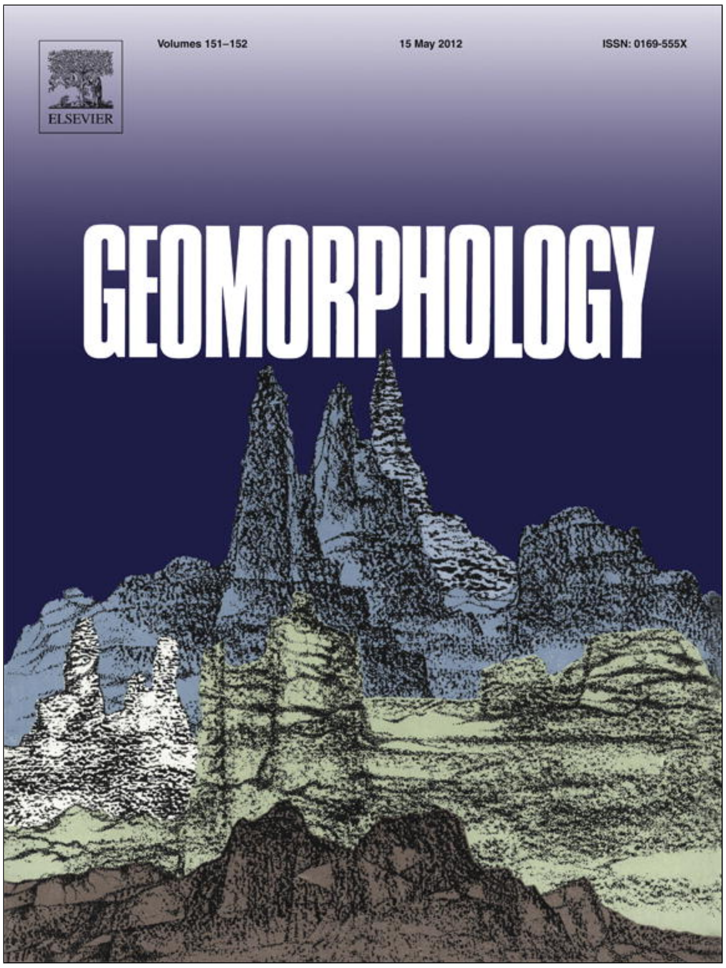
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The MultiRISK platform: The technical concept and application of a regional-scale multihazard exposure analysis tool

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ABSTRACT

Many regions worldwide are threatened by multiple natural hazards with the potential to cause high damages and losses. However, the modeling of multiple hazards in a joint analysis scheme is still in the early stages of development as a range of serious challenges emerges in the multihazard context such as differing modeling approaches in use for contrasting hazards; the time- and data-demanding conduct of each single preparative, intermediate and analysis step; and the clear visualization of the modeling outcome. Under consideration of these difficulties, a regional multihazard exposure analysis concept is developed for five natural hazards: debris flows, rock falls, shallow landslides, avalanches, and river floods, complemented by a visualization scheme to present the modeling outcome. An automation of the two schemes resulted in a beta version of the MultiRISK modeling and the MultiRISK visualization software tool forming together the MultiRISK platform. To test the analysis scheme and the software implementation of MultiRISK a case study is performed in the Barcelonnette basin in France with a worst-case parameterization of the models on the basis of extensive literature reviews. Experiences from this case study offered many insights into the multihazard topic and even more questions, e.g. with respect to coherent multihazard model parameterization, validation or the comparability and interpretation of single-hazard modeling results, respectively. Although analysis schemes can be proposed and software tools can be provided to facilitate many steps, a well-conceived and reflective approach to multihazard settings is essential. The worst-case analysis based on literature values apparently leads to an overestimation of the susceptible areas and the number of exposed elements. Nevertheless, depending on the data situation of an area, especially in areas without any information on past events, this approach may offer the determination of general hazard distributions, overlaps, and areas of potential risk without data-demanding calibration.

1. Introduction

Many areas of this world – as for example coastal zones, mountainous regions, or volcano vicinities – are threatened by multiple natural hazards. However, natural hazards are usually still examined and managed separately. Only in a few studies are multiple threats analyzed jointly and the overall hazard and/or risk are assessed, e.g. by van Westen et al. (2002), Bausch (2003), Bell and Glade (2004), Glade and van Elverfeldt (2005), Reese et al. (2007), Bründl et al. (2009), or Marzocchi et al. (2009). Considering a joint analysis of multiple hazards, numerous challenges and difficulties arise (Kappes et al., in review): (i) hazards are not directly comparable as their characteristics and their describing metrics differ, for instance inundation depth of floods versus impact pressure of rock falls. Moreover, various hazard types act at very differing spatial and temporal scales. While rock falls are very local phenomena with an often high frequency of smaller events, earthquakes are regional scale processes with mostly low frequency but high magnitude. Furthermore, (ii) the analysis methods and models used for distinct hazards also diverge widely with respect to inherent assumptions and model principles. These differences complicate the comparability of analysis results (Kappes et al., 2010). Apart from the challenges concerning the comparability of modeling results, another major issue is (iii) the performance of such an analysis since knowledge and experience in many different disciplines is required. Moreover, (iv) the data acquisition and the preparation as well as the modeling and assessment of hazards, exposure (elements at risk/vulnerability) and risk for single-hazard procedures consist of a large number of different analysis steps that are complicated and thus time-consuming and prone to

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mistakes. However, re-running the analysis repeatedly would be desirable in order to evaluate, e.g., the effect of management options or to consider changes in land use, in the climate, in the general environmental setting, or in alterations of the elements at risk (Dai et al., 2002; Fuchs and Keiler, 2006; Slaymaker and Embleton-Hamann, 2009).

A possible approach considering these challenges is the selection of methods according to previously defined criteria, and their subsequent merging in one software tool in which preparative and intermediate steps are automated. Such a procedure leads to comparable single-hazard results since the single hazards are analyzed according to a coherent analysis scheme, and result in a higher time and effort efficiency for the user by automatically performing purely elementary steps. Although still expert input from different disciplines is needed to calibrate the models, profound knowledge on existing methods and models for the choice of the approaches is not necessarily required as they are included in the software tool. Current pioneer approaches include HAZUS in the USA (Schneider and Schauer, 2006; FEMA, 2008), that offers hurricane, earthquake and flood hazard and risk modeling. RiskScape in New Zealand (Reese et al., 2007) facilitates currently volcanic ashfalls, floods, tsunamis, landslides, storms, and earthquakes. CAPRA (Central America Probabilistic Risk Assessment) provides the analysis of hurricanes, heavy rainfalls, landslides, floods, earthquakes, tsunamis, and volcanic hazards (CEPREDENAC et al., 2010). Such tools enable user-friendly and straightforward performance of multihazard analyses and comparability between single hazards, furthermore their widespread and repeated use also guarantees comparability between results of analysis from different municipalities or departments and between analysis results over time.

A final issue in the multihazard context is the huge data requirement. Extensive and qualitatively high standard inventories of past events – including detailed spatiotemporal patterns, particularly with an equivalent standard for multiple hazards – are rare. In most regions huge differences in quality and dimension exist between the single-hazard inventories — if records of past events are available at all. Furthermore, the more detailed the models, the more detailed data on topography, geology, soils, land use, precipitation distribution, etc. is required. A possibility to partly overcome these constraints is a top-down approach. Thereby, a simple and fast analysis approach at a small scale provides an approximation. In a next step, more detailed and sophisticated (and thus also more data-requiring) methods at a larger scale are applied. By using the small-scale modeling results to define those areas for which detailed studies have to be carried out, resources can be utilized very efficiently.

Under consideration of the previously mentioned challenges, the MultiRISK platform has been designed. This software is projected to offer the analysis of multihazard risk according to a top-down approach, in relation with a visualization tool to display the results. In the current version of MultiRISK, the GIS-based regional-scale susceptibility and exposure analysis (elements at risk) is completed (1:10,000–1:50,000) for the typical mountain hazards avalanches, debris flows, rock falls, shallow landslides, and river floods. In the next step detailed vulnerability considerations and risk analyses at a scale <1:10,000 will be implemented (cf. Kappes et al., 2011b for a first attempt regarding vulnerability in the context of multihazard risk). Therefore, the name MultiRISK platform is chosen although until now only susceptibility/hazard and exposure analysis can be carried out by applying the current version of the tool while the vulnerability of elements is not taken into consideration so far. The applied scale levels correspond to the approaches used in several alpine countries such as Germany, France and Switzerland with hazard indication maps (Gefahrenhinweiskarten) at the scale 1:10,000–1:25,000 and the hazard zone plans <1:10,000 (Stötter et al., 1999). Thereby, the hazard indication maps comprise an overlay of susceptibility maps and elements at risk and provide a first approximation, while hazard zone plans offer a level of detail that allows decision making to reduce risks.

In this article, the development of the regional scale analysis of MultiRISK and the resulting methods and software will be presented together with the performance of a multihazard exposure analysis case study in the Barcelonnette basin, France. First, the analysis scheme for hazard modeling with well-available data used as input, hazard model validation, and exposure analyses is presented in Section 2. Thereafter, a visualization scheme to display and communicate the results in a well-structured way is outlined in Section 2.4. The analysis scheme is automated in a user-friendly software (Section 3.1). The visualization outline is implemented into a visualization tool to present the results automatically in a web browser interface (Section 3.2). In order to test the developed MultiRISK modeling and visualization tools, they are applied in the Barcelonnette basin (Section 4). Finally, the challenges and specifics in a multihazard setting are discussed in Section 5 based on the insights which emerged during the development and implementation of the analysis scheme and of the MultiRISK platform.

The definition of key terms differs between scientists as well as between disciplines and processes. This has become evident when working in the field of multihazards and risks. In this contribution the definition of hazard (in the general and technical context) and exposure are used according to UN-ISDR (2009b), and susceptibility considering Guzzetti et al. (2005, p. 277). The term risk is based on the definition of WMO (1999, p. 2) and the social dimension of risk (e.g., Wisner et al., 2004) is not addressed in this contribution.

2. Development of a regional-scale analysis and visualization scheme of multihazard exposure

The multihazard risk analysis scheme proposed in the present study follows a top-down approach in which a regional exposure analysis provides the identification of hazard distributions, hazard overlaps, and zones of potential damages and losses. Subsequently, detailed, local hazard and risk analyses on the basis of more sophisticated models are to be carried out for the previously defined points. In the present study, however, only the regional-scale exposure analysis scheme is outlined and its implementation into a software tool is presented, while the local-level analysis will be elaborated in future works and only its function is defined here.

The regional exposure analysis is composed of three components: the hazard modeling, the validation of the modeling results, and the exposure analysis. These will be explored in the following sections.

2.1. Hazard modeling

The first step in a multihazard top-down approach offers a regional approximation by means of fast and simple methods. As explained before, the data need for multihazard analyses is, in general, a limiting factor. Consequently, the availability of input data is a major criterion for the model choice and determines significantly the tool's applicability. For GIS-based models, *input* refers to two types of information: (i) areawide information, i.e. information layers (e.g., elevation, land use or geology) and (ii) information to calibrate or parameterize the model, e.g. inventory data, soil properties, and precipitation or discharge time series.

