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Case study

A graph-based approach to glacier flowline extraction: An application to glaciers in Switzerland

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ABSTRACT

In this paper we propose a new, graph-based approach to glacier segmentation and flowline extraction. The method, which requires a set of glacier contours and a Digital Elevation Model (DEM), consists in finding an optimum branching that connects a set of vertices belonging to the topological skeleton of each glacier. First, the challenges associated with glacier flowline extraction are presented. Then, the three main steps of the method are described: the skeleton extraction and pruning algorithm, the definition and computation of a travel cost between all pairs of skeleton vertices, and the identification of the directed minimum spanning tree in the resulting directed graph. The method, which is mainly designed for valley glaciers, is applied to glaciers in Switzerland.

1. Introduction

1.1. *Glacier morphology*

Glaciers are moving ice bodies which flow under their own weight, due to the accumulation of solid precipitations on the higher slopes of a mountain range. As the strain rate increases, ice viscosity decreases and the accumulated ice literally ‘flows’ downslope. Bahr and Peckham (1996) first explicitly drew a parallel between rivers and valley glaciers (i.e. glaciers that are confined by topography, as opposed to ice caps). They showed that glaciers also exhibit branching topologies, and computed classical river network indices such as bifurcation and area ratios for glacier networks. This analogy stems from the fact that in most recent orogens where valley glaciers are found (the Alps, the Andes, the Himalayas, the Rocky Mountains, etc.), glacier inception took place in a topography previously shaped by fluvial erosion (Gsell et al., 2015). Bahr and Peckham also pointed out that self-similarity properties could provide a ‘lever arm’ for tackling glacier flow dynamics for complex geometries, just as these properties are used for treating subgrid, hydraulic propagation in complex river networks with concepts such as the Geomorphological Instantaneous Unit Hydrograph (Rodríguez-Iturbe and Valdés, 1979; Gupta et al., 1980). One of the reasons why this approach has not been given much attention is maybe the difficulty lying in the first step of identifying networks of glacier flowlines.

1.2. *Limits of classical drainage network extraction methods*

Fig. 1 shows the downstream region of the Rhone glacier in Switzerland. In fluvial morphology, we typically find cross-sections such as A–A′ with a concave topography in the talweg. This translates into V- or U-shaped (for former glacial valleys) elevation contours, with the lowest point roughly in the medial axis of the talweg. Hence, river network extraction from a DEM is relatively straightforward, except for problems such as flat areas or closed depressions (see e.g. Garbrecht and Martz, 1997; Martz and Garbrecht, 1998).

Things are more complicated for ice-covered areas. In the accumulation (higher) area of the glacier, where hillslopes as well as valley floors are ice-covered, the topography is still concave (B–B′): the surface of the ice is more or less homothetic to the bedrock surface (with lower roughness though). In contrary, in the ablation area the glacier is limited to a narrow ice tongue confined between lateral, ice-free hillslopes. Since ice thickness is maximum in the medial axis of the ice tongue, we have a convex cross-section (C–C′) with seemingly two talwegs on each side of the glacier. Elevation contours in this area have the shape of a W with its two wedges pointing upstream, as opposed to the single wedge in concave topography. The central flowline of the glacier (i.e. the line of maximum ice thickness), which is also typically the line of the bedrock talweg, is a local maximum and not a local minimum of the ice surface (it looks like is a local water divide). Therefore, it

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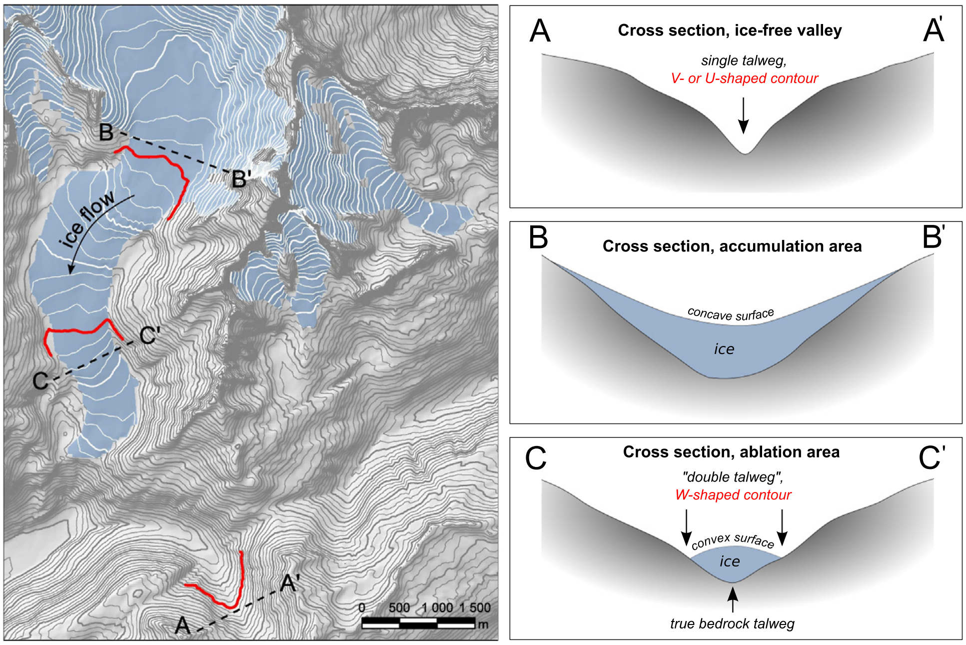

