Austrian Journal of Earth Sciences | Volume 105/2 | 113 - 127 | Vienna | 2012

Modelling geomorphological hazards to assess the vulnerability of alpine infrastructure: The example of the Grossglockner-Pasterze area, Austria

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KEYWORDS

Großglockner-Pasterze area
vulnerability maps
climate change
permafrost
modelling

Abstract

The vulnerability studies of human infrastructure in high-mountain areas influenced by geomorphological hazards in a changing climate are a rather young research field. Especially in high-alpine regions vulnerability maps are often not available, particularly regarding hiking trails or climbing routes. In this paper we present a heuristic approach to create vulnerability maps for Alpine trails and routes in the Großglockner-Pasterze area (47°05'N, 12°42'E), an high-mountain area ranging from about 2000-3798 m a.s.l.. Therefore, the hazard potential that arises from gravitational mass-movements (rock falls, debris falls, other denudative processes) has been modelled in a two step approach. In the first step, the potential source areas were detected using a Digital Elevation Model combined with different further sources of information such as a geological map and orthophotos. Based on the estimation of the volume of the mobilizable substrate – which largely depends on the active layer thickness of permafrost - the second step was carried out by calculating transport paths and dispersal of the downward-moving material. The process model is based on a mass-conserving multiple direction flow propagation algorithm. Both disposition and process model were set up for the current environmental conditions (2010) and for a future scenario (2030) that is driven by a moderate regional climate scenario. Based on the assessment of these processes, susceptibility maps were generated. In a final step, vulnerability maps were created by combining the susceptibility maps with the alpine infrastructure. Considering the length of the trails, 5.5 % are classified in higher hazard classes in 2030 compared to 2010. The presented maps display all known major vulnerable trail and route sections in the study area properly. Furthermore, the evaluation of the maps by local and regional authority experts showed satisfactory results. However, future adaptions of both models – disposition as well as process model – are desirable, especially by the inclusion of better input data based on more empirical information on the processes.

Die Vulnerabilität von Infrastruktur gegenüber geomorphologischen Naturgefahren unter dem Einfluss des Klimawandels wird nur selten untersucht, besonders Vulnerabilitätskarten für Wege und Routen in hochalpinen Gebieten sind oftmals nicht verfügbar. In dieser Arbeit wird ein heuristischer Ansatz zur Erstellung von Vulnerabilitätskarten des alpinen Wege- und Routennetzes im Großglockner-Pasterze Gebiet (Seehöhe ca. 2000-3798 m, 47°05'N, 12°42'E) vorgestellt. Hierzu wurde das Gefahrenpotentials von gravitativen Massenbewegungen, speziell Felsstürzen, Steinschlag und anderen denudativen Prozessen durch eine Modellierung der Prozesse abgeschätzt. Die Massenbewegungsprozesse werden in zwei Schritten nachgebildet: Im ersten Schritt werden die möglichen Herkunftsgebiete mittels eines Digitalen Geländemodells und weiterer Informationsebenen (u.a. geologische Karte, Orthophotos) identifiziert. Basierend auf einer Abschätzung der Volumina der mobilisierbaren Massen, die stark von der Auftautiefe des Permafrosts abhängen, umfasst der zweite Schritt die Berechnung des Ausmaßes und der Verteilung des sich abwärts bewegenden Materials. Hierfür wird ein Prozessmodell mit einem Algorithmus verwendet, welcher Massen konserviert und die Richtungsabhängigkeit der Ausbreitung der Bewegung berücksichtigt. Sowohl das Dispositions- als auch das Prozessmodell wurden für die gegenwärtigen Umweltbedingungen (2010) und für ein zukünftiges Szenario (2030), beruhend auf einem gemäßigten Klimaszenario, gerechnet. Durch Bewertung dieser Prozesse unter Berücksichtigung der Hangneigung und der mobilisierbaren Volumina wurden daraus Gefahrenhinweiskarten generiert, welche schließlich in einem letzten Schritt durch Überlagerung mit der alpinen Infrastruktur zu Vulnerabilitätskarten weiter entwickelt wurden. In Bezug auf die Länge der Wege und Routen fallen im Jahr 2030 5,5 % in eine höhere Gefahrenklasse verglichen zu 2010. Die Karten zeigen die vulnerablen Abschnitte der Wege sehr realitätsnah, wie deren Evaluierung durch lokale und regionale Fachleute ergab. Dennoch sind sowohl das Dispositions- als auch das Prozessmodell verbesserungsfähig, insbesondere was die Qualität der Eingangsdaten betrifft, die durch mehr empirisches Wissen über die beteiligten Prozesse wesentlich verbessert werden könnten.

1. Introduction

High-mountain areas are especially prone to gravitational processes due to their steep relief. The resulting processes such as landslides, rock falls or debris flows are largely influenced by weather and climatic conditions. These processes can quickly turn to natural hazards potentially endangering individuals or infrastructure when it comes to an interaction with human activity. In the context of the ongoing climate change, the mentioned aspects are of special importance because: (i) High-mountains attract a continuously rising number of tourists. The alpine environments are considered to be natural and untouched areas as well as suitable for outdoor leisure activities offering adventure-like experiences. Thus, the probability of the presence of persons and touristic infrastructure in the high mountains is on a very high level. For instance the number of visitors at Großglockner high alpine road was about 830.000 in 2009 (unpublished data kindly provided by Großglockner Hochalpenstraßen A.G., Salzburg). (ii) Several studies on climate change in the European Alps (e.g. Auer et al., 2007; Brunetti et al., 2009) pointed out an average warming trend of 1.4 °C within the 20th century which is a warming about twice as much as the global trend reported by IPCC (2007). Moreover, the precipitation in the Alps is likely to undergo seasonal shifts and higher interannual variability characterized by an increase in extreme rainfall events. Therefore, the morphodynamics in the high-mountain environments of the European Alps is potentially facing an increase of frequency and magnitude of mass movement processes.

Several studies show that there is a link between recent climate change and e.g. the frequency of debris flows in the European Alps (e.g. Zimmermann and Haeberli, 1992; Stoffel and Beniston, 2006). Besides the direct changes in temperature and precipitation, the highest parts of the Alps are affected by two evident impacts of climate change, i.e. permafrost degradation and deglaciation (Harris et al., 2009; Kellerer-Pirklbauer et al., 2011). Rock fall and landslides caused by permafrost degradation will further increase, particularly in warm summers (Kellerer-Pirklbauer et al., 2012), because permafrost degradation is affecting slope stability (Noetzli et al., 2003; Gruber et al., 2004b). In addition, glacier retreat leads to paraglacially induced morphological changes of the relief (Ballantyne, 2002), slope increasing and stress redistribution within adjacent valley slopes, which can cause mass-movements such as rock-slides (Kääb et al., 2005).

According to UNISDR (2009), the term (natural) hazard is defined as a process that my cause loss of life, injury or damage, whereas vulnerability is defined as the characteristics and circumstances of a system or asset that make it susceptible to the damaging effects of a hazard. Thus, the term vulnerability is very close to the meaning of risk which, however, is mostly described by combining the quantification of hazardous processes and the quantification of their consequences (Felgentreff and Glade, 2008, 106). In contrast to hazard, susceptibility does neither consider the temporal probability of failure nor the magnitude of an event (Committee on the Review of the National Landslide Hazards Mitigation Strategy, 2004). It only describes the degree of which an area can be affected by future slope movements (Guzzetti et al., 2006).

