

Morphometric Modelling of Rockglaciers – An Exploratory Case Study from the Alps

R. Frauenfelder^{1*}, B. Schneider^{2**}, B. Etzelmüller³

¹Department of Geography, University of Zurich, Switzerland

* now at: Norwegian Geotechnical Institute, Postboks 3930 Ullevaal Stadion, 0806 Oslo, Norway
Telephone: +47 22 02 19 87
Fax: +47 22 23 04 48
Email: rf@ngi.no

²Department of Earth Sciences, University of Basel, Switzerland

** now at: ilu AG, Zentralstrasse 2a, 0610 Uster, Switzerland
Telephone: +41 (0)44 944 55 54
Fax: +41 (0)44 944 55 66
Email: bernhard.schneider@ilu.ch

³Department of Geosciences, University of Oslo, Blindern, 0316 Oslo, Norway

Telephone: +47 22 85 72 29
Fax: +47 22 85 72 30
Email: bernd.etzelmuller@geo.uio.no

1. Introduction

Rockglaciers are landforms originating from periglacial talus ('talus-derived' rockglaciers) and/or glacier-transported debris, mostly from lateral and terminal moraines ('moraine-derived' rockglaciers). The occurrence of talus-derived rockglaciers (Fig.1) is influenced primarily by climatic and topographic preconditions (cf., e.g., Barsch 1996). They are found in areas characterized by specific topographic attributes; they occur, for example, within a certain altitudinal band, favour certain slope aspects, require a particular slope, and need a rock-contributing headwall above them (cf., e.g., Frauenfelder et al. 2003, Janke and Frauenfelder 2007).



Figure 1. Oblique photograph of an active talus-derived rockglacier in the eastern Swiss Alps. The rockglacier root zone (= RRZ, see explanations in the text below) is partly visible in the snow-covered upper right of the picture.

Modelling of the entire rockglacier bodies applying simple geomorphometric approaches is difficult as these landforms vary considerably in form and size. There are, however, areas within each talus-derived rockglacier that possess specific characteristics similar to all these forms: in the so-called *rockglacier root zone (RRZ)* the accumulated debris is triggered to

creep (cf. Barsch 1996). This zone is located within or at the end of a concave landform where debris can accumulate (see Fig. 1, area in the upper right corner).

Recent advances in statistical modelling triggered a considerable amount of studies to model periglacial features (e.g., Brenning 2009, Etzelmüller et al. 2001, Etzelmüller and Sulebak 2003, Hjort et al. 2007, Hjort and Luoto 2008, Hjort and Marmion 2009, Luoto and Hjort 2004, 2006, Marmion et al. 2009, to name just a few). While some of these studies apply sophisticated statistical modelling schemes, for example, generalized additive models, support vector machines, boosting, etc., our contribution reports about the application of a simpler approach. We present an exploratory approach to the analysis of relationships between multiple explanatory variables and a presence/absence response variable for the modelling of *RRZ* distribution. Our approach essentially consists of the study of histograms and descriptive statistics, and the construction of heuristic probabilistic and deterministic classification rules.

The focus in this contribution is on the distribution of talus-derived rockglaciers (i.e. *RRZs* of talus-derived rockglaciers), and the explanations in the following text refer, by implication, to these forms only.

2 Geographical Settings and Data Sources

The study is carried out in the Upper Engadine, eastern Swiss Alps (Fig. 2). The area covers approximately 530 km², stretching from 46°22'N to 46°35'N, and 9°39'E to 9°59'E. The study area is characterized by a high-situated valley floor with an average altitude of 1700 m a.s.l.

