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Compiling an Inventory of Glacier-Bed Overdeepenings and Potential New Lakes in De-Glaciating Areas of the Peruvian Andes: Approach, First Results, and Perspectives for Adaptation to Climate Change

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Abstract: Global warming causes rapid shrinking of mountain glaciers. New lakes can, thus, form in the future where overdeepenings in the beds of still-existing glaciers are becoming exposed. Such new lakes can be amplifiers of natural hazards to downstream populations, but also constitute tourist attractions, offer new potential for hydropower, and may be of interest for water management. Identification of sites where future lakes will possibly form is, therefore, an essential step to initiate early planning of measures for risk reduction and sustainable use as part of adaptation strategies with respect to impacts from climate change. In order to establish a corresponding knowledge base, a systematic inventory of glacier-bed overdeepenings and possible future lakes was compiled for the still glacierized parts of the Peruvian Andes using the 2003–2010 glacier outlines from the national glacier inventory and the SRTM DEM from the year 2000. The resulting inventory contains 201 sites with overdeepened glacier beds >1 ha (10^4 m^2) where notable future lakes could form, representing a total volume of about 260 million m^3. A rough classification was assigned for the most likely formation time of the possible new lakes. Such inventory information sets the stage for analyzing sustainable use and hazard/risk for specific basins or regions.

Keywords: climatic change; future glacier lake; glacier retreat; potential hazard; outburst flood

1. Introduction

With very few exceptions, glaciers, worldwide, are shrinking at a rapid, if not accelerating, rate [1]. As a consequence, high-mountain glacier landscapes are transforming into new landscapes of rocks, debris, sparse vegetation, and numerous lakes (Figure 1). The latter are interesting for tourism, hydropower production, and water supplies [2]. They can, however, also be amplifiers of hazards and risks, especially in connection with impact/flood waves triggered by rock/ice avalanches from glacially de-buttressed slopes and slowly destabilizing icy peaks [3,4]. With digital terrain information having become available at increasingly high-resolution, slope/flux-related approaches for estimating glacier thickness can produce realistic bed topographies for glaciers in entire mountain ranges [5,6] and even globally [7]. Such glacier-bed topographies often contain marked overdeepenings [8–12], i.e., closed topographic depressions with adverse slopes in the direction of flow, where lakes may form when they become exposed as a consequence of glacier retreat [13,14]. Modelling such sites of possible future lake formation provides an essential knowledge base for early planning in view of adaptation to impacts from climate change and sustainable use of the new water bodies [2].

Figure 1. Initial lake formation at Glaciar Artesonraju, Cordillera Blanca. The now already visible large pond may connect to the main lake, which is modeled to develop further up-glacier during the coming years to decades in the marked bed overdeepening underneath the flat glacier tongue (cf. Figure 5). Photography by D. Colonia, February 2016.

In Peru, climate change has caused a dramatic reduction in glacier extent. The national glacier inventories document an overall loss in glacier-covered area of more than 40% between 1970 and 2003–2010 [15]. Numerous new lakes have formed in previously glacier-covered areas, sometimes causing hazardous events with heavy damage and even many fatalities [16,17]. In view of the impacts caused by continued future warming and loss of glaciers [18] the identification of possible new lakes in the Andes of Peru is important for assessing changes in stored water and in hazard conditions. To this end, a systematic inventory of glacier-bed overdeepenings has been produced for all still glacier-covered mountain ranges in Peru, where new lakes may possibly form. A rough classification was applied concerning the most likely time period when these possible new lakes could form. Colonia et al. [19] provide a brief technical note in Spanish and publication of the full inventory with maps and tables is being prepared as an extensive report in Spanish for the political authorities. Work for the inventory had been initiated at the Unidad de Glaciología y Recursos Hídricos (UGRH) of the Autoridad Nacional del Agua (ANA) and was later completed by the Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña (INAIGEM) of the Ministerio del Ambiente (MINAM). The present contribution summarizes and reflects upon the applied procedure. The first results are presented and perspectives for their use are discussed. This work may serve as an example for similar future-oriented applied studies in other comparable mountain ranges. A brief description of the involved regions in Peru is followed by an outline of the applied methods and a presentation of the main results, using selected examples. A short discussion on the main added values, uncertainties, and perspectives for the future then leads to conclusions and recommendations.

2. Region under Study

The investigated zone (Figure 2) contains the largest concentration of tropical glaciers on Earth. It includes the Northern, Central, and Southern Andes between 7°32′1′′–16°48′52′′ south and 68°56′54′′–78°27′25′′ west, hydrologically situated on the slopes of the Pacific Ocean, the Atlantic Ocean and Lake Titicaca. According to the new glacier inventory of the country for the years 2003–2010 [15], 2679 glaciers still exist in 19 Cordilleras, covering a total area of 1298.6 km^2.

Figure 2. Study area with the glacier-covered Cordilleras of Peru in South America, between 7°32′1′′–16°48′52′′ south and 68°56′54′′–78°27′25′′ west, situated in the Northern, Central and Southern Andes, hydrologically located in the Pacific, Atlantic, and Titicaca catchments.

