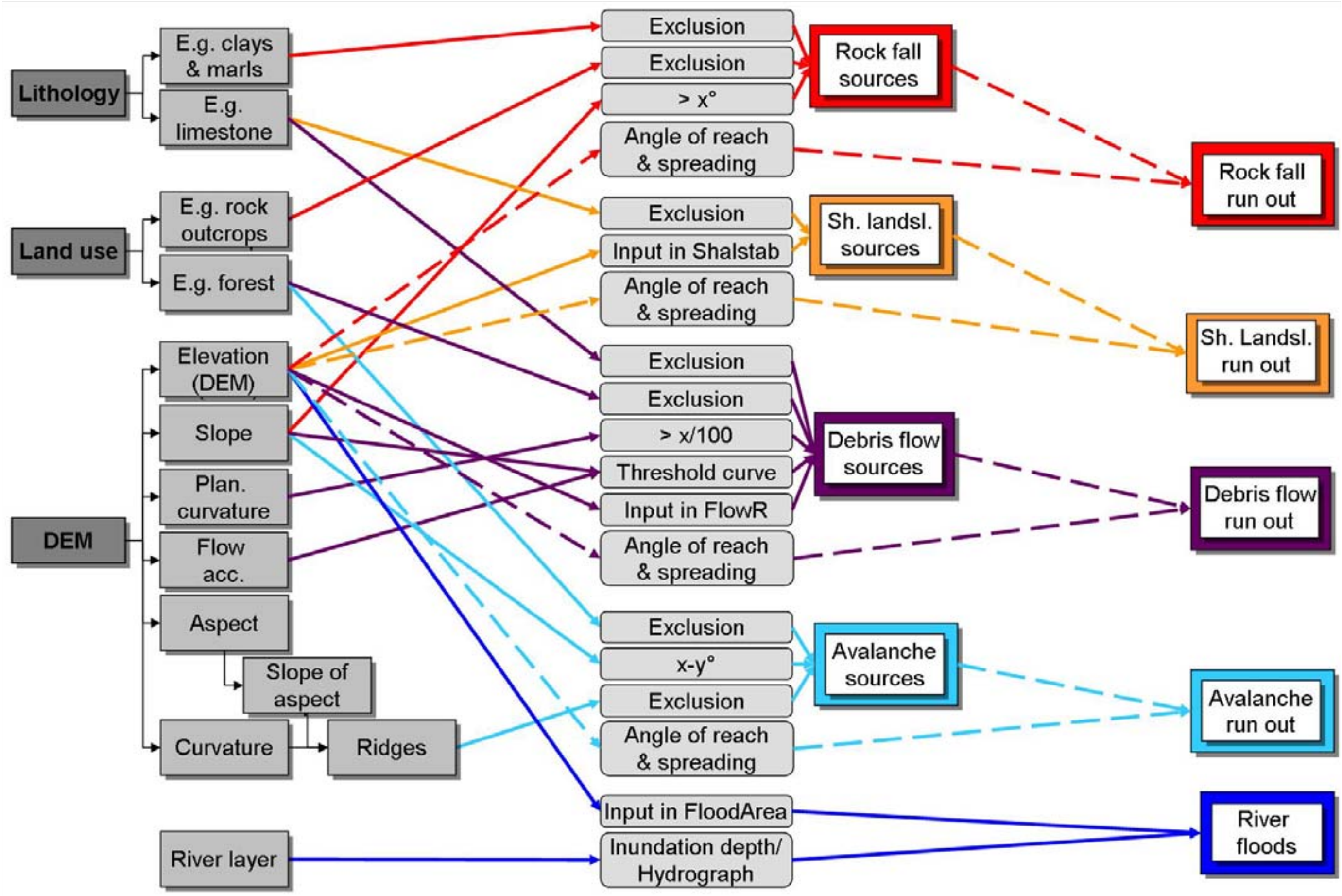

Figure 1 Analysis scheme for medium-scale multi-hazard analyses according to (Kappes et al. in prep)

The Barcelonnette valley

The Barcelonnette valley is situated in the “Département Alpes des Haute Provence” in the South-eastern French Alps. The altitude ranges between 1100 and over 3000 m a.s.l. Autochtonous black marls underlie allochtonous flysch in a geological window (Maquaire et al. 2003) and a multitude of torrents at the north- and south-facing mountain sides is drained by the Ubaye river. For more detail on the area refer to Kappes et al. (in prep).

The environmental characteristics give rise to several landslide types as rock falls (e.g. RTM 2000), rotational and translational landslides (Thiery et al. 2004), mud flows (Malet et al. 2004) and debris flows (Remaître 2006). Other hazards comprise flash floods (Remaître 2006), river floods (Le Carpentier 1963, Sivan 2000), earthquakes (CETE 1987) and snow avalanches (MEDD).