During the last decades, several approaches to model rock fall and landslide processes and to assess the resulting hazard potential or susceptibility on a regional scale have been developed (e.g. Ruff and Rohn, 2007; Wichmann, 2006; Neuhäuser et al., 2011). Since it is difficult to extrapolate mechanical parameters on a regional scale (Aleotti and Chowdhury, 1999), often qualitative (heuristic) methods that compare the mass movement with characteristics of geomorphology or geology are used (e.g. Ruff and Czurda, 2008; Ayalew et al., 2004; Reiterer, 2000). However, just a few of the existing regional models focus on high-mountain areas and include processes like permafrost degradation and glacier retreat into the identification of potential source areas (e.g. Allen et al., 2011). Furthermore, the vulnerability of alpine (marked) trails and routes (non-marked but frequently used tracks) is rarely considered in these studies. Nonetheless, the increasing number of hazardous events in high Alpine areas and the associated need of expensive technical measures to renovate, construct and maintain alpine trails and routes created a wide awareness of these processes not only by local and regional actors and institutions (e.g. mountain guides, mountain rescue teams, alpine associations, touristic organisations), but also by the general public at least in the Alpine countries (Umweltdachverband (Austria), 2006).

The main objective of this study is the generation of vulnerability maps for Alpine trails and routes in the Großglockner-Pasterze area for a current situation (2010) and a future scenario (2030). These maps should be easy to read and understand so that local stakeholders without expert knowledge in modelling or hazard assessment can use them for planning purposes. The creation of the maps is based on a simple heuristic approach that is easily applicable. Like most of the heuristic approaches, the utilized method is strongly dependent on the exercise of the surveyors (Ruff and Czurda, 2008), but a very practicable way to assess geomorphological hazards caused by different mechanisms. Further aims of this study are: (i) the estimation of the volume of mobilizable substrate, (ii) the modelling potential to source, transport and deposition zones of mass movements as well as (iii) the creation of susceptibility maps for rock and debris fall as well as for

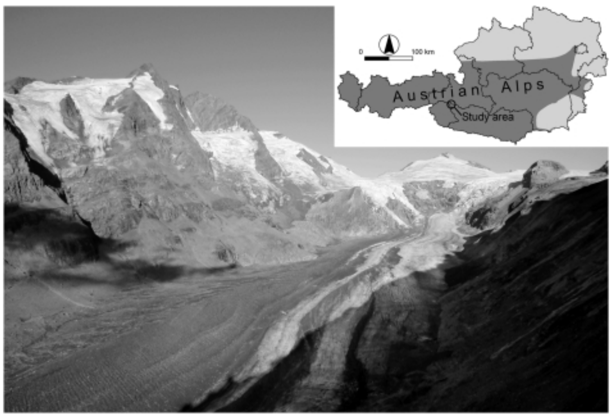

Figure 1: Location of the study area in the Austrian Alps (top right) and the famous view from Franz-Josefs-Höhe (2367 m a.s.l.) in western direction to the partly debris-covered tongue of Pasterze Glacier and Großglockner (3798 m a.s.l) (left) gives an impression of the high mountain relief and the processes occurring in it (photograph: G. K. Lieb, 13.9.2010).

landslides. In this paper the practical aspect of how to deal with hazardous events will not be discussed.

2. Study area

The study area (Fig. 1) comprises the closer vicinity of Austria's highest summit Großglockner (3798 m a.s.l.) and Austria's largest glacier Pasterze (17.3 km² in year 2006). The study area covers altogether an area of about 94 km² and is located to a large extent in the Hohe Tauern National Park. This area was chosen for three main reasons: (i) the high number of tourists visiting this remarkable landscape which gives the topic a high regional relevance. Up to one million persons per year visit the panoramic point Franz-Josefs-Höhe overlooking Pasterze Glacier, (ii) the good availability of base data (Chapter 3) due to a long tradition of scientific research in this area (e.g. Lieb and Slupetzky, 2011) and (iii) the good regional knowledge and the familiarity of the authors with the area. This circumstance is based on different research projects carried out in the past, among them the annual monitoring campaigns of glaciation changes, a previous study on geomorphic hazards within the FWF-project ALPCHANGE - Climate Change and Impacts in Southern Austrian Alpine Regions (Lieb et al., 2007) as well as PermaNET (Permafrost longterm monitoring network) a project within the European Union's Alpine Space Programme.

The entire study area is built of crystalline rocks belonging to the Penninic unit of the Tauern window itself part of the Central Eastern Alps (Krainer, 1994). The relief shows nearly all features of high mountain morphology with high vertical elevation differences (up to 2300 m within a horizontal distance of 1 km). Plateaus at high elevations considered to be glacially modified remnants of tertiary land surfaces form the accumulation areas of a still widespread glaciation. Climate conditions are typical for high elevations at the central Alpine crest with rapidly decreasing precipitation from some 2500 mm at 3000 m a.s.l. to less than 1000 mm in Heiligenblut at 1380 m, about 7 km to the SE of the study area (Auer et al., 2002). The potential timberline is at 2100-2150 m a.s.l. According to Lieb (1998) and Kellerer-Pirklbauer et al. (2012), the current lower limit of discontinuous permafrost is at 2500-2800 m a.s.l depending on slope exposition. Finally, the mean equilibrium line of glaciers in the area is located in 2900-3100 m a.s.l..

3. Data and Methods

3.1 Data

In this study, a Digital Elevation Model (DEM) provided by the Federal Office for Metrology and Surveying (BEV) with a raster spacing of 25 m was used to calculate slope and aspect. Geological units were delineated, labelled and grouped into four geotechnical units (solid rock, moderately solid rock, unconsolidated rock and others) based on the official geological map of Großglockner at scale 1:50 000 (Höck and Pestal, 1994). Since the glacier extent in the geological map was from 1985 and glaciation has decreased substantially over the last 25 years (Kellerer-Pirklbauer et al., 2008), the current glacier extent was delineated from the topographic map of the German Alpine Club (2006, glacier extent 2002) 1:25 000 as well as from orthophotos and the geological map. Areas that became ice-free between 1985 and 2002 were classified by visual orthophoto interpretation and by extrapolating the information of the geological map. Moreover, local adaptations of the content of the geological map needed to be made based on orthophotos, because unconsolidated rocks and debris have moved downslope during the last decades exposing solid rock. This indicates unstable ground conditions in this widely paraglacial environment (Ballantyne, 2002). Finally, the updated geological data set was converted to a raster with a cell size of 25 m consistent with the spatial resolution of the DEM.

True-colour-orthophotos were used to determine the vegetation cover in the study area. For this purpose, the orthophotos were classified by using an object-based classification approach into the four vegetation classes forest, dense vegetation, sparse vegetation and no vegetation.