(i) Topographic characteristics, derived from digital elevation models (DEM), are usually the most important spatial input data for GIS-based modeling of natural hazards. This information is already available in many regions of the world or can be produced with acceptable effort from topographic maps, satellite imagery, and laser scanning. From the DEM, a variety of derivatives such as slope angle, curvature, aspect, or distance to ridge/drainage line can be deduced. Mountain

hazards are particularly coupled with topographic characteristics and therefore these data are highly valuable for any model. Consequently, the regional analysis is primarily based on the DEM including its derivatives, and the required models to be chosen have to be operable with this topographic input.
To optionally extend the topographic information, additional data such as land use/cover were implemented. These data are rather easy to create, for example, from remote sensing images or, in coarse resolution, as free image sharing from GoogleEarth. Furthermore, lithological information is included into the modeling approach as geological maps exist in many countries and regions and the lithology and tectonic lineaments influence many natural hazards significantly.

(ii) The second criterion for the model choice is the straightforwardness of the model calibration/parameterization (in this article calibration is understood as the process of adjustment of a model to measured data, while parameterization refers to expert appraisal or adoption of parameters used in other studies). Models with indispensible need of data from field or laboratory analyses, time series, or extensive inventories do not fit the objective of a simple and fast first approximation of an area. The models have to be straightforward and comprehensive to enable a flexible calibration on the basis of detailed information, if available. For cases of low data availability, the objective is to choose models that allow completion with expert knowledge or even parameterization exclusively with expert experience or studies carried out in comparable settings.

Furthermore, only models developed for a regional scale (1:10,000–1:50,000) were selected to ensure, as far as possible in a multihazard environment, the comparability of the results. Apart from these criteria, the model choice is open and the models selected here can be exchanged by other suitable ones (concerning scale, data input needs etc.). In the current version of MultiRISK, the processes of snow avalanches, shallow landslides, debris flows, rock falls, and river floods are considered. The different selected models and the methodology of their implementation are presented in the following sections.

2.1.1. Debris flows

The source identification is carried out with the Flow-R model (Horton et al., 2008, 2011). This model is based on the three topographic parameters slope angle, upslope area, and planar curvature. These parameters represent directly (slope) or indirectly (upslope area and planar curvature) three major factors for debris flow disposition (Takahashi, 1981; Rickenmann and Zimmermann, 1993): slope gradient, sediment availability, and water input. Upslope area and planar curvature serve as indicators for the convergence of sufficient water and material in gully structures. Upslope area is considered in combination with slope angle because in smaller catchments, less material is accumulated and more water from steeper slopes is needed to enable the debris flow initiation. In contrast, larger catchments are supposed to accumulate higher volumes of sediment and water that start moving at lower angles (Fig. 1).

Additionally, certain land use/cover types and lithological units can optionally be excluded. For example, dense forest influences surface runoff and buildup areas or outcropping rocks determine material availability. For more details on Flow-R, refer to Horton et al. (2008, 2011), Blahut et al. (2010) and Kappes et al. (2011a).

For the runout modeling, again the methodology proposed in Flow-R has been applied. The spreading of the flow is computed with the multiple flow direction algorithm according to Holmgren

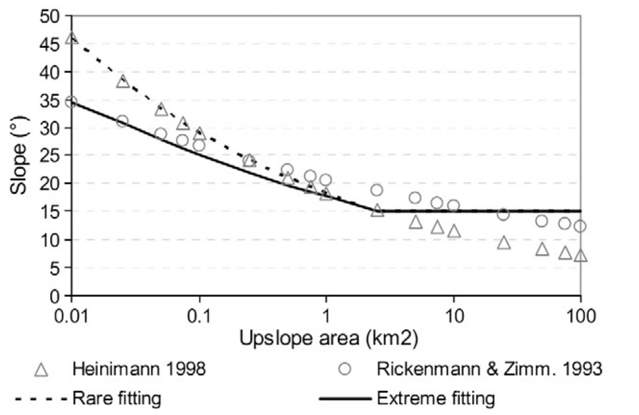

Fig. 1. Coupled consideration of slope angle and upslope area for debris flow modeling (Horton et al., 2008). Below an upslope area of 2.5 km^2, the slope angle to start the movement is rising with decreasing area, while above 2.5 km^2 it is assumed to be constant at 15°. Reasons for this approach are the difference in water and sediment availability.

(1994), an expansion of the basic multiple flow direction algorithm developed by Quinn et al. (1991):

$$f_i = \frac{(\tan\beta_i)^x}{\sum_{j=1}^{8}\left(\tan\beta_j\right)^x} \quad \text{for all} \tan\beta > 0 \tag{1}$$

where i,j = flow direction (1–8), f_i = flow proportion (0–1) [%] in direction I, tan β_i = slope gradient between the central cell and cell in direction I, and x is an exponent introduced by Holmgren (1994). For $x = 1$, the algorithm converts into the basic multiple flow direction after Quinn et al. (1991), and for $x \to \infty$, into a single flow. The spreading is complemented by a persistence function. This function accounts for the inertia of the flow by a weighting of the change of angle from the last flow direction. For 0°, a weight of 1 is assigned, for 45° 0.8, for 90° 0.4, for 135° and for 180° 0. The distance of the runout is computed with a constant friction loss angle, thus not considering the surface roughness. This angle corresponds to the *Fahrböschung* of Heim (1932), translated as *angle of reach* by Corominas (1996), which refers to the angle between a line from the highest point of the source area to the maximum runout and the horizontal. In Flow-R the angle is applied as a constant loss variable in an energetic computation while the flow propagates from pixel to pixel (Horton et al., 2008):

$$E^i_{kin} = E^{i-1}_{kin} + E^i_{pot} - E^i_{loss} \tag{2}$$

with the time step i, the kinetic energy E_{kin}, the change in potential energy ΔE_{pot}, and the constant loss E_{loss}. The flow stops as soon as the kinetic energy drops below zero. At the overlap of the flows from different sources, the maximum value of the spatial probability that this pixel might be hit and the maximum kinetic energy of all overlapping flows are calculated.

Two runout calculation modes are offered: quick and complete. In the complete mode, each single source pixel is propagated. In the quick models, first the superior sources are propagated. If lower ones follow the same path with a similar or lower kinetic energy, they are neglected. This reduction of single calculations enables significant time saving.

2.1.2. Rock falls

A commonly used method for automatic rock fall source identification is the classification of the slope gradient map. Hereby, a threshold angle is defined above which the area is identified as potentially rock fall producing rock face (Ayala-Carcedo et al., 2003; Guzzetti et al., 2003; Jaboyedoff and Labiouse, 2003; Wichmann and Becht, 2006; Frattini et al., 2008). As already described for the debris flow source modeling, specific land use/cover and lithological units, e.g., outcropping marls, can also be excluded as potential rock fall source areas. As for debris flows, the runout is modeled by means of the Flow-R model according to Horton et al. (2008).

2.1.3. Shallow landslides

In contrast to the processes treated until now, areas susceptible to shallow landslides are usually analyzed with statistical and physically based methods rather than with empirical models. However, statistical models are commonly not easy to transfer, and physically based models require a high quantity of geotechnical input data and thus are also not suitable for a regional approach. Nevertheless, a variety of physical models were adjusted to the input of information derived from DEMs. Because topographic characteristics control water confluence, downslope forces, etc. this effort proved to be successful as multiple models indicate, e.g. SLIDISP of Liener and Kienholz (2000), SHALSTAB of Montgomery and Dietrich (1994) and Dietrich and Montgomery (1998), or SMORPH of Shaw and Johnson (1995). Among these methods, SHALSTAB (SHAllow Landsliding STABility; Montgomery and Greenberg, 2009) was selected because it offers the option to compute a first approximation of an area without the need of detailed calibration. The slope stability package after Montgomery and Greenberg (2009), which refers to SHALSTAB, was chosen because it can be directly included as a toolbox in ArcGIS 9.x, while the original version of Dietrich and Montgomery (1998) is an ArcView 3.x application. SHALSTAB couples a "hydrological model to a limit-equilibrium slope stability model to calculate the critical steady-state rainfall (Q_c) necessary to trigger slope instability at any point in a landscape" (Montgomery et al., 1998, p. 944). Under negligence of soil cohesion, the following equation emerges (Montgomery and Dietrich, 1994; Montgomery et al., 1998):

$$Q_c = \frac{T\sin\theta}{a/b}\left[\frac{\rho_s}{\rho_w}\left(1-\frac{\tan\theta}{\tan\phi}\right)\right] \quad (3)$$

with the soil transmissivity T [m^2/d], the hillslope angle θ [°], the drainage area a [m^2], the outflow boundary length b [m], the soil bulk density ρ_s [kg/m^3], the water bulk density ρ_w [kg/m^3], and the angle of internal friction ϕ [°]. By using a "single set of parameter values" (ρ_s, ϕ and ρ_w are constants) plus the areawide DEM derivatives (a, b and θ) the "regional influence of topographic controls on shallow landsliding" can be assessed without any specific calibration (Montgomery et al., 1998, p. 943). Dietrich and Montgomery (1998) explained that SHALSTAB was not performing well in areas dominated by rocky outcrops or cliffs. Hence, an option is included to optionally exclude, e.g., limestone outcrops and other lithological units as potential sources.

Although much less used, the angle of reach principle can also be applied for the runout calculation of shallow landslides (e.g., Corominas et al., 2003), and thus the Flow-R model was applied in this case as well.

2.1.4. Avalanches

Maggioni and Gruber (2003) developed a methodology for the determination of potential release areas primarily based on topographic parameters that was simplified by Barbolini et al. (2011). This methodology applies the following criteria: For avalanche initiation, a certain minimum slope angle is necessary to enable the movement; however, very steep slopes will not accumulate enough snow for avalanche formation. Thus, avalanches can be expected at slopes between a lower and an upper threshold angle. Specific land use types, especially dense forest that will stabilize the snow pack in the release area, can be excluded as potential sources as well as ridges where too little snow accumulation can be assumed.

For the computation of the avalanche runout, apart from the angle α, which corresponds to the angle of reach, further angles are in use: β is the angle of the avalanche track between the source and the point of the slope with 10° (β point), and δ is the average angle of the runout zone between the β point and the stopping point of the avalanche (Bakkehøi et al., 1983; Keylock, 2005). To keep the methodology simple, the angle of reach (equivalent to the angle α) was chosen, and runout calculation is performed by means of Flow-R as well.

2.1.5. Floods

The simplest method to estimate floodplain inundations is the linear interpolation of a gauge water level in intersection with a DEM (Apel et al., 2009). Models representing hydrodynamic characteristics such as HEC-RAS (US Army Corps of Engineers, 2011), Sobek (Deltares, 2011), and others need more detailed information on channel geometry and roughness, hydrograph information, etc. The ArcGIS extension FloodArea of Geomer (2008) offers both methods: modeling on the basis of a certain inundation depth or by means of a hydrograph and several more options. In the modeling scheme of the MultiRISK software both options were included to offer a choice depending on the quantity and type of data available for the model calibration/parameterization.

