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The adaptation of technical risk analysis on natural hazards on a regional scale

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with 6 figures and 1 table

Summary. Mass movements mean a serious risk to human life and property in mountain regions. In this study, concepts and suggestions for applications of technical risk analysis required by the field of natural hazards were tested. This approach was carried out in a framework of an information system on natural hazards for the processes of debris flows, rock falls and avalanches in the research area of Upper Sulden Valley in the Autonomous Province of Bolzano-South Tyrol, Italy. The evaluation of technical hazards consists of risk analysis, risk assessment and risk management; where risk analysis provides the basis for the two subsequent steps. The main objectives of risk analysis are hazard identification, estimation of the future hazard potential and assessment of potential damage.

In our study, areas which were affected by natural hazards in the past, were identified in aerial photographs as well as by the means of field studies. In addition, both natural and anthropogenic features of the landscape were identified from available data sources. This information was integrated into a Geographical Information System (GIS), thus providing the framework for subsequent analyses. The hazard potential was determined and high-risk areas were defined. The estimation of hazard processes relies on the worst-case-scenario on a regional scale of 1:10,000. The analysis of potential risk areas was based on the evaluation of available databases, the geomorphological analysis and the modelling of mass movement processes. An additional focus of the study was the testing and evaluation of the concepts of the mapping techniques and the applied models for debris flow, rock fall and avalanche processes. Based on the modelled maximum extent and impact of future hazards, potential damages to traffic routes and buildings were estimated. An overlay of the process area with the damage potential indicates potentially endangered areas.

The results of our study show that the conceptual approach of technical risk analysis can be successfully applied to the analysis of natural hazards in alpine areas on a regional scale. This new approach provides advantages to the present-day natural hazard management.

Zusammenfassung. *Adaptierung der technischen Risikoanalyse für Naturgefahren.* Massenbewegungen in alpinen Regionen stellen ein erhebliches Risiko für Menschen und Sachgüter dar. Inhalt der Arbeit sind Konzepte für eine Anwendung der technischen Risikoanalyse im Naturgefahrenbereich. Die Beurteilung technischer Gefahren besteht aus Risikoanalyse, -bewertung und -management, wobei die Risikoanalyse die Grundlage für die beiden nachfolgenden Schritte bildet. Die Risikoanalyse gliedert sich weiter in die Gefahrenidentifikation, die Beurteilung des Gefahrenpotentials und die Analyse des Schadenpotentials. Dieser Ansatz wurde für Mur- und Sturzprozesse sowie für Lawinen im Rahmen eines Naturgefahren-Informationssystems im Untersuchungsgebiet Oberes Suldental in der Autonomen Provinz Bozen-Südtirol, Italien, getestet. Die Analyse der Gefahrenbereiche basierte auf der Auswertung bestehender Grundlagendaten, einer geomorphologischen Kartierung und der Modellierung der einzelnen Prozesse. Sämtliche Informationen wurden in ein Geographisches Informationssystem (GIS) integriert, welches die Grundlage für die nachfolgenden Analysen darstellte. Anhand des so ermittelten Gefahrenpotentials wurden gefährdete Bereiche im Maßstab von 1:10.000 für ein 'worst-case-scenario' (maximale Reichweite) ausgeschieden. Ein weiterer Schwerpunkt der Arbeit liegt auf der Anwendung und Beurteilung des Kartierungskonzepts sowie der verwendeten Prozessmodelle für Muren, Steinschlag und Lawi-

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nen. Im Untersuchungsgebiet wurden Personen, Gebäude und Verkehrswege als mögliches Schadenpotential analysiert. Durch die Verschneidung der modellierten maximalen Reichweiten der Prozesse und des Schadenpotentials konnten Konfliktbereiche mit unterschiedlicher Gewichtung ausgewiesen werden.

Anhand der vorgestellten Arbeit konnte die erfolgreiche Anwendung des konzeptionellen Ansatzes der technischen Risikoanalyse für alpine Naturgefahren im regionalen Maßstab veranschaulicht werden. Dieser neue Ansatz ermöglicht eine Verbesserung des derzeitigen Umgangs im Naturgefahrenmanagement.

1 *Introduction*

Mass movements are natural geomorphological processes in mountain regions. Depending on the evaluated process and the region, they occur more or less frequently. If they clash with the land-use, they become perilous to buildings and infrastructure as well as to persons. Therefore, they rank among the group of risks that are generally taken involuntarily (Smith 2001).

One way of evaluating the potential risk of natural hazards draws on concepts employed in the assessment of technical hazards such as described in Buwal (1991). From a technical point of view, the term 'risk' derives from the risk definition in actuarial science, which is outlined as function of probability of occurrence and damage extent of a certain event. As a formula this relationship is usually expressed as

$$R = p(a) \cdot d \qquad (1)$$

R = risk

$p(a)$ = probability of occurrence of a specific damage scenario

d = related damage potential

However, this mathematical-technical risk term assumes that the damage potential can be precisely defined. From an economic point of view, not only negative effects are considered, but also positive ones resulting from human activity. In contrast to this, the technical term for damage is regarded as a negatively evaluated event and is therefore a normatively assessing expression (Kaplan & Garrick 1981, Kröger et al. 1996). Nevertheless, this study distinguishes between the (objective) risk analysis and the (subjective) risk assessment.