Consideration of disposition alteration

An option to account for an alteration of the disposition has already been presented in Kappes et al. (2010). The potential influences are identified in a matrix (Tab. 1). Those influences relevant at the respective scale are determined and the implementation in the modelling procedure is designed.

Table 1 Matrix for the identification of disposition alterations between hazards. The hazard in the line causes and the hazard in the column receives the influence (modified after Kappes et al. 2010).

Ava-lances	Land cover	Land cover		
	Debris flows			River bed morphology
Slope roughness	Material supply	Rock falls		River bed morphology
Surface roughness	Material supply		Landslides	River course
	Material supply		Erosion/ saturation	River floods

In the case of a medium-scale analysis and with the input parameters proposed in Fig. 1, the alteration of the land cover by snow avalanches, e.g. the destruction of forest which protects from rock falls and debris flows but also from further avalanches, is the only type of disposition alteration which can be considered. River bed morphology, erosion processes or material supply are parameters which are not represented in the input information of this rather generalised modelling approach. By means of a feedback loop the influence of avalanches on the land cover can be accounted for as shown in Fig. 2.

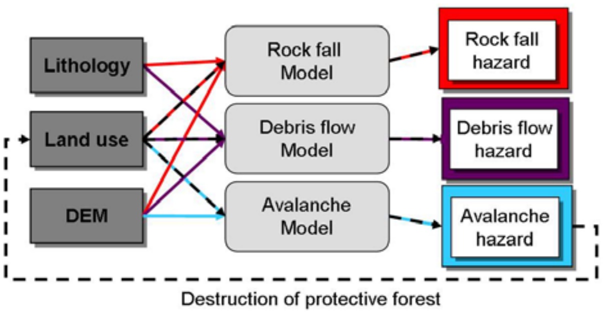

Figure 2 Feedback loop (indicated by dashed lines) implemented in the (simplified) modelling procedure (modified after Kappes et al. 2010).

After having modified the land use, the three processes depending on this input (rock falls, debris flows and snow avalanches - refer to Fig. 2) are re-calculated. This is a fast and user-friendly procedure with the MultiRISK software although the feedback loop itself is not automated.

Consideration of triggering

Within the set of hazards under consideration in this study only two major hazard cascades have been identified: (1) Landslides damming rivers or torrents with the potential to cause upstream flooding and dam break with downstream flooding (e.g. Costa and Schuster 1988), and (2) torrent and river floods undercutting slopes and leading to a slope failure. If this leads in further consequence to a damming of the river or torrent, the same potential consequences as previously described can be expected in addition.

The study of Carrasco et al. (2003) is very instructive concerning a method to identify spots where such cascading events could take place: Based on a landslides susceptibility analysis, (Carrasco et al. 2003, p. 361) determined those slopes that are "connected to streams and torrents (gorges)" as *restrictedly susceptible*, i.e. susceptible to a relation between slope and stream processes. This approach is in broad outline adopted but modified. In the following paragraphs, the adjusted method and the GIS operations used for this study are presented and applied to the Barcelonnette basin:

1. Undercutting of a slope:

By using the flood hazard analysis result and overlying it with the potential source areas of shallow landslides, those zones potentially destabilized by high water can be identified. However, influences can not only be expected in the overlap of both processes but also interferences due to e.g. water saturation of the slope toe and consequently changes in the slope hydrology are likely. This means, the influence may reach beyond the area of actual overlap. In a simple way, this effect can be accounted for by introducing a buffer around the flooded area. The main challenge is the definition of the buffer width, especially the scale, resolution of the DEM and specific characteristics of the area are of importance in this decision.

Example from Barcelonnette

For the Barcelonnette study a digital elevation model of 10 m was available thus a buffer of 10 m and 20 m was applied to the flooded area (Fig. 3). However, a definite decision about the buffer width can only be made after observations in the field.

