

# On the morphological characteristics of overdeepenings in high-mountain glacier beds

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**ABSTRACT:** Overdeepenings, i.e. closed topographic depressions with adverse slopes in the direction of flow, are characteristic for glacier beds and glacially sculpted landscapes. Quantitative information about their morphological characteristics, however, has so far hardly been available. The present study provides such information by combining the analysis of (a) numerous bed overdeepenings below still existing glaciers of the Swiss Alps and the Himalaya-Karakoram region modelled with a robust shear stress approximation and (b) detailed bathymetries from recently exposed lakes in the Peruvian Andes. The investigated overdeepenings exist where glacier surface slopes are low ( $< 5^{\circ}$ – $10^{\circ}$ ), occur in bedrock or morainic material and are most commonly a fraction of a kilometre squared in surface area, hundreds of metres long, about half the length in width and tens of metres deep. They form under conditions of low to high basal shear stresses, at cirque, confluence, trunk valley and terminus positions. The most striking phenomenon, however, is the high variability of their geometries: Depths, surface areas, lengths and widths of the overdeepenings vary over orders of magnitude and are only weakly – if at all – interrelated. Inclinations of adverse slopes do not differ significantly from those of forward slopes and are in many cases higher than so far assumed theoretical limits for supercooling of ascending water and corresponding closure of sub-glacial channels. Such steep adverse slopes are a robust observation and in support of recently developed new concepts concerning the question about where supercooling of sub-glacial water and closure of ice channels can or must occur. However, the question of when and under what climatic, topographic and ice conditions the overdeepenings had formed remains unanswered. This open question constitutes a key problem concerning the interpretation of observed overdeepenings, the understanding of the involved glacio-hydraulic processes and the possibility of realistic predictive modelling of overdeepening formation. Copyright © 2016 John Wiley & Sons, Ltd.

**KEYWORDS:** high mountains; glacier beds; glacier erosion; overdeepenings; glacial lakes

## Introduction

Overdeepenings or closed basins in glacier beds are common features in glaciated landscapes (Cook and Swift, 2012; Swift *et al.*, 2014). Models by Hooke (1991) and Alley *et al.* (2003) predict them to be equilibrium forms that all glacier beds tend towards. This study provides the first systematic quantification of overdeepening morphometry for glaciated high-mountain environments.

While areal denudation by glaciers is primarily associated with abrasion by debris-laden ice and quarrying/plucking of rock at the ice base, local maxima of depth erosion and the formation of overdeepenings may more strongly be linked to the complex system of sub-glacial meltwater drainage, which can in places be linearly concentrated (Creys *et al.*, 2013; Beaud *et al.*, 2016). Water flow in pressurized sub-glacial drainage systems at warm-based parts of glaciers not only affects basal sliding and the efficiency of direct glacier-bed erosion but likely also plays a predominant role in evacuating sediments produced by erosion and, hence, keeps eroded bed surfaces

accessible for further erosion. The coupling of sub-glacial hydraulics and erosion to models of glacier flow has so far only been attempted in a few studies (e.g. Herman *et al.*, 2011; Egholm *et al.*, 2012; Creys *et al.*, 2013; Beaud *et al.*, 2016) but remains an important research challenge for the future. An important aspect thereby relates to the topographic and glaciological characteristics, which may be typical for sites where glacial overdeepenings occur (cf. Frey *et al.*, 2010). What factors or factor combinations with their changes along the direction of flow are related to the occurrence of glacial overdeepenings: surface slope, ice thickness, driving stress, flow velocity, sub-glacial discharge, basal thermal conditions (temperate, cold, polythermal), water pressure, effective normal pressure, debris content, bed characteristics (sediment, rock)? Can empirical 'rules' be found for understanding and predicting the formation and evolution of overdeepenings in glacial systems, past and future?

A need for quantitative morphological data of overdeepenings also exists in connection with safety aspects concerning flood hazards from outbursts of lakes developing

within de-glaciating overdeepenings or related to the possibility of deep glacial erosion excavating repositories for radioactive waste during future glacials (Fischer *et al.*, 2014; Haerberli *et al.*, 2016; see Supporting Information S1). This quantitative information, however, is not easily accessible. In currently glacier-covered regions, bed-overdeepenings are not directly visible and in formerly glacier-covered regions they are often filled with sediments and must be explored using labour- and cost-intensive methodologies (drillings, geophysical soundings). Two developments recently ameliorated the situation: the availability of high-resolution digital terrain information and the exposure of glacier beds as a consequence of the rapid glacier retreat.

High-resolution digital terrain information enables the modelling of realistic and detailed bed topographies for existing glaciers across entire mountain chains (Farinotti *et al.*, 2009; Linsbauer *et al.*, 2009, 2012; Huss and Farinotti, 2012; Clarke *et al.*, 2013) and provides corresponding data about bed-overdeepenings and potential future lakes (see also Patton *et al.*, 2015; Supporting Information S2). For the Swiss Alps, for instance, several hundred overdeepenings were modelled in the beds of currently existing glaciers (Linsbauer *et al.*, 2012) and comparable information is now available for thousands of glaciers in the Himalaya-Karakoram region (Linsbauer *et al.*, 2016). For the first time, this opens up opportunities to analyse a large statistical sample with respect to morphological characteristics of bed-overdeepenings. The plausibility of the corresponding database can be assessed but the data remain a modelling product that depends on model assumptions including the applied basal shear stresses and the smoothing function to account for effects of longitudinal stress coupling in glaciers (cf. Adhikari and Marshall, 2013).

The rapid retreat of glaciers leads to the formation of numerous new pro-glacial lakes in high mountain regions. Bathymetries of new lakes that became recently exposed as a consequence of de-glaciation and that are still weakly affected by sedimentation processes constitute directly measured model-independent information about morphological characteristics of bed overdeepenings (Figure 1). In connection with safety questions, numerous and detailed lake bathymetries

have been measured in the Cordillera Blanca of Peru. Such measured bathymetries are much less numerous than the modelled data but provide an important independent check of the latter.

The present study attempts to analyse quantitative data about the morphological characteristics of glacial overdeepenings by using high-resolution glacier-bed models and measured bathymetries of newly formed lakes. The question is investigated whether such data may have the potential to be used for calibrating numerical models of glacial erosion (Herman *et al.*, 2011; Egholm *et al.*, 2012) and for testing hypotheses of stabilizing feedbacks associated with the erosion of glacial overdeepenings (Alley *et al.*, 2003; Hooke, 1991; Werder, 2016).

