Attempt at detecting cases of connectivity between rock glaciers and torrents using morphometrical indices

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Abstract— **This contribution describes the application of a new approach aiming at detecting rock glaciers connected to the torrential network system in Alpine catchments. The method first uses morphometric variables to identify steep rock glaciers fronts. The sedimentary connection between these fronts and torrents is then assessed through the computation of a sediment connectivity index. Results are then compared to an inventory of connected rock glaciers performed by visual analysis of aerial images. 20 rock glaciers were identified as connected visually while 85 were detected via the geomorphometric approach. If the latter overestimated the level of connectivity for several cases, other error sources such as the use of low-quality input data or the uncertainties in the visual connectivity assessment were identified by the study.**

I. INTRODUCTION

The climatically-driven acceleration of rock glaciers has been largely documented for many mountain ranges, in particular in the European Alps [1-3]. The resulting increase in slope instabilities is likely to represent a threat to the integrity of infrastructures and activities that stand directly on permafrost [4] but also in valley bottoms [5]. In particular, the acceleration of rock glaciers creep rates is expected to increase the magnitude and/or the frequency of rock falls and debris flow events through enhanced release of rock debris at their margins [6,7]. However, it can be assumed that high surface velocities would only impact the occurrence of debris flows if an efficient sediment connection exists between rock glaciers fronts and vulnerable infrastructures such as roads or buildings [8]. Yet, there is a lack of knowledge in the potential propagation of gravitational and torrential processes, especially because the level of connectivity within the sediment cascade of alpine torrential catchments is generally not known. This is particularly the case for rock glaciers which are commonly identified in the European Alps through specific inventories but whose level of connectivity with torrential channels is rarely documented. With rock glaciers frequently presenting high surface velocities, knowledge about the location of rock glaciers efficiently connected to the torrential network system can be considered as important.

Assessing connectivity within Alpine catchments is not an easy task if one considers both structural connectivity, i.e. the direct proximity between slope units, and functional connectivity, i.e. the actual occurrence of sediment transfer from one upslope geomorphological unit to a downslope one [9]. If the structural connectivity can be relatively easy to retrieve from simple visual analysis of aerial images, the level of functional connectivity is often more difficult to establish. In a visual, qualitative approach, geomorphological indications such as the presence of fresh sediments in a channel or traces of fresh erosion at the margin of a landform can be used as clues to determine the occurrence of a functional connectivity between two slope units [8]. However, such visual, geomorphological approach remains quite subjective because it is clearly dependent on the geomorphological expertise of the observer. Recently, several studies proposed methods to infer connectivity in a semi-quantitative way using morphometric indices [10, 11]. Among these studies, the Index of Connectivity (IC) proposed by [10] and adapted from [12] is the most commonly used [13, 14]. The IC is well adapted to high mountains environments but only computes relative values of connectivity and is therefore not suited to differentiate connected landforms from unconnected ones [13, 14]. Specific adaptations must thus be undertaken in order to use the IC for the detection of rock glaciers connected to torrential channels, and thus to the Alpine valleys where most infrastructures lie.

In this work, we propose a new approach especially designed to detect rock glaciers connected to torrents at the regional scale. It reposes on the combination between the use of morphometric indices and the IC computed on a 5 meters DEM. The method is here tested on several catchments of the French Alps and compared for the same areas to an inventory of connected rock glaciers compiled solely based on geomorphological analysis of aerial images, as proposed by [8].

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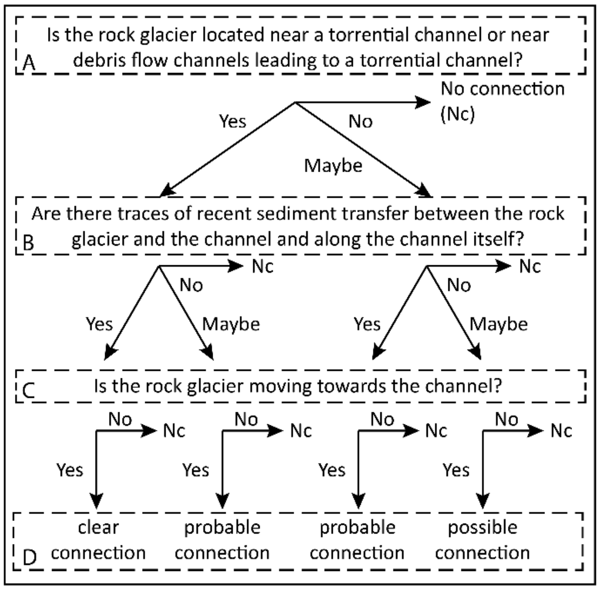

Figure 1. Conceptual workflow representing the different steps used for the visual detection of rock glaciers connected to torrential channels. Letters refers to the text.

II. METHODS

In this study, two main methodological approaches have been used to detect rock glaciers connected to the torrential network system. First, an inventory developed from visual geomorphologic interpretation of aerial images is proposed (Figure 1) and serves as a comparison basis with a second approach based on the aggregation of several morphometric indices. Both methods were applied in an area corresponding to the sub-catchments shown in Figure 2. These sub-catchments are characterized by the highest densities of active rock glaciers in the French Alps, hence their selection for the study.