The combination of the previously described single-hazard models to one overall analysis scheme is challenging. However, it is evident that different natural hazard models require similar data, and therefore the combination of these models in a multihazard analysis provides a major advantage in order to gain synergies and consequently time-savings in a joint study. The flow chart of the resulting model setup is presented in Fig. 2.

2.2. Validation

Because comprehensive event inventories at a comparable quality and extent for a multitude of hazards are scarce, not only the calibration/parameterization of the models but also the validation has to be flexible concerning the input of information on past events. Because of their simplicity, confusion matrices as described by Beguería (2006) and Carranza and Castro (2006) meet exactly this need. They are based on an overlay of the binary (yes/no) layer containing the modeling result with the layer of the recorded events. The models described in the previous section produce directly binary source maps while the runout computations yield spatial probability and kinetic energy, respectively, and the flood modeling outputs the inundation depth. Reclassifying the continuous results, binary maps were produced. Two options of validation of the modeled source and of validation of the complete area as a composite of the modeled sources and runout are given. Since, especially in the case of shallow landslides, a clear differentiation between source area and runout is often not possible this division in sources and complete area seems to be much more practical than to differentiate between sources and runout. Furthermore, river flooding cannot be subdivided into source and runout zone; however, the area susceptible to floods can be perfectly assigned to the *complete* category.

From the overlay of the modeling results and the recorded events, four classes emerge. In these classes, the totality of pixels is classified and the numbers are depicted in a confusion matrix (Table 1).

The true positives (TP) refer to the recorded events that were correctly modeled as threatened, while the false negatives (FN) draw attention to those zones that were missed by the model. The false positives (FP) are de facto not errors but "cases highly propense to develop the dangerous characteristic in the future" (Beguería, 2006, p. 322). The identification of these areas in which still no events took place, but a high potential for future incidences exists, is the objective of hazard modeling. However, a too conservative modeling approach

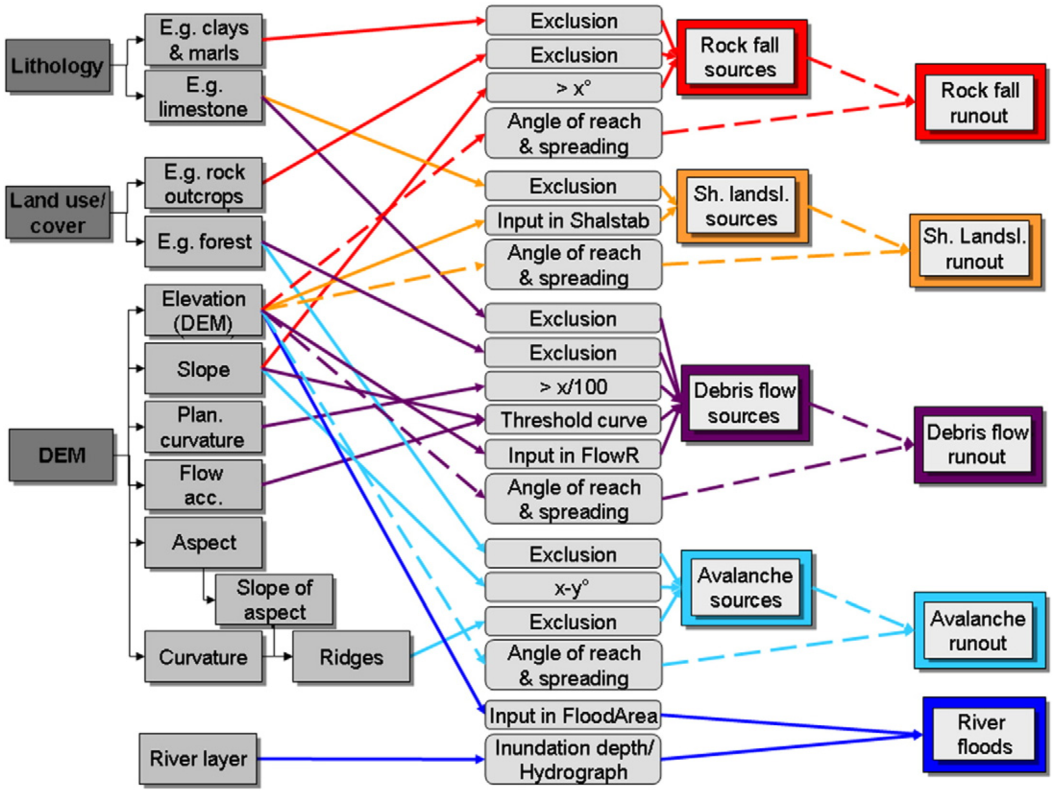

Fig. 2. Flow chart of the analysis scheme for rock fall, shallow landslides, debris flows, avalanches, and floods. On the basis of the DEM and optionally land use and lithology (in dark gray boxes on the left side), a multitude of derivatives (such as slope, planar curvature or flow accumulation; medium gray boxes) are computed. They form the input for the models (light gray boxes with rounded edges) by means of which first the source areas are identified and second the runout is modeled (dashed lines).

could lead to a strong overestimation of the actual threat, thus the proportion of false negatives should be compared to the proportion of true positives to better appraise the quality of the prediction. The true negatives (TN) are even more difficult to evaluate because, in general, inventories indicate only the recorded zones but not *unsusceptible* ones. Thus, the remaining area adjacent to zones of recorded events is not *surely safe* but events might simply not have been recorded or happened yet. However, this does not indicate a sure exclusion of the possibility that it could happen and consequently no *true negatives* exist in the strict sense of the term.

On the basis of the four classes of the confusion matrix (Table 1), Beguería (2006) proposes several quality indicators. Two of them were chosen for the multihazard context:

$$\text{Sensitivity: } TP/(TP+FN) \quad (4)$$

$$\text{Positive Prediction Power: } TP/(TP+FP). \quad (5)$$

While the sensitivity indicates which proportion of the recorded events has been modeled correctly and which proportion not, the positive prediction power (PPP) serves as a measure of the effectiveness of the modeling. For instance, a very high sensitivity might suggest a very good modeling result; however, a coincident low PPP indicates an overestimation of the threatened area.

Table 1
Confusion matrix according to Beguería (2006). Either the area [m^2] or the area proportion [%] can be depicted in the cells.

		Observed	
		Yes	No
Predicted	Yes	True positive (TP)	False positive (FP)
	No	False negative (FN)	True negative (TN)

2.3. Exposure analysis

The exposure is analyzed by overlaying the process footprints with the elements at risk, and endangered elements are marked. As for the validation, two options are offered: the area susceptible to source instabilities and the complete susceptible area. Especially for the comparison with the elements exposed to river flooding, the *complete* options is very important; however, for shallow landsliding, a significant difference exists between those houses situated on the slide and those possibly being hit by a slide. By offering both options (sources and complete), the specifics of landslides and floods are accounted for, as well as for the comparability between them.

In accordance to overlay options and the feature classes available in ArcGIS, three different exposure analyses are possible:

(i) Punctual, lineal, or areal elements (points, lines, or polygons) are uploaded and are treated as entire units: the element is identified as exposed if it intersects at least partly with the susceptible area and the number of affected elements is counted. This option is suitable for elements such as buildings or pylons.
(ii) Linear elements (lines): the length of the line intersecting with the susceptible area is identified, marked, and measured. This option is offered for the examination of the exposure of lineal elements such as roads or water supply lines.
(iii) Areal elements (polygons): the area intersecting with the susceptible area is identified, marked measured. This option especially suits the analysis of built-up areas and land use units.

2.4. Visualization scheme for the display of multihazard risk analysis results

As identified in the review of Kappes et al. (in review), the visualization of the multidimensional result of a multihazard risk analysis poses a major challenge. Several options to depict the different facets of the output have been identified in this contribution (refer to Kappes et al., in review, for details):

- Visualization of susceptibility, hazard, exposure or risk of each single hazard type separately and in detail (e.g. Odeh Engineers, Inc., 2001; Bell, 2002; Dilley et al., 2005). This option allows discovering and recognizing single-hazard patterns without confusing the map reader with too much information.
- Visualization of the overlay of several hazard types (e.g., Bell, 2002; UN-ISDR, 2009a). The number of hazards that can be included is limited because overloading with too much information may lead to confusion.
- Visualization of a joint variable such as the number of overlapping hazards (e.g., Odeh Engineers, Inc., 2001).

The identified options were adopted and used as the core of a visualization scheme that communicates step by step the different aspects and results of the multihazard exposure analysis. Details are described in chapter 3.2.

3. The MultiRISK platform

3.1. MultiRisk modeling tool

Because of the large number of single steps (Fig. 2) and the time-consuming and error-prone performance of a multihazard analysis, the whole procedure was automated in the software called MultiRISK Modeling Tool. MultiRISK is programmed in Python accessing ArcGIS 9.x toolboxes and offers a graphical user interface for the straightforward operation. The single models are implemented either by activation of external software (e.g., the Matlab-programmed stand-alone software Flow-R), direct inclusion (e.g., the ArcGIS toolbox Flood-Area) or programming in Python on the basis of ArcGIS tools of the ArcToolbox (e.g., the source identification method after Maggioni, 2004). The user is guided through the single steps of the three main components of the modeling tool (Fig. 3): the process modeling, the process model validation, and the exposure analysis. If for one or several processes an analysis has already been carried out, the tool offers the upload of this project and the subsequent performance of any of the three further steps (see bended arrows in Fig. 3). After having finished the multihazard exposure analysis, the preparation of the MultiRISK visualization can be directly launched to view the results thereafter.

The preparation primarily implies the copying of all result files in a previously defined project folder from which the visualization tool obtains the information for display. Running all modeling, validation and exposure analysis steps up to 29 result files are produced. Thus, to not burden the user with the naming of the many output files, the names are generated automatically according to a modular terminology. Appended to the user-defined project name (max. seven letters), extensions referring to the process (_av for avalanches or _rf for rock fall), to the area (_s for sources, _r for runout, and _c for complete), and to the analyses carried out (_val for validation) are added. Consequently, the VALidation result of the Complete area susceptible to AValanches for a project called Barcelo would be named Barcelo_av_val_c (for more detail refer to Kappes, 2011).