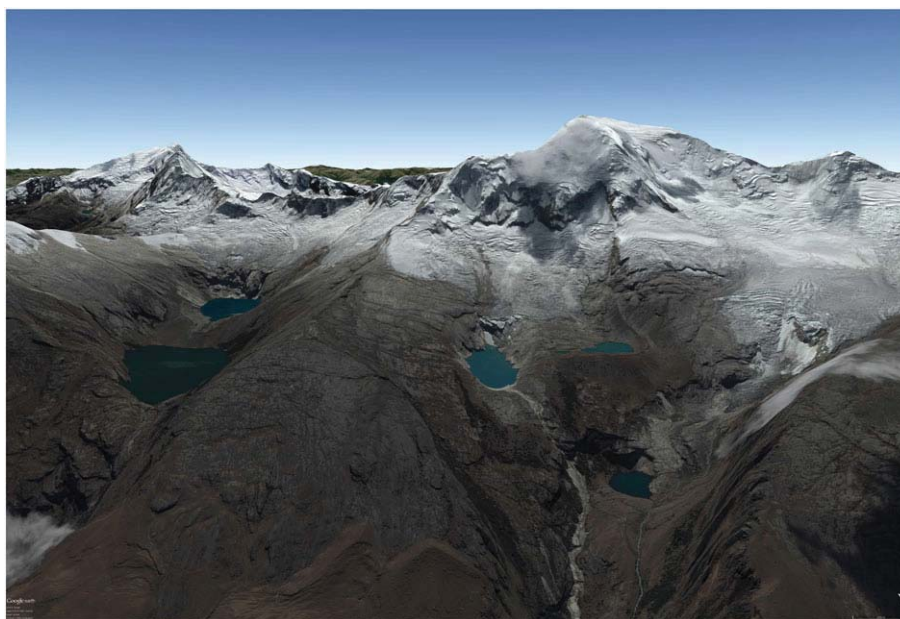
Three main steps were followed:

1. Development of a strategy and geographic information system (GIS)-based automated procedure for extracting morphometric data on the basis of modelled overdeepenings in the Swiss Alps.
2. Inclusion of morphometric information from modelled overdeepenings in the Himalaya-Karakoram region and from measured lake bathymetries in the Cordillera Blanca, Peru.
3. Expert judgements about general morphological characteristics and statistical analysis of morphometric data concerning the investigated overdeepenings.

## Study Sites and Methods

### Swiss alps

Ice thickness and bed topography of the glaciers in the Swiss Alps were calculated with GlabTop (Linsbauer *et al.*, 2009, 2012) which only requires three data sets as input: a digital elevation model (DEM), glacier outlines and a set of manually digitized glacier branch lines. The DEM used is the DHM25 (Swisstopo, 2005); two versions are available – level 1 from around 1985 and level 2 from around 1995. The glacier



**Figure 1.** Newly formed lakes in bed overdeepenings of formerly glacier-covered bedrock at the foot of Nevado Hualcán, Cordillera Blanca, Peru. Laguna 513, the lake in the centre of the image, has a maximum depth exceeding 100 m (cf. Figures 4 and 9) as measured in connection with hazard assessments (cf. the rock/ice avalanche causing impact waves and corresponding floods/debris flows down to the main valley at Carhuaz; Carey *et al.*, 2012). Google Earth view, image date 20 August 2013. This figure is available in colour online at [wileyonlinelibrary.com/journal/espl](http://wileyonlinelibrary.com/journal/espl)

outlines are from the Swiss Glacier Inventory 1973 (Müller *et al.*, 1976, Maisch *et al.*, 2000) which covers a glacier area of about 1304 km<sup>2</sup> and from the Swiss Glacier Inventory 2000 (Paul, 2007) which covers a glacier area of about 1040 km<sup>2</sup> and includes an estimated ice volume of 68 ± 20 km<sup>3</sup>. Detailed comparison with ice depths obtained from field measurements (mainly radio-echo soundings) shows that the uncertainty range of absolute depth values calculated by GlabTop is about ±30% (Linsbauer *et al.*, 2012). The data sample concerning bed topographies comprises results from four different model runs using variations in input data and interpolation methods, each with more than 500 modelled overdeepenings. These modelled overdeepenings have a total area of about 50 to 60 km<sup>2</sup>, a total volume of about 1.5 to 2.5 km<sup>3</sup> (about 3% of the existing glacier volume) and can be seen as sites of potential future lake formation when becoming exposed as a consequence of glacier retreat. While the modelled overdeepenings based on the four different model runs differ in exact shape, their locations are mostly robust and the values for the extracted parameters are comparable (cf. Figure 2).

### Himalaya-Karakoram region

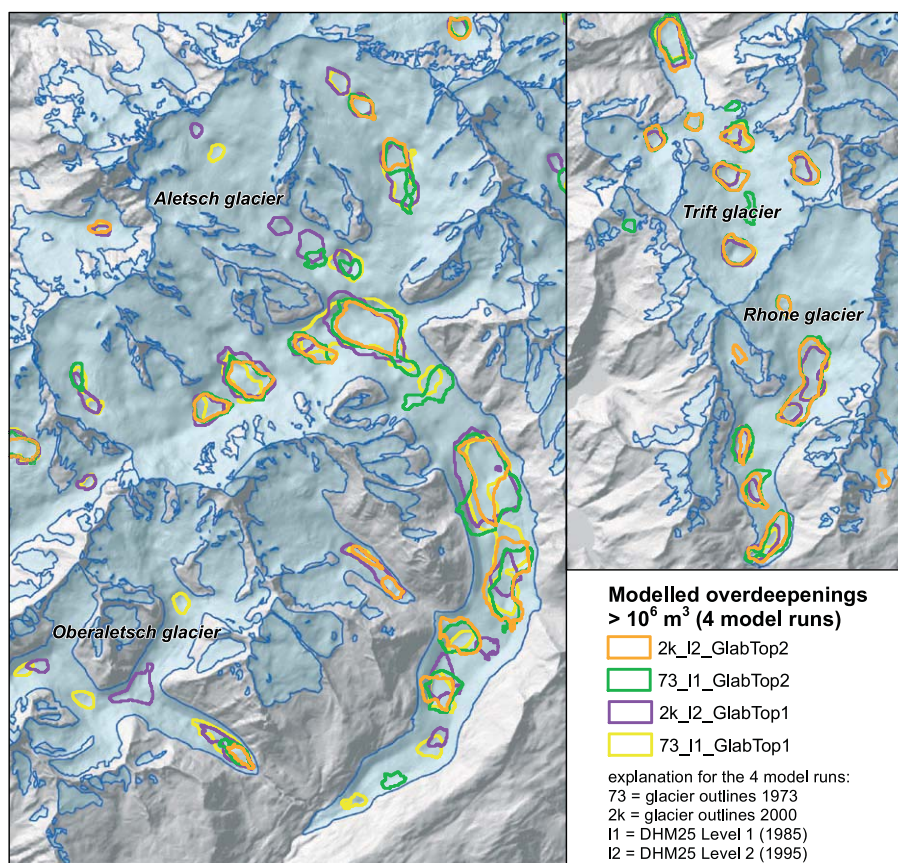
The estimate of glacier coverage for the Himalaya-Karakoram region is about 40 800 km<sup>2</sup> resulting in a total ice volume of 2955 to 3360 km<sup>3</sup>. To model the ice thickness distribution for the very large region, the fully automated GlabTop2 was developed (Frey *et al.*, 2014), which requires only a DEM and glacier outlines as input. GlabTop2 is based on the same concept as GlabTop (Linsbauer *et al.*, 2009, 2012; Paul and Linsbauer, 2012), but involves two major changes from the original approach: branch lines become obsolete, and surface slope is not derived along lines but as the average surface