The data set was completed with the potential extent of discontinuous permafrost distribution of the Großglockner-Pasterze area. This map was previously created in the framework of the Project ALPCHANGE (see Lieb et al., 2007). To model the potential extent of permafrost, the empirical-based program PERMAKART (Keller, 1992) was adapted to the conditions of the study area. In addition, the lower limits of discontinuous permafrost occurrence were used as defined by Lieb (1998), resulting in the classification of areas with probable, possible and no occurrence of discontinuous permafrost with respect to altitude, aspect and topographical position. Since there was no extensive field information about the current lower limit of permafrost in the study area available, the vertical rise of the lower limit of permafrost distribution was assumed to have been 24 m (2 m/a^{-1} from 1998 to 2010) as indicated by studies in Central Switzerland (Frauenfelder et al., 2001)

3.2 General notes about modelling in this study

For the Großglockner-Pasterze area a preliminary map of geomorphological hazard for tourists has already been developed by Lieb et al. (2007). This map was created by combining and weighting different input parameters like recent deglaciation, permafrost distribution and slope gradient to receive two-dimensional information about areas with potential risk of hazardous processes. Although a validation of the map (by the locations of mass-movement events and accidents that already occurred) showed satisfactory results, the lack of some important parameters remained in place. Therefore, in this study a significantly wider approach was taken. In addition to the assessment of hazard source areas, rock and debris falls as well as denudation processes (Selby, 1993) in the study area were modelled. The term denudation processes is used as a collective term for shallow landslides, debris and mud flows as well as sheet erosion, processes that mainly occur in deposits of paraglacial and periglacial environments. The simplification regarding denudation processes was necessary due to the lack of respective information. Moreover, with the utilized process model, which is a mass-conserving algorithm to parameterize gravitational transport and deposition based on a DEM originally developed to model snow avalanches, it was not possible to distinguish different propagation processes (Gruber, 2007). Therefore, in this study, only flow propagation processes were modelled.

Potential source areas for mass-movements were detected by a disposition model and the range and dispersal of the downward-moving rock material were determined by a process model. This approach allows distinguishing spatially the processes in source, transport and deposit areas. Figure 2 provides a general overview of the workflow used to generate vulnerability maps of alpine infrastructure in this project.

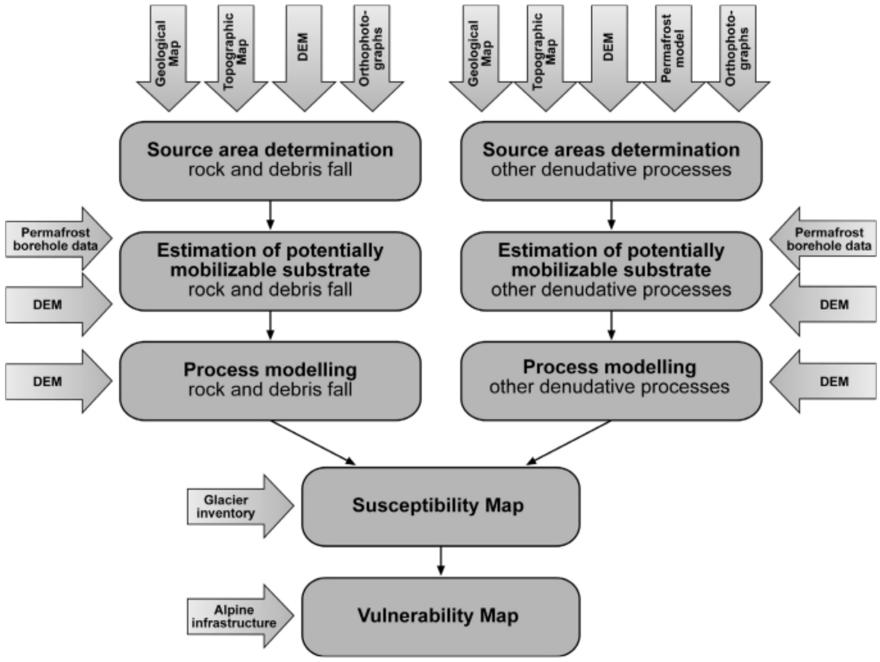

Figure 2: Flow diagram presenting the main steps in the generation of the vulnerability maps of alpine infrastructure for the Großglockner-Pasterze area.

3.3 Disposition modelling for the current status (2010)

One of the main difficulties in mapping and modelling mass-movement processes at a regional scale is the identification of potential source areas (Loye et al., 2009). The used disposition model is based on the assumption that certain geo-factors that triggered a mass-movement in the past will most likely trigger the same processes in the future (Wichmann, 2006). Due to the fact that not all gravitative mass-movement processes are triggered by the same factors and do not proceed in the same way, two different disposition and process models were developed. One was developed for rock and debris falls and a second one for other denudative processes.

Potential rock and debris fall source areas were determined on the basis of slope, geotechnical units and vegetation cover. For this purpose, the geotechnical units and the vegetation map were intersected with the slope information derived from the DEM. Areas with a slope less than 40° (Dorren and Seijmonsbergen, 2003; Wichmann, 2006) and a continuous forest cover (Meißl, 1998) were disqualified as potential source areas. With the chosen slope of 40°, potential rock and debris fall source areas comprise not only solid rock and moderately solid rock areas, but also some small areas of unconsolidated rock. The latter was considered to be part of the potential source areas too, because unconsolidated rock on steep slopes can be dislodged and become debris fall (Fig. 3). Due to constraints of the process model, the few potential disposition areas smaller than two pixels (<1250m^2) were excluded from the disposition model.

An important factor in the origin of denudative processes is the existence and composition of unconsolidated rock. Thus, only areas classified as unconsolidated rock in the geological map were considered as potential source areas. Since source areas for debris flows and landslides are mostly located between 20° and 40° (Ruff, 2005; Corominas et al., 1996), areas with a slope smaller than 20° and areas equal or greater than 40° were eliminated. Zones of unconsolidated rock in areas with a slope angle steeper than 40° are covered by the disposition model for rock and debris fall processes (see previous passage). Moreover, areas with a high possibility of discontinuous permafrost in the permafrost model were excluded to be potential source areas. Besides permafrost, a complete vegetation cover (Tilch et al., 2011) can protect from denudation. However, even dense vegetation can prevent the formation of debris flows only to some extent. The highest probability for disposition occurs in areas without vegetation cover. Therefore, areas without or with sparse vegetation cover were considered to be potential source areas for other denudative

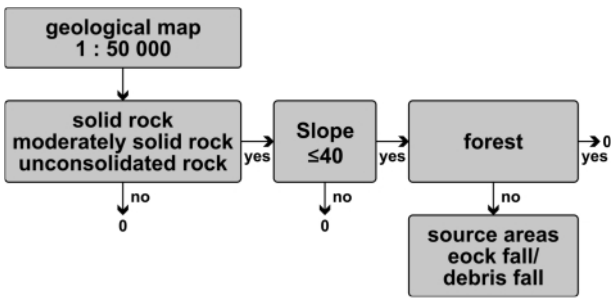

Figure 3: Flow diagram presenting the determination of rock and debris fall source areas.

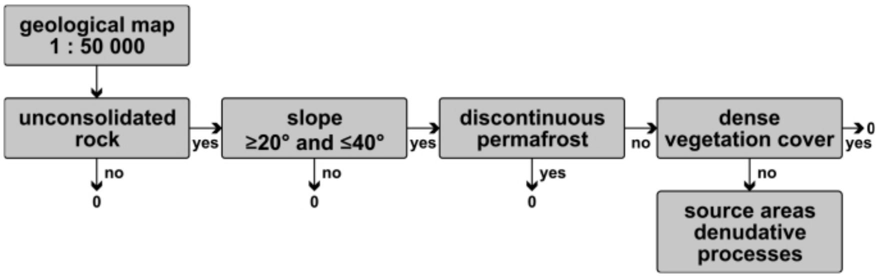

Figure 4: Flow diagram presenting the determination of the source areas of other denudative processes.

processes (Fig. 4). As with the disposition model for rock and debris fall, all areas smaller than two pixels were eliminated.