The main objectives of risk analysis are 1) hazard identification, 2) estimation of present and future hazard potential, 3) determination of potential damage. Risk assessment is understood as 1) a comparison with other risks and benefits, 2) an evaluation within value systems 3) a decision on acceptance. Risk analysis is therefore a precondition for the following risk assessment as well as for an efficient risk management (see Fig. 1).

The technical risk approach can provide an important tool for natural hazard prediction and risk management (Heinimann et al. 1998, Hollenstein 1997). Paralleling technical analysis, natural hazard research describes damages as a result of an unwelcome occurrence of a certain event and its effects on all aspects of human life (Borter et al. 1999, Liu & Lei 2003). However, consequential positive effects from these events are not examined. So far, only few studies

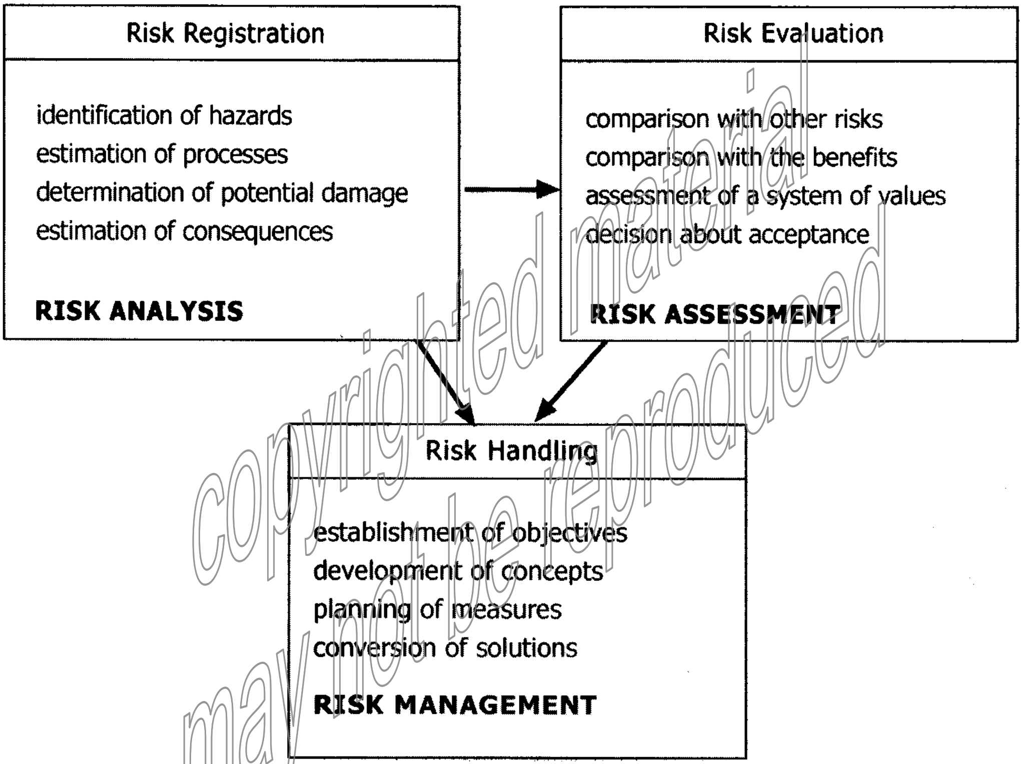

Fig. 1. Concept of risk and natural hazard. Risk analysis is the basis for risk assessment and risk management (HEINIMANN et al. 1998, modified).

have applied these concepts in combination with Geographical Information Systems (GIS) (e.g. BOLLINGER et al. 2000, BORTER 1999, CARDINALI et al. 2002, EGLI 1996, FUCHS et al. 2001, MEJÍA-NAVARRO et al. 1994, VAN WESTEN 1994).

In this study, concepts and suggestions for applications of technical risk analysis required by the field of natural hazards, were tested. This approach was carried out in a framework of an information system on natural hazards for the processes of debris flows, rock falls and avalanches in the research area of Upper Sulden Valley in the Autonomous Province of Bolzano-South Tyrol, Italy.

As a base for a comprehensive risk evaluation for spatial planning, an information system on natural hazards contains collecting and processing of all available data for the hazard potential in the research area. The modelling of the processes was calculated with the assumption of a worst-case-scenario in order to consider also events with a probability of occurrence beyond the valid recurrent design event. The 'avalanche winter' 1998/99 (e.g. Galtür, Austria), or the flood events in August 2002 in extensive areas of Europe show that these scenarios are highly important. On a regional scale, a wide cover of overview information is generated by intersections and analysis functions in the information system. This information provides a general basis for decision-making concerning current and future use as well as for a ranking of priorities for both more detailed investigations and new mitigation measures, which are to be developed.