slope of all grid cells within a certain distance. This avoids the laborious process of manually drawing branch lines and allows for applying the model to the immense glacier sample of the entire Himalaya-Karakoram region. By subtracting the modelled ice thickness distribution from the input surface DEM, the overdeepenings in the Himalaya-Karakoram mountain range are extracted (Figure 3). The limited quality (filled data voids) and the coarse resolution (about 90 m) of the surface DEM [SRTM (Shuttle Radar Topography Mission); Jarvis *et al.*, 2008] causes the calculation of bed overdeepenings to be correspondingly more uncertain for the Himalaya-Karakoram region than for the Swiss Alps where the DHM25 with a 25 m grid was used. Furthermore, the geo-referencing of glacier outlines in the Randolph glacier inventory (Pfeffer *et al.*, 2014) remains problematic in some areas.

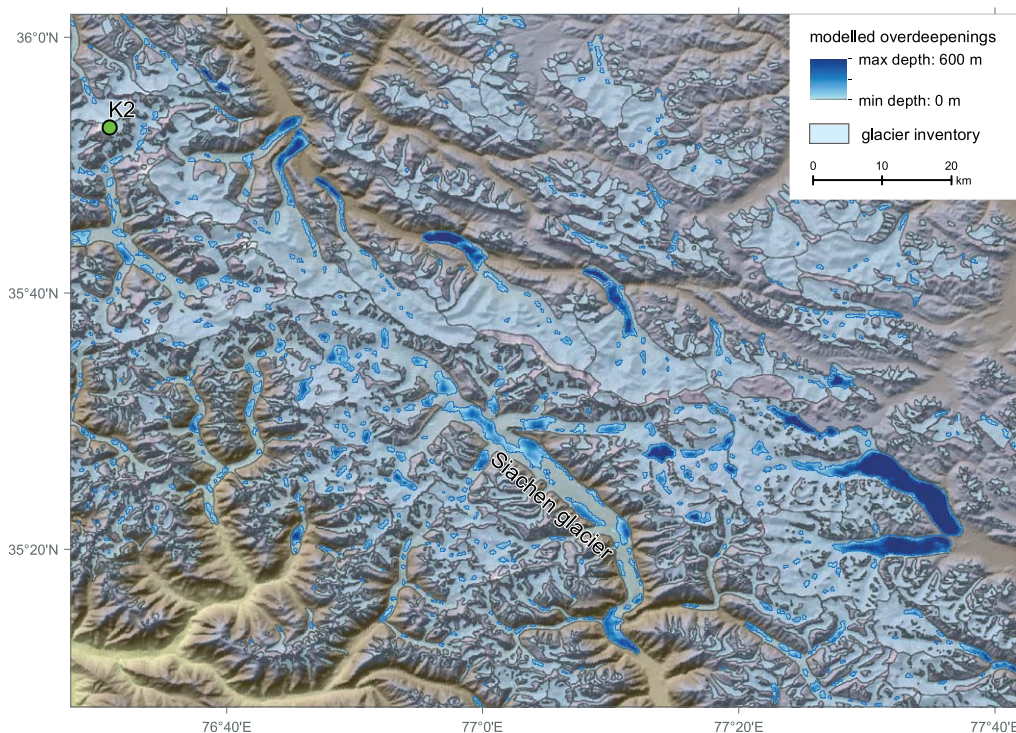
For the Himalaya-Karakoram region about 16 000 modelled overdeepenings larger than 10<sup>4</sup> m<sup>2</sup> were detected in the modelled glacier-bed topography (Linsbauer *et al.*, 2016), covering an area of about 2200 km<sup>2</sup> and having a total volume of about 120 km<sup>3</sup> (3–4% of the currently existing glacier volume). About 5000 of these overdeepenings (1800 km<sup>2</sup>) have a volume larger than 10<sup>6</sup> m<sup>3</sup>. The largest calculated bed depression (cf. Figure 3) covers an area of more than 50 km<sup>2</sup> and has a volume of about 11 km<sup>3</sup>.

### Peruvian andes

In connection with questions of lake hazards, detailed bathymetries have been measured since the 1960s in lakes exposed by ongoing glacier retreat in the Cordillera Blanca by the Glaciology and Water Resources Unit, ANA, Huaraz, and its predecessor organizations. In the earlier years probes and later a graphic



**Figure 2.** Map showing modelled overdeepenings with volumes larger than 10<sup>6</sup> m<sup>3</sup> based on four different model runs for Aletsch/Oberaletsch (left) and Trift/Rhone glaciers (right). This figure is available in colour online at [wileyonlinelibrary.com/journal/espl](http://wileyonlinelibrary.com/journal/espl)



**Figure 3.** Bed overdeepenings modelled with GlabTop2 for the glaciers between K2 and the Karakoram-Pass in the Karakoram Range, including the largest modelled depression (lower right of image). This figure is available in colour online at [wileyonlinelibrary.com/journal/espl](http://wileyonlinelibrary.com/journal/espl)

echo sounder were used in combination with geo-referencing by theodolite triangulation. Since the year 2000 measurements (Figure 4) were carried out with a Zodiac rubber boat and a digital echo sounder (GARMIN GPS MAP 188C SOUND). With long- and cross-profiles arranged at a distance of  $\pm 20$  m, a dense network of measured points was obtained. Even closer spacing was chosen at sites where sharp irregularities in the lake-bottom topography were observed. Topographic surveys using a total station (TOPCON GPT 7005 L) were made to define the lake perimeters, the surrounding surface topography and interesting points like river entrances and lake outlets. Data analysis was achieved with MAPSOURCE of the global positioning system (GPS) map applying a value of  $1400 \text{ m s}^{-1}$  to the propagation speed of the ultrasonic pulse in freshwater. The data sample comprises 92 lakes, covering an area of about  $24 \text{ km}^2$  and resulting in a volume of  $0.6 \text{ km}^3$ . Most lakes in this sample are moraine-dammed and only 15 are bedrock overdeepenings. Emphasis here is on the bedrock overdeepenings (cf. Figures 1, 4, and later Figure 6).