3.2. MultiRISK visualization tool

The visualization has been automated to prevent the user from having to open each of the max. 29 result files in ArcGIS, and define colors, patterns, and symbols. Additionally, the contemplation of the outcome in such an application does not require GIS and cartography experience and in this way enables the presentation of the results to a broader audience. The visualization tool is designed with the comprehensive and free Web-GIS framework CartoWeb and is embedded in a MapServer engine. The visualization is accessible by the user with a standard internet browser. Currently the visualization tool is applied in a local host environment but can be modified in the future to be published in the internet, potentially also considering different user groups and respective access to the various data sets. It is structured in different switches, i.e., interactive maps (Fig. 4):

(i) General settings: display of basic information on the area as the input data of the hazard models (e.g., slope, curvature, lithology, land use/cover, etc.) and others. The user gets the possibility to become acquainted with the area and its characteristics. All basic information of interest to the users can be included.
(ii) Single hazards: only one hazard type can be visualized at a time, but in detail, i.e., the spatial probability of the runout (e.g. of debris flows) or the inundation depth (floods) is presented. The color scheme for the hazard types is adopted from the Swiss *Symbolbaukasten* after Kienholz and Krummenacher (1995).
(iii) Overlapping hazards: a maximum of three hazards can be shown simultaneously. The overlapping areas are displayed

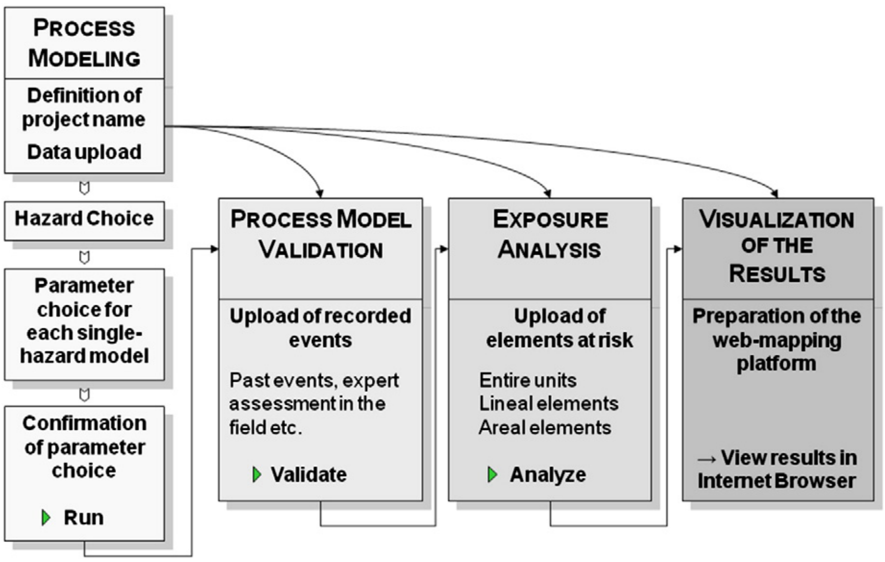

Fig. 3. Flow chart of the MultiRISK modeling tool.

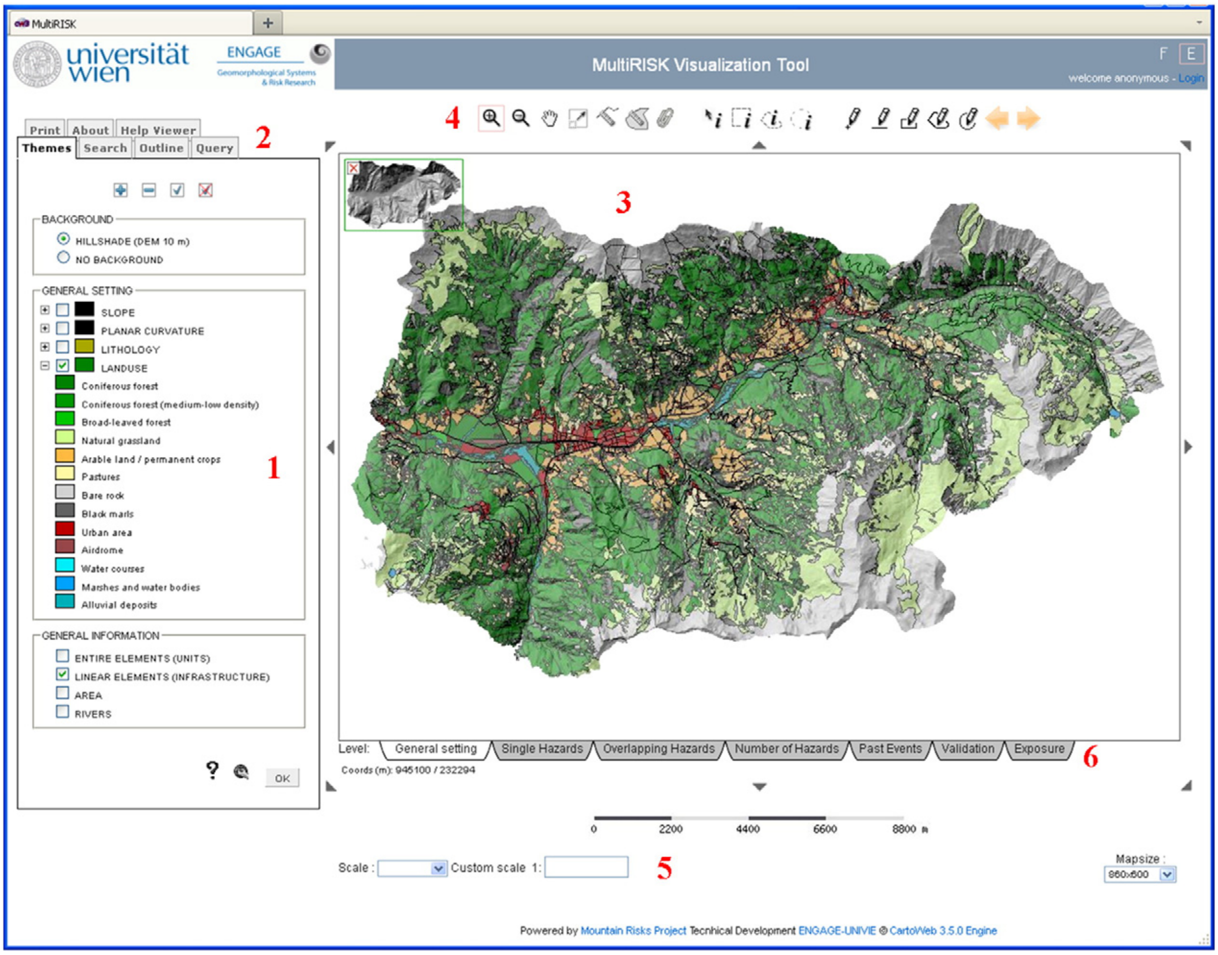

Fig. 4. Screenshot of the visualization tool. The following descriptions refer to the red numbers in the graphic: (1) Layers tree, managed by the user. According to predefined options layers can be switched on, off, overlain, etc. (2) Tabs for query, printing, and online guide. (3) Map area and key map visualization. (4) Tools for cartographic interaction as zoom in/out, spatial query, etc. (5) Scale and map size customization. (6) Tabs to access the different interactive maps.

as combinations of the colors and patterns of the respective hazards. No details are given on the single hazards; only the footprints are shown to not confuse the map reader.

(iv) Number of hazards: to give the full overlay information but not confuse the reader, the number of overlapping hazards is shown without depicting the type of hazards summing up to this number. By means of a spatial query the user obtains the information which hazards combine to the respective number.

(v) Past events: the records on past events that were uploaded for the validation are presented. The user gets the opportunity to observe the distribution, coverage, and patterns of recorded past events.

(vi) Validation: visualization of the overlay of records and modeling result for each single hazard separately showing the true positives, the false negatives, and the false positive. The distribution of true positives and false negatives may indicate situations the model can account for very well and others it cannot. Furthermore, the pattern of those zones that have not been affected until now (or at least no events have been recorded) but might in the future be hit, the false positive manifests. By clicking on a hyperlink, an additional tab opens showing the confusion matrix as a table indicating the areas in each class in [m^2].

(vii) Exposure: for one hazard at a time the process areas (either source or complete area) are depicted together with the highlighted exposed elements. By clicking on a hyperlink, an additional tab opens with, e.g., the number of buildings (entire elements), length of infrastructure and/or built-up area (proportion of polygons) exposed.

Basic information is offered for display in each tab and includes the hillshaded DEM, buildings, infrastructure, buildup areas, and water courses.

4. Case study: an exposure analysis in Barcelonnette, France, considering multihazard

A case study is performed to accomplish two objectives: (i) to test the practicality and user-friendliness of the MultiRISK platform; and (ii) to appraise the ability of the multihazard exposure analysis scheme to account for challenges arising in this context. By contrast, the objective is not to perform scenario analyses based on detailed calibration offering as reasonable results as possible, since the time-consuming data gathering and model adjustments go beyond the scope and possibilities of this case study.

4.1. The Barcelonnette basin

The Barcelonnette basin is located in the southern French Alps in the Département Alpes des Haute Provence. It covers the major part of the Community of Communes 'Vallé de l'Ubaye', an alliance of eight communities with a population of ~6500 inhabitants. The valley varies between an altitude of 1100 and 3100 m asl and is drained by the Ubaye River which consists of a large number of torrents (see Fig. 5). The study area exhibits (i) a mountain climate with pronounced interannual rainfall variability (735 ± 400 mm) and 130 freezing days per year, (ii) continental influence with large intraday thermal amplitudes (>20°) and multitudinous freeze–thaw cycles, and (iii) Mediterranean influence with summer rainstorms providing occasionally more than 50 mm/h (Flageollet et al., 1999; Maquaire et al., 2003; Kappes et al., 2011a). Apart from summer rainstorms, heavy precipitation onto melting snow accumulations in spring result in high discharge (Flageollet et al., 1999). Mesoclimatic differences emerge because of the east–west orientation of the valley, especially between the north- and south-facing slopes. Geologically, the valley presents a structural window with autochtonous Callovo-Oxfordian black marls (the 'Terres Noires') below allochtonous Autapie and Parpaillon flysch (Évin, 1997; Maquaire et al., 2003).

The geological setting is reflected in the specific morphology. The upper slopes between 1900 and 3000 m asl are composed by thrust sheets of cataclastic calcareous sandstones and exhibit slope angles steeper than 45°. These slopes are partly covered by layers of nonconsolidated debris with thickness ranging between 0.5 and 5 m. The lower slopes from 1100 to 1900 m asl consist of Callovo-Oxfordian black marls, fragile plates, and flakes in a clayey matrix that are much gentler with slope angles between 10 and 30°. These slopes are mostly covered by Quaternary deposits as poorly sorted debris at taluses, moraine deposits, or landslide material (Kappes et al., 2011a).

The situation and the specific characteristics of the basin give rise to the occurrence of several natural hazards. A large number of river floods produced by the Ubaye are recorded with major events in 1856 and 1957 (Le Carpentier, 1963; Sivan, 2000). Likewise, the torrents are very active, Remaître (2006) collected information from ~100 debris flows and 461 flash floods in the period between 1850 and 2004. Three large earthflows (Super Sauze, La Vallette, and Poche) pose a threat of possible unexpected mobilization and release of debris flows (Malet et al., 2004). In the year 2000, about 250 active rotational and translational landslides were mapped by Thiery et al. (2004). Although rock falls occur predominantly in the higher parts of the valley, several low-lying regions, for example in the municipality of Jausiers, also are threatened (RTM, 2000). The avalanche inventories of the 'Enquête Permanente sur les Avalanches' (EPA) and 'Les Donnees de la Carte de Localisation des Phéonoènes d'Avalanche' (CLPA, MEDD, 2009) indicate a rather high avalanche activity. As in the case of rock falls, however, their concentration is in the upper zone of, e.g., the Riou Bourdoux and the Sanières catchment or in uninhabited catchments such as the Abries.

