LANDSLIDE SUSCEPTIBILITY ANALYSIS AT A REGIONAL SCALE - A QUALITATIVE APPROACH AT THE EASTERN ALPS

GEFÄHRDUNGSANALYSE FÜR MASSENBEWEGUNGEN IN EINEM REGIONALEN MAßSTAB – EIN QUALITATIVER ANSATZ IN DEN OSTALPEN

(GEORISIKOKARTE VORARLBERG)

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ABSTRACT

The aim of the project "Georisikokarte Vorarlberg" was landslide susceptibility assessment at a regional scale. Using a qualitative approach, the susceptibility to sliding and falling movements was analysed according to five categories (very low, low, medium, high, very high). All data layers were handled as grids with a cell size of 25 m. The susceptibility to sliding was analysed with an index method based on the data layers slope angle, slope aspect, slope curvature, lithology, distance to tectonic faults, vegetation and erosion. The trajectories of potential rockfall blocks were compared using a cost analysis based on rolling friction. The methods were tested at three different study areas in Vorarlberg and calibrated with a landslide inventory. Special focus was laid on the presentation of the results. The susceptibility map should be understandable for spatial planners as well as local people, municipal employees and politicians.

Keywords: Susceptibility, Slides, Rockfall

ZUSAMMENFASSUNG

Ziel des Projektes "Georisikokarte Vorarlberg" war es, die Gefährdung für Massenbewegungen in einem regionalen Maßstab vorherzusagen. Mithilfe eines qualitativen Ansatzes wurde die Suszeptibilität für Rutschungen und Sturzprozesse in fünf Kategorien eingeteilt (sehr gering, gering, mittel, groß, sehr groß). Alle Daten wurden als Raster mit der Zellengröße 25 m bearbeitet. Die Suszeptibilität für Rutschungen wurde mit einer Index-Methode analysiert, welche die Datenebenen Hangneigung, Hangrichtung, Hangwölbung, Lithologie, Abstand zu Störungen, Vegetation und Erosion beinhaltete. Die Trajektorien potenzieller Steinschlagkörper wurden mit einer einfachen Kostenanalyse aufgrund der Rollreibung gewichtet. Die Methoden wurden in drei unterschiedlichen Arbeitsgebieten in Vorarlberg getestet und die Ergebnisse mittels Ereigniskarten geeicht. Ein besonderes Gewicht wurde auf die Präsentation der Ergebnisse gelegt. Die Suszeptibilitätskarten sollten für Raumplaner genauso lesbar sein wie für Anwohner, Verwaltungsangestellte und Politiker.

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INTRODUCTION

Living in a typical Alpine landscape, the people in Vorarlberg are aware of both sides of the same medal: a beautiful landscape on the one side and landslide hazard through erosional processes on the other. Although mass movements have been constantly taking place since the end of the last ice age – and will prevail onto the next – the problems for the Vorarlberg communities seem to increase. Like in many other regions of the Alps the growing population density and the rising values of buildings and infrastructure force the government to find a new security treatment against natural hazards. As landslides cannot be prevented in every settled area, spatial planning shall prevent large financial or even personal loss. As a beginning of hazard and risk management, a project called "Geohazard Map Vorarlberg" was initiated to give spatial planners and communities a first insight into the hazard situation.

The Department of Applied Geology (AGK) at Karlsruhe University carried out the study in cooperation with the INATURA Museum Dornbirn and the Federal Government of Vorarlberg. The project started in 1999 with the following key tasks:

- Usage of GIS-Technology
- Collection of data with geological and geotechnical mappings
- Analysis of recent events (landslide inventory)
- Proposing of a method at a scale of 1:25'000
- Method understandable and applicable for non-geologists

Although the interpretation of a geological map (if available) is telling most of the story of landslide hazard to the expert, it has to be underlined that these maps are unreadable for laymen. Because of the sometimes cryptic signatures and names even modern geological maps are often ignored in land use planning. During the years of our fieldworks, many discussions with engineers, residents and politicians have indicated that another interpretation of geological and morphological information, presented in a more general way, would be helpful for a lot of applications and users.