### Parameters

Qualitative/quantitative information is available from (a) general model assumptions (average basal shear stress) or expert judgements (for instance, rock/moraine glacier bed, topological situation with respect to glacier flow, morphological indications) and from (b) numerical values of morphometric parameters for a very large number of modelled bed overdeepenings in the Swiss Alps and the Himalaya-Karakoram region and for a few measured lake bathymetries in the Cordillera Blanca, Peru. Of primary interest for a statistical analysis of the morphometric characteristics of overdeepenings are area, maximum and mean depth, volume, length (longest line and orientation), maximum width (perpendicular to the longest line) and mean width, elongation (width-to-length ratio to obtain convenient numbers between zero and one), length and orientation with respect to the ice flow direction, maximum and mean

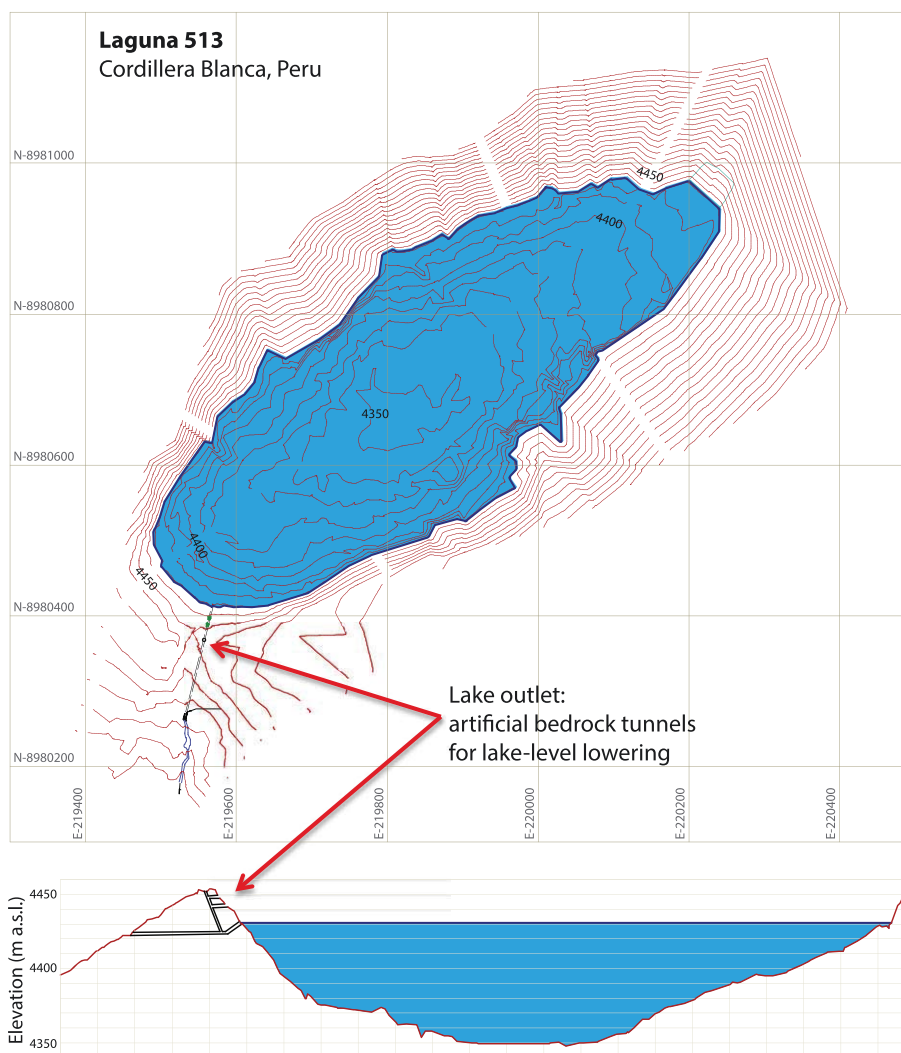
inclination of adverse and normal slopes. Average basal shear stress of the glaciers, basal ice temperature, topological classification with respect to glacier flow (cirque, confluence, diffuence, trunk valley, terminus) and substrate/dam material represent important complementary information. The technical procedures used for the determination and GIS-extraction of these parameters are described in the Supporting Information S3.

### Results

Information estimated using general model assumptions and expert judgements is first summarized. This information provides an impression of the general geomorphological and glaciological characteristics involved. The morphometry of the investigated overdeepenings is then quantified in a second step using statistics (histograms, correlations). This is the basis for discussing possibilities and limitations of quantitative predictions in comparison with existing theories where available.

### Parameters estimated using general model assumptions and expert judgements

Values for the average basal shear stress as a function of elevation range (governing mass turn-over) result from the basic model assumption in the GlabTop approach. Information about the bed characteristics (rock/moraine), topological situations with respect to glacier flow and morphological indications for sites with overdeepenings are based on expert judgements or independent model calculations and require some additional commentary. One key uncertainty thereby relates to the unknown time of overdeepening formation and the corresponding glacier characteristics (in particular geometry and thermal aspects).



**Figure 4.** Measured bathymetry of the Laguna 513 above Carhuaz, Cordillera Blanca of Peru. This lake formed after 1980 in a bedrock overdeepening (cf. Figures 1 and 9) as a consequence of glacier retreat. For safety reasons, the lake level had been artificially lowered by about 20 m in the early 1990s through construction of tunnels (left-hand side of the long profile across the lake). Note that the local maximum adverse slope of the lake bottom is much steeper than the average between the deepest point of the lake and the lake outlet (at left). This figure is available in colour online at [wileyonlinelibrary.com/journal/espl](http://wileyonlinelibrary.com/journal/espl)

#### Average basal shear stress

GlabTop estimates an average basal shear stress for every glacier as a function of its elevation range (cf. Haeberli and Hoelzle, 1995). Aletsch glacier, for instance, with its large overdeepenings at Konkordiaplatz and other locations receives the maximum possible value of 150 kPa (1.5 bar) while smaller glaciers like the cirque glacier at Chüebodenhorn (Figure 5) have lower values of a few tens of kilopascals. If the

overdeepenings in such cirque situations had formed during time periods with larger glaciers (glacial maxima, for instance) the attributed shear stress could have been larger. In the case of Chüebodenhorn, however, ice flux in such situations would have been to both sides of the ridge and, hence, small shear stress values even close to zero remain plausible. This underpins the impression that marked overdeepenings can form where basal shear stresses are small or large.