4.2. Input data

A digital elevation model (DEM) with a resolution of 10 m was interpolated from the digitized contour lines and breaklines of channels of the 1:10,000 topographic maps from IGN (Institut Géographique National) by Thiery et al. (2007). Furthermore, a digital surface model (DSM) and a digital terrain model (DTM) with a resolution of 5 m are available, derived from airborne interferometric synthetic aperture radar (IFSAR). The DEM was used due to the higher quality for the processes primarily occurring on the slopes (debris flows, rock falls, shallow landslides, and avalanches); while for the flood modeling, the DTM was employed because no forest cover interferes with the radar image and consequently quality-reducing filtering of forest was not necessary.

On basis of the aerial photographs of the year 2000, land use was digitized and classified into 13 classes (e.g., dense coniferous forest, natural grassland, arable land/permanent crops and urban areas) by Bordonné (2008). The information on the lithology was digitized from the geological map (1:50,000) constituting 10 classes (e.g., marls, torrential alluvium, limestone, lacustrine deposits, moraines; Bordonné, 2008).

With respect to elements at risk, databases with the footprints of all buildings, outline of the settled areas, and infrastructure (roads and paths) were provided from the LIVE institute (Laboratoire Image, Ville, Environment) of CNRS, University of Strasbourg.

Considering past events the following information was available:

- Debris flows: envelopes (polygons) of the deposition of the debris flow events observed in 1996, 2002, and 2003 based on post-event field observations (Remaître, 2006). For the 2003 event in the Faucon catchment, the full process area is available (source, transport, and deposition).
- Shallow landslides: translational (debris) slides were extracted of the landslide inventory compiled by Thiery (2007) and Thiery et al. (2007) compiled at a scale of 1:10,000 on the basis of literature analysis, aerial photo interpretation and field surveys. A limitation of this inventory is its restriction to the eastern part of the study area, from Faucon and Galamonds to the east.
- Rock fall: rock fall records were also taken out from the landslide inventory of Thiery (2007). This information was merged with

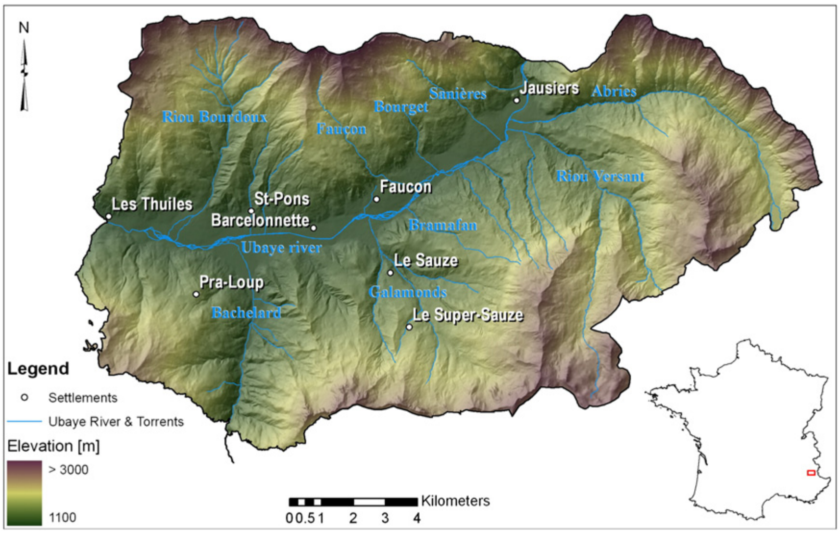

Fig. 5. Presentation of the study area indicating the principal settlements and catchments (in blue letters).

the rock fall zones indicated by the risk prevention plan of Jausiers (RTM, 2000).

- Avalanches: the CLPA inventory (Les Donnees de la Carte de Localisation des Phéonomènes d'Avalanche, MEDD, 2009) provides information on terrain observations and photo interpretation results for the southeastern part of the study area comprising primarily the north-facing slopes.
- Flood: no spatial information on the extent of past events is available. Thus, the flood risk zones indicated in the different risk prevention plans (RTM, 2000, 2002, 2008) were collected and used for the flood model validation. Based on the hydrological reports of IDEALP and Hydroetudes (2008, 2010) information about the 100-year discharge values was derived for the Ubaye River at five points between Jausiers and Barcelonnette.

4.3. Hazard modeling — parameter choice

The calibration and/or parameterization of a model is a very difficult task, especially in a multihazard setting. To enable the comparison of the exposure to single hazards, the reference of the analyses has to be synchronized primarily. The reference relates to qualitative or quantitative scenarios as *medium-frequency events*, *events with a 100-year return period*, *high-magnitude events*, *worst-case*, or the like. The selection of parameters or the model calibration for such scenarios can either be based on statistical inventory analyses, expert knowledge, or on literature review of comparable studies and transfer of the parameter values. A challenge all options share in the multihazard environment is the unequal availability of information for the different hazards:

- Inventories hold much more information on frequently occurring hazard types having affected settled areas and might completely underestimate very rare processes or events outside of settlements.
- Experts have in very few cases a profound background concerning a wide range of different hazards.
- Literature of studies with very similar conditions is not for any constellation and for any hazard equally available.

Although the Barcelonnette basin has been investigated for numerous years by many scientists, not enough inventory data are available to calibrate all five processes without further detailed literature examination, field surveys, and photo interpretation. Thus, in this study, in accordance with the objective to facilitate the computation of a fast and simple approximation without high data requirements, the computation of *worst-case scenarios*[1] has been chosen. Based on the literature of comparable settings, parameter values are chosen that are related to the largest recorded events or methodologies selected to estimate empirically these parameter values. Consequently, no inventory data are needed for the calibration but can, if available, be used for the validation. Scientific journals and reports were searched for the necessary input parameters and always the rounded value leading to the largest area identified as threatened was chosen. In the following, the examined literature is presented shortly.

4.3.1. Debris flows

Sources: for the identification of gullies for debris flow initiation, a planar curvature of $<-2/100$ m was adopted as proposed by Horton et al. (2008). Between rare and extreme fitting, the second one was chosen because, in the case of small upslope areas, the existence of a source is assumed, though without very steep slope angles. Areas of outcropping limestone can be excluded as potential sources.

Runout: Rickenmann and Zimmermann (1993) mapped about 800 debris flow events triggered in the Swiss Alps during intense rainstorms in the summer of 1987 and identified a minimum slope angle of nearly 11°. Bathurst et al. (1997) mentioned an angle of about 0.2 (~11°) for Japan according to personal communication with Takahashi in 1995. Huggel et al. (2002) established a worst-case angle of reach for debris flows resulting from glacier lake outbursts. Reviewing a quantity of cases in the Alps and Canada, they fitted a curve to the angle of reach as a function of the maximum discharge and assessed a threshold angle of 11°. Zimmermann et al. (1997) studied a set of debris flows especially in the Swiss Alps and found a minimum average slope angle of 0.2 (~11°) for coarse and middle-granular debris flows and 0.12 (~7°) for fine-grained debris flows. Prochaska et al. (2008) identified, reviewing a large quantity of investigations, a minimum angle of reach of 6.5°. Consequently, the lowest value detected, 7° rounded, was adopted for the worst-case modeling.

4.3.2. Rock falls

Sources: Guzzetti et al. (2003) identified a slope angle threshold of 60° for Cretaceous granitic rocks, including granite, granodiorite, and diorite for a 10-m DEM resolution. Ayala-Carcedo et al. (2003) worked with 45° in a granitic paleozoic zone for 5-m distance elevation lines; and Jaboyedoff and Labiouse (2003) determined an angle of 40° for local and 45° for regional analyses for a valley in Vaud, Switzerland, consisting of carbonates. Wichmann and Becht (2003) used an angle of 40° for two catchments in the northern Limestone Alps, Germany, with a DEM resolution of 5 m, and Frattini et al. (2008) applied an angle of 37° for an area composed of sandstones and carbonate rocks, mixed intermittently with intrusive and effusive rocks and a DEM resolution of 10 m. Because material and DEM resolution fit, the lowest identified angle of 37° was adopted for the rock fall source modeling under exclusion of outcropping black marls and clays.

Runout: Rickli et al. (1994) distinguished the angle of reach according to the resistance and the size of the blocks: 33° for small rocks if the resistance is low and the underground smooth or the blocks are larger, resistance is high and the underground is not smooth, 35° for middle to small blocks, and 37° for small blocks with high resistance and no smooth underground. For the Solà d'Andorra la Vella (granodiorite and hornfels), a statistical analysis of a set of past events resulted in the 90, 99, and 99.9 percentiles at 41.3°, 39.5°, and 36.9°, respectively (Copons and Vilaplana, 2008; Copons et al., 2009). Jaboyedoff and Labiouse (2003) applied in their study an angle of reach of 33° (carbonates) and Domaas (1985, cited by Toppe, 1987) detected that 95% of the rockfalls stop within an angle of 32°. Onofri and Candian (1979, cited in Jaboyedoff, 2003) assumed 100% of rock fall events within the 28.5° runout. The lowest slope angle was 28.5°, and thus the rounded value of 29° was applied in this study.

4.3.3. Shallow landslides

Sources: concerning the parameterization of SHALSTAB, Real de Asua et al. (2000) suggested that for comparison purposes standard values of 1700 kg/m^3 for the bulk density and 45° for the friction angle. With this high friction angle, Real de Asua et al. (2000) attempted to compensate the negligence of factors as the root strength of forest and understory as well as for the elimination of cohesion (Montgomery and Dietrich, 1994; Dietrich et al., 1998; Real de Asua et al., 2000). However, for a worst-case scenario, the assumption of areawide stabilization from these effects is not meeting the objective of identifying all susceptible areas. Montgomery et al. (1998) applied a friction angle of 33° while Meisina and Scarabelli (2006) used an angle of 28°, which was adopted for this study. For the determination of the critical steady-state rainfall, a study on rainfall thresholds for shallow landslides and debris flows in the Barcelonnette basin carried out by Remaître et al. (2010) has been consulted. Because the landslide threshold values are much more influenced by antecedent rainfall than the debris flow values, Alexandre Remaître (personal

[1] In this study, worst-case is defined as an event of very high magnitude and rather low frequency.

Table 2
Summary of the parameters to be defined in the software for the modeling of the different hazards and the selection made for the case study.

	Source		Runout	
	Parameters	Values chosen	Parameters	Values chosen
Debris flow	Planar curvature threshold	$<-2/100\ m^{-1}$	Holmgren exponent	1
	Slope angle–upslope area threshold	Extreme fitting		
	Land use/cover & lithological units to be excluded	Outcropping limestone	Angle of reach (= constant friction loss angle)	7°
Rock falls	Slope threshold	37°	Holmgren exponent	1
	Land use/cover & lithological units to be excluded	Outcropping marls & clays	Angle of reach	29°
Shallow landslides	Soil bulk density	1700 kgm^3	Holmgren exponent	1
	Slope threshold (friction angle)	28°		
	Critical rainfall threshold	30 mm	Angle of reach	20°
	Lithological units to be excluded	Outcropping limestone		
Avalanches	Slope threshold	30–60°	Holmgren exponent	1
	Land use/cover units to be excluded	Dense forest	Angle of reach	14°
River flood	Hydrograph, 100-year flood x 1.6 48 h duration			

communication, 14th February 2011) recommended to the use of debris flow thresholds and advised daily rainfall values of 30–50 mm on the basis of a database of past records (Remaître et al., 2010). The lower value of 30 mm per day was adopted for this study. For areas without comparable information, the web page of the 'Istituto di Ricerca per la Protezione Idrogeologica' (IRPI, 2011) gives an overview on general rainfall thresholds and can perfectly serve as first orientation in cases for which no statistical analyses have been carried out.