The project tried to analyse the geological and morphological causes of mass movements. Working on the whole area of Vorarlberg with the available data sets, places should be recognized which are prone to landslides. Trigger mechanisms like rain or earthquakes were not taken into account because areal data sets of triggers were not available (and usually are critical). The natural and static characteristics of a slope, exposing or stabilising it to mass movements is also referred to as the susceptibility (IAEG 1990). At an early stage of the project it became obvious that only a qualitative approach would be reasonable (Kassebeer & Ruff 2003). The susceptibility would be analysed according to five categories (very low, low, medium, high, very high).

FIELD STUDIES

In the years 1999 – 2006 several study areas in Vorarlberg were geologically and geotechnically mapped to identify causes and mechanisms of active mass movements. Three of the study areas are presented below: the Hochtannberg/Arlberg Region, the Gr. Walsertal and the Walgau (Fig. 1).

The locations of these study areas were orientated to roads and settlements and not to geological or morphological structures. This project was intended to concentrate on the potential damages to existing infrastructure. High mountain environments were not considered because of the scarcity of elements at risk.

According to our field experience within the Alps, the lithology of bedrocks and soils is the most important cause for mass movements. In spite of the importance of this information, the geological maps in the Alps – analogue and digital – are not up-to-date or are even nonexistent. Extended field mappings at the scale of 1:10’000 (mainly executed by students of engineering geology) should assure the quality and precision of the analysed data sets. Although this procedure is educational and economical, it was also time consuming and the results had to be gathered step by step.

Fig. 1: Three of the study areas of the project.
Abb. 1: Drei der Arbeitsgebiete des Projektes.

GEOLOGY OF THE STUDY AREAS

Vorarlberg is one of the most favourite working areas for geologists, because all of the Alpine tectonic units are at hand within very close range. These units are from North to South: Molasse, Helvetic Nappes, Ultrahelvetic Nappes, Rhenodanubian Flysch, Northern Calcareous Alps and Silvretta Basement. The different geodynamic and tectonic evolutions produced a confusing multitude of formations of mainly sedimentary rocks. The landscape of Vorarlberg is highlighting the change between Mesozoic carbonate platform sediments marking the highest mountains and clayey deep-water deposits exposed within the smoother valleys.

During the Alpine Orogeny the incompetent (clayey) formations acted as detachment levels of nappe thrusts between the tectonic units. The competent (calcareous) formations were folded at various scales and internally deformed by thrust and strike-slip faults. Lateral facies changes within the units make the tectonic interpretation even more difficult. Within the three study areas the fieldworks gave valuable insights in the formations and tectonic structures.

The Hochtannberg/Arlberg region is situated within the Northern Calcareous Alps. The steep rock outcrops are mainly consisting of Triassic shallow water limestones and dolomites. Also important are Jurassic turbiditic sediments. Because of the high relief, rockfall is the main hazard in this area. But slides within the strongly layered formations are also common, leading to damages at roads and touristic buildings (Ruff 2005).

Tertiary turbiditic sediments of the Rhenodanubian Flysch dominate the Gr. Walsertal. The bedding planes of the sandstones, marls and clays are generally dipping to the south leading to a large number of rock slides at the northern flank of the valley (Ruff & Rohn 2007). Rockfall is an uncommon hazard within the rather smooth landscape.

The Walgau is lying within the tectonic thrust zone between Rhenodanubian Flysch and Northern Calcareous Alps. Tectonic sub-sheets and the widespread alluvial cover make the interpretation even more difficult. At the Northern part of the Walgau appear some rock slides whereas the southern part is dominated by rockfall hazard.

Quaternary glacial and postglacial sediments locally cover the base rocks of all study areas. Moraine material is widespread and apparently prone to sliding at steeper slopes. Erosion of the dolomites and marlstones lead to debris cones of various scales. The valley floors are filled with postglacial gravels and recent fluviatile sediments.

It is obvious that the differences in lithology induce completely different situations of landslide hazards. Although the stability of a slope is a quite local problem with numerous of factors and specialities, the proposed method should be able to cover the most important factors for a large region. It should give an overview into the whole area of Vorarlberg and all geological formations.