**Figure 5.** Overdeepening at the cirque of Chüebodenhorn (Gotthard region, central Swiss Alps) with a new and expanding lake. Maximum depth of the lake is 30 m, width about 170 m. Photograph: Y. Schaub 2012. This figure is available in colour online at [wileyonlinelibrary.com/journal/espl](http://wileyonlinelibrary.com/journal/espl)

### Rock and sediment beds

For the glaciers of the Swiss Alps, bed characteristics were estimated based on an erosion/sedimentation-index (Zemp *et al.*, 2005; see Supporting Information S4). Most glaciers have mixed beds with combinations of sedimentary and rocky parts. Large glaciers tend to have more rock components, because their abundant meltwater can evacuate debris more easily. The largest overdeepenings are found in the beds of the largest valley glaciers (Aletsch, Fiescher, Gorner, Corbassière) and are thus probably cut into rock beds. Where debris-providing rock walls are absent or ice-covered, bedrock overdeepenings can also exist underneath small glaciers (cf. Figure 1). Modelled overdeepenings in the morainic beds of heavily debris-covered glaciers like Unteraar or Zmutt are especially uncertain. In short: overdeepenings can form in rock and sediment beds but the large ones seem to preferably form in rock beds.

### Topological situation with respect to glacier flow

Thirty-two overdeepenings in the beds of Swiss glaciers, which are among the largest modelled, were analysed concerning their topological situation with respect to ice flow [cf. a similar analysis for the Himalaya-Karakoram region presented by Linsbauer *et al.* (2016)]. In this Swiss sample, trunk valley situations in sections without confluence/diffluence are most frequent (16=50%), followed by confluence situations (10=31%), cirque situations (5=16%) and undefined (1=3%). No marked diffluence situation presently exists in the Swiss Alps. Terminus (end of tongue-) situations were disregarded, because these situations have in many cases been trunk valley situations until most recently. The proportion of cirque situations would become larger if smaller overdeepenings were to be included.

### Morphological indications

Frey *et al.* (2010) used three morphological criteria indicating overdeepenings from surface features of glaciers:

1. down-glacier increase of surface slope;
2. transition from a crevasse-free to a crevassed area;
3. lateral narrowing.

It is interesting to test the 32 analysed overdeepenings with respect to these morphological criteria as defined by the present-day surface conditions (using Google Earth images). All the analysed overdeepenings had a break (steepening) in slope – even though sometimes rather weak – in the down-glacier direction, which can indicate the existence of a riegel in the glacier bed. A transition from crevasse-free compressing flow to extending flow with crevasses can be observed in 27 cases. Lateral narrowing which points to the possible occurrence of hard bedrock riegels exists in 25 out of the 32 studied cases. All three criteria together are found for 23 cases, six cases fulfil two criteria and three cases satisfy one criterion only. In this sample, the probability for confluence and cirque sites to satisfy three criteria is 80%, while it is only 56% for trunk valley situations. An application of these morphological criteria to old maps (Topographischer Atlas; very close to Little Ice Age maximum glacier extent) in the Swiss Alps documents that lakes had formed with a probability of 75% where all three criteria applied (Rüesch, 2013). The limited quality of the topographic information on the past glacier parts makes further interpretation difficult. Overall, these tests show that the overdeepenings modelled with GlabTop are reasonably well documented by indications of surface morphology and observations of lakes, which had already formed in the recent past. Trunk valley, confluence and cirque situations are most typical.

### Thermal conditions at glacier beds

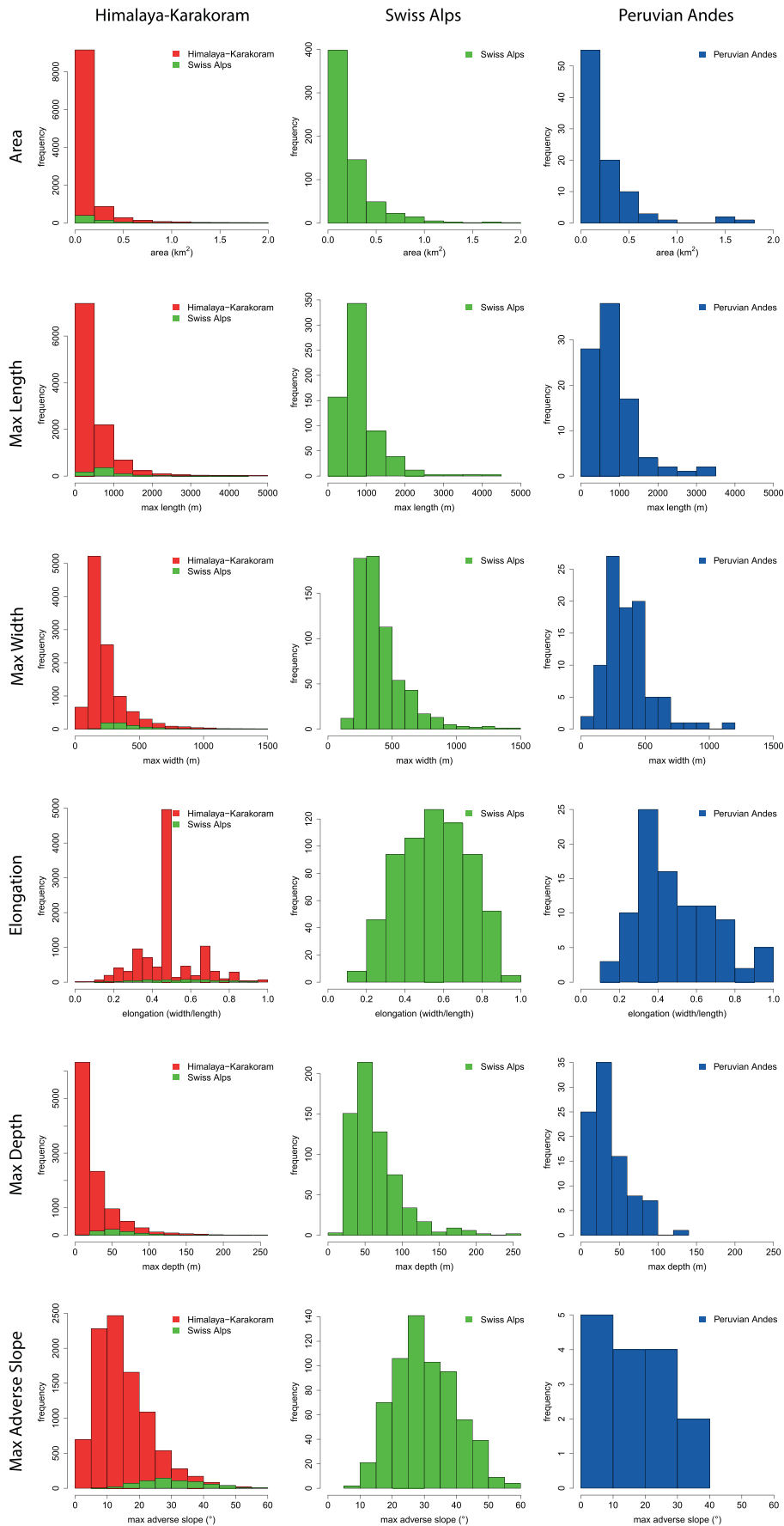
Even though a good number of the investigated mountain glaciers – especially in the dry parts of the Alps and of the Himalaya-Karakoram – may be polythermal with some cold parts at high elevation or even cold ice margins in contact with peri-glacial permafrost (Haeberli and Hoelzle, 1995; Suter *et al.*, 2001), most of the analysed overdeepenings most probably exist or have formed underneath glaciers with a temperate base and an unfrozen glacier bed. The presence and influence of water is plausible in such cases. The existence of overdeepenings in the bed of cold-based glaciers can, however, not be excluded.