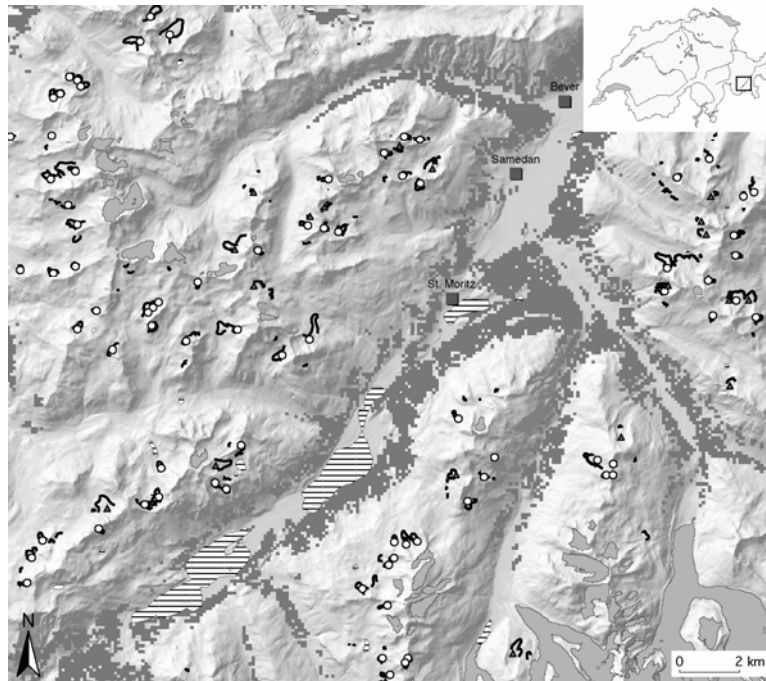


Figure 2. Shaded DEM25 of the study region. Size of original DEM (25 m resolution): 2201 x 1781 Pixels (ca. 55 x 44.5 km). Rockglacier outlines are represented by black lines, circles mark empirically derived talus-derived *RRZs*. Glaciers are depicted with light grey, lakes are striped, dark grey pixelated zones represent forested areas. Data sources: glacier extent from Paul (2003), rockglacier distribution from Hoelzle (1989, 1998), forest areas extracted from the data base of the Swiss Land Use Statistics (BFS 1992), DEM25 © 2004 *swisstopo* (BA046054).

Hoelzle (1989, 1998) identified 84 active rockglaciers in the study area by means of field investigation and analyses of aerial photography; 64 of these rockglaciers were identified as (periglacial) talus-derived forms. Together with 22 additionally mapped rockglaciers, a total of 86 rockglaciers was analysed.

To map potential *RRZs*, topographic attributes need to be identified that correlate well with their occurrence. The surface parameterization must be carried out at an appropriate scale, determined by the considered process. Potential *RRZs* are influenced by landforms in the range of decametres to hectometres. Therefore, the reference scale for the modelling is several tens of metres to hundreds of metres. For this purpose, the use of a raster-based digital elevation model (DEM) with a resolution in the range of decametres seemed adequate. A DEM with 50 metres or 100 metres cell size would be too coarse to allow *RRZ* detection, as they do not capture all topographic features relevant for the development and occurrence of rockglaciers. Hence, primary and secondary topographic attributes are extracted from a DEM with a 25 m cell size from *swisstopo* (the former Swiss Federal Office of Topography).

2. Methods and Results

2.1 Derivation of Topographic Attributes

Comprehensive compilations of topographic attributes to be computed from DEM data are given, for example, in Moore et al. (1990) and Wilson and Gallant (2000). We selected attributes with close relationships to gravity-driven slope processes, namely:

- *primary* topographic attributes:
altitude, aspect, slope (for scale levels equivalent to 25 m and 50 m resolution), total curvature, plan curvature and profile curvature,
- *secondary* topographic attributes (i.e. statistical, mathematical or logical combinations of primary attributes):
local relief, elevation-relief ratio, skewness of altitude, distance to nearest ridge (slope length), topographic wetness index, roughness index, radiation balance.

These topographic attributes were calculated for all *RRZs* using standard routines within GIS and were stored as individual grids. Together with the DEM these new grids represented a multidimensional geometric description of the *RRZs*. A thoughtful choice of selected topographic attributes from this geometric description should result in a set of measures that describe the *RRZs* well enough to distinguish them from other different landforms.