Because of the different mechanical behaviour, landslide types have to be considered separately. This paper concentrates on two main types of mass movements: sliding and falling. Debris flows were also analysed at the Walgau but are not described in this paper.

DATA MANAGEMENT

The information collected in the field and from literature was organized according to Fig. 2. Existing geological maps were reviewed and after the fieldwork geological maps at a scale of 1:10’000 were drawn. The orthophotos gave an excellent overview about the rockfall scarps and the type of vegetation. At the beginning of the project only a 25 m Digital Elevation Model (DEM) of Vorarlberg was available. The accuracy was given as 1-2 m at flat and 5-10 m at steep slopes (Land Surveying Office, BEV). The field investigation has shown that the quality of the model was nevertheless good enough for our investigations. As nowadays a 10 m DEM and even finer resolutions are at hand, the future works will have an even better working basis.

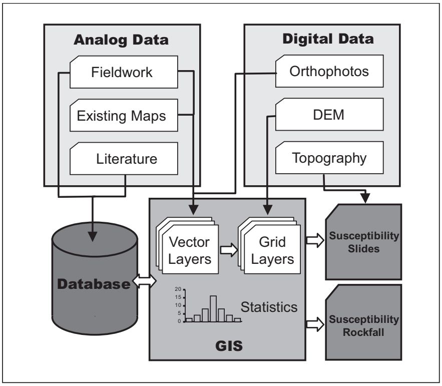


Fig. 2: Data Management of the project.
Abb. 2: Datenquellen und Verarbeitung im Projekt.

As one of the goals of our studies was fast and effective processing of various data sources, it was agreed to work with grid layers (Kassebeer & Ruff 2003). Although geological data is usually used as vectors, the grids have clear advantages in fast and easy processing of various data sources. To get a reasonable geological database, the formations were distributed into lithological classes according to Moser and Üblagger (1984) into "soil", "homogenous hard rock", "heterogeneous hard rock" and "soft rock". In reference to grain size and sorting, the soil was subdivided into "alluvial sediments", "torrential deposits", "glaciofluviatile gravels", "glacial tills" "slope debris" and "rockfall debris". Active areas of slides and rockfalls were classified according to Cruden and Varnes (1996) and special interest was laid on scarp- and accumulation zones of the movements. All field data was implemented into a Geographical Information System (ArcGIS 8.3). The cell size of all data layers was adjusted to the resolution of the DEM.

SUSCEPTIBILITY ASSESSMENT FOR SLIDES

The susceptibility assessment for slides was accomplished using an index method after Juang et al. (1992). In this method the susceptibility is described by an index ranging from 0 to 1. Comparing the preparatory factors to the landslide inventory, the data layers lithology, distance to faults, slope angle, slope aspect, slope curvature, vegetation and erosion were used. In a three step iterative method the layers were combined (Fig. 3).