### Quantification of overdeepening morphometry

Selected histograms of the automatically extracted parameters concerning the morphology of bed overdeepenings in the Swiss Alps, the Himalaya-Karakoram region and the Peruvian Cordillera Blanca are provided in Figure 6. The statistics are influenced by the fact that only overdeepenings with sizes  $>10^6 \text{ m}^3$  were included. The emphasis is therefore on maximum rather than minimum values. Modelled overdeepenings in the Swiss Alps are mostly less than  $1 \text{ km}^2$  in area, a few kilometres in length and 1 km in width. Elongation appears to have a peak around 0.5 indicating that oval-shaped overdeepenings are most common. Maximum depths of several hundred metres are possible but mean depth rarely exceeds 100 m and volumes commonly remain below a few tens of millions of cubed metres. Mean adverse slopes have a maximum around  $10^\circ$ – $20^\circ$ , which largely exceeds the glacier-surface slope of  $<5^\circ$ – $10^\circ$  considered critical for overdeepening formation (cf. Frey *et al.*, 2010) and hence is in many cases above the critical slope ratio (1.6 times the surface slope) for supercooling and channel closure as commonly mentioned in the literature (Hooke, 1991; Alley *et al.*, 2003; Cook and Swift, 2012; Werder, 2016). Maximum adverse slope is most frequently around  $25^\circ$ – $30^\circ$ , which in some cases could be high enough for sub-glacial lake formation (Clarke, 2005; Cook and Swift, 2012). Mean normal slope at the upper end of the overdeepenings shows similar characteristics, however with a tendency to somewhat less inclined geometries. The largest modelled overdeepenings, for instance the one at Konkordiaplatz with an estimated mean/maximum depth of around 100/300 m, an area of around  $2.5 \text{ km}^2$  and a total volume of some 200 million  $\text{m}^3$ , are found at Aletsch glacier, the largest glacier in the Alps.

Length, area and volume of the overdeepenings in Peru and in the Himalaya-Karakoram are generally comparable to the ones in the Swiss Alps but have more extreme volumes in the Himalaya-Karakoram where the largest modelled form (cf. Figure 3) has an area of  $56 \text{ km}^2$ , a maximum length of 18 km, a maximum width of 3 km, a maximum depth of 400 m and a volume of  $11 \text{ km}^3$ . Maximum and mean depth of the measured Cordillera lakes appear to be a bit smaller than in the Alps, an effect which may be partly due to sediment infilling. The fact that some levels of Peruvian lakes had been artificially lowered (cf. Figures 1, 4 and 7) should also be taken into account. In such cases, morphometric information relates to the remaining water body. Despite the large size of some involved glaciers, maximum and mean depths for the modelled Himalaya-Karakoram overdeepenings are hardly different from the ones in Peru and in the Alps. This somewhat surprising result may be due to the stronger smoothing by the coarser DEM.

Elongation of the lakes in Peru has a peak at 0.3–0.4 rather than 0.5–0.6 as in the modelled overdeepenings. This



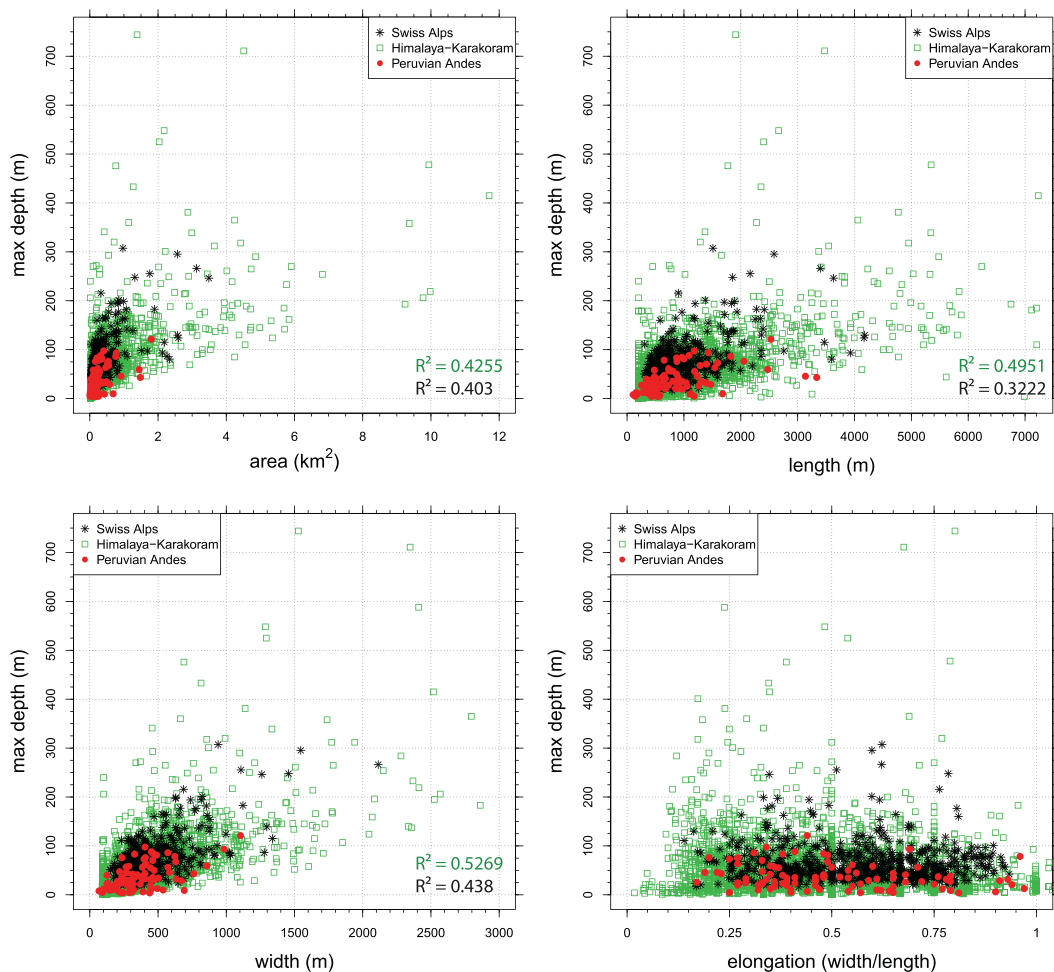
**Figure 6.** Selected histograms of morphological overdeepening parameters for the modelled overdeepenings from the Himalaya-Karakoram and the Swiss Alps and the measured lake bathymetries from the Peruvian Andes. Note that extreme values (mainly for the Himalaya-Karakoram sample) have been cutoff to obtain the same horizontal and thus comparable scale for the three datasets. This figure is available in colour online at [wileyonlinelibrary.com/journal/esp](http://wileyonlinelibrary.com/journal/esp)