3.4 Disposition modelling for a future scenario (2030)

The procedure of the construction of the disposition model for 2030 follows the same steps as for the 2010 model. Only the input parameters needed to be adapted to future climate conditions, i.e. the anticipated glacier retreat and the rise of the lower limit of permafrost. The modelling of the 2030 scenario is based on a climate scenario for the Alpine region (reclip:more) from Gobiet et al. (2007). The 'reclip:more' scenario is computed for a grid cell size of 10 km and focuses on the middle of the 21st century (2041-2050, reference period 1981-1990). Further, it is based on two regional climate modes, ALADIN (http://www.cnrm.meteo.fr/aladin/) and the PSU/NCAR mesoscale model MM5 (Dudhia et al., 2004) that are applied for dynamical downscaling of parts of the ERA-40 re-analysis (Uppala et al., 2004) and global climate scenarios of the German ECHAM5 global circulation model (Roeckner et al., 2003). From this climate scenario an average increase in temperature of about 0.76 K from 2010 to 2030 can be assumed for the study region.

The estimation of the 2030 glacier surface was based on the assumption that in the next 20 years the glaciers in the study area will retreat with the same speed as they did over the last decade. For this purpose, data from the annual glacier monitoring carried out by the Lieb (2011) were used. For the 2030 scenario, the annual average surface elevation variations and glacier terminus retreating rates from 1999–2009 of three main glaciers (Pasterze, Wasserfallwinkel Kees and Freiwand Kees) were extrapolated linearly. The retreat of all other glaciers in the study area was estimated by extrapolating the difference of the positions of the glaciers in the geological map and the topographic map of the German Alpine Club of 2006. Finally, in all areas which were assumed to be ice-free by 2030, the DEM was adjusted and the geotechnical units were added according to the ones adjacent to the current glacier position.

Besides the glacier retreat, the vertical rise of the lower limit of discontinuous permafrost distribution needed to be considered in the scenario. With regards to the climate scenario used for the 2030 scenario and the assumptions made for the future glacier retreat, the average vertical rise of the lower boundary of permafrost distribution was assumed to continue linear with around 2 ma^{-1} until 2030 (Frauenfelder et al., 2001).

3.5 Estimation of potentially mobilizable substrate

Due to the fact that the active layer in permafrost environments is decisive for the thickness of mobilizable masses, data valid for the study area was required. Since there are no deep permafrost boreholes situated in the study area, temperature data of one of the three 20 m deep boreholes (Borehole 1) at Hoher Sonnblick (3106 m a.s.l., 15 km E of Pasterze), were used instead. The maximum active layer thickness at Hoher Sonnblick was 0.8 m during the summer months of 2008 and 2009 (Klee and Riedl, 2011; Schöner et al., 2012). In this context it has to be pointed out that there are no other permafrost boreholes in Austria apart from the three at Sonnblick and five very recently drilled permafrost boreholes at the nearby Kitzsteinhorn mountain (Hartmeyer et al., 2012). Therefore, permafrost temperature data are very sparsely available in Austria.

Concerning the active layer thickness, differences related to aspect had to be considered. Based on the data reported by Gruber et al. (2003, 2004a) from the Swiss Alps, the following assumptions were made: (i) a temperature difference between north- and south-facing slopes of ±4.5 K; (ii) active layer thicknesses of 0.80 m in SSE-SSW in 3.106 m a.s.l., 0.63 m in SSE-ESE and SSW-WSW, 0.45 m in ESE-ENE and WSW-WNW, 0.28 m in ENE-NNE and WNW-NNW, and 0.10 m in NNE-NNW aspects.

Besides aspect also the altitude needed to be considered regarding the active layer thickness. Therefore, a mean air temperature gradient of –0.55 K/100 m was included to calculate the average active layer thickness for different elevations. In terms of calculating the thickness, we referred to the aspect related thickness differences: a difference of ±4.5 K between north- and south-facing slopes causes a change in thickness of 0.7 m. For the calculation of the altitudinal gradient of the active layer thickness (AL_{grad}) the following equation was used (Eq. 1):

$$AL_{grad} = \frac{AL \cdot T_{grad}}{\Delta T} \quad (1)$$

where AL (m) represents the active layer thickness and ΔT (°C) the temperature difference between north- and south-facing slopes, whereas T_{grad} (°Cm^{-1}) represents the temperature gradient. Hence, the altitudinal gradient causes thickness differences of 8.5 cm/100 m. Finally, for each altitudinal step of ±25 m an active layer thickness of 2.1 cm was added or subtracted, respectively.

Since there were no study results on potentially mobilizable substrate for areas below the limit of discontinuous permafrost available for the study site, the calculation procedure for the estimation of the active layer thickness was extrapolated to areas below the limit of discontinuous permafrost. This assumption is plausible because in high-mountain areas with no or sparse vegetation cover (forested areas have already been eliminated in the disposition model) significant amounts of mobilizable substrate are available even if permafrost is not existent.

The implementation was done according to the following procedure in ERDAS Imagine: (i) starting with 800 mm thickness at 3106 m, for each altitudinal difference of ±25 m, 21 mm thickness were added or subtracted; (ii) the aspect data set was classified into 5 classes; (iii) thus the different aspect classes have thicknesses of 0 mm (SSE-SSW), 175 mm (SSE-ESE, SSW-WSW), 350 mm (ESE-ENE, WSW-WNW), 525 mm (ENE-NNE, WNW-NNW) and 700 mm (NNE-NNW) that had to be subtracted from the thickness calculated in (i); (iv) the resulting data (considering altitude and aspect) was clipped with the areas of potential disposition considering both rock and debris falls and other denudative processes, and (v) the varying geotechnical units were considered within the rock and debris fall processes with respect to the thickness calculated in (iv): solid rock 100 %, moderately solid rock 75 % and unconsolidated rock 50 %.

To calculate the active layer thickness for 2030, the assumed temperature increase of 0.76 K from 2010 to 2030 (Gobiet et al., 2007) needed to be related to the different active layer thickness values of the aspect calculation: ±4.5 K difference between north- and south-facing slopes causes thickness differences of 0.7 m. Hence, +1 K causes an increase of thickness of +0.156 m. Based on this assumption, the expected temperature increase of 0.76 K between 2010 and 2030 causes an increase of the active layer thickness of permafrost of 12.2 cm. This calculated value was added to the mobilizable material as a general value.

3.6 Process modelling

Choosing the most suitable model depends on several factors like purpose, availability of data, computing time and scale. Within the models the following components are commonly computed: basic disposition (disposition model), process trajectories (trajectory model) and deposition range (friction model). Modelling the process trajectories is possible using various approaches. Almost all of them are based on the height differences of adjacent raster cells of a DEM to compute material or energy propagations (Wichmann, 2006; Gruber, 2007).