The distributions of the *RRZs* were derived with respect to the selected topographic attributes. Firstly, the statistical values (min, max, mean, and standard deviation) of each of the topographic attributes were derived. The values obtained were then used to classify each topographic attribute into six classes of equal size with class borders at μ , $\mu \pm 0.5\sigma$, and $\mu \pm \sigma$, where μ is the mean of the attribute values and σ the relevant standard deviation. These results were plotted as histograms, which allowed for the qualitative distinction between attributes for which the *RRZs* are evenly distributed, i.e. attributes that are ineffective for modelling, and attributes showing clear accumulations of *RRZs* in distinct classes, in other words, attributes suitable for the modelling. Based on the results of the histogram analyses, topographic attributes which seemed to be representative of the sought *RRZs* were chosen for the modelling procedure. Three different terrain classification methods were applied (see sections 2.2, 2.3, and 2.4).

2.2 (A) Probabilistic Approach

The quantitative information of the frequency distribution histograms was interpreted as an indication of probability where higher occurrence of *RRZs* in individual attribute value classes indicates higher probability, and vice versa, i.e. lower occurrence of *RRZs* in individual attribute value classes indicates lower probability. An example of this procedure is given in Table 1 for the topographic attribute ‘slope’. The same procedure was applied for all topographic attributes which were found suitable for the modelling, i.e. which were inhomogeneously distributed between the classes (see above).

The following topographic attributes were used: altitude, aspect, slope, curvature (plan, profile), local relief, elevation-relief ratio, skewness of altitude, wetness index and roughness index.

The probabilities for these topographic attributes were multiplied in order to obtain combined probabilities of rockglacier occurrence for all locations in the test area. This was done for different combinations of topographic attributes.

Class	Relative boundaries	Absolute boundaries	Number of <i>RRZs</i>	Percent	Prob.
1	< m-s	< 12.1°	9	8.3	0.083
2	m-s to m-0.5s	12.1°–18.9°	16	14.7	0.147
3	m-0.5s to m	18.9°–25.7°	34	31.2	0.312
4	m to m+0.5s	25.7°–32.5°	23	21.1	0.211
5	m+0.5s to m+s	32.5°–39.3°	14	12.8	0.128
6	> m+s	> 39.3	13	11.9	0.119

Table 1. Absolute and percent distribution of the *RRZs* relative to the topographic attribute ‘slope’ (Prob. = Probability).

With a probabilistic approach the regions classified as potential *RRZs* were (a) too large, and (b) had a significant number of *RRZs* located in areas that were assigned low probabilities of rockglacier occurrence.

The modelling results can neither be improved by removing a topographic attribute from the criteria list, nor by adding a new one. Removing would enlarge the area with high probability, while adding would result in even more rockglaciers being located in areas with low probability for rockglacier occurrence.

2.3 (B) Deterministic Approach

In this approach, the range of occurring values for the significant topographic attributes (again altitude, aspect, slope, curvature (plan, profile), local relief, elevation-relief ratio, skewness of altitude, wetness index and roughness index) is used and values outside these ranges ruled out. For example, active rockglaciers in the study area are found at elevations between 2230 m a.s.l. and 3500 m a.s.l., in areas with medium wetness index, and on slopes with a steepness between 7° and 52°. In a boolean procedure, values outside the defined ranges (between the minimum and maximum values for all attributes) are marked as ‘no *RRZs* possible’.

Compared to the results of approach (A), two main differences become obvious when modelling the *RRZs* with a deterministic approach: (a) the problem of rockglaciers occurring outside the modelled zones could be solved, i.e. all *RRZs* lie within the modelled potential *RRZ* areas, and (b) the zones modelled as potential *RRZs* (depicted in red) are, however, much

too large. This results from the very conservative procedure that is applied. Additionally, there is no weighting of the modelled zones included. A specification of the probability of occurrence within the modelled zones as in approach (A) is, therefore, not possible.

2.4 (C) Inclusion of Rockfall Accumulation Areas

The third approach broadens the *deterministic approach (B)* to include rockfall accumulation areas, which can be modelled using a (semi-)geomorphometrical approach. The expansion is based on the (rather banal) observation that rockglaciers can only develop where rock debris is available. As mentioned above, does the rock debris incorporated in talus-derived rockglaciers originate from contributing headwalls. Hence, if it were possible to locate these debris-supplying headwalls geomorphometrically and to estimate the extent of the relevant rockfall, the number of potential *RRZs* (cells) would get significantly reduced.