Runout: the angle of reach is rarely used for the shallow landslide runout computation and only a few studies were found. Corominas (1996) mentioned a tangent of the angle of reach of <0.8 (about 39°) for all recorded shallow landslides in his inventory. Corominas et al. (2003) assumed in their study 26° (30°) for small <800 m^3, 22° (25°) for medium 800–2000 m^3 and 20° (23°) for large slides >2000 m^3 for unobstructed (obstructed) paths. On the basis of the scarce literature, a constant friction loss angle of 20° was assumed.

4.3.4. Avalanches

Sources: in accordance with Maggioni (2004), hillsides with a slope between 30° and 60° were chosen while densely forested regions were excluded. Ridges, identified by a curvature >1/100 m and a change of aspect >40° (refer to Maggioni, 2004, for further detail), are automatically excluded in MultiRISK.

Runout: according to Mc Clung and Schaerer (1993), the runout angle of avalanches ranges between 15° and 50°, while Liévois (2003) mentioned a range between 55° and 28–30°, in exceptional cases even as low as 20° for slush flows. Lied and Bakkehøi (1980) investigated 423 avalanches and observed values between 18° and 50° with a mean value of 33°. Hereby, 95% showed a gradient >23° and about 75% >27°. Mc Clung et al. (1989) investigated four mountain ranges and found for the set of 100-year avalanches a minimum angle of 14° (the Sierra Nevada) and a maximum of 42° (western Norway). Mc Clung and Lied (1987) investigated 212 avalanches and found a range of 18–49° with a mean of 30.3°. Barbolini et al. (2011) calculated an average slope angle of 27.3° with a standard deviation of 5.1° for an inventory of 2004 extreme avalanches in the Italian mountain range (Alps and Apennines). The lowest detected angle of 14° was adopted for this study.

4.3.5. Flood

A parameter value choice, as for the previous processes, is not possible in the case of floods because the maximum possible discharge values or inundation depths depend more strongly on the specific setting then in the case of the previous processes. An equivalent of a worst-case run-out is presumably the probable maximum flood (PMF), which is defined by Francés and Botero (2003 p. 223) as the "biggest flood physically possible in a specific catchment". The PMF can be computed on the basis of the probable maximum precipitation and a precipitation-runoff model as proposed in Ely and Peters (1984) or alternatively, empirically by means of statistical analyses of discharge time series (Francés and Botero, 2003). An alternative concept to the PMF is the extreme flood, defined by the CEC (2006) and in the Flood Assessment and Management Directive (EP and EC, 2007) as an event of low probability and, as the term indicates, of very high magnitude. Alternatives to compute extreme floods differ widely but are, in general, more pragmatic and exhibit lower data requirements than the methods used for the PMF:

- Assumption of a certain return period of the extreme flood: Ruiz Rodriguez et al. (2001) used the 1250–10,000-year return period for the flood modeling of the Rhine delta. Bründl (2008) applied a 1000-year event as an extreme flood in a case study of the river Lonza in the communities of Gampel and Steg in the Canton Wallis.
- Increase of a certain flood scenario by a defined inundation depth as *extreme value addition* (Extremwertzuschlag; UVM, 2005): UVM (2005) proposed the 100-year or 200-year flood + *x* m: for one partition of the Oder, the 200-year flood + 1 m is used (OderRegio, 2006); and for the extreme flood computation for several parts of the Rhine, Ruiz Rodriguez et al. (2001) applied the 200-year flood + 0.5 m.
- Multiplication of a certain discharge scenario by a defined factor: the practitioners having participated in the workshop on risk management of alpine torrents and rivers (Klumpp and Hörmann, 2010) defined the threshold for acceptable residual risk, which corresponds to the extreme event of the EU flood directive to 100-year flood × 1.6. This method is also frequently used for the designing of spillways as shown in the study of the TU Wien (2009) and in rivershed analyses (André Assmann, Geomer GmbH, personal communication November 2010). Hydrotec (2009) used the 100-year flood × 1.3 for identification of areas beyond the flood protection goal for the Solmsbach.

The methods to assess the PMF are rather sophisticated and data-demanding. For the statistical computation of a very low frequency scenario as, e.g. a 10,000-year event, an extensive inventory is necessary — if such estimations are *possible* at all, on the basis of rather short-period inventories. The increase of a certain flood scenario by a defined inundation depth depends strongly on the specific morphology and is not really transferable to other regions. Furthermore, this method is also very problematic if channeled and braided river sections alternate, as is the case in the Barcelonnette basin. Therefore, the multiplication of a comparably *frequent* and thus better assessable event (100-year event) with a certain factor was chosen to determine the discharge of the *extreme flood*, which is assumed to be a suitable equivalent to the worst-case modeling of the other hazards. The modeling was run for 48 h at the constant discharge of the 100-year flood × 1.6 to achieve a steady-state flooding.

In Table 2, an overview of the parameters to be defined in the MultiRISK modeling tool and the values assumed for the worst-case analysis in the Barcelonnette basin are compiled.

4.4. Validation and exposure analysis

The validation has been carried out for the complete susceptible areas by means of the inventory information described in the input data section. No use has been made of the option to validate the source susceptibilities separately because respective inventory information is lacking.

The exposure analysis has been performed for the available building database, while the buildings are treated as entire units. Likewise, the exposure of infrastructure and settled areas was examined; in these cases the exposed fractions were quantified.

4.5. Results and discussion

The setup of the model took about 5 min including definition of the project folder and name, upload of the input files and entering of the parameters. With the choice of the *quick* mode for the runout calculations, the modeling ran in total about 50 h[2] whereof the processes runout computation took most of the time. Moreover, the duration of the computation is dependent on the number of sources identified. The *complete* modeling takes much longer as the values in brackets behind the duration of the *quick* analysis indicate (Table 3). Thus, with the present computer characteristics, the *complete* approach does not offer fast and therefore flexible modeling; while the *quick* run serves, as comparisons with the *complete* method indicated, very well. Hence, the modeling has been carried out in the *quick* mode. The data preparation, derivative production, and source identification of all processes lasted for about 20 min in total. The validation for all five processes took about 5 min, and the exposure analysis around 5 min. The preparation of the data for the visualization accounted for another max. 10 min.

4.5.1. Process analysis

The results indicate the largest susceptible area for snow avalanches with over 200 km^2, directly followed by shallow landslides with almost 200 km^2 (Table 3). Rock falls (~87 km^2) and debris flows (~63 km^2) affect a much smaller region. River floods exhibit the smallest susceptibility zone with only about 11 km^2, however, affecting the most densely populated region. Apart from the parameterization, this area distribution is a result of the repartition between slopes and floodplains in the study site. Moreover, processes characteristics are also of a major relevance, e.g. rock falls or debris flows are spatially not as extensive as snow avalanches.

In Fig. 6, examples for the presentation of the results of the hazard modeling step in the MultiRISK visualization tool are given. The produced information is shown in three different shifts: first, the single hazards are displayed; secondly, the overlay of three hazards; and finally, the number of hazards with the option to spatially query the underlying processes. The map depicting the number of overlapping hazards (Fig. 6 at the bottom) indicates a high potential of the coincidence of two, three, or even four hazards, especially on the slopes. The upper slopes are prone to three or four processes, while the torrent channels at lower altitudes mostly unite only two hazards.

4.5.2. Process validation

The sensitivity of all five hazards is rather high with at least 83% for debris flows and up to 95% for avalanches (Table 4). This means that between 83% and 95% of the recorded events are covered by the corresponding hazard modeling results. However, a very high sensitivity is to be expected in a worst-case analysis that aims at indicating all susceptible areas. In return, a rather low positive prediction power (PPP) can be suspected for worst-case scenarios, and indeed the good sensitivity results are relativized by PPP values below 1% for debris flows and rock falls followed by shallow landslides with about 7%. In addition to the very conservative modeling approach that underlies worst-case studies, the amount of records within the inventories regarding these three processes are particularly small and consequently result in low proportions of true positives and low PPP.

[2] Computer specifications: Intel® Core(TM)2 CPU 6400 @ 2.13 GHz, 2.13 GHz, 3.25 GB RAM, Windows XP.

Table 3
Overview over the analysis results for the processes debris flows (DF), rock fall (RF), shallow landslides (SL), avalanches (AV) and floods (FL) (TP — true positives, FP — false negatives, FN — false negatives, and TN — true negatives).

	Quick	Complete area susceptible	Validation of the complete susc. area		Exposure to sources	Exposure complete
	(complete)	(% of the whole area)	TP, FP, FN, (TN)		No. of buildings [−] Road length [m] Settled area [m^2]	
	[h]	[m^2]	[m^2]	[%]		
DF	~1 (36)	62,995,900	210,936	0.06	1	1143
	→ runout	(17%)	62,784,964	16.90	463	110,911
			42,259	0.01	225	1,249,831
			(308,442,833)	83.03		
RF	~4 (11)	86,629,178	555,834	0.15	10	49
	→ runout	(23%)	86,073,344	23.17	6,638	40,081
			53,328	0.01	4,389	34,765
			284,798,486	76.67		
SL	10 (~336)	195,782,092	503,463	0.14	297	872
	→ runout	(53%)	195,278,465	52.57	104,327	228,825
			40,394	0.01	157,803	651,148
			(175,658,670)	47.29		
AV	~10 (>340)	212,672,507	49,144,230	13.23	36	1633
	→ runout	(57%)	163,528,277	44.02	18,111	254,718
			2,377,168	0.64	11,628	1,684,640
			(156,431,317)	42.11		
FL	~24	10,447,502	3,366,192	0.91		1319
		(3%)	7,081,310	1.91		64,419
			296,430	0.08		1,902,747
			(360,737,060)	97.11		

The positive prediction power of avalanches (~23%) is exceeded only by the flood result (~32%). The same two processes exhibit also the highest sensitivity values. However, the validation results cannot be interpreted without considering the hazard type and its specific characteristics (cf. Fig. 7). One example for a necessary careful interpretation of the validation results is flooding. The positive prediction power is high because river floods take place in the limited area of the floodplain which leads to a high potential that the modeled areas were already covered by a few records of past events. By contrast, the area susceptible to the occurrence of shallow landslides is much less restricted to a certain region such as a floodplain and, additionally, landslides will not recur as this is the case for river floods.

Accordingly, the false positive proportion of shallow landslides is probably always higher than for floods because of the described process characteristics. Consequently, PPP values achievable for flood modeling may not be realistic for shallow landslide models. Furthermore, floods, avalanches, rock falls and debris flows are (to a greater or lesser extent) recurring events; while shallow landslides may reactivate but the characteristics differ from the initial failure. These different aspects complicate a clear ranking of the modeling result.

For the present study, a clear quality difference is notable, at least between the avalanche and flood modeling results with comparatively high sensitivity and the outcome of the rock falls, debris flows, and shallow landslides computation. A more detailed ranking is difficult and depends on the weighting of sensitivity versus the PPP or the FN versus TP and objective of the analysis procedure. The susceptibility of 53% and 57% of the study area to shallow landslides and avalanches may suggest an overestimation of modeling result, yet the objective was the worst-case scenario. However, the validation based on mostly rather low number of records within the inventories does not enable a clear judgment.