Some 41% of this glacier area is found in the Cordillera Blanca, 22% in the Cordillera Vilcanota, 10% in the Cordillera Vilcabamba, 5% in the Cordillera Ampato, and some 4% each in the Cordilleras Huayhuash and Central, around 3% each in the Cordilleras Apolobamba and Carabaya, around 2% each in the Cordilleras Urubamba, Huaytapallana and Raura, and 1% or less in the Cordilleras Chila, Huanzo, Volcánica, La Raya, Chonta, La Viuda, Huagoruncho, and Huallanca. A total of 87% of all inventoried glaciers are smaller than 1 km^2. Mean equilibrium line altitude (ELA) where accumulation and ablation are in balance is around 4800 to 5000 m a.s.l. [15,20]. Above this altitude steep mountain peaks are in (mostly warm) permafrost conditions—often in combination with small cold hanging glaciers on their flanks [17,21].

During the past decades and in general accordance with the development in the tropical Andes [20], glacier shrinking was rapid and clearly accelerated in comparison with earlier decades of the 20th century. According to data analysis by UGRH [15], the average loss in glacier area between the first national inventory of 1970 and the second national inventory of 2003–2010 amounted to 31% in the Northern Andes, 63% in the Central Andes, and 55% in the Southern Andes. For the Cordillera Vilcanota, Salzmann et al. cf. [22,23] found only marginal changes between 1962 and 1985, but massive ice loss of 30% in area and an estimated 45% in volume between 1985 and 2006. The disproportional loss in volume indicates that flat/thick glacier tongues at relatively low altitude were primarily affected. Such gently-inclined (valley) glaciers with rather flat/thick tongues have dynamic response times on the order of a few decades (see next section for explanation) and are, therefore, far out of equilibrium and, in part, remnants from the 20th century, while the many steep mountain glaciers have shorter response times and remain closer to equilibrium conditions. This phenomenon may also be one of the reasons why rapid ice loss continued into the 21st century despite an intermittently decelerated increase in atmospheric temperature [24].

A total number of 8355 lakes >5000 m^2 have formed as a consequence of glacier retreat since the cold period of the Little Ice Age which terminated towards of the late 19th century [25,26]. The number of new lakes is especially high in the Cordilleras Carabaya (Cusco and Puno departments; 1314 lakes), Central (Lima-Junín; 1006), Blanca (Ancash; 830), La Viuda (Lima-Junín-Pasco; 816), and Chonta (Huancavelica-Ayacucho; 804). Catastrophic outburst floods occurred repeatedly [16,17], necessitating extensive work for hazard protection [26,27]. Concern about possible disasters originating from lakes at the foot of steep icy slopes continues.

3. Materials and Methods

The existence, position and approximate size of glacier-bed overdeepenings in still glacier-covered areas and, hence, the possible formation of future lakes can to some degree be predicted on the basis of morphological criteria concerning glacier surface characteristics and geometry [13] and numerical models [5,14]. In the present study, the Digital Elevation Model (DEM) produced by the Shuttle Radar Topography Mission (SRTM) in 2000 with a spatial resolution of 3 arcseconds (90 m) was used in combination with glacier outlines and digital data (especially elevations) from the second national glacier inventory of Peru in 2003–2010 [15]. Estimations concerning features >10^4 m^2 in area, i.e., exceeding limits of SRTM resolution, were made in three steps using geographic information systems (GIS; cf. [13]):

(1) All glacier areas with surface slopes <10° were mapped from the DEM as a pre-selection of sites with potential bed overdeepenings;
(2) Three morphological criteria concerning glacier surfaces (increasing slope in flow direction, onset of crevasse formation at the down-flow end of crevasse-free areas and lateral narrowing in the flow direction; Figure 3) were used in a visual interpretation based on high-resolution imagery as available in Google Earth; and
(3) The results of the first two steps were compared with results from the GlabTop model for estimating ice thickness distribution [5,28] (Figure 4).

Step 1 was the basis for focusing the visual analysis of morphological indicators. This, in turn, allowed for the attribution of probability or confidence levels concerning the existence of the inventoried glacier-bed overdeepenings by using the number of fulfilled morphological criteria (MC) for each site (step 2):

Number of MC fulfilled	Attributed probability/confidence level
1	low
2	medium
3	high