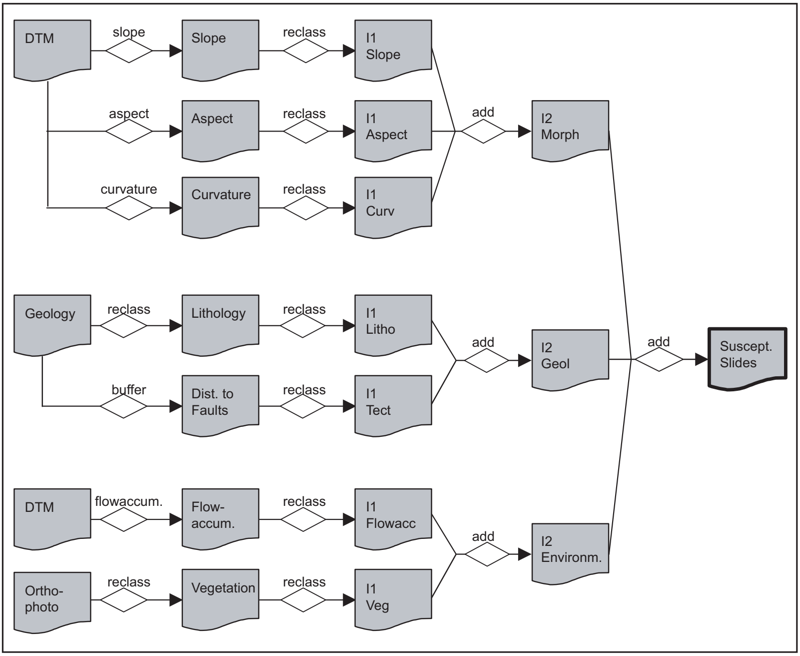


Fig. 3: Flowchart of the data analysed for sliding.
Abb. 3: Fliessdiagramm der Gefährdungsanalyse für Rutschungen.

The first index (I1) is derived by a one by one comparison of each data layer to the landslide inventory. This was done by bivariate statistics with most of the factors (for details see Ruff & Czurda 2007). After that the layers are combined into the three groups; morphology (slope angle, aspect and curvature), geology (lithology and distance to faults) and environment (vegetation and erosion). To give one layer a certain prominence within the group, the second index (I2) is used. In a third step the groups are combined with a third index (I3) into the susceptibility map.

At first the indices were set by expert opinion. Comparing the result to the landslide inventory they were improved iteratively. In the years of research these indices were found for each study area separately. After the fieldworks were accomplished all the data was combined and the indices could be adjusted to describe all of the different geological environments. At this last phase of the project the grid data type was extremely helpful. Layers and classifications could be combined and distributed with little technical trouble. Vector data would have been much more complicated and would have slowed down the progress immensely.

The most realistic result in all study areas (in comparison to the active slide areas) was achieved using the indices of Tab. 1. The combination of I2 and I3 is showing the weighting of the different layers. As it was expected, the most important factors were slope angle and lithology. Slope aspect has a surprisingly high influence, which is supposed to reflect the weathering conditions (Ruff 2005). Other factors have local importance and can strengthen or soften the cumulative susceptibility at specific places.

Tab. 1: Indices used for weighting of the layers.
Tab. 1: Indizes für die Gewichtung der Ebenen in der Analyse.

Layer	Group	Layer Index (I2)	Group Index (I3)	Combined Index (I2 * I3)
Slope Angle	Morphology	0.5	0.4	0.2
Slope Aspect		0.3		0.12
Slope Curvature		0.2		0.08
Lithology	Geology	0.8	0.4	0.32
Dist. To Faults		0.2		0.08
Erosion	Environment	0.6	0.2	0.12
Vegetation		0.4		0.08
		Each Group ∑ = 1	∑ = 1	∑ = 1

The result of the susceptibility assessment is a value between 0 and 1 for each cell (25*25 m) of the study area, which is – at first – not enlightening the problem of landslide risk. The mathematical result has to be interpreted and presented to the various users. As we had decided to use five susceptibility classes before, the results of each study were reclassified (very low, low, medium, high, very high) and plotted as a map (see below).

Fig. 4 gives the comparison of the active slide areas to the susceptibility values. At first the differences between the three study areas became obvious. Although the total area of the three study areas is of comparable size, the number of cells representing slides in the Gr. Walsertal exceeds the other two by far. As mentioned above, this is caused by the geology of this area. In spite of the differences of the count of cells the culmination of cells with values between 0.6 and 0.8 is clearly visible in this diagram. On behalf of the field experience and this diagram, the five susceptibility classes have been defined rather empirically. Some mathematical approaches have been tried, but it was after all decided to rely rather on common sense than on statistics (the data basis was mostly made by humans after all).

