The Swiss Alps Without Glaciers – A GIS-based Modelling Approach for Reconstruction of Glacier Beds

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1. Introduction

Due to the ongoing and expected future increase in global mean temperature, the Alpine environment will continue to depart from equilibrium (Watson and Haeberli 2004). As glaciers form a significant part of the mountain cryosphere and their changes are considered to be the best natural indicators of climatic change (IPCC 2007), they constitute a key indicator within global climate related observing programs (Haeberli 2004). The already observed as well as the expected changes in glacier geometry and volume could have large impacts on global (sea level rise), regional (water supplies) and local scales (natural hazards, hydropower). The calculation and visualization of future glacier development thus plays a vital role in communicating climate change effects to a wider public (Paul et al. 2007).

Of particular interest regarding hydrological aspects is the water volume that is stored in the glaciers (Jansson et al. 2002). This requires information on the glacier bed which is only accessible after the glacier has disappeared (e.g. Maisch and Haeberli 1982). Otherwise, glacier thickness has to be obtained in the field at discrete points or profiles using a range of techniques (e.g. GPR, seismic or drilling). The spatial extra- and interpolation of this local thickness information for reconstruction of the entire glacier bed is again based on a wide range of methods and assumptions with related uncertainties, but at least mean glacier thickness values can be derived. In order to overcome the scarcity of available measurements, a set of empirical (e.g. Chen and Ohmura 1990, Maisch and Haeberli 1982) or more physically based (Driedger and Kennard 1986, Haeberli and Hoelzle 1995) relationships have been proposed to obtain glacier volume for large samples of glaciers.

Apart from the amount of available water stored in glaciers, there is also an urgent need to have topographic information on the glacier bed itself. Anticipation and quantitative modelling of changes in surface topography and characteristics in large regions related to future climate change, and corresponding developments (landscape evolution, water cycle modifications, natural hazard potentials, tourism, hydropower, etc.) in cold mountain regions has become an important task. In this respect, an estimated topography of the glacier bed would facilitate a large number of applications including the visualization of future ice-free ground. Using examples from the Swiss Alps, this contribution presents a fast and robust GIS-based approach to construct digital elevation models (DEMs) "without glaciers" in currently glacierized mountain chains from a minimum set of input data (DEM, glacier outlines and flowlines).

2. Method

The glacier surface reflects a smoothed image of the underlying bed. One basic parameter that influences glacier thickness is mean slope: the steeper the glacier, the thinner the ice and vice versa. This relation is also given from the so-called shallow ice approximation (SIA) which is a theoretical concept for highly idealized glacier geometries (Paterson 1994), but has been shown to reveal good results compared to more comprehensive approaches (Leysinger Vieli and Gudmundsson 2004). The required calculation of the mean basal shear stress in our approach is based on data from late glacial glacier geometries (Maisch and Haeberli 1982) and a concept that calculates average shear stress as a function of mass turnover determined by vertical extent (Haeberli and Hoelzle 1995). This concept was applied to large glacier ensembles, using numerical information as available in detailed glacier inventories (Haeberli and Hoelzle 1995). Corresponding thickness and volume estimates for individual glaciers thereby became much more realistic as glaciers are 3-dimensional rather than planar bodies, and flow-related glacier thickness is primarily slope rather than area dependent. A decisive further step is introduced by combining this approach with geomorphometric analysis of DEMs and automated GIS-based data processing, which now make ice-depth estimates possible for individual parts of glaciers (Linsbauer 2008).

The method requires only the DEM, glacier outlines and a set of flowlines for individual glacier branches. For each glacier, an average basal shear stress is then estimated as a function of vertical extent, and ice depth is calculated along selected points of the flowlines as a function of surface slope (Fig. 1). The subsequent spatial interpolation of the thickness values is performed with the topogrid interpolation as implemented in the GIS software Arc/Info from ESRI. Topogrid has been designed to generate hydrologically consistent DEMs from elevation contours/points and other vector data (Hutchinson 1989), resulting in preferably concave-shaped landforms. It is thus well suited to mimic the typical parabolic shape of glacier beds without explicitly considering mass fluxes as applied in the approach by Farinotti et al. (in press). The most time consuming part of the work is the determination of flowlines on the individual glacier branches. For various reasons, this digitizing is still best and most reliably made by hand, starting at the lower end of the glacier tongue and cutting at a right angle through the elevation contour lines of the glacier surface.