2 *Methods*

The structure of the information system on natural hazards follows the concept of a technical risk analysis, which was adapted to natural hazards research. The main objectives of risk analysis are, apart from hazard identification, the estimation of present and future hazard potential and the determination of potential damage (Hollenstein 1997) (see Fig. 2). The estimation of hazard processes is based on the worst-case-scenario on a regional scale of 1:10,000. The results from the overlay of the process areas with the damage potential indicate on the detailed level of a regional scale potentially endangered areas. The consequences resulting from the impact of future hazards are given in the number of endangered persons, the value of the buildings affected and the length of obstructed or damaged sections of roads. This procedure corresponds with a semi-quantitative methodology of a technical risk analysis (Buwal 1991). All results of these investigations were implemented in the GIS and processed for further analyses. The different methodical steps are described more detailed below.

2.1 *Hazard identification*

The system delimitation and description includes all elements in a research area, which are relevant for the estimation of risks as well as their causal connections (see e.g. Heinimann 1998). Thus, the basic conditions of the risk analysis are comprehensibly defined. The geographic system delimitation is derived from the research questions and covers explanatory notes on the research area in respect to the individual process area. The investigated processes and damage objects are described by the system delimitation of the content. The dominant environmental conditions are illustrated by conditional system delimitations. In addition to the natural environment (geology, topography, climate and vegetation), these conditions are data of the cultural area, e.g. number of population, buildings and traffic routes.

2.2 *Estimation of hazard processes*

Based on natural hazard features identified in the research area, the hazard potential was estimated and high-risk areas were defined. The establishment of data on intensity and probability of occurrence of processes is not necessary on a regional scale, because the extractions of an overview of affected areas by natural hazard processes was emphasized (Bollinger et al. 2000). The estimation of potential risk areas was based on the evaluation of available data, the geomorphological terrain analysis and the modelling of mass movement processes.

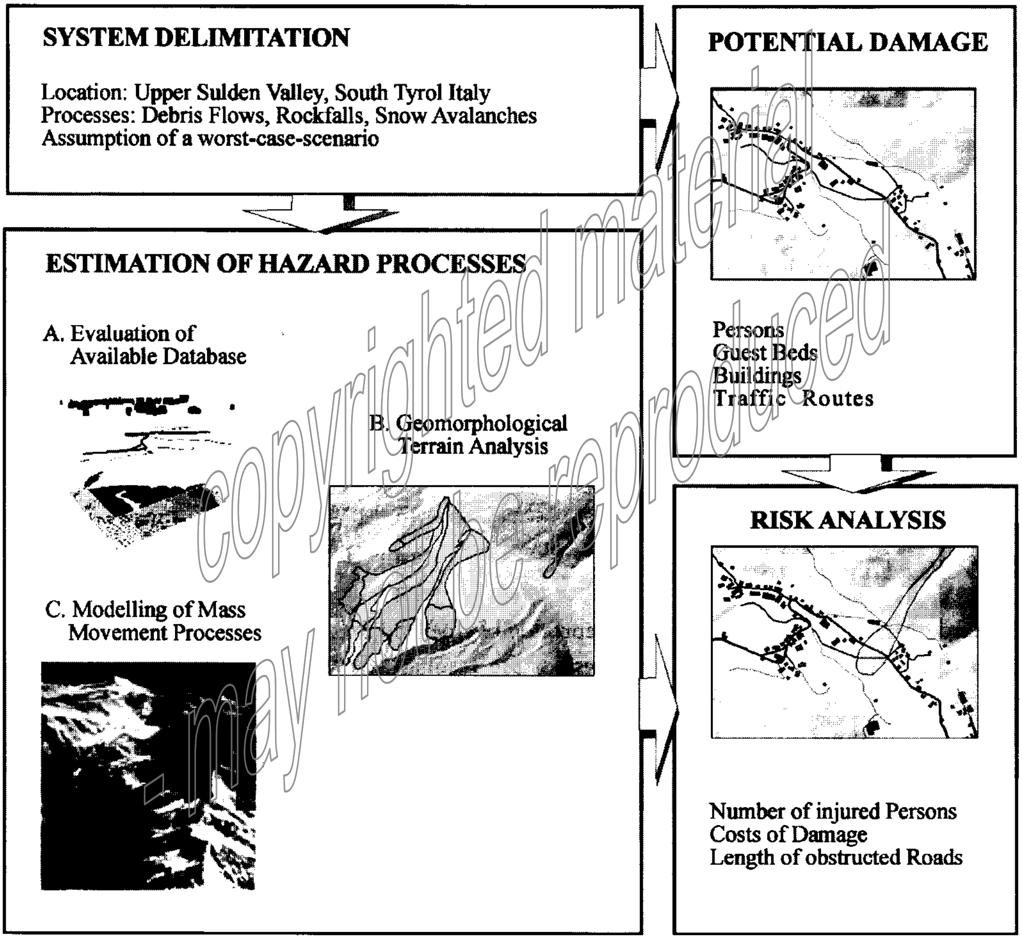

Fig. 2. Schematic diagram of the major steps of risk analysis on a regional scale.

2.2.1 *Evaluation of available database*

As a database for the investigations, several analogous topographical maps and the digital topographical base map at a scale of 1:10,000 were used. In addition, multitemporal black and white aerial photographs as well as the matching orthophoto were analysed and two digital terrain models were utilised (other spatial datasets, like colour digital orthophotos, or a map of land-use, have only become available recently, and therefore could not be used in this case study). Furthermore, historic sources (community archives, recordings of the torrent and avalanche authority, reports of the fire-brigade, etc.) were evaluated for the region.