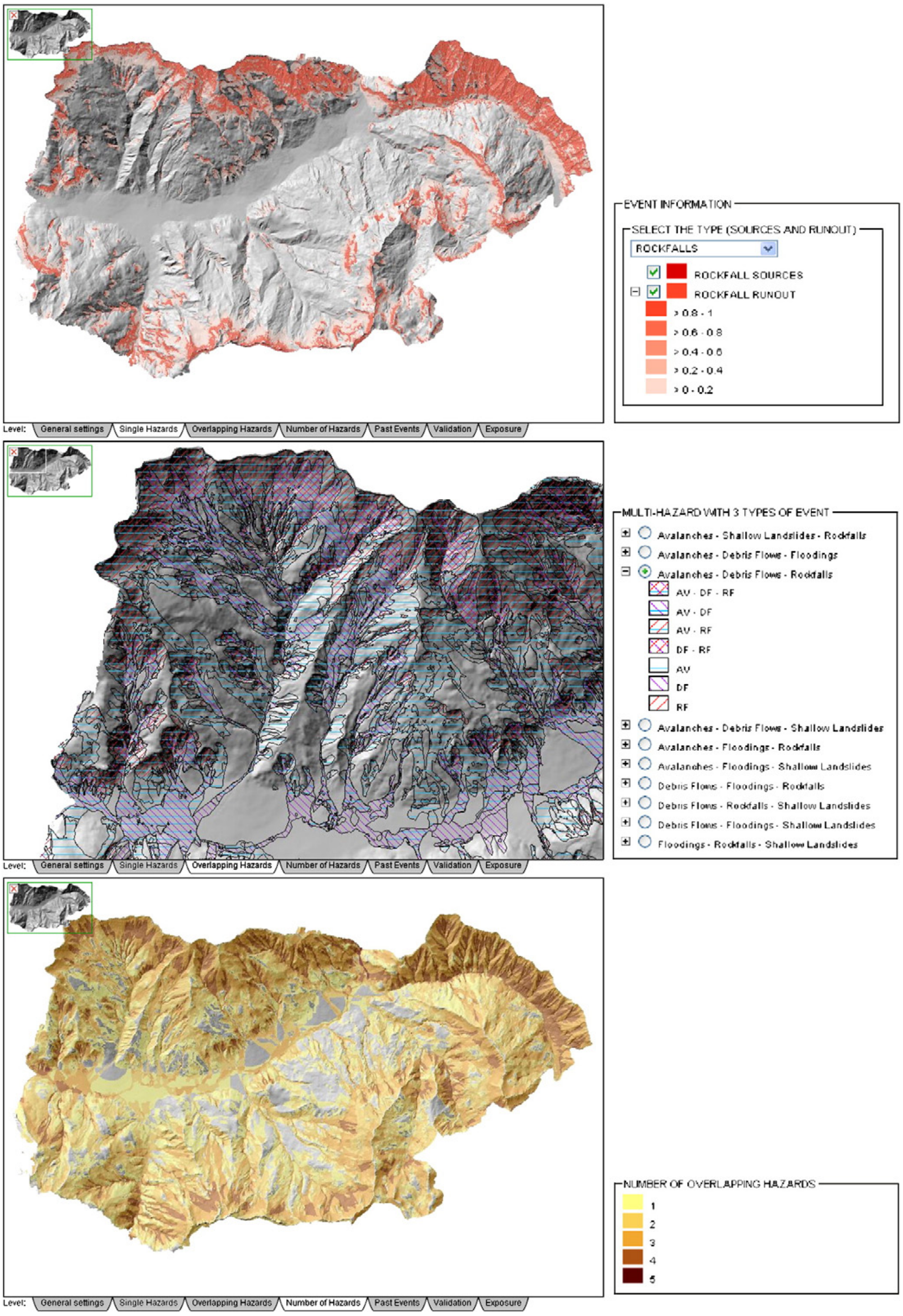

Fig. 6. Examples for the presentation of the hazard modeling results in the MultiRISK visualization tool (note: the brown colors in the lower graphic refer to the number of hazards in each pixel).

In summary, confusion matrices proved well-utilizable in a multihazard context. Nevertheless each single validation result has to be interpreted carefully considering of the process specificities, the inventory size, etc. The same is true for the comparison between process validations. Nevertheless, these difficulties are rather issues related to the multihazard context than to the choice of the validation method.

4.5.3. Exposure

The lowest exposure results from rock fall with only ~40 km of roads and paths, 49 buildings, and 34,765 m^2 of settled area (Table 3). In contrast, the highest numbers exhibit debris flows, floods, and avalanches with far more than 1000 buildings exposed. Because of the close vicinity of many cities and villages to the river course, a very high exposure arises from river flooding, although, only about 3% of the study area are susceptible to this threat. On the contrary, shallow landslides cover more than 50% of the area, but the exposure concerning buildings and built-up area amounts to less than half of area of the avalanches. In Fig. 8, an example for the visualization of the exposures in MultiRISK is provided.

Table 4
Presentation of the proportions of TP, FN, and FP as well as the quality indicators sensitivity (SY) and positive prediction power (PPP) of the modeling results.

	DF	RF	SL	AV	FL
TP	0.06%	0.15%	0.14%	13.23%	0.91%
FN	0.01%	0.01%	0.01%	0.64%	0.08%
FP	16.90%	23.17%	52.57%	44.02%	1.91%
SY	83.31%	91.25%	92.57%	95.39%	91.91%
PPP	0.33%	0.64%	7.43%	23.11%	32.22%

Summarizing, the analysis of the Barcelonnette case study using the software tool MultiRISK proved much more comfortable, user-friendly, and much less error-prone than the separate modeling of all single steps; previous attempts to step-by-step perform the analysis enabled the authors to come to this conclusion. By means of a literature review complemented by advice from experts and statistical analyses, a worst-case parameterization followed by hazard model validation and exposure assessment could be carried out. Thus, it can be concluded that the MultiRISK tool leads to a higher efficiency in susceptibility and exposure modeling for multihazards so far. However, due to the partly very low PPP values, which stands for a high overestimation of the modeling result, the effectiveness in the case study shows quite some potential for optimization. Nevertheless, a considerable advantage is that long time- and resource-consuming data acquisition has been avoided. However, the applicability and usefulness of such an approach for a very first approximation of an unknown area has to be examined in future studies together with stakeholders.

5. Overall discussion and conclusions

In this study, the development of a modeling and a visualization scheme was presented, their automation in software tools was outlined, and a case study was performed. Thereby, many challenges arising in a multihazard context were faced. Although many issues and difficulties could be coped with, this study raised even more new perspectives and questions which will be discussed in the following.

(i) The comparability of modeling results is one of the main objectives of the analysis scheme proposed here. To achieve this goal, similar or at least somehow equivalent models should be selected. However, two major problems emerged: (a) the existence and detection of similar models and (b) the question if similar models assure comparability. (a) In the presented set of hazards, difficulties arose with the selection of similar models; for instance with respect to methods for source identification: while simple empirical methods are commonly in use for rock falls, debris flows, and avalanches, slopes susceptible to shallow landsliding are usually analyzed by statistically and physically based models. Moreover, while two-step approaches of source identification and runout modeling are commonly applied for rock falls, debris flows, and avalanches, the analysis of floods follows completely different procedures, assumptions and decisions. Other processes (such as earthquakes, storms or forest fires) differ even more strongly from the processes presented here, not only with respect to the

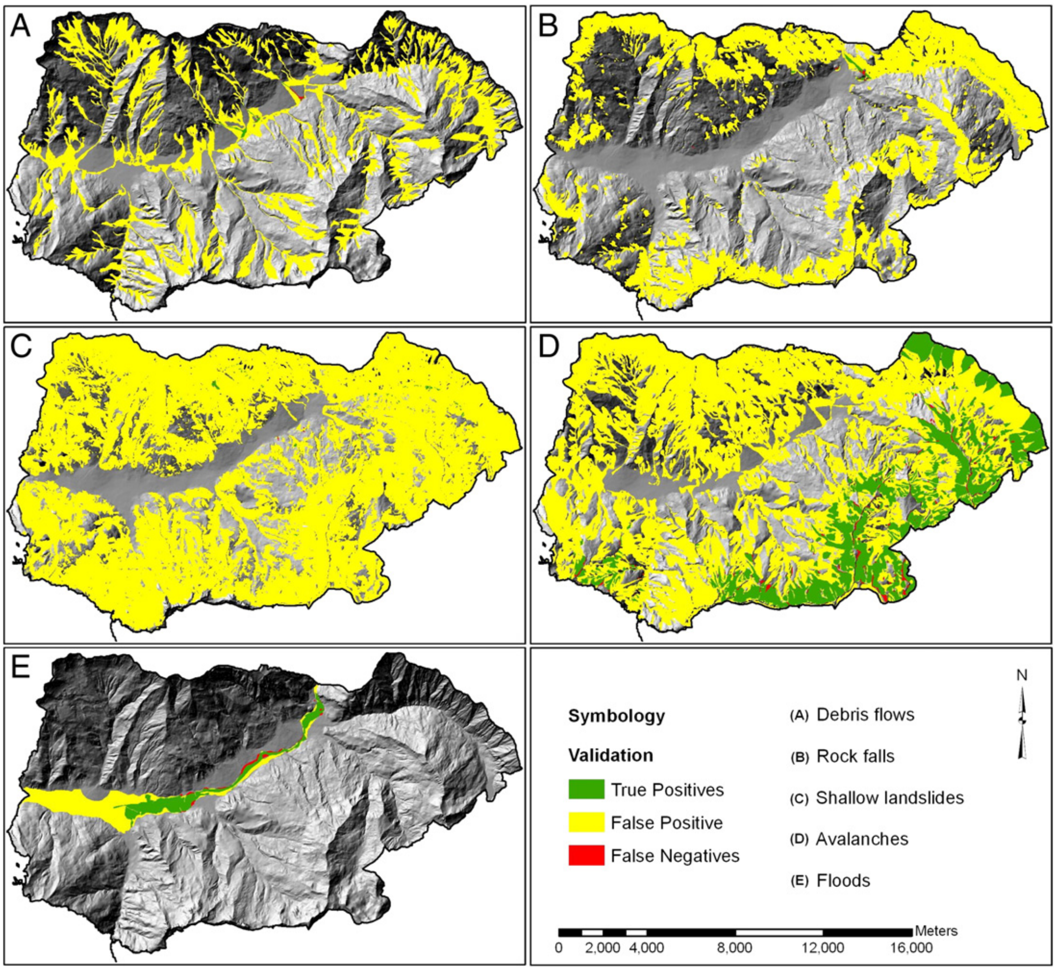

Fig. 7. Maps of the validation result.