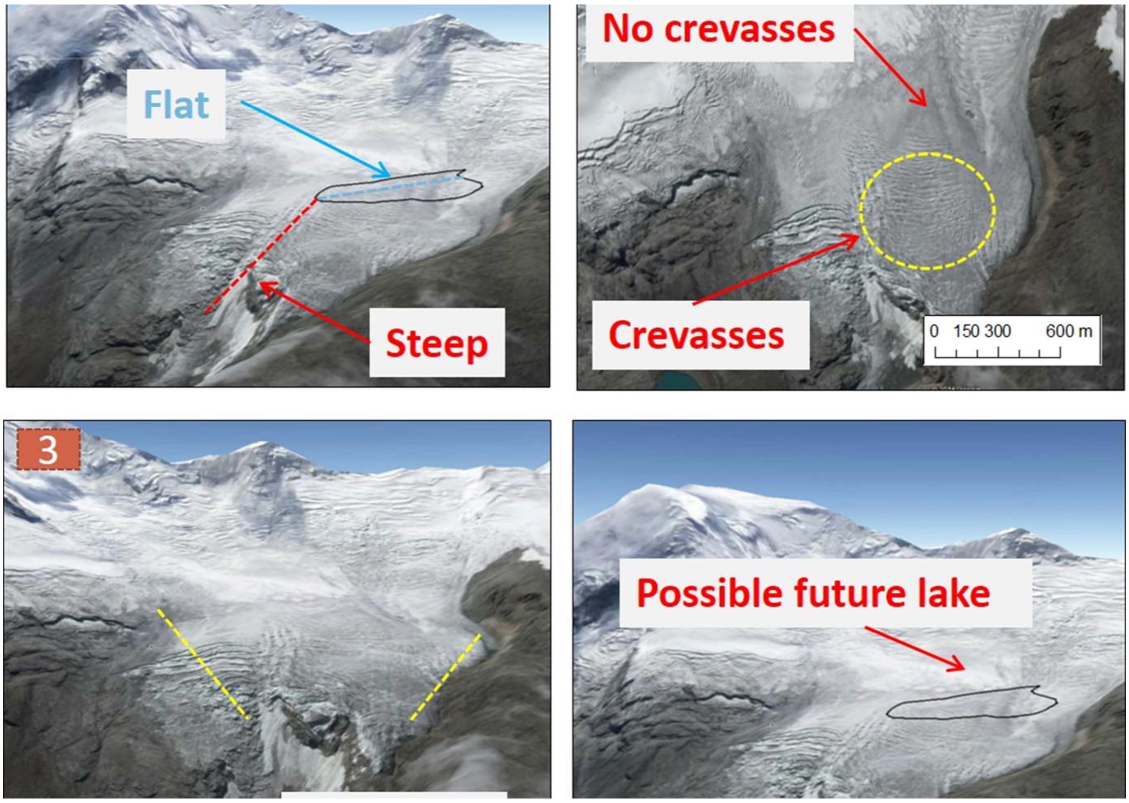
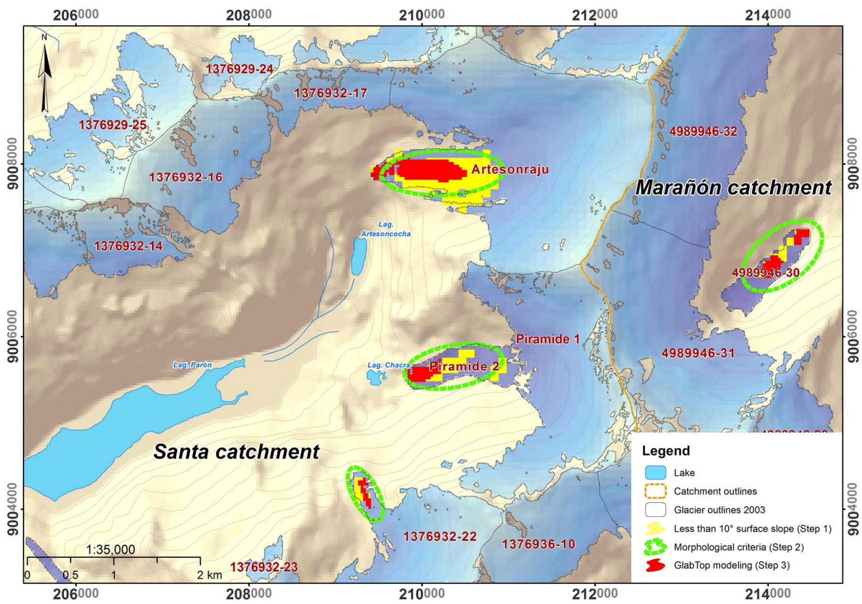


Figure 3. Morphological criteria (numbers 1, 2, 3) that indicate the existence of glacier-bed overdeepenings: Glaciar Rajupaquinan, Cordillera Blanca. Images from Google Earth.



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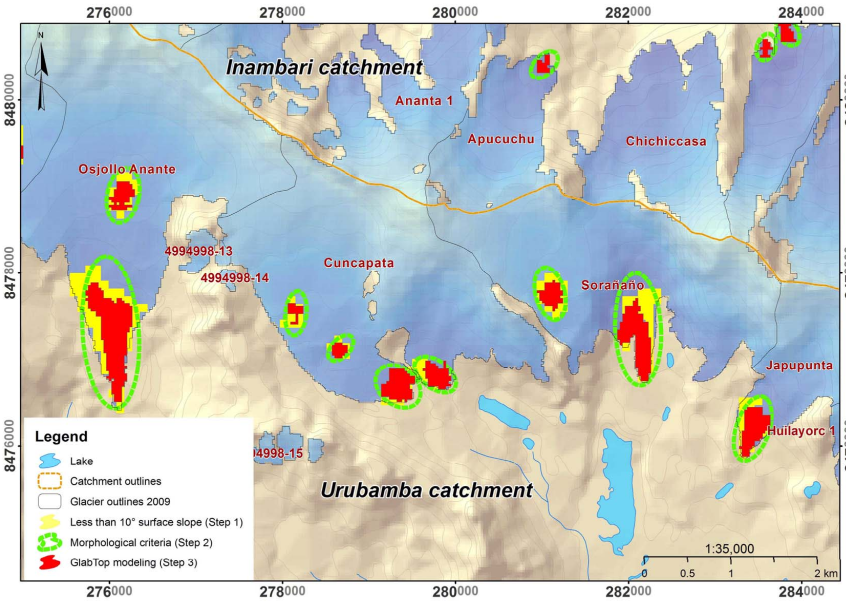
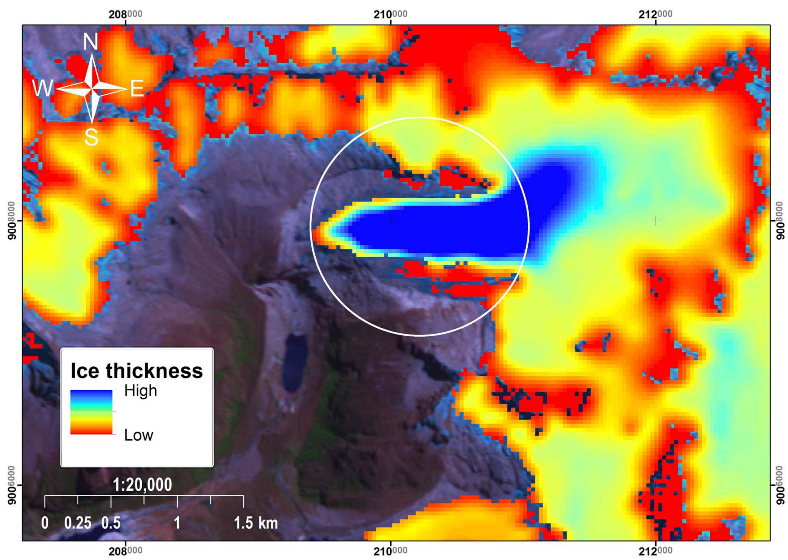