2.2.2 *Geomorphological terrain analysis*

The geomorphological terrain analysis was carried out on a working scale of 1:5,000 following the mapping procedures outlined in KIENHOLZ & KRUMMENACHER (1995). The main focus was put on key positions of relevant processes that had been identified in the stereoscopic aerial photograph analysis. The mapping concept is particularly convenient for the following reasons. First, the standardized components of the legend, such as information concerning geomorphology, hydrology, mitigation measures, different hazard types etc., can even be applied if spatial databases are incomplete (see Table 1). Second, the symbols of the legend can be differently combined depending on the question. Third, the approach is suitable for a digital adaptation, because of its modular structure (KEILER et al. 2000), even in the finally used output resolution of 1:10,000. The terrain analysis supplies, in combination with the evaluation of the available database (digital terrain model and ground cover), the input data for the modelling. The starting point for debris flows, the head scrape for rock falls and the fracture line for avalanches can be determined by this analysis.

2.2.3 *Modelling of mass movement processes*

Hazard estimation must result from a reproducible method, in order to be able to ensure comprehensibleness and objective correctness of the results (STÖTTER et al. 1999). According to this postulation it seems reasonable to calculate trajectories and the maximum run out distance of hazardous processes by modelling or use of empirical arithmetic techniques. Thus, a cost- and time-efficient application with blanket coverage is possible. In the research area, the estimation of the processes was carried out with models which correspond to the above mentioned criteria.

The maximum extent of debris flows was calculated using the model 'FLOW-VEC' (WICHMANN 2000). The model was developed to simulate debris flows, which starts on slopes. Using the programming language 'Avenue', the idea and structure of the model was converted for the software 'ArcView'. On the basis of an interactively selected starting point, the model creates, based on a TIN based terrain model, trajectories in the form of vectors. The trajectory follows in each case the flow direction of the processed triangle. In each calculation step the length and the inclination of a segment are determined, followed by the computation of the velocity on the segments by use of the friction model of PERLA et al. (1980), which is included in the program. The friction model draws on two parameters for this calculation: the friction coefficient μ and the relationship of mass to drag M/D. If the velocity is higher than zero, the complete triangle is covered and the processing of the subsequent triangle starts. As soon as the velocity equals zero, the length of the last segment is calculated and the computation is terminated. Information on the coordinates of the individual segments, the length of the segment, the inclination as well as the velocity is stored in the 'shape file' associated tables. The program allows the modelling of a lateral spreading in the deposition area. Based on a selected starting point, several cycles of the model with different angles ($\pm 10^\circ$) are required to determine the maximum deviation from the flow direction.

Table 1. Mapped phenomena according to Kienholz & Krummenacher (1995). The table shows the excellent modular structure of the used legend.

Processes	Signatures
Avalanches	avalanche polygons mapped in the field avalanche polygons taken from the register several hazard indicators for avalanche activity
Floods, Debris Flows	accumulation areas of debris flows, active/inactive, inclusive gullies fluvial accumulation areas debris flow starting zones in loose material lateral channel erosion redepositional areas
Slumps, Slides, Erosion	burst niches of slips in loose material active slides slow slides, creeping subactive slides, very slow slide material with vague boundaries bulges surface creeps in loose material erosion plane in loose material/in bedrock
Rock Fall (with additional information on particle diameter and activity)	head scrape of rock fall processes head scrape of ice avalanche processes accumulation areas of rock fall processes

Supplements	
Hydrology	headwaters tapings of springs channels with/without debris flow potential erosional base levels in bedrock erosional base levels in superficial deposits
Geomorphology/Single Features	fractures of slumps and slides terrain edges rock glaciers moraines debris-flow lobes
Mitigation Measures	shuttering dams groynes bioengineered protection measures

Rock falls were calculated with the model 'Sturzgeschwindigkeit' (MEISSL 1998). The model estimates the run out-zones of rock fall and rock slides with simple formulae, based on the principles of the conservation of energy. It is suitable for simulations of rock fall processes that show no or only slight interaction between the components. The program was developed using 'ArcMacro-Language' (AML) of the software ARC/INFO, and it applied mainly commands of the raster module GRID. The model by MEISSL (1998) is based on the approach of VAN DIJKE & VAN WESTEN (1990) and was extended by an improved trajectory model as well as the implementation of free fall in the calculation of the fall velocity. The head scrape must be specified by the user. Based on the start-pixel, those neighbour-pixels, which can be affected by the rock fall material, are iteratively searched, and added to the process area. The trajectories are determined with a 'multiple-flow-direction-method', which includes 16 possible directions (D16), and a lateral spreading is taken into account. The velocity of the rock fall material is decreased by 75 % after the free fall, because the kinetic energy is converted into other forms of energy after the impact (BROILLI 1974). On the slope, the gliding velocity is calculated with regard to the friction coefficient μ in order to consider the 'worst case'. The rock fall track ends as soon as the determined velocity equals zero.