In this study, a mass-conserving flow propagation algorithm (Gruber, 2007) that allows a divergent distribution into several neighbouring cells was used. The algorithm only uses simple parameters to express mass transport and deposition. The potential mass propagation from one cell to another cell is exclusively dependent on topography. Thus, the material accumulated in one raster cell defined as starting point is supplied to all surrounding raster cells with lower altitude values than the starting raster cell. These raster cells are then defined as end points. Since only elevation differences between cells are used in the flow propagation scheme, kinetic energy is entirely neglected. Furthermore, no mass is propagated over horizontal areas or uphill. Since the physical parameters of the respective transport and deposition process are not considered, the process variety (i.e. fall, rolling or flow) is not examined and only flow propagation is modelled. The input parameters for the process model consist of an altitude grid (i.e. DEM) as well as grids of disposition areas and the (parameterized) maximum deposition per raster cell (Dmax), which is calculated as follows (Gruber, 2007):

$$D_{\max} = \begin{cases} \left(1 - \frac{\beta}{\beta_{\lim}}\right)^{\gamma_s} \cdot D_{\lim} & if \beta < \beta_{\lim}, \\ 0 & if \beta \geq \beta_{\lim}. \end{cases} \qquad (2)$$

The slope limit β_{lim} is defined as the maximum slope inclination at which deposition occurs. The deposition limit (D_{lim}) is defined as the maximum deposition on horizontal planes. The value γ_s is considered in case D_{max} increases in a linear or exponential manner in areas where the slope limit decreases.

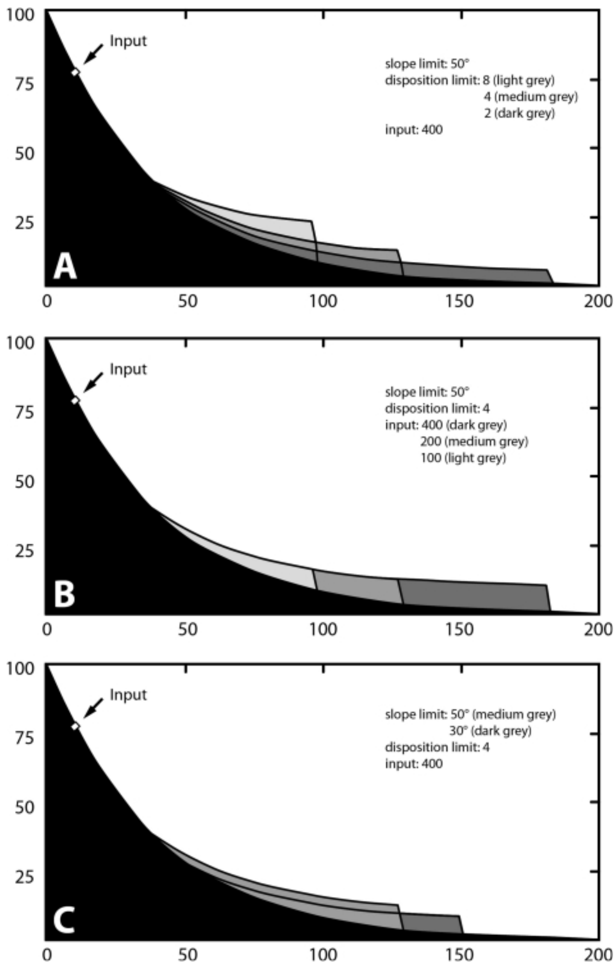

Figure 5: One-dimensional examples of disposition. Disposition controlled by disposition limit (A), input (B) and slope limit (C), whereas both vertical and horizontal axes are illustrated as units of distance, input has units of mass, and the deposition limits are given as unit mass per unit length (Gruber, 2007, modified).

The interrelation of these changed parameters is comprehensibly visualized in Figure 5. An increased value of D_{lim} (A) results in thicker accumulation in upper slope areas. If D_{lim} and β_{lim} are constant, but there is more mobilizable material input

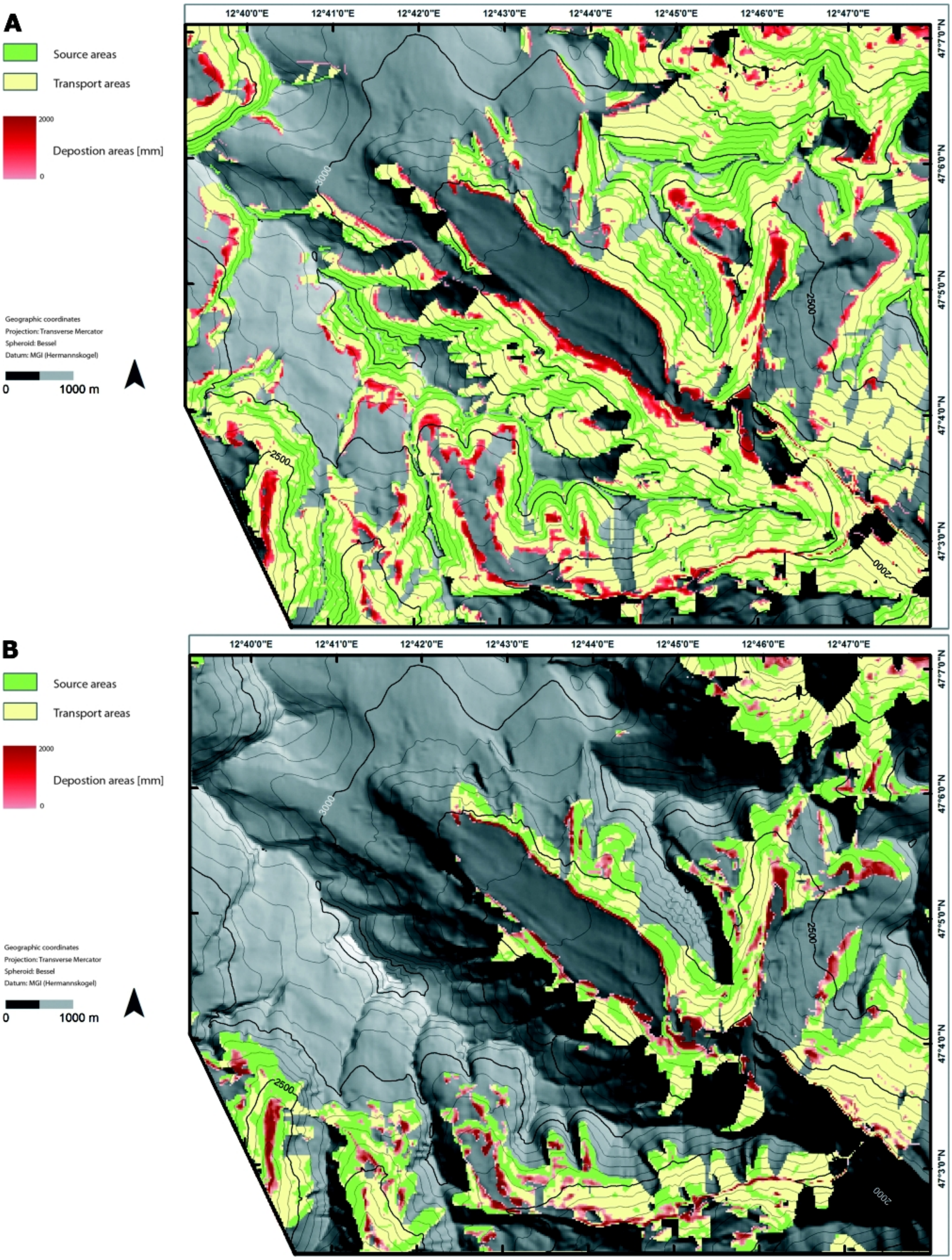

FIGURE 6: Map of modelled distribution of rock and debris fall processes (A) and other denudative processes (B) 2010 in the Großglockner-Pasterze area.