Figure 4. Comparison of results from step 1 (surface slope < 10°) and step 2 (three morphological criteria) with step 3 (GlabTop modeling of bed topographies) for a region in the Cordillera Blanca (**top**) and one in the Cordillera Vilcanota (**bottom**). Glacier outlines are from [15] and coordinates from UTM zones 18s (Blanca) and 19s (Vilcanota).

Maps and longitudinal profiles (Figures 5 and 6) were compiled in step 3 using the results from the GlabTop model. This model applies a constant shear stress approximation following [29] and calculates ice depth from surface slope taking into account effects of elevation range on mass turn-over and interpolating between constructed branch lines for individual glaciers. Within the general uncertainty range of distributed ice-thickness estimates, the predictive quality of the approach is equal to more complex methods [30]. Major advantages of GlabTop are its simplicity, transparency, robustness (no tuning necessary), easily accessible input information, and rapid calculation. Details of the GIS-implementation for GlabTop are provided by [31].



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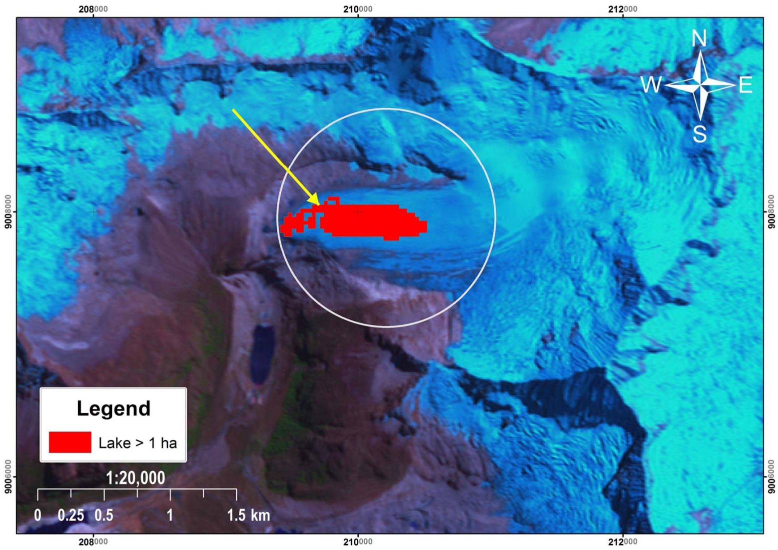
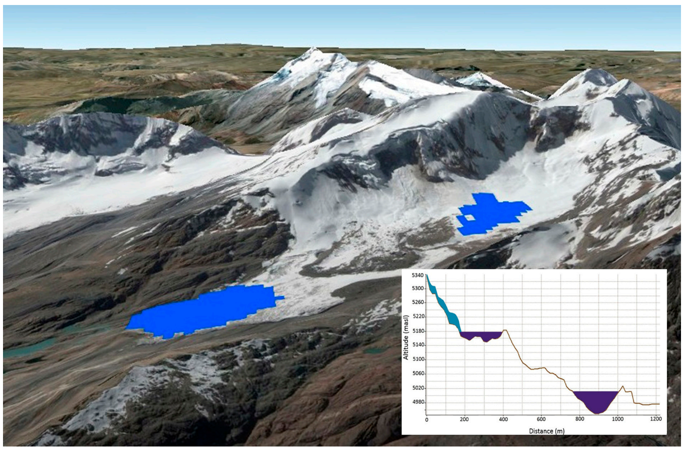


Figure 5. Identification of an overdeepening in the bed of Glaciar Artesonraju (Cordillera Blanca) with possible lake formation: ice-thickness distribution (**top**, maximum calculated ice thickness is 186 m) and glacier-bed overdeepening (**bottom**), both from the GlabTop model. The pond now already visible in nature (Figure 1) at the western glacier margin may be connected (arrow) at the orographic right (northern) side of the flat glacier tongue with a larger lake probably forming at a later stage. Image SPOT 5 of 2003.

This three-step procedure was chosen to enable the combination of independent information from visual inspection and numerical modelling. A further goal of the visual inspection was for the authors to become familiar with the involved glaciers and individual sites of possible future lake formation. In the case of Glaciar Artesonraju, comparison with radio-echo soundings [32] was possible. Maximum depth and volume of the future lake at this flat glacier tongue as calculated using GlapTop are 58 m and 4.45 million m^3. Best estimates from inter- and extrapolated radio-echo soundings (about 10 predominantly parallel longitudinal profiles) provide corresponding values of 80 m and about 10 (4.5 to 17.3) million m^3. This confirms that ice-depth estimates using GlabTop are within about ±30% of real ice thicknesses [5]. It illustrates that the results of the here-applied procedures are robust with respect to the general existence/location of overdeepened bed parts and their approximate shape but may only provide a rough order-of-magnitude estimate on potential lake depths and volumes cf. [9].