For the calculation of the avalanche process area, a simulation model was used that is presently developed and advanced at the Institute of Geography of the University of Innsbruck. The model uses the 'average gradient' approach by LIED et al. (1995): The maximum range of the avalanche is defined by the angle α, which is enclosed by the connecting line between the head of the fracture line and the maximum extension point of the deposition area and the horizontal. The gradient of the straight line connecting the highest point of the potential fracture line with the point in the avalanche track, which has an inclination of 10°, is called β. If β is known, the 'average gradient' can be determined with the formula:

$$\alpha = 0{,}946\,\beta - 0{,}83^\circ \qquad (2)$$

(regression equation, derived from a sample of 80 avalanches in the Eastern Alps; see LIED et al. 1995).

The avalanche simulation model was implemented in the raster module of ARC/INFO using 'ArcMacroLanguage' (AML). The user defines the upper delimitation of the avalanche fracture line. Based on the highest start-pixel of each fracture line, a cone is created. Its curved surface shows the gradient of the average gradient, which was calculated before. The external line of the area potentially endangered by avalanches (of each fracture line) results from the section boundary between the cone and the terrain surface. The avalanche track of every start-pixel is determined according to the trajectory model D16 (MEISSL 1998) described above. Only those pixels actually affected by the avalanche, are selected on the basis of the trajectory model.

The results of the estimation of processes are described separately for each process area thus forming the base for the subsequent step of risk analysis.

2.3 *Potential damage*

Following the estimation of hazard processes, the damage potential created by natural hazards was determined and visualized. The damage potential was semi-quantitatively divided into two different categories (buildings and traffic routes). Buildings were extracted from both sources the topographical map and the orthophoto of the Autonomous Province of Bolzano-South Tyrol and subdivided into the classes of residential buildings, holiday accommodation and commercial buildings by intersection with the urban land use plan of the community. The ground plan area of the buildings was multiplied by the maximum of the legal building height according to the urban land use plan. The resulting cubature was multiplied by the valid price of cubic meter (261.00 € per m^3) for the calculation of construction costs of residential buildings in the Autonomous Province of Bolzano-South Tyrol (ASTAT 2002). Due to the lack of an accurate database, the number of persons per building could not be determined. Therefore, an average number of 2.4 persons per building was assumed. This value results from the number of the inhabitants of Sulden divided by the number of buildings. The number of guest beds was assigned according to the data of the Sulden tourist information. Roads were divided into three categories (primary roads, secondary roads and service tracks) according to their relevance (see Fig. 3). Undeveloped properties and other damage potential, like farm animals and movable goods, were not evaluated.

3 *Results*

The applied approaches make it possible to investigate the natural hazards potential of large areas efficiently and extensively. In the following, the results of the applied methodology are presented for the research area of the 'Upper Sulden Valley'.

3.1 *Hazard identification*

The geographic delimitation of the study area 'Upper Sulden Valley' (a part of the community of Stilfs) was determined and implemented in the GIS. A definition and description of all components of the system delimitation as regards content would be too far-reaching. Fields of the risk analysis are the processes debris flow, rock fall and avalanche as well as types of damage like casualties, loss of material assets and roads. The conditional system delimitations result from the analysis of the predominant environmental condition. The research area is part of the Central Alps and displays all their associated geological, climatic and geomorphological conditions. Further data of the socio-economic structure such as number of population and buildings as well as traffic routes are relevant for the damage potential in this touristic region.

3.2 *Estimation of hazard processes*

In the research area, potential hazards caused by dynamic processes were identified and estimated by the use of methods mentioned above. The results are demonstrated below.