Fig. 1. Illustration of the spurious ‘double talweg’ in glacial landscape. This feature mainly appears in the glacier's ablation area where a narrow ice tongue is confined in a valley (C–C′). On a map, elevation contours in this area have the shape of a W with its two wedges pointing upstream, whereas contours in classical (ice-free) valleys are V- or U-shaped with a single wedge pointing upstream (A–A′).

cannot be extracted in a stable way from a DEM with classical algorithms.

1.3. Automatic methods for glacier flowline extraction

The problem of glacier flowline extraction has received some attention recently, due to the need of feeding glacier databases with attributes such as glacier length. A flowline or a set of flowlines has to essentially meet two requirements: (i) to stay as far as possible from the glacier boundary, and (ii) to cross elevation contours orthogonally. Le Bris and Paul (2013) propose to construct a set of waypoints located at the center of ‘traverses’ drawn perpendicular to a single, rectilinear ‘main axis’, and then connect them. However, the method can only extract one centerline per glacier. Kienholz et al. (2014) use a more complex approach based on a cost function which quantifies the trade-off between the two requirements; a set of flowlines is then extracted between glacier heads and a single snout (terminus) per glacier. Other methods apply alternate procedures in the accumulation and ablation zones (Machguth and Huss, 2014), also resulting in a large number of parameters.

1.4. Objectives of the study

In this paper, a new method is presented that aims at extracting glacier flowlines with an emphasis on preserving their tree-like structure, i.e. the structure of tributaries within the glacier.

As in Le Bris and Paul (2013), our method first identifies a set of waypoints (i.e., vertices of a graph) that are subsequently connected. However these waypoints are identified with a more general operation called skeletonization. Once these waypoints are identified (including special ‘snout’ vertices), we compute a travel cost between every pair of them: the cost function is designed so as to penalize displacements that deviate from the steepest slope direction. The main difference with Kienholz et al. (2014) is the formulation of an anisotropic cost function. The final step is to construct a directed minimum spanning tree (DMST) that allows to visit all waypoints at minimal cost, starting from a snout (root) vertex. Edges of this DMST meet the two requirements: they stay ‘far’ from the glacier's boundary (since they link waypoints belonging to the skeleton), and they deviate little from the steepest slope direction since they are least-cost paths with respect to the slope-dependent cost function. The overall procedure requires only 5 parameters, in contrast with other methods (e.g. 16 parameters in Kienholz et al., 2014 and 17 in Machguth and Huss, 2014).

The method is mainly designed for valley glaciers, as ice caps usually do not exhibit strong branching topologies. It is tested on a dataset of Swiss glaciers (Fig. 2a), covering a total area of 1200 km^2 and mainly located in the headwaters of the Rhone, Rhine, and Danube rivers. The steps of the method are illustrated with a focus on a particular glacier complex in the Bernese Alps (Fig. 2b), straddling the water divide between the Rhone and Rhine rivers.

2. Data

2.1. Digital elevation model

In this study we use the 25-m Digital Elevation Model from the Swiss Federal Office of Topography (SwissTopo, 2004).

2.2. Randolph Glacier Inventory (RGI) glacier contours

Glacier outlines are taken from the Randolph Glacier Inventory (RGI, Arendt et al., 2012). The RGI provides a segmentation of glacier complexes (continuous ice bodies) into individual glaciers; we chose to dissolve (re-aggregate) these elements and to work with the complexes in order test the ability of our approach to identify multiple snouts in such complexes. The segmentation is not a prerequisite and is even a by-product of our method.