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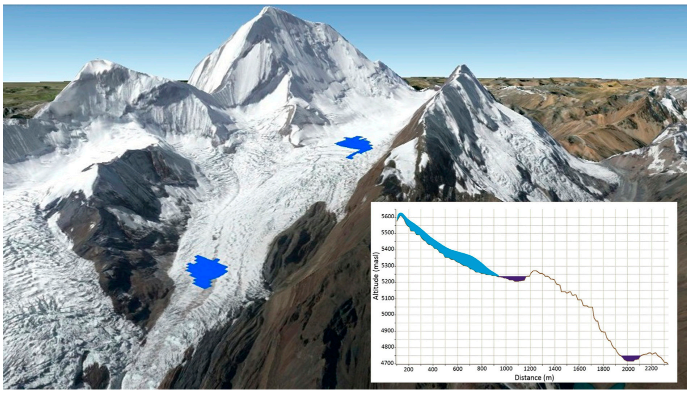

Figure 6. Glaciar Yerupajá 3, Cordillera Huayhuash, in 2007 with two possible future lakes; Google Earth image with longitudinal topographic profile through the two possible lakes (both approximately 400 m in length) in case of continued glacier retreat (**top**). Glaciar Shullcon 3, Cordillera Central, in 2009 with two possible future lakes; Google Earth image and longitudinal topographic profile through the two possible lakes (both approximately 500 m in length) in case of continued glacier retreat (**bottom**).

An important aspect concerning lake safety and potential outburst mechanisms concerns the question of whether potential lakes will become dammed by bedrock or till/moraine would be blocking the potential lakes. Procedures to roughly estimate the occurrence of rocky, sedimentary, or mixed rocky/sedimentary beds underneath existing glaciers compare estimated debris input from surrounding rock walls onto the glacier surface with the potential transport capacity/evacuation of debris in the melt-water stream at the lower glacier margin [33]. As a first approximation to such principles, clean glaciers with small or absent debris input from surrounding rock walls can be assumed to predominantly have rock beds while heavily debris-covered glaciers tend to have-sometimes very thick/elevated–moraine beds [34]. As an example, the future lake at Glaciar Artesonraju (Figure 5) will most likely be bedrock-dammed as is the already existing new pond at the present glacier margin (Figure 1).

With regards to the timing of possible lake formation, in regions with a high density of quantitative glacier information such as the European Alps, spatially distributed model simulations can be used to estimate realistic time sequences of glacier retreat followed by the formation of possible new lakes in glacier-bed overdeepenings, which become exposed through glacier retreat or even vanishing [3,35]. The density of information in the Cordilleras of Peru, however, is low, especially concerning the upper parts of the still existing glaciers. In order to get a rough impression concerning the possible time when the formation of such future lakes could initiate, simple extrapolation schemes had therefore to be used (Figure 7), which could be rapidly applied to the many unmeasured glaciers on the basis of inventory information.

The average annual horizontal and vertical change (along an assumed flow line) of the lowest point H_{min} of each glacier between the first and the second inventory (times vary between regions but, on average, roughly 1970–2005) was calculated from the inventory data. Both, the corresponding rates of horizontal ($\Delta L/\Delta t$) and vertical ($\Delta H/\Delta t$) changes in the position of the lowest point at each glacier were then extrapolated to the future for each individual glacier. Comparison with the calculated position and elevation of the modelled possible new lake levels provided an indicative time for the onset of their formation in case of continued change at constant rates. Values reflecting in a simple way possible future accelerated trends in global warming and glacier retreat were obtained by doubling the average rates of change and by correspondingly dividing the time to the onset of possible lake formation by 2. This acceleration scenario mirrors an increase in area losses during the past decades (about 1% per year) to about 2% per year in the near future. Glaciers in Peru would, thereby, largely be eliminated already before mid-century. Such a potential development cannot be excluded but is considered here to represent an assumed upper-bound and would require a return to, or even an overshooting of, the high warming rates of around 0.3 °C per decade as documented for the late decades of the 20th century (before the intermittent reduction to around 0.1 °C per decade took place after the turn of the millennium [22,24]). As the basic goal of the study is to anticipate future developments under conditions of on-going to accelerating atmospheric temperature rise and glacier melting, deceleration scenarios with longer or even indefinite times to lake formation were not considered. Even though being less probable, such deceleration trends cannot be entirely excluded.

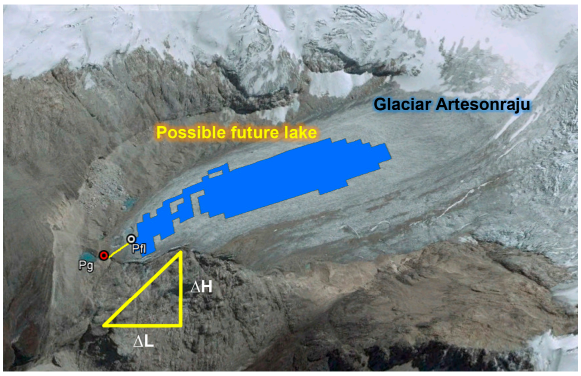

Figure 7. Calculating the time of initial lake formation at Glaciar Artesonraju; P_g: the lowest point of the glacier where H = H_{min} in the glacier inventory, P_{fl}: the point of starting lake formation, ΔL: the length between P_g and P_{fl}, and ΔH: the elevation difference between P_g and P_{fl}. Google Earth image of 2003.