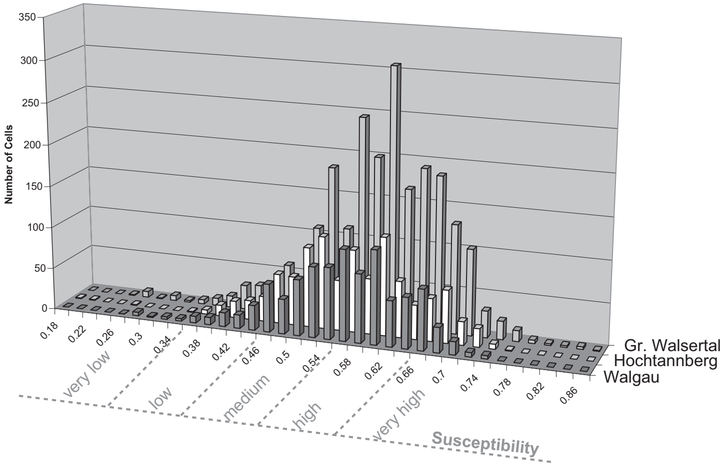
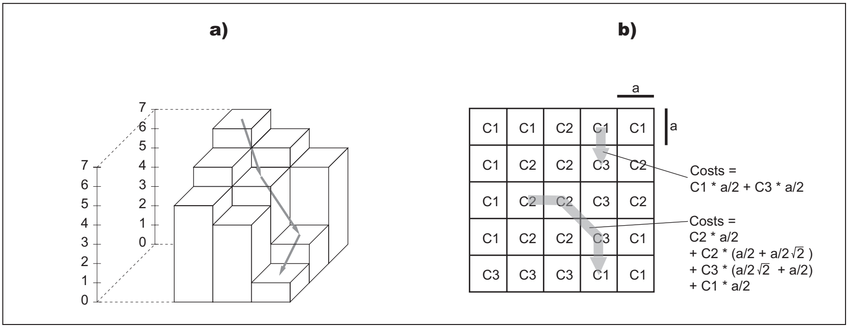


Fig. 4: Result of the analysis at active slide areas and the susceptibility classification.
Abb. 4: Resultat der Analyse an aktiven Rutschungsflächen und die Gefährdungsklassierung.

SUSCEPTIBILITY ASSESSMENT FOR ROCKFALL

The danger of rockfall is not only mechanically different from that of slides, the range of falling, bouncing or rolling blocks is also significantly higher. Therefore the hazard assessment is usually divided into three steps: Firstly, finding the potential source area of rockfall blocks, secondly, finding the potential rockfall trajectories down slope, and thirdly, calculating the range of specific blocks.



C1	C1	C2	C1	C1
C1	C2	C2	C3	C2
C1	C2	C2	C3	C2
C1	C2	C2	C3	C1
C3	C3	C3	C1	C1

Fig. 5: Principle of the cost analysis for rockfall trajectories.
Abb. 5: Prinzip der Kostenanalyse der Steinschlag-Trajektorien.

Using the possibilities of focal functions in the GIS, the susceptibility has been modelled on the basis of a cost analysis (Ruff & Rohn 2007). Potential source areas of rockfall material were calculated out of the DEM (slope angle > 45°) and refined with the layer lithology (hard rock or heterogeneous hard rock). Starting from each source cell the GIS is able to find all possible downhill trajectories. As the resolution of the DEM was relatively low, only the D8-Algorithm after Jenson and Domingue (1988) was applied. The range of moving blocks was modelled with a simplified rolling movement of a spherical rock sample after Scheidegger (1975). In his formula the range of a rolling block is dependent on the slope angle and the coefficient of rolling friction (Ruff 2005). The influence of rolling friction was realised by a cost analysis. If a certain cost for trespassing of a cell is defined, a cost analysis is able to summon the costs of all potential trajectories and to find the "cheapest" trajectory down slope (Fig. 5). In our case the "prize" is describing the susceptibility. The lower the prize, the higher the possibility of a block reaching this cell, the higher is the susceptibility.

Using the DEM and some benchmark coefficients derived from literature (Azzoni et al. 1991), a cost grid for the analysis could be defined. It has to be stated that this cost grid is not able to give quantitative ranges of rockfall events. But if the costs of all possible trajectories are calculated, the result is again a distribution of susceptibility values that can be divided into five classes. The layers used in the susceptibility assessment are shown in Fig. 6.