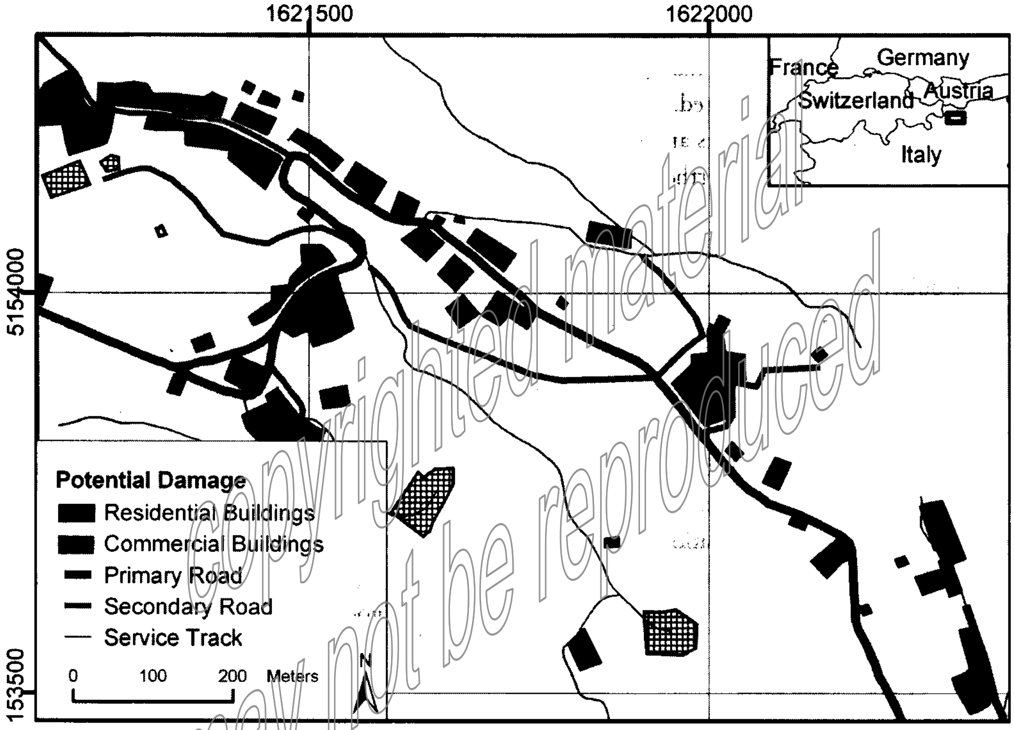

Fig. 3. Map of potential damage of the village of Sulden; illustrated with different categories of buildings and traffic routes. Inset shows the investigation area in Northern Italy. Coordinates in Gauss-Boaga Projection (m).

3.2.1 *Evaluation of available database*

Geological information has to be extracted from a general map 1:100,000 because of lacking of detailed maps. Topographical maps were available in both digital and analogous form, with their usual limitations, in the scale 1:10,000 and 1:25,000. In addition, current black and white aerial photographs and matching orthophoto maps were used. This base provides an efficient preparation for the field mapping (1:5,000). However, the orthophoto maps were printed with out-dated contour lines, which did not conform with the real location. The evaluation of historic sources provided almost no usable findings, because relevant records were lost during wartime. Important information could only be derived from the avalanche inventory and the avalanche hazard map.

3.2.2 *Geomorphological terrain analysis*

Basing on the used data, the geomorphological terrain analysis can be conveniently conducted on a regional scale. The terrain analysis is an adequate base for the estimation of hazards and the further proceeding, in particular, if spatial data is insufficient. The expectations on handling and integration in the information system are fulfilled by the applied mapping concept (Fig. 4). Additional information on the research area, such as photo and text documentation, was interactively retrievable through links and updated in a user-friendly way.

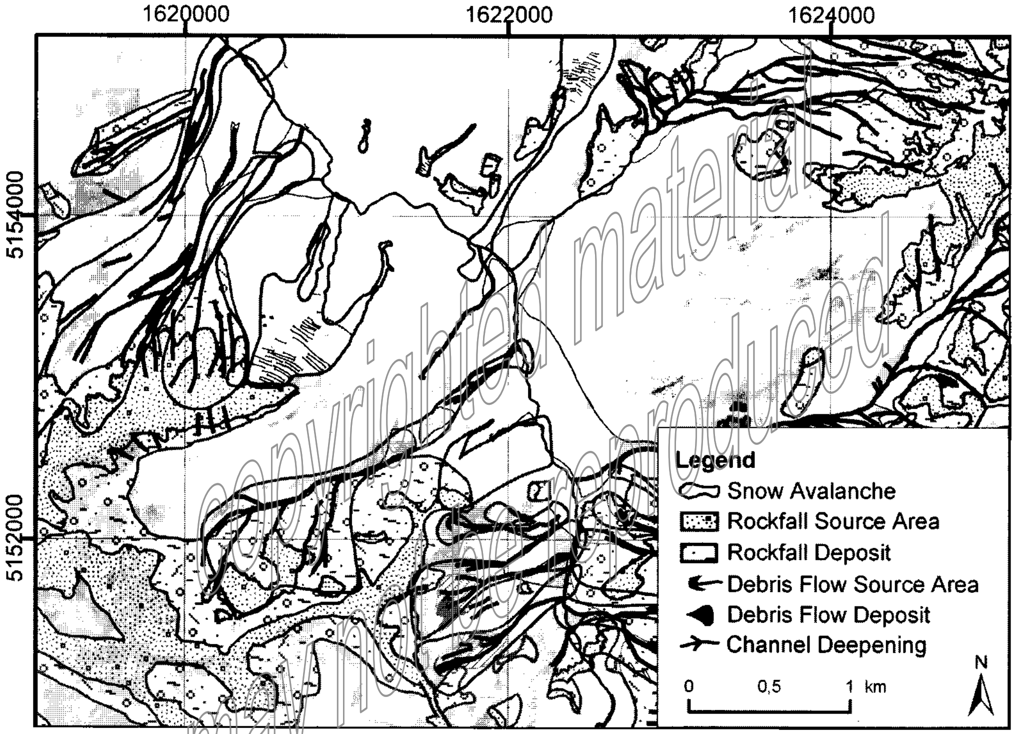

Fig. 4. Results of the terrain analysis in part of the research area implemented in a GIS. Coordinates in Gauss-Boaga Projection (m).