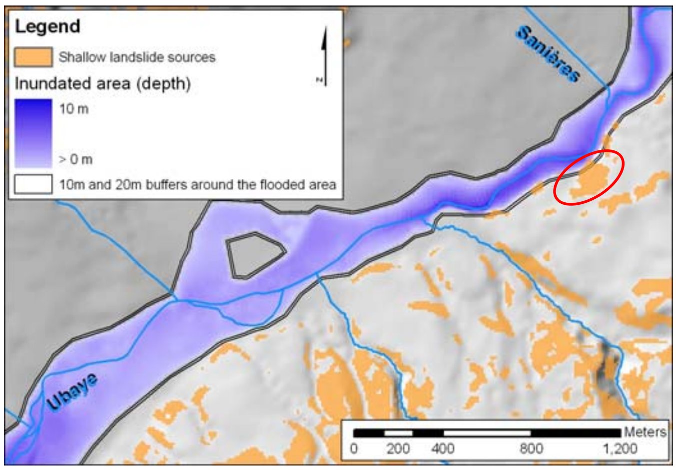

Figure 3 Identification of zones of potential slope undercutting. The area marked with the red ellipse is shown in photograph of Figure 4

As shown in Fig. 3 several locations were identified as susceptible to undercutting. In a field survey multiple spots have been examined and proved to be prone to undercutting. An example is given in Fig. 4 depicting the area situated in the red ellipse of Fig. 3.

Figure 4 Area of potential undercutting of the slope, situated at the Ubaye river close to the confluence of the Sanières torrent with the Ubaye (area located in the red ellipse of Fig. 3).

2. Damming of a torrent/river by a landslide:
To identify those torrent and river sections which could possibly be dammed by landslide material the river and torrent network is overlaid with the landslide run out. However, only in "gorge-type" valleys a damming has to be expected (at least for moderate debris volumes) while in wide valleys the sliding material is most probably not sufficient to block the whole riverbed (Carrasco et al. 2003). In Carrasco et al. (2003) gorge-type valleys are valleys with a bottom not wider than 25 m and identified with a neighbourhood analysis. Since Carrasco et al. (2003) do not provide sufficient detail to reproduce the presented methodology, the landform classification after Jenness (2006) has been applied in this study. The landform classification is based on the topographic position index (TPI) proposed by Guisan et al. (1999) and Weiss (2001). The TPI operates by "calculating the difference between the elevation of the cell and the mean elevation calculated for all cells of a moving circular window centered in the cell of interest" (Guisan et al. 1999, p. 110). The application of thresholds for the TPI values allows the identification of different topographic positions such as ridge, slope, valley, etc. The TPI depends strongly on the size of the neighbourhood taken into account: the larger the considered neighbourhood, the larger are the classified forms. In contrast, small neighbourhoods lead to small-scale classification. For the identification of certain landforms Jenness (2006) combines two TPIs which differ in the size of the neighbourhoods considered for the TPI calculation and defines thresholds at both scales for the different landforms.

When defining the parameters for the landform classification, an important aspect is that the size of the valleys potentially blocked by landslide masses depends on the volume of the slide. This means, large slides can block wider valleys while the material accumulated by small slides may not fill the full width of the riverbed. Thus, the definition of the TPI neighbourhoods implies to a certain degree already an assumption on the volume of the sliding mass.

The gorge-like torrent partitions are determined by overlay of the valleys with the water courses. By a further overlay of these partitions with the area susceptible to be hit by shallow landslides the areas of potential river/torrent damming are identified.

Example from Barcelonnette

Based on expert judgement, the landform classification of Jenness (2006) was carried out with a smaller neighbourhood of 3×3 and a larger neighbourhood of 6×6 pixels. With this combination, areas known by the authors as valleys with steep slopes and small bottoms were determined best. Fig. 5 shows the result for one catchment, the Riou Bourdoux, situated in the Western part of the Barcelonnette basin.