(B), the result will be similar in the upper slope areas. However, the deposition will also affect lower slope areas. If the value of $ß_{lim}$ (C) is changed, the result will be similar to the examples A and B. A lower value of $ß_{lim}$ – with respect to $γ_s$ – will result in less thick accumulations in lower slope areas. The results of the process modelling are presented in Figure 6.

3.7 Susceptibility and vulnerability maps

Frequency and magnitude of mass movements are primarily enforced by the slope inclination (Wichmann, 2006). Hence, the two-dimensional illustration of the assessment of mass-movement processes also depends on this factor. Therefore, the potential disposition areas as well as the transport and deposition areas were classified into 4 classes depending on the local slope inclination (see Tab. 1).

Due to the fact that glaciers were not considered specifically in the model, glaciated areas were only assessed based on their inclination because gravitational processes are more likely on steeper glacier surfaces than on flatter ones. By adding the intensity classes to the modelled process areas, finally two susceptibility maps, one for the recent conditions and one for 2030, were generated.

In a final step, the susceptibility maps were combined with the existing alpine infrastructure (roads, hostels and huts, trails, routes). In this way, two vulnerability maps that show which trail and route section are located in which susceptibility class were produced.

4. Results

Based on the methodological considerations described above, three different data sets were calculated: (i) four maps, two for 2010 and two for 2030, showing the modelled distribution of rock and debris falls as well as of other denudative processes differentiated into source, transport and deposition areas. An example of these maps is given in Figure 6, where source areas are represented in green, transport areas in yellow and deposit areas in red. The deposit areas are further differentiated according to the amount of deposited material ranging from light red (0 mm) to dark red (2000 mm). Due to the lack of inventory maps (event cadastre, rock fall and landslide inventory map) a quantitative validation of the modelling results in the study area was not possible. Therefore, a visual validation of the maps was performed through comparing the modelling results with field observations and current orthophotos. The field observations included mapping of e.g. the occurrence and spatial extent of rock fall deposits as indicators for accumulations areas and landslide scars or fresh rock outcrops as indicators for starting zones, whereas orthophotos were used to identify transit and accumulation areas.

An example is given in Figure 7 (A) which shows a comparison of the modelling results for rock and debris fall with a documented large rock fall event (volume about 57 000 m³) that occurred between 2007 and 2009 at the southern crest of Mittlerer Burgstall (Kellerer-Pirklbauer et al., 2012). The detachment area of the event has been entirely captured by the disposition model. In contrast, the deposition areas have only partly been captured, especially the large deposition area in a less steep terrain on the SW-facing slopes of Mittlerer Burgstall. This can be related to three factors (i) the rock and debris fall events that have been model were magnitudes smaller than the event at Mittlerer Burgstall, (ii) due to the coarse resolution of the DEM (25 m) smaller hollows and depression that stop material from moving further in a natural environment are not represented in the DEM and (iii) the utilized process model doesn’t represent processes like falling or rolling. In addition, the example of Mittlerer Burgstall, Figure 7 shows a visual comparison of the modelled flow processes (C) with a photograph (B). In contrast to the fall processes, the model for landslides and other flow processes captured all existing events.

Besides the maps representing the results of the process modelling, (ii) two susceptibility maps (one for 2010 and one for 2030) showing the spatial distribution of the susceptibility classes according to Table 1 were generated. The classes in Table 1 were not defined according to specific quantitative thresholds, but are congruent to preceding study of Lieb et al. (2007). The two maps, rock and debris fall as well as for other denudational processes, were integrated into one map to give areal information on potential susceptibility in the entire study area. The two maps, (iii) two vulnerability maps, one for 2010 and one for 2030 (Fig. 8), give the same “background” information as the susceptibility maps, but additionally allow to identify the vulnerability of trails and routes. In order to make the vulnerability maps intuitive a green-yellow-orange-red colour code system (green = hazards are hardly possible, yellow = improbable, orange = to be expected and green = probable) was used.

Slope	Source areas				Transport areas	Deposit areas		Glacier areas
	Unconsolidated rock		Solid rock					
	> mean	< mean	> mean	< mean		> mean	< mean	
>40°	4	3	4	4	4	-	-	4
≥20° - ≤40°	4	3	-	-	3	-	-	3
>1° - <20°	-	-	-	-	-	4	3	2
0 - ≤1°	-	-	-	-	-	3	2	1

Table 1: Assessment of process intensities according to particular slopes. Areas with an amount of mobilizable substrate (no differentiation between source or deposition areas) higher than the arithmetic mean are classified to the higher intensity class. Explanation of hazard classes: hazardous processes are 1 = hardly possible, 2 = improbable, 3 = to be expected, 4 = probable.