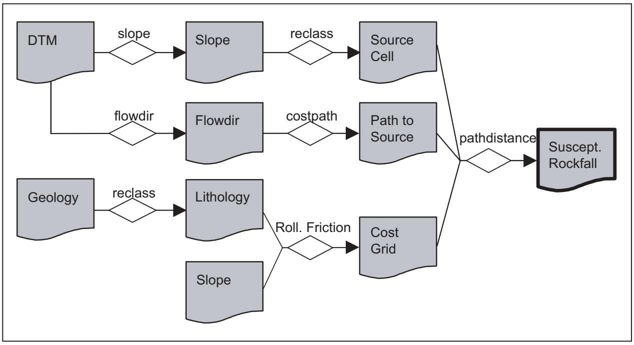


Fig. 6: Flowchart of the data analysed for falling processes.
Abb. 6: Fliessdiagramm der Gefährdungsanalyse für Sturzprozesse.

Analogue to the slides, the result of the cost analysis was compared to active rockfall debris cones in the landside inventory (Fig. 7). The histograms of the three study areas are showing the different geological environments again. In the Hochtannberg/Arlberg area the number of cells representing debris cones is significantly higher than in the Gr. Walsertal. This is influenced by the relief and the different lithology (see before). The culmination of cells bearing low cost values is apparent and this can be used to define the five susceptibility classes. Because of the resolution of the DEM not all source areas of rockfall and their accompanied debris cones are recognized. Therefore some debris cones – especially in the Gr. Walsertal – are shown with very low costs. Nevertheless the most important rockfall areas mapped in the field were identified correctly.

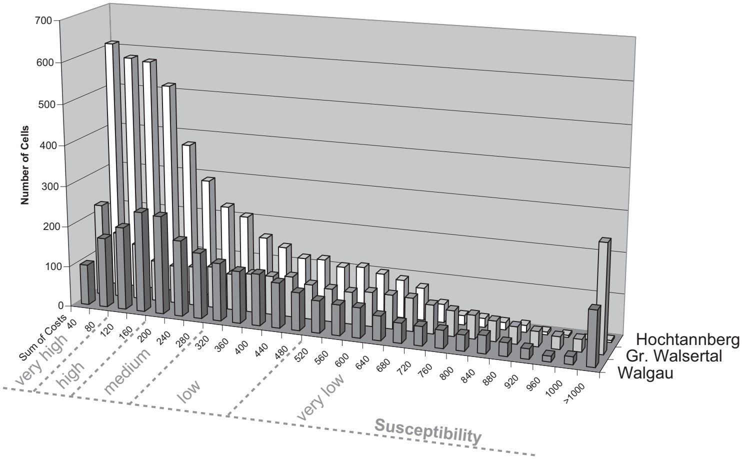


Fig. 7: Result of all mapped debris cones and classification of susceptibility.
Abb. 7: Resultat der Gefährdungsanalyse an den aktiven Steinschlag-Ablagerungen.

SUSCEPTIBILITY MAPS

The results of the susceptibility assessment were presented by plotting the five susceptibility classes as two different maps (Fig. 8 and 9). To create intuitive information, the maps are usually drawn with a green-yellow-red colouring, the red colour for high susceptibility and the green for low. These maps have been shown to different users and all of them could grasp the hazard information without further explanation.

For optical control of the maps, the slide areas and debris cones of the landslide inventory are also illustrated. The statistic comparison showed that 75 % of the active mass movements were recognized with our methods. The remaining 25 % were either extremely slow moving slides (with minor significance in case of landside risk) or translational slides at an anticline of limestones (shown on the geological map) upon claystones (not shown on the map). Bearing in mind the imprecise data basis and the working scale this result was acceptable.

CONCLUSION

The tectonic situation of the study area causes different types of mass movements. Because of the complex geological setting and the low density of events, a semi-quantitative method had to be applied. It was concentrated on the susceptibility for slides and rockfalls, induced by geology, morphology and environment.

Lithology and slope angle were found to have the strongest influence on slides. With help of an index method, the susceptibility could be distinguished descriptively using fundamental data layers. The method is transparent and can be adapted to various new data layers (i.e. from Remote Sensing). Like most qualitative methods it is dependent on expert knowledge of the executing geologist. The simplified model for falling movements based on a cost analysis was in surprising good conformity to our field experience. This method is more objective but strongly dependent on the quality of the DEM.