Based on the estimates for constant and accelerated rates of change, a rough distinction was made between three classes (Figure 8):

(1) lake formation already underway or imminent (within the coming about 10 years);
(2) lake formation likely during the first half of the century (within about 10–40 years); and
(3) lake formation probable around mid-century or later (after 40 years or more).

As an example, $\Delta L/\Delta t$ at Glaciar Artesonraju (Figure 7) between 1970 and 2003 was about 9 m per year and $\Delta H/\Delta t$ about 3–4 m per year. Extrapolation of these values to the possible future lake end at a distance of 45–50 m and at a 5 m higher elevation, is leading to a probable onset of lake formation within 1–5 years from 2003. Lake formation would, therefore, have to be classified as "imminent" based on the perspective of the inventory information relating to the year 2003. In reality, lake formation already started around 2005 and lake formation can now be classified as "underway".

As for the glacier responses and long-term commitment, the dynamic response times (t_r) were estimated for all inventoried glaciers following the concept of Johannesson et al. (cf. [29,36] concerning its implementation with glacier inventory data):

$$t_r \approx h_{max}/b_t \qquad (1)$$

with h_{max} being the maximum glacier thickness as obtained from the GlabTop modelling and b_t the annual mass balance at the lower glacier margin. This latter value was estimated for the lowest altitude (H_{min}) in the recent glacier inventory for each individual glacier by assuming an average mass balance gradient in the ablation area of 1.75 m per 100 m and year [18] and from ELA (equilibrium line altitude) values calculated as:

$$\mathrm{ELA} \approx H_{max} - 0.8\,(H_{max} - H_{min}) \qquad (2)$$

The factor 0.8 produces an altitude which is lower than the mid-range elevation, which in most other cases would be a realistic approximation for the ELA [37–39] under equilibrium conditions. This reflects that (a) accumulation area ratio (AAR) values are especially high for tropical glaciers due to extreme ratios of mass balance gradients in accumulation/ablation areas [18] and that (b) the value of H_{max} in the Peruvian glacier inventories relates to the mountain peaks rather than to the uppermost point of pronounced glacier flow.

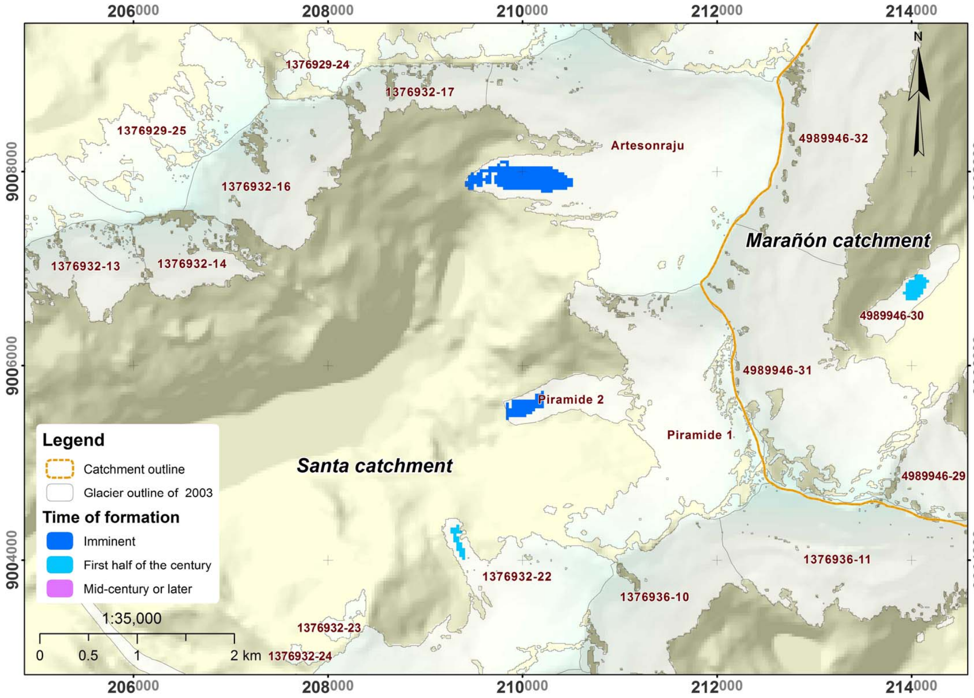

Figure 8. Time classes of possible future lake formation in the catchment of Laguna Parón, Cordillera Blanca, showing two lakes with formation imminent or underway and two lakes with probable formation during the first half of the century. The calculation was done using an acceleration scenario and extrapolated altitude changes. Glacier outlines are from [15].

Based on the frequency distribution of the so-calculated t_r-values, a rough distinction was made between three classes: (1) t_r = 0–10 years, (2) t_r = 10–20 years, and (3) t_r > 20 years. Figures 9 and 10 illustrate examples in the catchment of Laguna Parón.