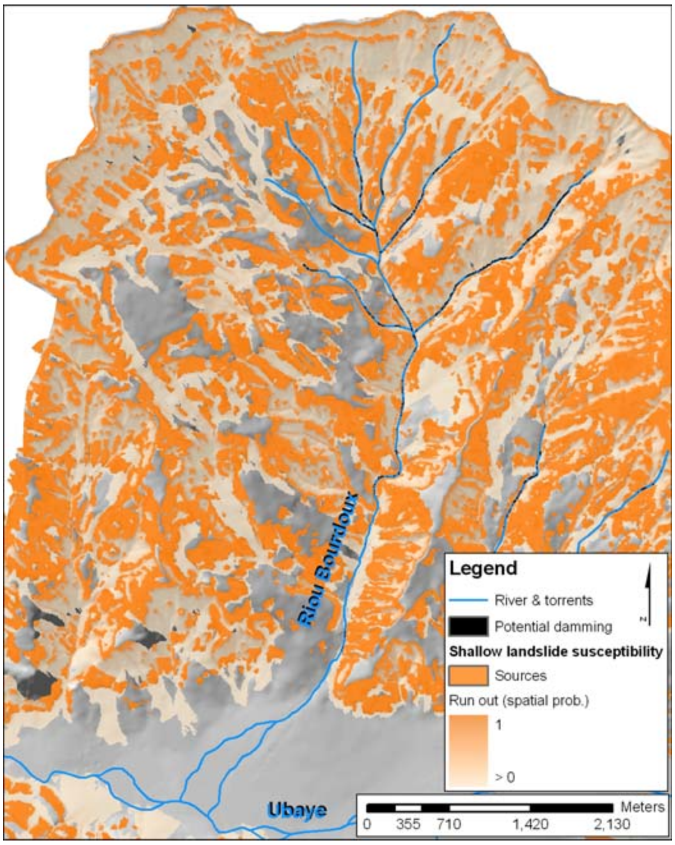

Figure 5 Areas of potential damming of the torrent by landslide masses, example of the Riou Bourdoux.

Apart from the explicit cascades also the triggering of multiple hazards by one event which is not necessarily a hazard (e.g. prolonged rainfall) or a process not included in the multi-hazard analysis should be considered. In the present study, this would primarily include floods, debris flows and shallow landslides as a consequence of precipitation or rock falls and shallow landslides triggered by an earthquake.

Example from Barcelonnette

Concerning the triggering by precipitation the rainfall patterns have to be considered. For the Barcelonnette Basin Remaître et al. (2010) identified heavy daily rainfall as trigger for debris flows while cumulative rainfall, i.e. rainy periods of about 30 days, rather lead to shallow landslide events. However, heavy rainfall after antecedent precipitation could lead to a combination of landsliding and debris flows. In contrast, river floods of the Ubaye, in contrast, are in the Barcelonnette basin the result of prolonged rainfall in autumn or related to very rapid snow melts in spring (Sivan 2000). Consequently, the creation of one map with all three rainfall triggered hazards would not be realistic but a splitting into short heavy and long cumulative rainfalls is advisable. In Fig. 6 an example is given for the case of heavy rainfalls with the potential to trigger shallow landslides and debris flows. The areas susceptible to the effect of one or both are identified.

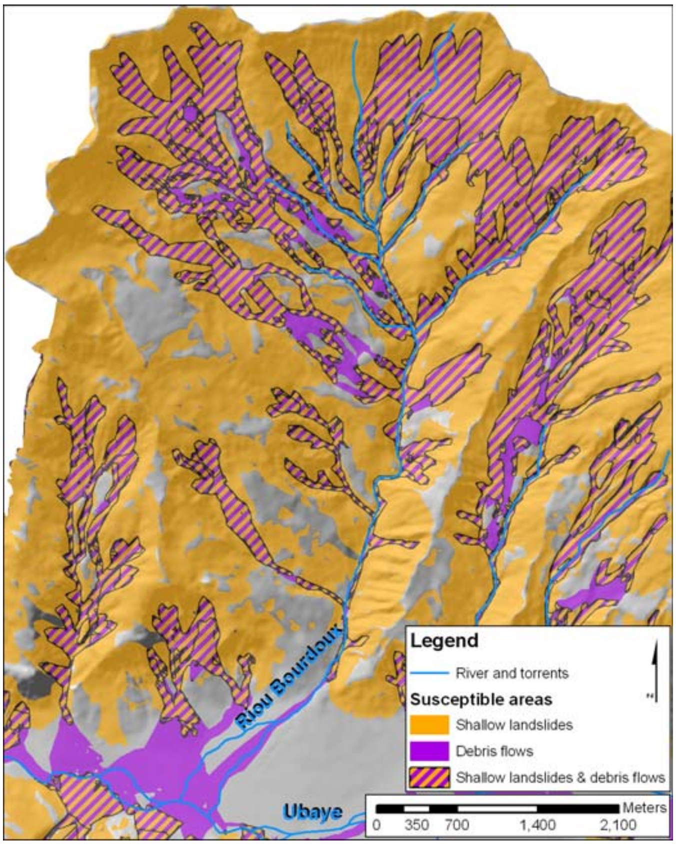

Figure 6 Identification of the area susceptible to being affected shallow landslides and / or debris flows triggered by heavy rainfalls in the Riou Bourdoux catchment.

Conclusions

The integration of hazard relations into hazard analyses is necessary to avoid facing unexpected effects in the aftermaths arising from cascades or feedbacks. The way this can be done depends on the scale level, the methods and models chosen and the hazards combined. However, by means of general identification techniques as matrices a general overview over potential effects can be gained. On this basis, methods suitable to account for relations relevant at the respective scale can be chosen. In this study an example is given for the regional scale at which primarily an identification of spots of potential relations can be performed. However, this is an important starting point for subsequent detailed and time- and data-intensive analyses of the full cascades and effects possibly resulting at these points.

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