The developed method is a raster-based GIS-tool, which is implemented in a short Arc Macro Language (AML) script. The basic steps of modelling are illustrated in Fig. 1 along with a schematic diagram of the modelled parameters. The steps are: (a) data preparation, (b) calculation of glacier thickness for base points of the flowlines from the SIA using mean slope for 50 m elevation bands, (c) spatial densification of base points along the flow lines using an IDW interpolation, and (d) the interpolation of the bed with topogrid and addition of the bed elevations to the DEM. When all input data (DEM, glacier outlines, flowlines) are prepared, a few hundred glacier beds are automatically calculated in a short time (minutes).

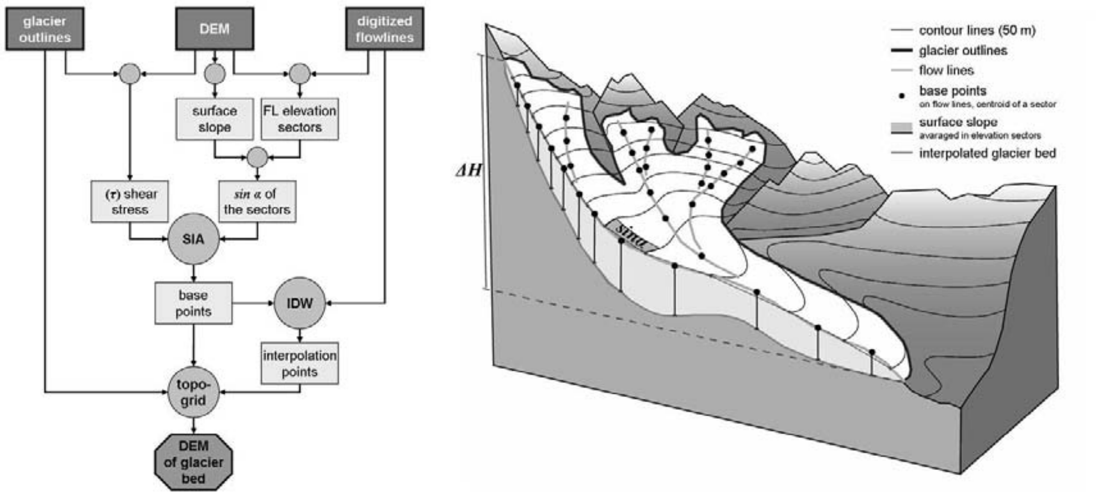

Figure 1. Flowchart of the method and schematic diagram of the modelled parameters.

3. Fields of Application

As mentioned above, the basic intention behind the development of this approach lies in the reconstruction of glacier beds over large regions, e.g. the entire Swiss Alps. The direct result is (1) an ice thickness distribution of all glaciers (Fig. 2) and (2) a DEM without glaciers (Fig. 3). From these data sets a number of further products and applications can be derived. At first, (3) mean thickness and (4) total volumes can be derived for each glacier in the sample. A comparison of (1) and (3) with direct measurements or results from other (more generalized/sophisticated) approaches can be performed, while (4) yields improved estimates of available water resources in the respective region.