difference, if significant, may be due to the mostly simpler geometry of the smaller Cordillera glaciers in comparison with

the larger and more complex Swiss glaciers with many pronounced confluences.



**Figure 7.** Exposed adverse slope of the Laguna 513 bedrock overdeepening in the Cordillera Blanca (cf. Figures 1 and 4). The level of the lake had been artificially lowered by 20 m with the construction of tunnels in the bedrock threshold for hazard prevention (Carey *et al.*, 2012); the original overflow was about 20 m above the person in the foreground. Note the absence of a deeply incised rock channel in the smoothly polished 'riegel'. Photograph: C. Giraldez 2012. This figure is available in colour online at [wileyonlinelibrary.com/journal/esp](http://wileyonlinelibrary.com/journal/esp)



**Figure 8.** Scatter plots of maximum depth as a function of area, length, width and elongation. This figure is available in colour online at [wileyonlinelibrary.com/journal/esp](http://wileyonlinelibrary.com/journal/esp)

Adverse slopes of the few measured lakes in bedrock-overdeepenings of the Cordillera Blanca have a higher percentage of low values but include inclinations well above 20°. The case of the adverse slope of Laguna 513 (Figure 7) made visible as a consequence of artificial lake level lowering is quite unique – such adverse slopes of overdeepenings without deep cuts (gorges) cannot usually be seen, because they are under water or under sediments. Again, a great number of modelled overdeepenings in the Himalaya-Karakoram region have adverse slopes steeper than 10° with a weak tendency for normal slopes to be slightly less steep.

As a general result the modelled and measured overdeepenings show well-comparable morphological characteristics. This points to the fact that the modelling of overdeepenings in the beds of currently existing glaciers is quite realistic despite uncertainties about smoothing in the models/DEMs and about sediment infill in the freshly exposed lakes. Maximum depth of bed overdeepenings below high mountain glaciers seems to be limited to a few hundred metres.

In a next step, statistical regressions were calculated for all retrieved parameters of the Swiss Alps. The highest correlations are from meaningless self-correlations. An example is the regression between volume and area, which relates a mathematical product (volume = area times depth) to one of the factors (area) from which it had been calculated. All plots without self-correlation effects show very large scatter and weak to near-zero correlations (see also Supporting Information S5). The primary conclusion is, therefore, that the variability of morphological parameters is extreme.

Selected plots of especially relevant parameters (maximum depth and maximum adverse slope as a function of length, area, width and elongation) for all investigated overdeepenings are presented in Figures 8 and 9 (for Peru only bedrock lakes are included). These scatter plots show only vague relationships with high scatters.

As a general rule, the larger, longer or wider an overdeepening is the deeper it can be. There is, however, no clear relation. The relation between maximum depth and area appears to be especially weak: overdeepenings with small surface areas can be deep and those with larger surface areas shallow. Somewhat better confined in the sample of modelled overdeepenings in the Swiss Alps and the measured Peruvian bathymetries are upper-bound ratios between maximum depth and length of about 0.2 and between maximum depth and width of about 0.3. The values from modelled overdeepenings in the Himalaya-Karakoram region seem to confirm that such ratios tend to decrease with increasing size but are less reliable because of the coarse DEM resolution. This can be seen as a – still weak – indication of decelerating depth erosion following a rapid initial phase and perhaps even an upper limit of overall erosion depths. Similarly, a still weak indication exists that erosion depth can reach a maximum within an optimal elongation range (width/length ratio) of about 0.25 to 0.75. Normal and adverse slopes seem to be rather independent of each other and maximum values of the latter can be much higher than mean values.

For overdeepenings with a mean depth less than 50 m the range of the observed maximum adverse slope ranges from 10° to 60° but narrows down to 25° to 55° with larger mean