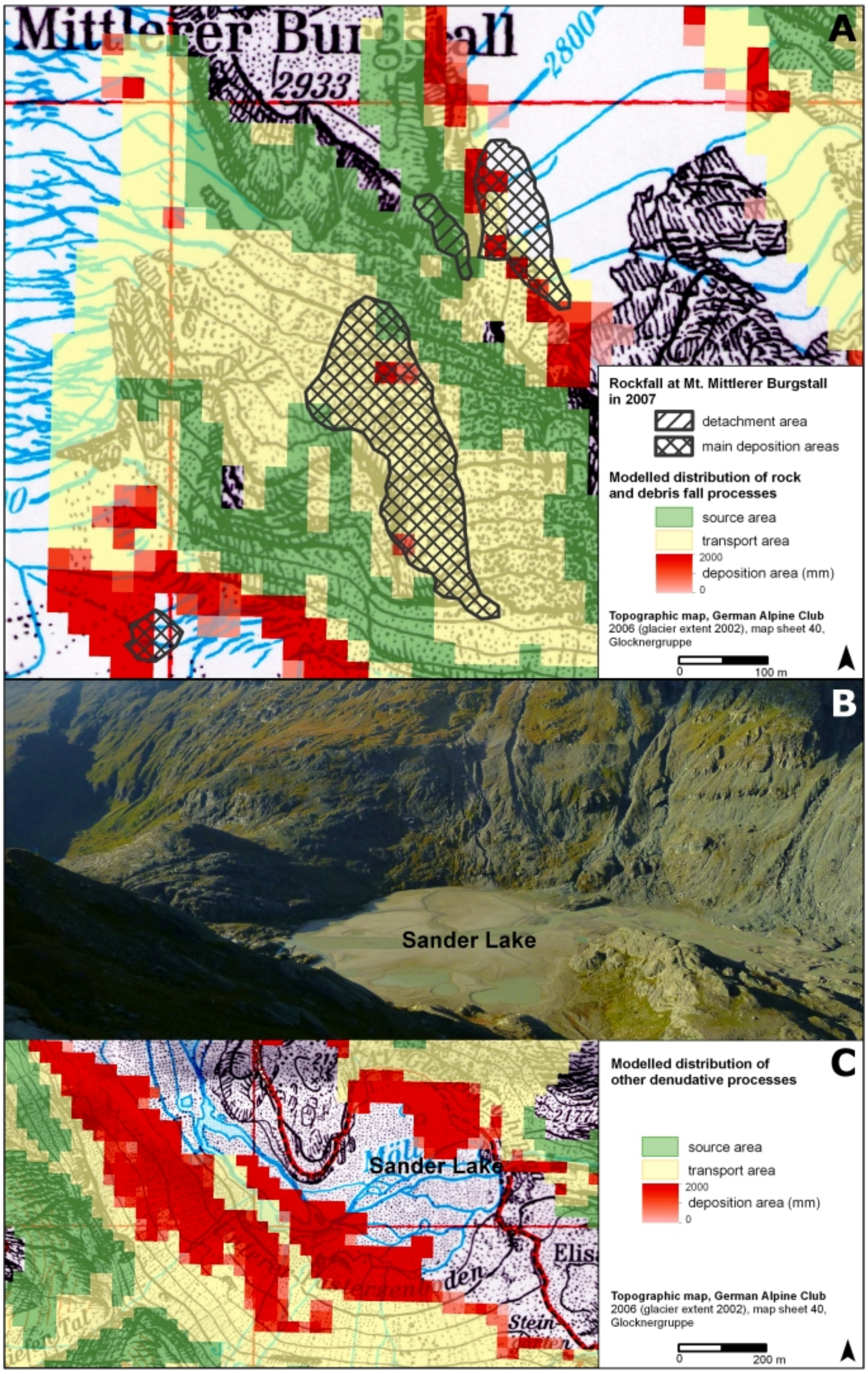

Figure 7: Validation of the rock and debris fall model results with a documented rock fall event at Mt. Mittlerer Burgstall (A) and visual comparison of the model results for other denudative processes (C) at Sander Lake with a photograph (B) taken in southern direction (photograph: G. K. Lieb, 13.9.2010).

Both vulnerability maps clearly reveal that most of the trails and routes in the study area are situated in the zones 3 and 4, i.e. in zones where hazardous processes have to be expected or are probable. Table 2 gives detailed information on the length of trails and routes classified in the respective susceptibility classes. The results show that in 2010, 60.7 percent of the 108 kilometres of marked trails and routes were identified to be in areas were hazardous processes have to be expected or are probable and only 39.3 percent were found to be in less vulnerable areas (zone 1 and 2). When comparing trails and routes, it shows that only 27.3 percent of the trails were classified as less vulnerable (zone 1 and 2), whereas 58.7 percent of the routes were classified in the same zones. This can be explained by the fact that a large part of the routes lead over glaciers with relatively low inclinations. A comparison with the results of 2030 shows that the changes of hazard classes are generally relatively low and range from 0.4 to 2.6 percent; thereby trails and routes combined. This might lead to the assumption that the network of trails and routes does not change which, however, has already happened and will very likely happen in future too.

Besides the statistical evaluation of the results, the vulnerability maps (Fig. 7) were also qualitatively evaluated (Braun, 2009) within the framework of a workshop with local and regional stakeholders held in Mallnitz (Austria) in October 2010. The group of experts consisted of 10 persons representing mountain guides, mountain rescue service, mountain hut holders, alpine associations and the authority of the Hohe Tauern National Park. One of the tasks of the workshop was to review the contents of the 2010 and 2030 vulnerability maps. This was done by discussing extensively all considered trails and routes in the study area jointly in the group of experts. The experts considered the vulnerability maps to be a suitable decision support tool for planning purposes. According to them, all known danger spots in the study area on which either accidents have already occurred or gravitational processes affecting the respective trail or route have already been observed, were properly displayed in the vulnerably maps. Nonetheless, the workshop participants determined some sections of the trail and route network in the maps where the vulnerability was slightly overestimated. However, this kind of evaluations gives only information if the location of hazardous processes and the degree of vulnerability is properly displayed in the maps, but it is not possible to evaluate the modelled differentiation between source, transport and deposition areas nor if the processes themselves are properly captured.

5. Discussion and Outlook

The method developed in this study proved to be suitable to reach the defined aims. The resulting vulnerability maps for Alpine trails and routes in the Großglockner-Pasterze area for

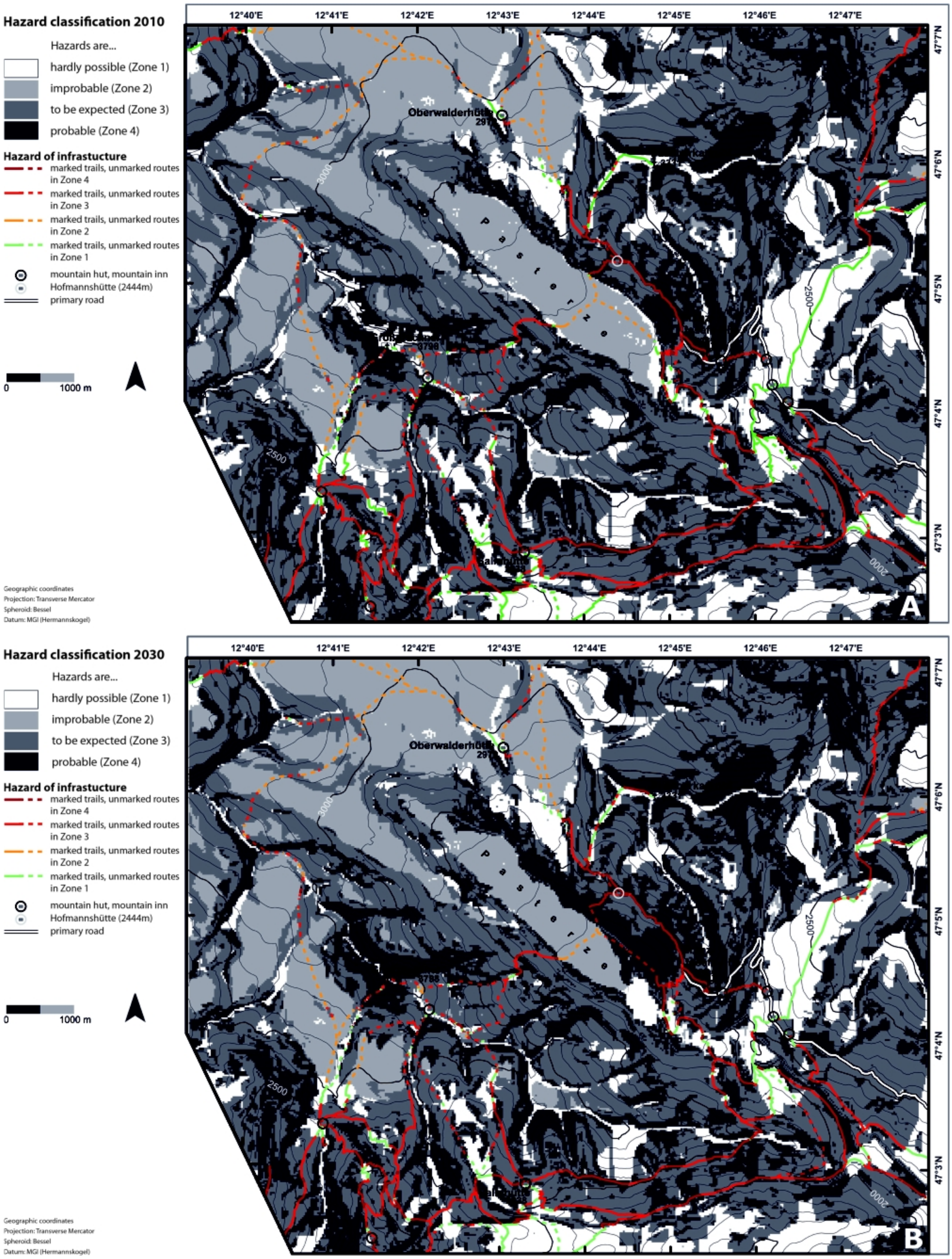

Figure 8: Vulnerability maps of the Großglockner-Pasterze study area in 2010 (A) and 2030 (B).