The so-called ‘overall-slope’ or ‘reach-angle’ approach (also known as ‘Fahrböschung’, Heim 1932) was used to compute rockfall and rockfall accumulation (Brändli 2001). Assuming that a rockglacier can only emerge where rock accumulation takes place, the potential *RRZ* occurrence areas resulting from approach (B) were intersected with the rock accumulation areas. With the inclusion of rockfall accumulation areas in the modelling, the number of falsely modelled potential *RRZs* was significantly decreased compared to the results from Approach (A) and (B); however, overestimations still occurred (see Fig. 3).

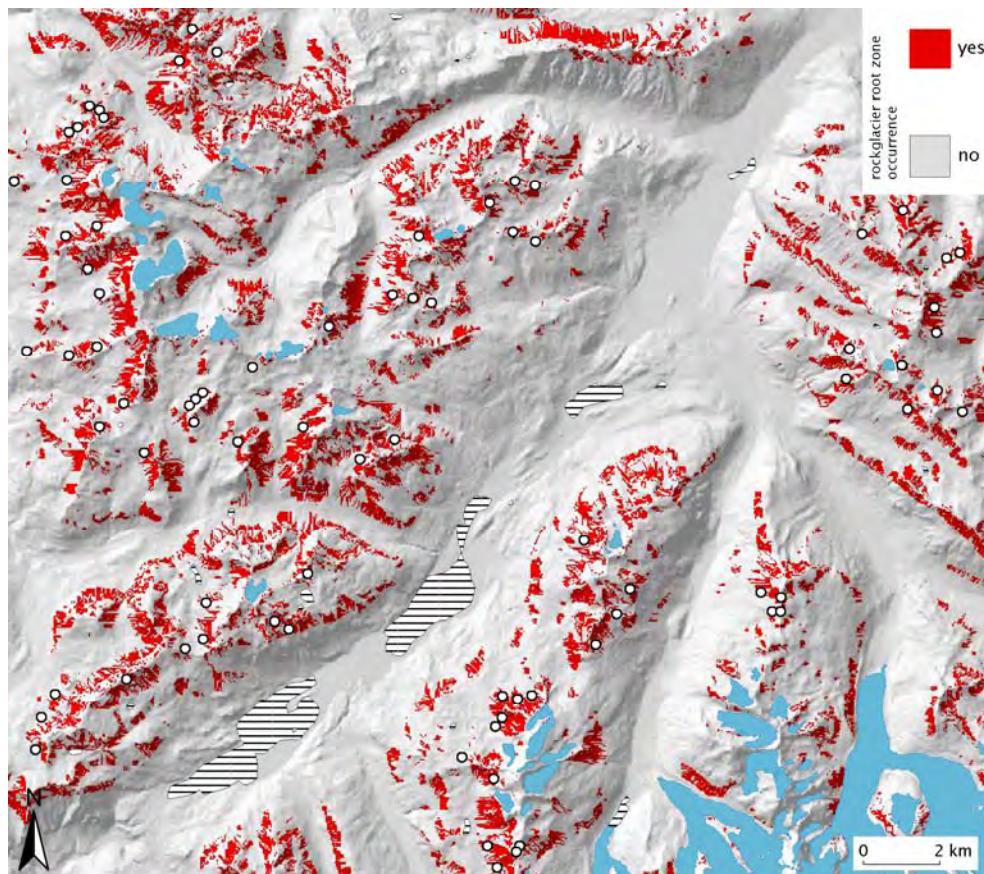


Figure 3. Approach (C): approach (B) with inclusion of the modelled rockfall accumulation areas, representing zones where debris is available. *RRZs* of active talus-derived rockglaciers are depicted with circles, glaciers are coloured light-blue and lakes are striped, data sources as in Fig. 2.