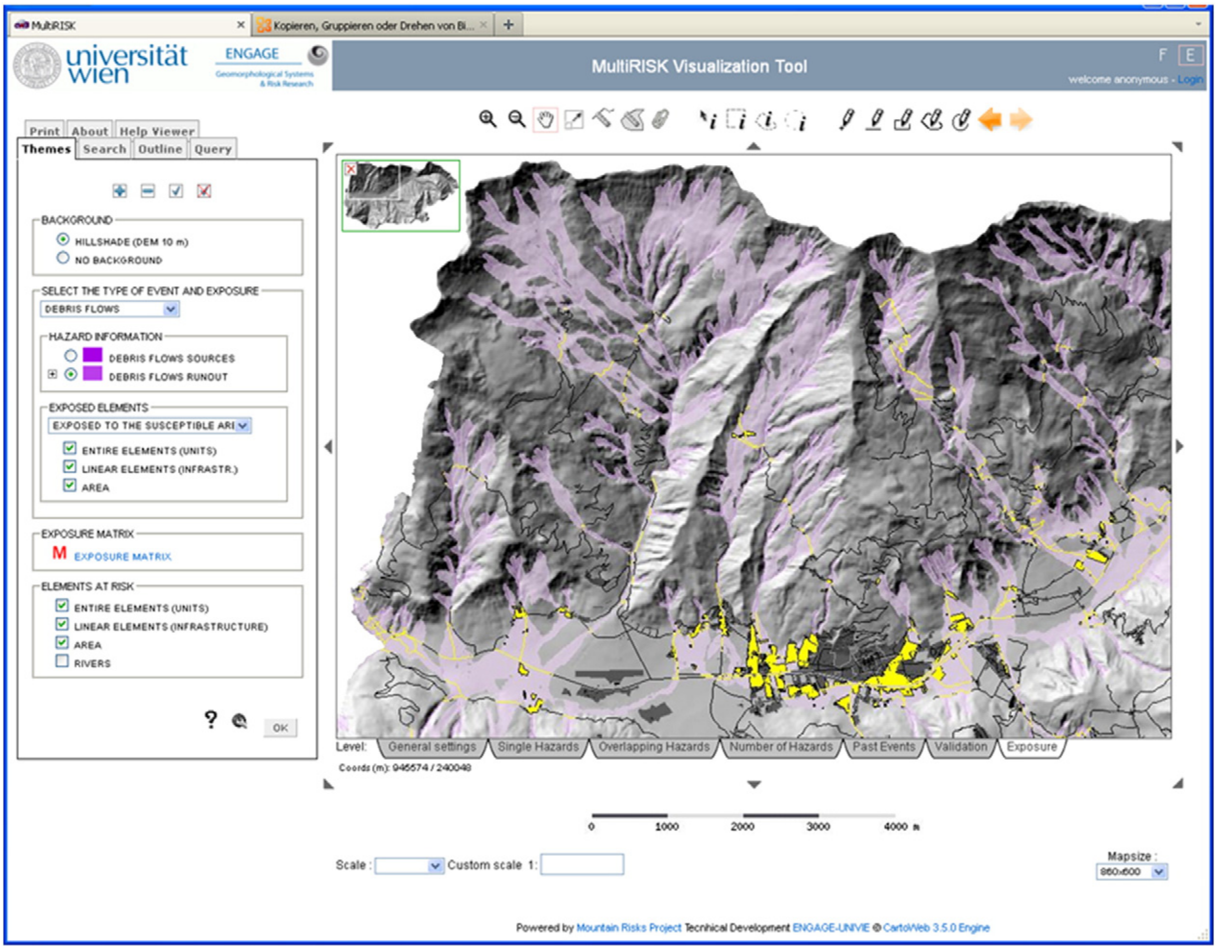

Fig. 8. Screenshot of the visualization of exposed elements in the MultiRISK visualization tool — exposure to debris flows.

modeling approaches and the spatial extent but also regarding the temporal scale at which they act. This leads to difficulties in defining common scenarios as, e.g. the modeling of the 20-year events may be possible for floods, rock falls, or debris flows but such events are of very low relevance in the earthquake context. Likewise, the rock fall or debris flow with a 1000-year return period is a very rough assumption, while much more in use for earthquakes. This also applies for the worst-case parameterization used for the case study. The inclusion of a process of such low frequencies but extremely high magnitudes with high spatial extent would lead to a distortion of the result because of the dominance of the earthquake threat. (b) Furthermore, the question arises if the utilization of similar or even equal methods for the modeling of distinct hazards – as in the case of runout modeling by means of the angle of reach concept – automatically assures comparability of the results. While for debris flows or rock falls a large quantity of studies was detected, in the case of shallow landslides only two articles were found — an indication of the less frequent use of this technique for shallow landslides and possibly a lower suitability of this method. The validation results especially indicate very well that differences between hazards from contrasting characteristics cannot simply be overcome and comparability is not automatically assured by the application of the same methodology. Differing suitability and applicability of an approach when used for contrasting processes may result in very distinct model qualities. However, if the previously proposed attempts to achieve comparability do not in any case meet the objective to produce comparable results, then how can comparability be assured? By aiming at similar quality and uncertainties of the models? How can this be measured, and is it possible to meet this goal? Or is it sufficient to produce results of the same metrics at a predefined scale and all the differences have only to be considered in the interpretation of the outcome? Especially when the model choice is constrained by data availability, this is may be the most realistic strategy.

(ii) A challenge becoming apparent in the case study is the parameterization or calibration of the models. Despite the fact that the chosen study area has already been investigated for many years by several universities, insufficient inventory information is available to carry out a complete multihazard model calibration. A rather simple approach has been chosen with the modeling of worst-case scenarios on the basis of literature information, multiple assumptions, and generalizations. Although this approach apparently led to an overestimation of the susceptible areas and the number of exposed elements, it offers the determination of general hazard distributions, overlaps, and areas of potential risk without data-demanding calibration. By now a parameter set is available by means of which a very fast approximation of a completely unknown area can be performed and much time can be saved. The actual usefulness of this worst-case scenario parameter set and the resulting grade of overestimation have to be examined in additional regions. Nevertheless, the meaningfulness of such a blind analysis depends primarily on the objective and restrictions of the respective study. In areas without any inventory information and previous hazard analyses, such a worst-case analysis may offer helpful indications of which areas have to be regarded in more detail.

For better adjusted parameterization or calibration of the models, difficulties have to be solved in each single situation individually. This means that solutions have to be found according to the available data and the legislative framework requiring the computation of certain scenarios or the like. Thereby, expert appraisal seems to be an indispensible component in multihazard analyses. Multihazard information, especially regarding inventory data, is probably always fragmentary and has to be complemented and pieced together. Nevertheless, a problem is that only a few experts have real multihazard experience.

(iii) Although the presented analysis concept is designed as a top-down approach, in this study only the first step is outlined: the regional exposure analysis scheme. Nevertheless, in the elaboration of a local analysis scheme many additional problems will emerge, such as the development of a vulnerability analysis scheme. Depending on the type of hazard, different methods are used such as curves, matrices, or indicator-based approaches (Kappes et al., 2011b). For instance, vulnerability curves are frequently applied for flood and earthquake modeling but are still not available for rock falls. Thus, the question is how to combine different methods or identify one method (e.g., vulnerability matrices) that can be applied for all processes. Moreover the vulnerability is altered by simultaneous or sequential hazard impacts (Kappes et al., 2011b). Furthermore, local multihazard risk analyses require much detailed information; and although with the regional analysis zones of special interest are identified, the acquisition of the necessary information for these areas is a challenge.

An extension of MultiRISK toward hazard and risk modeling at a local scale is planned to facilitate detailed examination of those areas determined at a regional scale. Moreover, the inclusion of further processes as, for instance, earthquakes and flash floods is under consideration.

(iv) Important phenomena arising in a multihazard context are relations and interactions between hazards. This issue has not been dealt with in this article due to two reasons: first, because hazard relations are, until now, not automated in the MultiRISK modeling tool, they were not presented in the present study. Nevertheless, ideas and recommendations for regarding this issue at a regional scale are already presented in Kappes et al. (2010) and Kappes and Glade (in press). Primarily, the implementation of feedback loops and the identification of areas susceptible to hazard chains with the overlay of modeling results are proposed.

(v) Multihazard analyses have to be followed by the interpretation of the results, which especially includes the determination of acceptable and tolerable levels of risk for certain types of use or the planning of mitigation measures. In Switzerland and France, broad guidelines for the performance of multihazard analyses already exist, directly linked to the implementation of the modeling results into spatial planning. This implies, that any modeling approach has to be adjusted to the legal framework and the requirements of the stakeholders taking decisions on the basis of this information.

(vi) So far, the MultiRISK Platform has been developed without intensive stakeholder interaction. The major reasons were, first, the objective to approach the challenge to develop a multihazard analysis scheme and implement it into a software from a scientific point of view, to identify general challenges and to not only provide practical solutions to one specific problem. Second, to develop a beta version that offers a basis for discussions with stakeholders and prevents from abstract design processes. The experience of the usefulness of a first software proposal as starting point for a detailed adjustment to user needs has also been made with RiskScape in New Zealand (Stefan Reese, NIWA, personal communication, December 2010). Thereby, adjustment refers to requirements in terms of spatial resolution, quality and level of uncertainty of the results, processes to be considered, data availability and user-friendliness of the software but also to the administrative and legal setting of the country and the hazard and risk modeling capacities. So far, the performance of hazard and risk analyses is often outsourced to consultants since technical know how and personnel situation do not permit the realization within the administrative units. However, this involves the danger of low transparency of and little information on the modeling procedure and does not offer the option to flexibly compute scenarios, update the analyses etc. The performance of multihazard risk analyses by means of a specific software tool – which has to be adapted to the specific requirements, legislation, and other user-specific needs – would accelerate and simplify the procedure and make the results more transparent. Nevertheless, at least the first parameterization and adaptation to the specific area and user needs will in most cases require expert support from outside, the tool itself could stay in the hand of, e.g., the municipalities and offer flexible and fast rerunning. How realistic the introduction of such a tool in administrative bodies and institutions is depends on the legislation, the duties of the administrative units, and many more aspects. An interesting example offers HAZUS, elaborated by and freely available from FEMA (U.S. Federal Emergency Management Agency). With a variety of videos and manuals as well as HAZUS training courses, FEMA provides support with the tool. Moreover, HAZUS is delivered together with a nationwide database offering sufficient information to carry out a first overview analysis of any region in the U.S.

Transferring this approach to the Alpine context, a tool adjusted to the necessity to first, perform a susceptibility analysis at a scale 1:10,000–1:50,000, and second, to elaborate a hazard zoning map could be adjusted to the local conditions and calibrated in first place by external (consultants) or national governmental experts. The model itself, not only the results, remains with the respective administrative units, offering this way an update by consultants, governmental experts, or, according to the respective experience and expertise, by the technicians of this unit. Due to differences in the administrative structure and legal framework of each country, the authorities in charge of arranging/performing these analyses vary. In France, the municipality, with the support of the RTM service, has to take care of the elaboration of hazard and risk information while in Germany governmental agencies as the hydrological or the geological survey are in charge.

Concluding, multihazard settings pose a wide range of challenges. Although several difficulties can be solved by a coherent analysis scheme and the automation of the analysis procedure, many problems persist and require experience in handling and analyzing of multiple hazards as well as careful interpretation of analysis results.

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