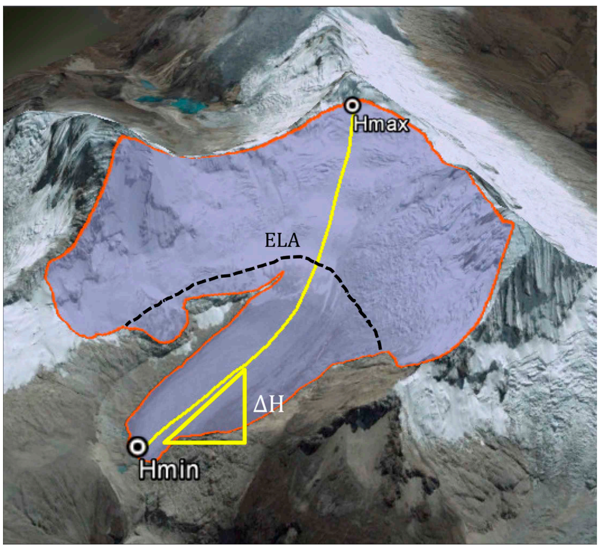

Figure 9. Estimation of glacier response time at Glaciar Artesonraju; H_{max}, H_{min} = maximum, minimum elevation, ΔH = elevation range ($H_{max} - H_{min}$), ELA = estimated equilibrium line altitude.

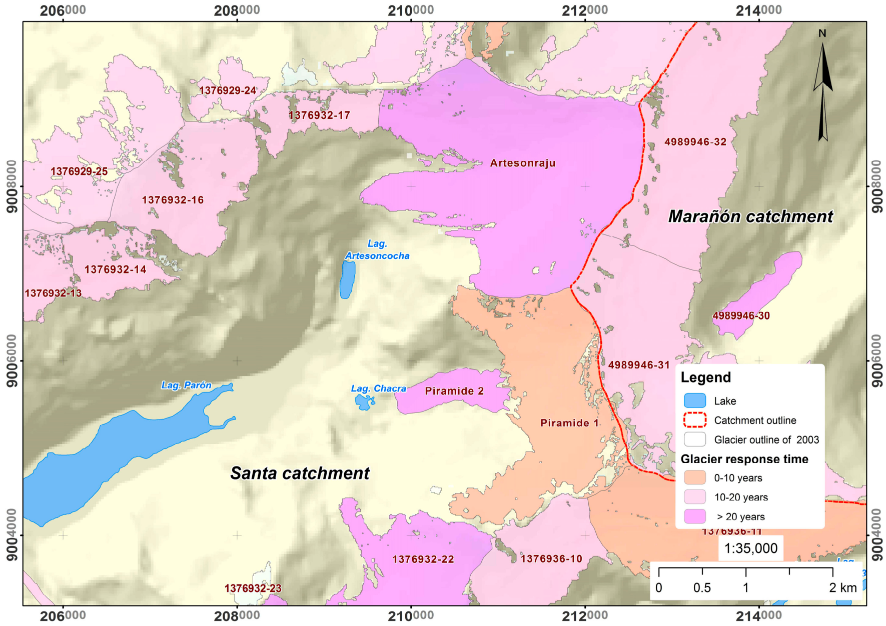

Figure 10. Calculated glacier response times in the catchment of the Laguna Parón. Piramide 2 (like 4989946-30 in the Marañon catchment) is a debris-covered glacier tongue essentially decoupled from the upper glacier parts. Calculated response times in such cases concern disintegrating and downwasting ice. They primarily indicate generally long but still unknown response times rather than specific values. Glacier outlines are from [15].

For the classes (1) and (2), glaciers can be assumed to be rather close to equilibrium conditions, because air temperature in Peru during the first decade of the 21st century did not change much [24]. These classes include the many small and steep glaciers which represent the now predominating glacier type in the Cordilleras of Peru. Future formation of larger lakes can be quite safely excluded in such cases due to steep topography and limited ice area/thickness. Glaciers in class (3) are assumed to be out of equilibrium. For these glaciers with response times >20 years, adjustment to the rapid temperature increase at the end of the 20th century can be assumed to be still incomplete. Further retreat of such mostly flat glacier tongues, as a delayed response to late 20th-century warming, can be considered unavoidable. In the case of Glaciar Artesonraju, h_{max} from the GlabTop model is about 190 m and b_t about 4.5 m water equivalent per year, with $H_{max} \approx 5980$ m a.s.l., $H_{min} \approx 4735$ m a.s.l., $H_{max} - H_{min} \approx 1245$ m and ELA ≈ 4985 m a.s.l. This leads to a response time t_r of about 40 years (cf. [24] who estimated 10–40 years). The still existing flat glacier tongue can be seen as a left-over from the colder past, still reflecting climatic conditions during the last decades of the 20th century. Even without further warming, this glacier part is likely to disappear and, thereby, expose the marked overdeepening at its rock bed. The full development of the modelled lake can, thus, be expected to continue during the coming years.

4. First Results

The information now becoming available about possible future lake formation in the cordilleras of Peru must be critically evaluated with regard to foreseeable process dynamics, added values and uncertainties, and possible applications/perspectives concerning research and planning.

4.1. Future Lakes and Related Process Dynamics

Using the techniques described in Section 3, a total number of 201 glacier-bed overdeepenings exceeding 10^4 m^2 in area were found across the Peruvian cordilleras (Figure 11, Tables 1 and 2) with an estimated total volume of about 260 million m^3 (Figure 12). Preliminary results presented here are limited to regional synopses of this modeled inventory. Publication of detailed data about location and characteristics of individual features is in preparation by the Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña (INAIGEM), Ministerio del Ambiente (MINAM), and the Unidad de Glaciología y Recursos Hídricos (UGRH) of the Autoridad Nacional del Agua (ANA), both in Huaraz, Peru.