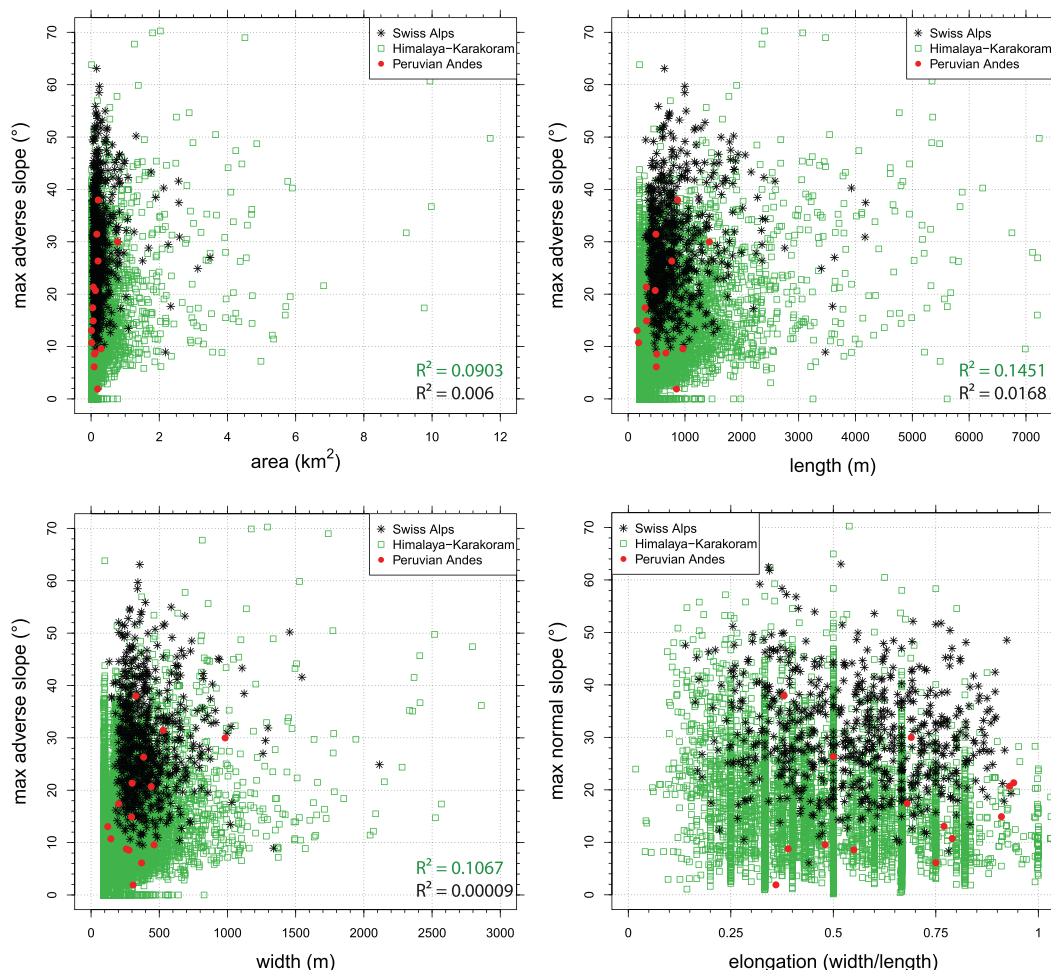


Figure 9. Scatter plots of maximum adverse slope as a function of area, length, width and elongation. This figure is available in colour online at [wileyonlinelibrary.com/journal/espl](http://wileyonlinelibrary.com/journal/espl)

depths for the Swiss and Peruvian samples. Furthermore, the range for deeper overdeepenings is far above the critical slope (1.6 times the glacier surface slope or about 10°–20° in the case of mountain glaciers) so far often assumed for supercooling and channel closure along the adverse slopes of overdeepenings (Alley *et al.*, 2003; Cook and Swift, 2012; but see also Werder, 2016).

## Discussion

The need for quantitative information about the morphology of glacial overdeepenings is growing. Special interest relates to the challenge of estimating maximum possible glacial erosion depths during future glacial periods for the case of long-term disposal of radioactive waste. Similarly, overdeepening morphometry is important for anticipating hazards from lake outbursts but also options for use (hydropower, water supply, tourism) in the case of newly forming lakes in presently still glacier-covered areas. Despite the encouraging new possibilities from numerical model calculations of glacier-bed topographies and from bathymetric measurements in newly exposed lakes, such quantitative information is still limited and associated with considerable uncertainties. Important improvements are possible. On the model side, a better definition of filtering approaches to account for longitudinal stress coupling would help. On the side of field evidence, the rapid formation with continued glacier retreat of numerous new lakes offers an opportunity to collect many more lake bathymetries of overdeepenings before lake sedimentation increasingly hides the original geometry.

The main result of the analysis presented here is nevertheless clear: the variability of overdeepening geometries is extreme and useful empirical statistical relations are hardly recognizable. This confirms what has long been known from statistics about glacial lake area and depth (Huggel *et al.*, 2002; Cook and Quincey, 2015): lake/overdeepening area is not a good general predictor of lake/overdeepening depth. The very large scatter in the relations between the extracted parameters indicates little hope for significant improvement with the use of sophisticated statistical analysis such as, for instance, multiple regressions. A more promising way out of the dilemma may be to consider geomorphological context and processes of lake formation possibly affecting lake geometries (Cook and Quincey, 2015). These processes, however, should be better understood. Especially the role of sub-glacial water in connection with erosion and evacuation of sediments on adverse slopes could be critical (Creys and Clarke, 2010; Werder, 2016). The steep adverse slopes documented in this study should receive special attention as they clearly exceed the 'classical' value of 1.6 for the ratio of adverse slope to surface slope (Alley *et al.*, 2003; cf. critical discussion by Creys and Clarke, 2010; Werder, 2016). The rather unique case of Laguna 513 in the Cordillera Blanca with a very steep adverse bedrock slope recently exposed by artificial lake-level lowering illustrates in a striking way that this result is not simply an artefact from model calculations. A recent analysis by Werder (2016) indicates that the 'classical' value of 1.6 for the ratio of adverse slope to surface slope represents the limit where supercooling is possible but not inevitable. Correcting for water pressure below overburden at the downstream end of the overdeepening provides a higher critical limit at which supercooling *must* occur. Even though an exact test is hardly possible, the values for the adverse slopes documented in the present study seem to be in much better agreement with such concepts.

A crucial and unsolved question relates to the time of formation of the overdeepenings and the related glacier conditions.

As good answers to this key question are not in sight for the near future, large uncertainties will likely continue to exist in relation to quantitative assessments of glacial depth erosion and corresponding geometries of glacial lakes.

## Conclusion

A first systematic morphometric analysis of a large number of overdeepenings modelled for the currently glacier-covered parts of the Swiss Alps and of the Himalaya-Karakoram region was carried out and compared to precisely measured bathymetries (water depths) from recently exposed lakes in bedrock overdeepenings of the Cordillera Blanca in Peru. Parameters were extracted manually (bathymetries) or with specifically developed/adapted GIS-based algorithms (modelled bed topographies), which define corresponding morphological characteristics. The results of the study primarily document that the morphometric variability of the investigated overdeepenings is extreme – only weak and hardly significant correlations exist between the investigated parameters. This variability especially also concerns the relation between depth and area, length or width – overdeepenings with small surface areas can be deep and those with larger surface areas can be shallow. Adverse slopes can be markedly steeper than 'classical' theoretical threshold values for supercooling and channel closure but are in better agreement with new concepts recently introduced by Werder (2016). Overdeepenings can exist under very small cirque glaciers with low shear stresses, but also at confluences and in straight trunk valley configurations under larger glaciers with higher shear stresses. A fundamental problem with respect to the interpretation/analysis is the uncertainty about the time of formation of the overdeepened glacier beds and about the corresponding glacier characteristics (geometry, thermal state, flow). Empirical 'rules' for estimating overdeepening geometries remain at best vague.

It becomes clear from such results that the knowledge and process understanding about depth erosion by glaciers and overdeepened topography of their rock beds is still strongly limited and must be greatly improved to enable quantitative predictions.

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