One explanation for this comes from the fact that rockfall accumulations were modelled by calculating a random number of rockfall trajectories. Due to undesired side-effects caused by the raster data model of the DEM, rockfall accumulation patterns tend to exhibit ‘holes’ between the individual trajectories. *RRZs* that are located in such ‘holes’, which presumably do not exist as frequently in nature as implied by the model results, are considered as ‘falsely’ modelled. Upon analyzing the individual cases it can be argued with reasonable certainty, however, that *RRZs* modelled ≤ 25 m away (which corresponds to 1 grid-cell), can be considered as ‘correctly’ modelled as well (Table 2).

Distance to mapped <i>RRZs</i> (in m)					
0	≤ 25	≤ 50	≤ 75	≤ 125	>150
67	7	5	5	2	0

Table 2. Amount of correctly and falsely modelled *RRZs* with approach (C).

3. Discussion and Conclusions

In approach (A), the size of the areas that are classified as potential *RRZs*, without actually having any rockglaciers in reality, is considerably large. At the same time, some rockglaciers that actually do exist lie in areas with low probabilities ($p \leq 0.7$) for the occurrence of *RRZs*. As the results of this approach indicate, a model based only on an univariate consideration of topographic attributes seems inadequate. Hence, simply multiplying the probabilities of the individual attributes is not a suitable approach for the detection of rockglaciers *RRZs*. This is partly caused by the implicitly underlying assumption that the conditional probability distributions of rockglacier occurrence on individual explanatory variables are independent, which is a rather strong assumption. Logistic regression would help to reveal individual attribute values only occurring in specific combinations. Such multivariate classification schemes have been successfully applied in geomorphological studies (e.g., Brenning and Trombotto 2006, Hjort et al. 2007, Sulebak et al. 1997, Wood-Smith and Buffington 1996) but were not carried out in this study.

Modelling with the deterministic approach (B) enables the inclusion of the *RRZs* of all talus-derived rockglaciers which occur. However, due to the very conservative procedure, the number of areas that are falsely modelled as potential *RRZ* areas unsurprisingly increases significantly compared to approach (A).

In contrast to this, the inclusion of rockfall accumulation areas in approach (C) leads to a distinct decrease in falsely modelled areas. A certain number of problematic cases remain even with this approach, however. They are basically of three kinds: (a) for very small (and often steep) rockglaciers the contributing headwall is not represented in a DEM with 25 m resolution. Therefore, rockfall is not modelled in these areas, and consequently, the root zones lie outside the modelled potential *RRZ* areas. (b) Some rockglaciers do not (any longer) have a contributing headwall in nature. It is likely that their activity will decrease in the near future, due to a lack of debris supply. (c) The main difficulty, however, is the modelling of rockfall accumulation areas itself. Both the localization of contributing headwalls and the estimation of the rockfall extent are calculated with very simple models, partly because topographic information alone is employed.

In summary, we could show that the inclusion of rockfall accumulation areas, even if based on simple modelling schemes, allows a much better estimate of *potential RRZ* areas than mere univariate probabilistic or deterministic classification rules (Table 3).

No. of <i>RRZs</i>	A ¹⁾	Approach	
		B	C
within modelled area	49 (57 %)	86 (100 %) ²⁾	74 (86 %)
outside modelled area	37 (43 %)	0 (0 %)	12 (14 %)
Total	86 (100 %)	86 (100 %)	86 (100 %)

Table 3. Summary table. ¹⁾ Fulfilment criteria: $p > 0.7$ (see section 2.2). ²⁾ Seemingly good result, however, zones modelled as potential *RRZs* are much too large.

However, as mentioned initially, a number of more sophisticated statistical methods exist today; their application would help to overcome the deficiencies we met with our approach. Hjort et al. 2007, for example, used logistic regression and hierarchical partitioning for the modelling of the distributions of periglacial forms such as palsas and earth hummocks. Hjort and Marmion (2009) successfully applied the boosting method in periglacial distribution modelling of, amongst other things, sorted solifluction. Brenning (2009) compared the performance of eleven statistical and machine-learning techniques including logistic regression, generalized additive models, linear discriminant techniques, and the support vector machine for automatic rockglacier detection. Future efforts to model *RRZs* or entire rockglaciers in the Swiss Alps should certainly focus on such refined statistical methodology.

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