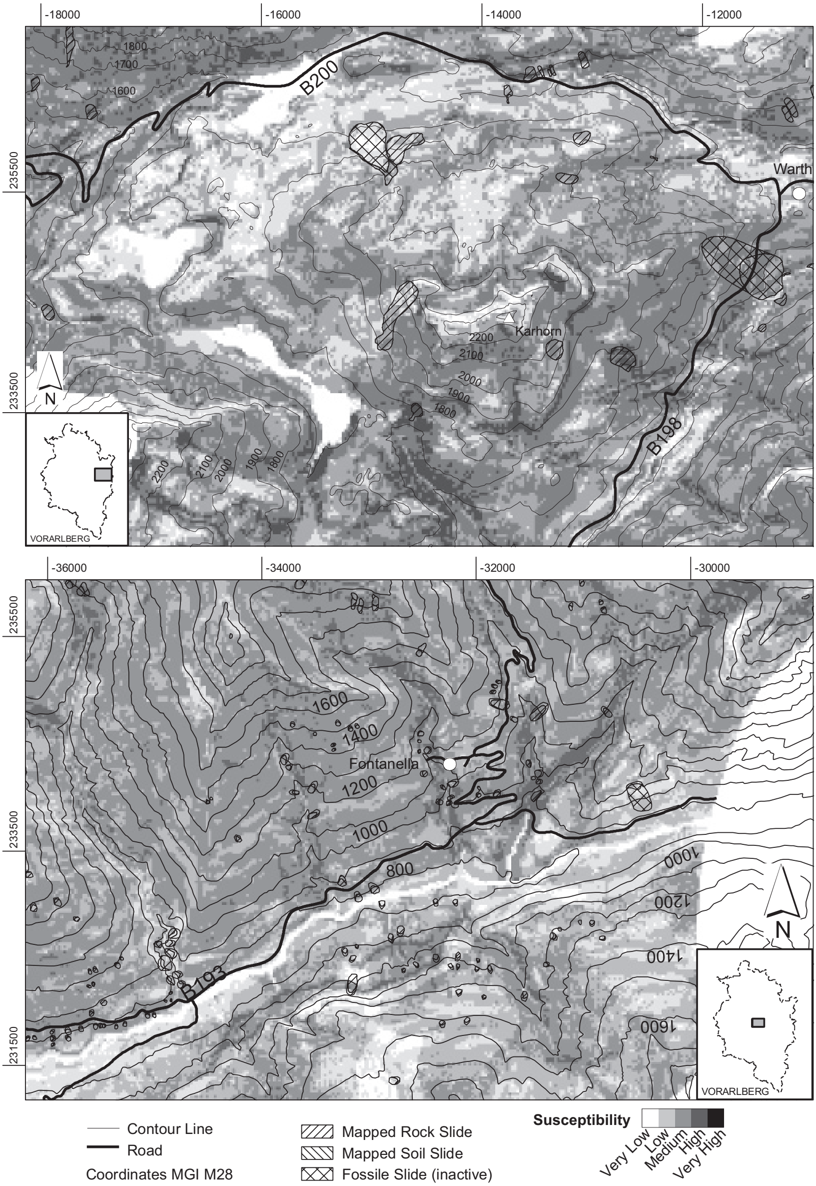


Fig. 8: Two examples for susceptibility maps for slides at the Hochtannberg area (Warth) and the Gr. Walsertal (Fontanella). The maps are usually printed in colour to make them self-explanatory.

Fig. 8: Zwei Beispiele für die Gefährdungskarten im Hochtannberg Gebiet (Warth) und im Gr. Walsertal (Fontanella). Die Karten werden normalerweise in Farbe gedruckt, um sie noch eingängiger zu machen.