3.2.3 *Modelling of mass movement processes*

When modelling processes, run-out-distances of extreme events in settlement areas were given priority. The maximum extent of debris flows was calculated using the standardized physical parameters outlined in WICHMANN (2000), as well as WICHMANN et al. (2002). These parameters ($\mu = 0.20$; $M/D = 0.75$) are apparently independent from variations in the local terrain. Model outputs from FLOW-VEC (WICHMANN et al. 2002) show that the calculated process trajectories closely follow the mapped extent of debris flow deposits. Nevertheless, a calibration of the friction coefficient μ for different substrates is advised for a wider applicability of the model.

Rock fall run-out-zones calculated with the model 'Sturzgeschwindigkeit' (MEISSL 1998) closely correspond with areas of rock fall deposits identified in the geomorphological terrain analysis. Consequently, the model results with the average friction coefficient $\mu = 0.575$ are considered realistic (Fig. 5). Information on the geology of the research area is still too insufficient to allow the use of material-dependent friction coefficients.

Process areas of avalanches determined with the 'average gradient' (LIED et al. 1995) and the trajectory model of MEISSL (1998) are only to some extent realistic: Avalanche tracks along gul-

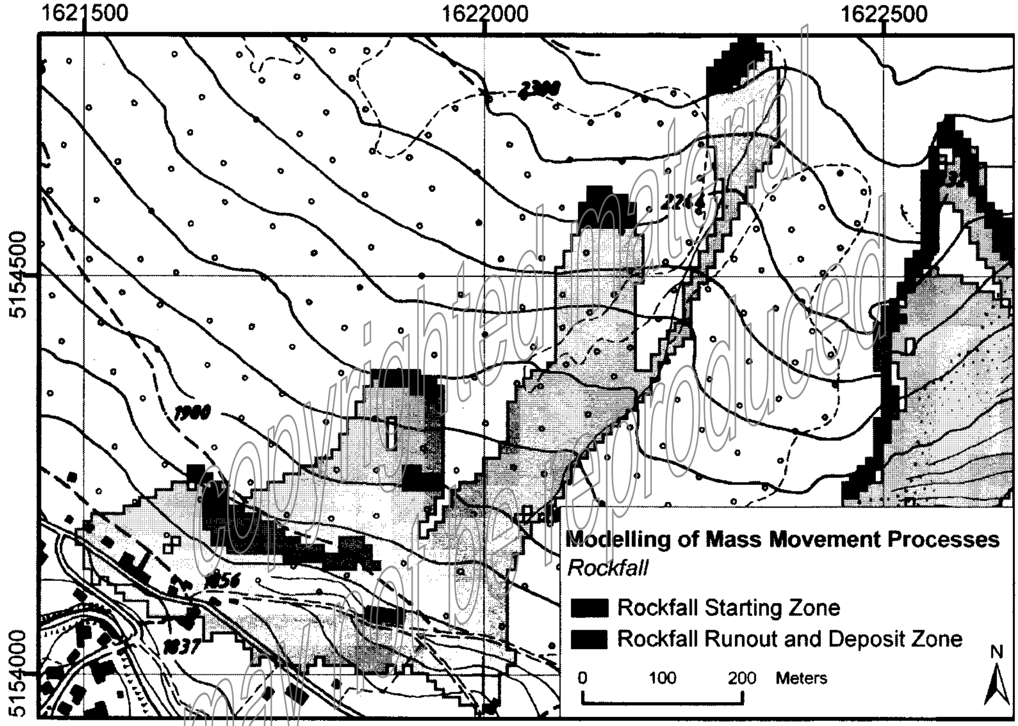

Fig. 5. An example of the modelling results of rock fall processes with the model 'Sturzgeschwindigkeit' (MEISSL 1998). The model was developed in order to calculate run-out-distances of extreme events on a regional scale. Coordinates in Gauss-Boaga Projection (m). Topographic Map 1:10,000 reproduced with permisssion according to the decree of the government of the Autonomous Province of Bolzano – South Tyrol no. 3940, November 5th 2001.

lies, which are insufficiently presented in the Digital Terrain Model (DTM), are calculated too wide. In contrast to this, the extent of the avalanche cone is accurately simulated. It is so far not possible to calculate an extent of the avalanche on the reverse slope with the applied trajectory model. Adequate adaptations are in preparation. The run-out-distances of smaller avalanches are computed too largely, however concerning question and scale the results defensible.

This study bases on two raster based DTMs with different resolutions: At the time of investigation, the official DTM of the Autonomous Province of Bolzano-South Tyrol with a raster resolution of 20 m was used. Additionally, a model with a resolution of 10 m was applied, which was derived from digitised contour lines (base map 1: 10,000) as well as from selective altitude information. A comparison of the model calculation basing on two different DTM with same starting positions and conditions shows that the resulting areas may differ up to 100 m in range. This clearly revealed that the accuracy of modelling results strongly depends on the quality and resolution of DTMs (FUCHS et al. 2001, MEISSL 1999).

3.3 *Potential damage*

This methodology allows a simple description and estimation of the imminent loss affected by natural hazards. It is possible to differentiate the damage potential in a spatial way (see Fig. 3). For a temporal differentiation, no such data as seasonal fluctuation of the number of persons and real value was available. On a regional scale, the overlay of process areas with the estimated damage potential requires no establishment of data on intensity and occurrence-probability of processes. Thus, no analysis of effects and absolute determination of risk is necessary. In this study, the results of the risk analysis are given in the number of endangered persons, the value of all buildings affected and the length of the obstructed or damaged sections of roads. The corresponding data can be queried from the database. Based on these results, it is possible to visualize the potential clash areas and to define areas with a need of more detailed investigation on a local scale as well as planning of mitigation measures (Fig. 6).