Susceptibility zone	Trails 2010		Routes 2010		Trails and Routes 2010		Trails 2030		Routes 2030		Trails and Routes 2010	
	km	%	km	%	km	%	km	%	km	%	km	%
1	17.9	27.0	7.4	17.9	25.3	23.4	16.5	24.8	6.9	16.7	23.4	21.7
2	0.2	0.3	16.9	40.8	17.1	15.9	0.2	0.3	15.5	37.4	15.7	14.6
3	30.1	45.3	13.2	31.9	43.3	40.2	30.5	46.0	13.3	32.1	43.8	40.6
4	18.2	27.4	3.9	9.4	22.1	20.5	19.2	29.0	5.7	13.8	24.9	23.1
Sum	**66.4**	**100**	**41.4**	**100**	**107.8**	**100**	**66.4**	**100**	**41.4**	**100**	**107.8**	**100**

Table 2: Absolute and relative lengths of trails and routes in the Großglockner-Pasterze study according to hazard classes in 2010 and 2030. Explanation of hazard classes: hazardous processes are 1 = hardly possible, 2 = improbable, 3 = to be expected, 4 = probable.

a current situation (2010) and a future scenario (2030) were proved to be suitable for planning purposes by the local stakeholders. However, due to the fact that the disposition and process modelling on regional scale was only based on simple assumption, not all source and deposition areas could be captured and needs further investigations.

In all steps of the method (identification of source areas, estimation of potentially mobilizable substrate and process modelling) further refinements of the models possibly improve the results. Looking at the disposition model and the identification of source areas a striking disadvantage is the lack of empirical information on the resistance of different (solid and unconsolidated) rock types against weathering and erosion processes. Therefore, the differentiation of rock properties is only based on rough estimations and not on observed field data. The same is the case for the current permafrost distribution. However, in the meantime better modelling data is available at regional scale (unpublished data and Götz 2011, personal communication) as well as for the entire Alps (Mair et al., 2011) which could be used in a subsequent study.

Besides the quality of the lithology and permafrost distribution input data, the influence of different slope thresholds and the resolution of the utilized DEM needs further investigation. The topography showed by DEMs with a raster spacing of 25 m is much smoother than the real topography. Due to the use of the simple threshold values for identifying the rock fall and other denudative processes source cells, the disposition model produced source areas in locations where this is not the case in reality. On the other hand it missed smaller source areas. Furthermore, small hollows and depressions are not represented in the DEM and therefore material that would come to rest in these areas is further propagated downwards by the process model.

To produce approximate results about potential susceptibility zones the 25 m DEM is sufficient (Stolz and Huggel, 2008), but with a 10 m DEM or with new high-resolution DEMs derived from airborne laser scanning (ALS) data with a grid size of 1-2 m, it is possible to better define source areas and identify source areas of medium and small events. Especially the small but more frequent rock fall events endanger hikers and hiking infrastructure. However, high-resolution ALS data are currently not available for many high-mountain areas, generally we can expect point densities of around 1.5 pt/m² which is not appropriate for applications like presented. The steep terrain and a small field of view of the sensor can lead to large horizontal and vertical errors of the resulting point cloud (Kellerer-Pirklbauer et al., 2012).

Another challenging area is the estimation of the volume of the mobilizable substrate in solid rock as well as in deposits. Since no detailed information on the active layer thickness in the study area is available, data from Hoher Sonnblick situated in considerable distance and with quite special environmental conditions in terms of geology, aspect and inclination have been used and extrapolated. Hence, in this study all estimations concerning permafrost distribution are assumptions, and facts like seasonal frost or frost-thaw-cycles, which are crucial for weathering processes, have not been taken into account at all (e.g. Kellerer-Pirklbauer et al. 2011, Schoeneich et al. 2011).

Regarding the process model, there is a need to better differentiate and represent the different types of mass propagation. So far, the model that has its origins in avalanche modelling can only represent flow propagation.

Nonetheless, for this study that aimed to create vulnerability maps for Alpine trails and routes, the results of the process model were sufficient. The process areas (source, transport and deposition areas) for both process groups (rock and debris falls as well as other denudative processes) were spatially proper captured by the model. In addition the improvement of the propagation algorithm and the adaption of the input parameters, the influence of DEMs with higher spatial resolution on mass propagation needs to be investigated in future.

The uncertainty of regional climate simulations of the Alpine region is at 20-25 % (Déqué et al., 2007). The regional climate scenario used for the calculation of the 2030 scenario shows a maximum overall uncertainty of ±1.25 °C (Gobiet et al., 2007). Hence, all estimations based on the climate scenario (e.g. estimation of potential mobilizable substrate) are also subject to this uncertainty. Besides, changes in the estimations of glacier retreat and the average vertical rise of the lower boundary of permafrost distribution may have high impacts on the quantity and volume of future estimated mass-movements and, in further consequence, on the susceptibility classification and the vulnerability assessment.

Finally, the vulnerability maps were positively evaluated by local and regional stakeholders in a workshop. The usage of the colour code system made the maps readable and comprehensible without any expert knowledge about geomorphology or mass-movements. The workshop participants considered the maps to be suitable tools for the construction and maintenance of trails and routes as well as a useful database for planning local measures. As a consequence of this feedback, the results of the study were incorporated into a modern manual for persons and organisations responsible for maintaining alpine trails (Deutscher Alpenverein & Österreichischer Alpenverein, 2011).

Acknowledgements

The study was carried out within the framework of StartClim 2009 and financially supported by the Austrian Ministry of Economy, Family and Youth. Field studies providing valuable information concerning the model input were done within the Projects ALPCHANGE (Climate Change and Impacts in Southern Austrian Alpine Regions) funded by the Austrian Science Foundation (FWF, Project Nr. P18304) and PermaNET (Permafrost longterm monitoring network) within the Alpine Space Programme funded by the European Territorial Cooperation. The annual glacier monitoring at Pasterze Glacier is funded by the Austrian Alpine Association (OeAV). Furthermore, we gratefully thank Claudia Riedl of the Central Institute for Meteorology and Geodynamics (ZAMG) for providing the permafrost borehole data from Hoher Sonnblick, Florian Hanzer and Ulrich Strasser for their great support in process modelling and Christian Bauer and Michael Avian for their valuable suggestions and feedback. Finally, we want to thank the two anonymous reviewers for their remarks and comments, which significantly improved our manuscript.

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Received: 15 February 2012
Accepted: 20 August 2012

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