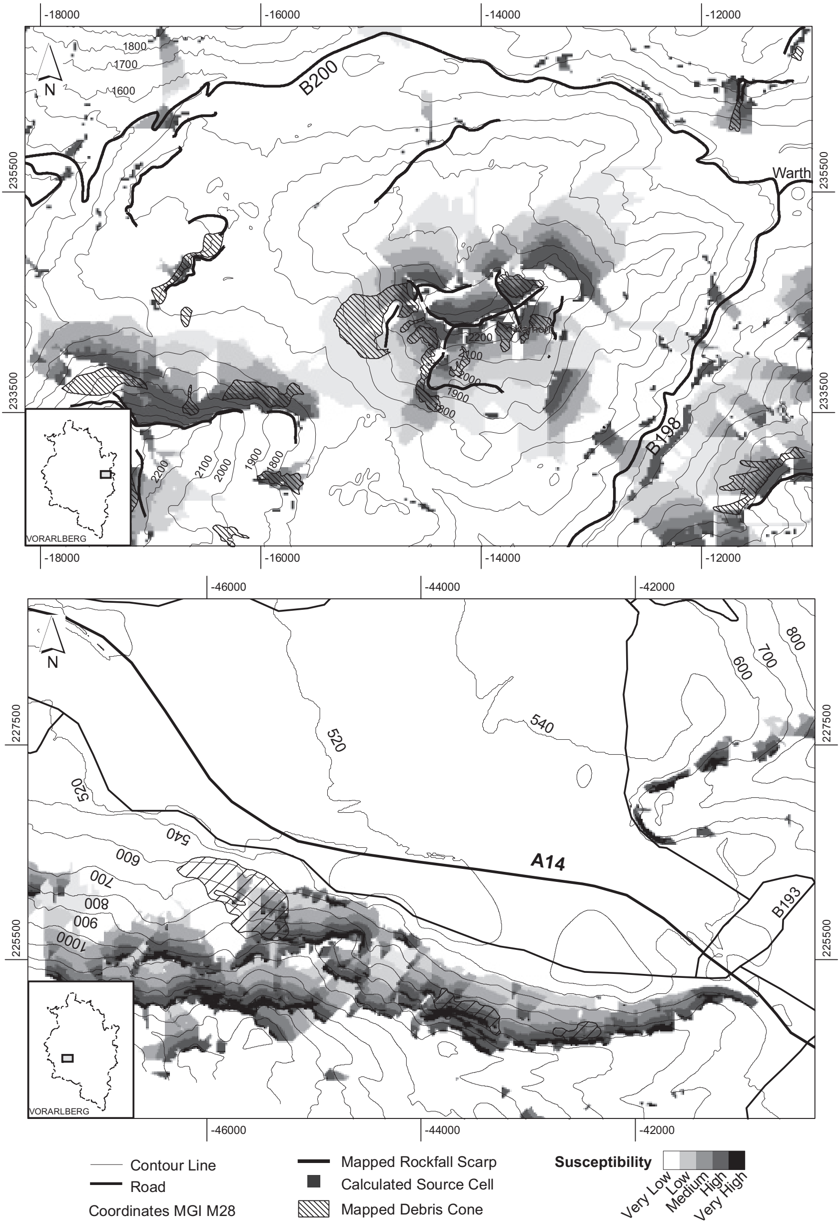


Fig. 9: Two examples for susceptibility maps for rockfall at the Hochtannberg area (Warth) and the Walgau (Nenzing). The maps are usually printed in colour to make them self-explanatory.

Fig. 9: Zwei Beispiele für Gefährdungskarten Sturzprozesse im Hochtannberg-Gebiet und im südlichen Walgau (Nenzing). Die Karten werden normalerweise in Farbe gedruckt um sie noch eingängiger zu machen.

The results of the susceptibility assessment were presented with maps in a general way. These maps are understandable for users without any geological or geotechnical background. Therefore these maps represent a useful tool for spatial planners, politicians and citizens. As a first step of risk management people can be informed about the geological hazards of their homelands.

Other types of mass movements (i.e. debris flows and snow avalanches) can also be analysed with aid of the GIS and presented as susceptibility maps. The rapid evolution of GIS technology and the improving availability of data will permit more complex models. The maps of each process can be overlaid with land use information and conceptional risk maps can be drawn.

At the moment the presented method has been applied to several of the main valleys of Vorarlberg (Bregenzerwald, Hochtannberg/Arlberg, Gr. Walsertal, Walgau, Klostertal). It is planned to use it on the entire territory of Vorarlberg to get a complete view for further risk discussions and management.

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