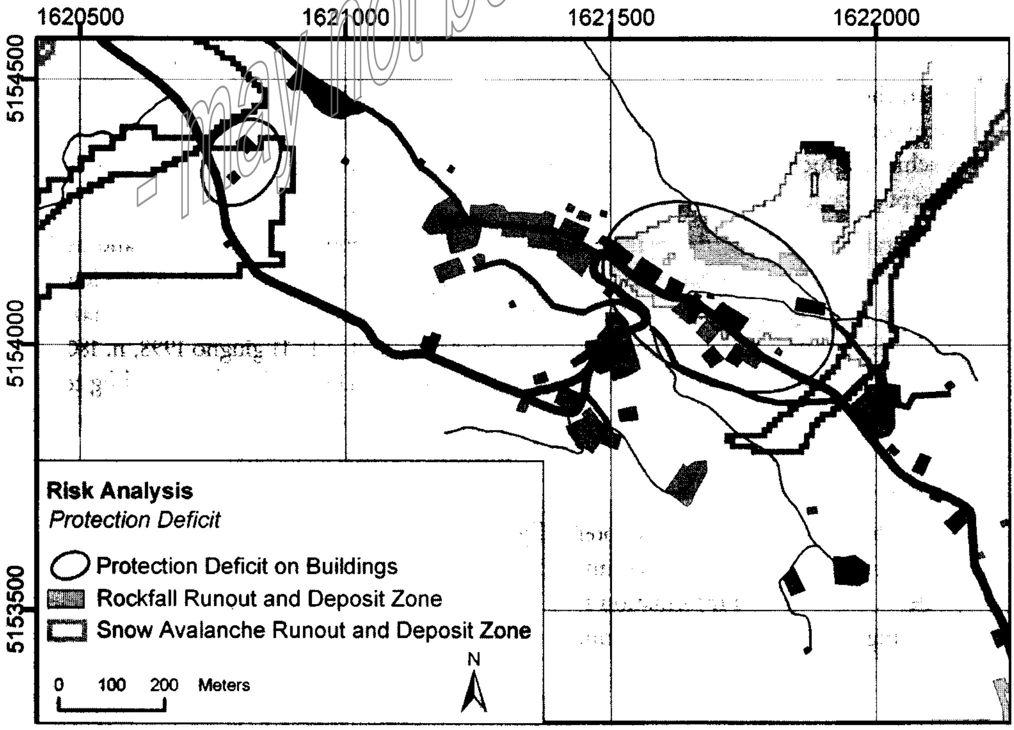

Fig. 6. The results of the risk analysis can be presented in two different ways. High risk areas are visualized in a map by the intersection of the modelled process area and the potential damage. Coordinates in Gauss-Boaga Projection (m).

4.1 *Discussion*

In the paragraphs above, the application of the approach of technical risk analysis on natural hazard research was described. This concept can successfully be applied to the analysis of natural hazards in alpine areas on a regional scale. The present-day natural hazard management approaches are inadequate for the challenges of the future, due to their mono-disciplinary and non-standardized nature. A standardized procedure provides the following advantages:

- The publication of the methodology makes the procedure comprehensible at any time (see HEINIMANN et al. 1998). The subjective scope of individual consultants is largely eliminated.
- Due to the use of an information system on natural hazards, a cost- and time efficient risk analysis of potential hazards is possible, as all necessary input data for the evaluation of risk is included. Thus, a spatial-orientated processing of information, modelling, interpretation of results, visualization and archiving records is provided. The continuation and updating of the entire volume of data, model algorithms and visualization possibilities are ensured by the standardized structure.
- Risk analysis integrated in an information system on natural hazards allows an area-wide application and generation of an overview of areas affected by natural hazards.

The following problems still occur:

- So far, the lack of adequate spatial databases renders this type of analysis time-consuming and expensive. The systematic improvement of spatial databases is therefore essential in order to achieve a more accurate hazard estimation and to encourage a wider application of the concept presented in this study.
- In general, natural hazards are insufficiently taken into account in present-day land-use planning in Italy and a national standard for hazard assessment was enforced only a few years ago. The delimitation of different so-called 'high-risk-areas' affected by natural hazards is principally prescribed by the regulations of the decree 'DD.LL. 11 giugno 1998, n. 180' (G.U. n. 134/1998), as well as the 'D.P.C.M. 29 settembre 1998' (G.U. n. 3/1999). According to those decrees the authorities of the Autonomous Province of Bolzano-South Tyrol carried out some pilot studies and are now working on the definition of standardized guidelines for the delimitation of risk-zones.

In general, this concept determines potentially endangered areas on a regional scale. This information is necessary for more detailed investigations as well as the delimitation of risk-zones on a local scale. A standardized information system on natural hazards can provide an important decision-making-tool for political and administrative authorities.

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