A. *Visual method*

The inventory of rock glaciers connected to torrents is performed through visual observation of aerial images following the methodological framework developed by [8]. Compared to this previous study, the method applied here uses a slightly improved workflow which is shown in Figure 1. For each rock glacier previously inventoried in the study region [15], the structural connectivity is first inferred by visually determining the topographical proximity between the rock glacier and channelized structures leading to the main torrential channel (which in turn leads to the main valley, see A in Figure 1). When a rock glacier is detected as "structurally connected" to a torrent, the analysis continues by estimating the level of functional connectivity through the visual identification of recent sediment transfer activity between the rock glacier and the torrent until it reaches the main valley (B in Figure 1). Basically, traces of fresh sediments lying in the channel are interpreted as indicators for efficient functional connection while their absence points towards an inactive connection. Finally, the use of time series of aerial images allows a qualitative determination of the rock glaciers movement direction (C in Figure 1). This is useful to check if sediments are actually being actively transported towards the torrential channel or not. At the end of the workflow, different classes of connectivity can be assigned to each rock glacier as reported Figure 1 (D).

B. *Morphometric approach*

As the visual detection of connectivity remains subjective, the 2nd method applied here aims at detecting rock glaciers connected to torrents using morphometric parameters. Terrain curvature (with distinction between planar and profile curvature) and slope angle appear in the literature as the most important parameters to identify debris flow prone areas [16,17]. They are here calculated from the French IGN (National Geographical Institute) 5 meters DEM. Thanks to an already existing database of 35 frontal areas known as being directly connected to torrents in the western Swiss Alps [8], threshold curvature (planar and profile) and slope values could be determined by adding (maximal threshold value) and subtracting (minimal threshold value) the standard deviation to the mean value of each morphometric parameter respectively. The thresholded curvature (x2) and slope rasters obtained for the studied catchments were then coupled with the surface of rock glaciers as provided from existing polygon inventories [15] to highlight areas of rock glaciers where the morphology favors the occurrence of water-driven sediment transport (i.e. mainly the steep fronts). In a second step, the identified areas are intersected with zones where the IC [10] exceeds a threshold value (-2.8), also previously determined from zonal statistics performed on the 35 connected frontal areas detected in the western Swiss Alps. The targets used for the IC calculation are here the main rivers of the chosen catchments (Figure 2). As a result, areas of rock glaciers prone to water erosion and sediment transfer and for which the IC value exceeds a given threshold are detected. Each rock glacier for which such area exists is thus considered here as connected to the main valley river.

III. RESULTS

The application of the morphometric approach led to the identification of 85 rock glaciers connected to the valley bottom through the torrential network. As a comparison, 20 rock glaciers were classified as connected (classified as possible, probable or clear connection) by the use of the visual method. Among these 20 cases, 10 are identified as connected by both approaches while the rest is characterized by differing results (Figure 3). All the rock glaciers classified as "clear connection" by the visual method are also recognized as connected in by the morphometric approach.

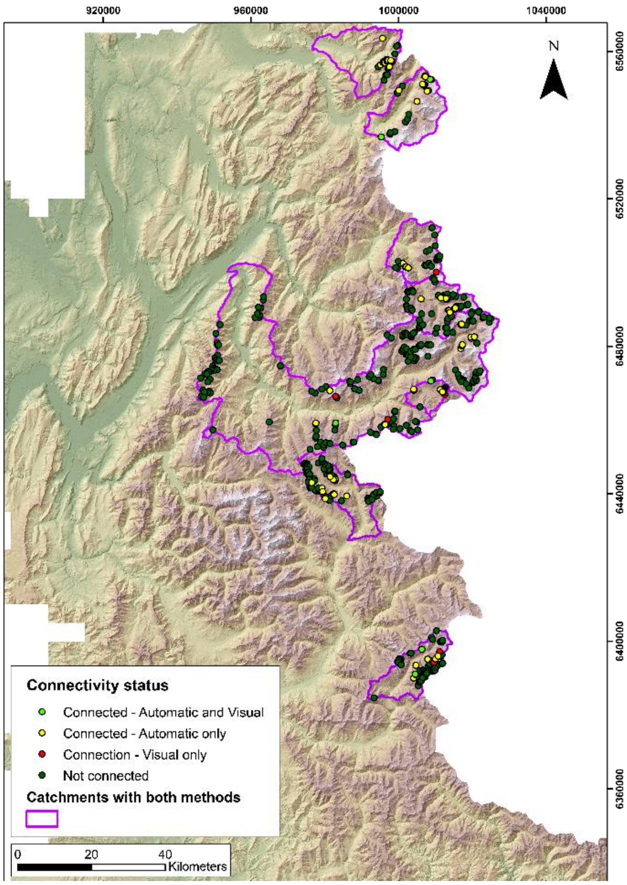

Figure 2. Subdivision of the French Alpes in 7 hydrological basins (purple polygons), within which both visual and automatic detection were carried out. The comparison between the results of both methods are represented with the colored dots on the map.