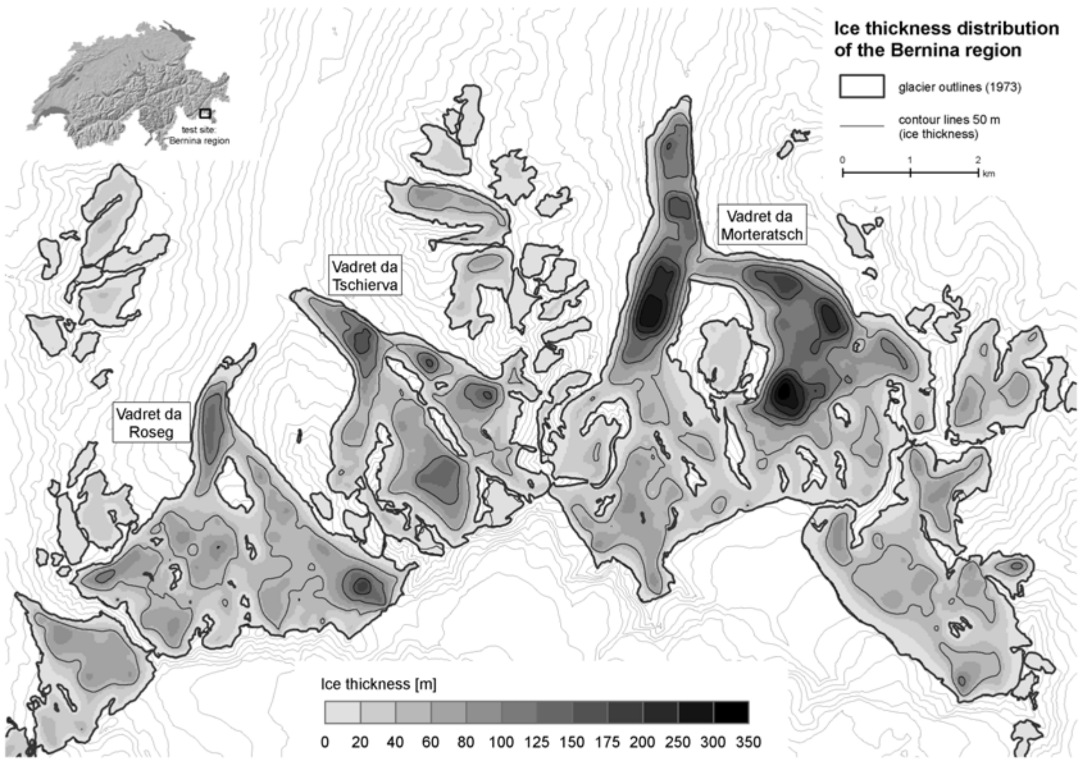

Figure 2. Modelled ice thickness distribution of the entire Bernina region, Switzerland. Reproduced by permission of swisstopo (BA091300).

A direct application of (2) is (5) the detection of overdeepenings in the glacier bed which can be easily visualized in the GIS by filling-up the depressions (Fig. 3). Dependent on the sedimentary nature of the glacier bed (Maisch et al., 1999), the depressions can fill with water and form lakes in the glacier forefield after the glacier has disappeared. These potential future lake formation sites can pose a hazard to downstream communities when the lake is located underneath steep rock walls or hanging glaciers (e.g. Haeberli and Hohman 2008). The glacier bed topography will also (6) facilitate the modelling of flow paths of potential outburst floods, which might help for the planning of mitigation measures (Rothenbühler 2006).

Furthermore, (7) a more realistic visualization of future glacier change than in Paul et al. (2007) can be achieved when the lost volume is eroded from the DEM and the bedrock becomes visible. Combined with a mass balance and hydrological model, the glacier beds can also be used for (8) improved modelling of changes in run-off from glacierized catchments (Huss et al. 2008). Finally, the bedrock can also serve as (9) an input for glacier flow models.

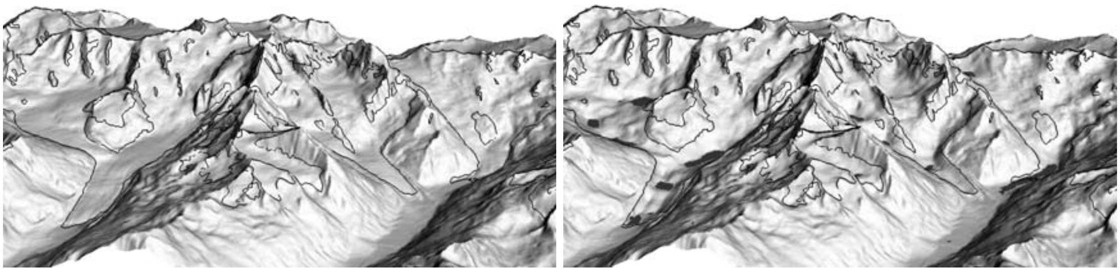

Figure 3. Input data and modelled glacier bed topographies with detected overdeepenings (potential lake formation sites) in the Bernina region, Switzerland. Reproduced by permission of swisstopo (BA091300).

4. Discussion and Conclusion

This simple approach of calculating glacier beds from geomorphometric properties of the glacier surface alone has of course several shortcomings. However, the modelled glacier beds were in a good agreement with field measurements (GPR profiles) and results from more complex approaches as described by Farinotti et al. (in press). Our approach is independent of glacier size and can be adjusted to different glacier types or climatic settings by considering glacier specific values of the form factor or a different calculation of the basal shear stress (τ) from the elevation range, respectively. It is also possible to incorporate a more localized (slope-dependent) calculation of τ for each glacier (e.g. Driedger and Kennard 1986) to consider the effect of higher shear stresses in steep ice falls than in flat glacier parts (Haeberli and Schweizer 1988). However, these modifications only change the estimated ice thickness of a glacier without influencing the general shape of the modelled glacier bed. Changing of the latter can only be achieved by digitizing new flowlines.

Apart from the required further validation of our approach with independent field data and more specific calculation of some parameters, we see a large potential for Alpine-wide application of the approach in the context of forthcoming climate change impact studies and hydrological assessments.

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