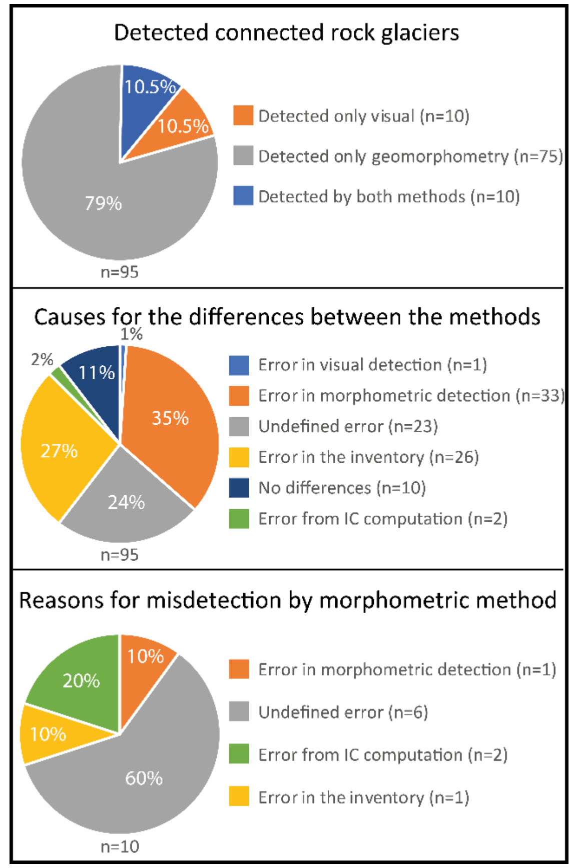

Figure 3. Pie charts showing the results and the relative performance in the detection of rock glaciers connected to torrential channels. The term "undefined error" is used when it is not clear which one of the semi-automatic or the visual method is yielding wrong results while "error from IC computation" refers to issues related to the choice of the target in the IC calculations. "Error in the inventory" designates mistakes in rock glaciers status and outlines in the original rock glacier inventory used as input data.

The main causes of discrepancy between the two approaches have been evaluated for each rock glacier identified as connected by one method or the other (or both) and are shown in Figure 3. If it appears that the most common reason of disagreement are errors in the automatic detection, two other sources of difference are characterized by significant percentages, namely errors in the rock glacier inventory (errors in the polygon outlining and errors in the landform interpretation) and undefined errors issuing from the difficulty to identify the error source between the visual and the morphometric approach (Figure 3). This is especially the case for rock glaciers located far from the main valley and separated from it by long flat channel sections which might stop debris flows propagation. In such cases, it is difficult to clearly identify which of the two approaches yields the correct connectivity status.

IV. DISCUSSION

At first glance, the performance of the morphometric detection of connected rock glacier can be questioned, given the large number of cases identified as connected which do not appear in a more classical visual inventory. However, the results show that discrepancies between visually and morphometrically identified connected landforms do not only arise from errors in the morphometrical detection, but also from other sources of errors.

Among these other sources of error, the study underlines the primordial importance of good source data quality. Indeed, 27%

of all rock glaciers identified as connected (visual and/or morphometric) have been wrongly detected due to errors in the rock glacier inventory used as a base for the analysis. These errors comprise (i) talus slopes included by mistake in the inventory and (ii) bad delimitation of rock glaciers outlines preventing our approach to efficiently detect the fronts. In addition, our results show that determining which of the two methods yields wrong results is often difficult. This is for instance the case when a rock glacier is connected to the main channel but long flat sections may prevent the propagation of debris flows downstream. In such cases, we expect that the automatic method using morphometric parameters is probably more capable of identifying flat sections that will effectively decouple the upslope area from the valley.

Finally, part of the errors in the morphometric detection derives from misidentification of rock glaciers fronts. Indeed, it appeared that the developed approach sometimes detects debris flow prone areas in the rooting zones of rock glaciers and does not correspond to what was targeted (rock glaciers fronts). Future development of the method should thus imply a better use of morphometric variables in order to better distinguish rock glaciers fronts from steep areas in the rooting zones.

Improvements should also include a better identification of the target zones for the connectivity investigations. In this study, the targets used for the connectivity assessment and the IC computations the catchments main rivers as they generally coincide with the location of most vulnerabilities. However, cases may exist where vulnerable objects such as roads are located further upslope than the main river. Specific investigations using alternative targets could thus be sometimes necessary. Inventories of vulnerable objects could facilitate forthcoming developments.

V. CONCLUSION

The developed morphometric approach yielded quite promising results. It detected well cases of rock glaciers which were identified as clearly connected with the visual approach and partly detected rock glaciers classified as possibly connected and probably connected. The approach however slightly overestimated connectivity. Improvements in the morphometric detection of rock glaciers fronts could help enhance the quality of the results. We thus suggest to use the developed morphometric approach as a first step to identify potentially connected cases and to associate it with a more traditional visual analysis in a second step to verify the actual presence of an efficient connection.

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