Table 1. Distribution of possible future lakes by river basins (cf. Figure 11 for corresponding information about individual Cordilleras).

Andes	Catchment	Number
North	Santa	23
	Marañón	24
	Pativilca	5
	Huallaga	2
Central	Mantaro	12
	Rímac	4
	Mala	1
	Perené	3
	Cañete	3
	Ocoña	8
	Camaná	1
	Alto Apurímac	6
Central and South	Urubamba	67
South	Alto Madre de Dios	1
	Inambari	29
	Azángaro	5
	Suches	7
	Total	**201**

Of the total number of these sites with possible future lake formation, 54 are found in the Northern Andes, 43 in the Central Andes, and 104 in the Southern Andes. Compared to the total glacier volume of about 38 km^3 as calculated for the years 2003–2010 from the same data basis and approach (SRTM, glacier inventory, GlabTop model; cf. also the slightly lower earlier estimates from simpler approaches [40]), the calculated total potential lake volume corresponds to about 0.5–1%.

Table 2. Possible future lakes with volumes >4 × 10^6 m^3.

No.	Future Lake	Volume (×10^6 m^3)	Name	Glacier Code	Catchment	Subbasin	Microbasin
1	LF31-CB	24.3792	Jankapampa 1	4989944-13	Marañón	Yanamayo	Pomabamba
2	LF21-CVN	18.792	Osjollo Ananta	4994899-13	Urubamba	Yavero	Tinquimayo
3	LF22-CVN	13.4055	Osjollo Ananta	4994899-13	Urubamba	Yavero	Tinquimayo
4	LF51-CVN	12.6522	Osjollo Anante	4994998-12	Urubamba	Vilcanota	Salcca
5	LF45-CVN	11.1456		4994978-15	Urubamba	Vilcanota	Pitumarca
6	LF12-CAP	5.5962		4664898-10	Inambari	Huari Huari	Sina
7	LF26-CB	5.3982		4989967-4	Marañón	Puchca	Mosna
8	LF56-CVN	5.3676	Sorañaño	4994999-2	Urubamba	Vilcanota	Salcca
9	LF5-CAM	5.2398	Coropuna	1364499-1	Ocoña	Chichas	Collpa Huayco
10	LF5-CVN	4.7115	Jollepunco	4994897-4	Urubamba	Yavero	Tinquimayo
11	LF4-CAM	4.5981	Coropuna	1364499-1	Ocoña	Chichas	Collpa Huayco
12	LF4-CB	4.4505	Artesonraju	1376932-18	Santa	Llullán	Parón

Notes: CB = Cordillera Blanca, CVN = Cordillera Vilcanota, CAM = Cordillera Ampato, CAP = Cordillera Apolobamba.

This is significantly less than corresponding percentages calculated for the Swiss Alps or the Himalaya-Karakoram region [5,14], a fact which can easily be explained by the limited extent of remaining flat glacier parts in the Peruvian Cordilleras. In fact, many of the flat/clean glacier tongues-in contrast to more slowly downwasting debris-covered ice-have already disappeared in the recent past. A striking example is Qori Kalis glacier at the Quelccaya ice cap [23]. The clearly higher number of possible future lakes in the Cordillera Vilcanota on a flat high-altitude plateau than in the Cordillera Blanca with its deeply cut valleys mirrors this effect.

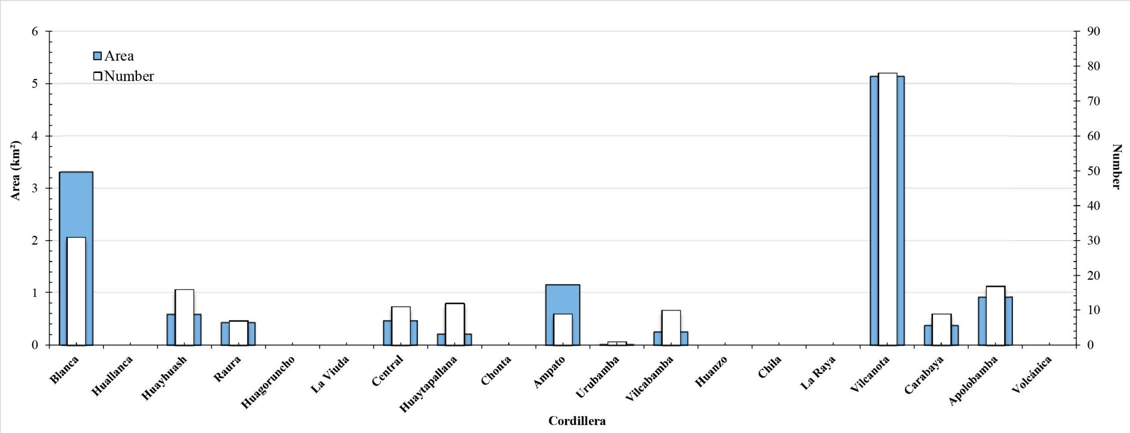

Figure 11. Areas and numbers of possible future lakes in the Cordilleras of Peru. A number of mountain ranges were identified where no further lake formation appears likely because the glaciers there are located on steep slopes and have small areas.

As a consequence of the ongoing reduction in glacier area and increase in average glacier slope, the rate of lake formation can be expected to be on the decline (Table 3).

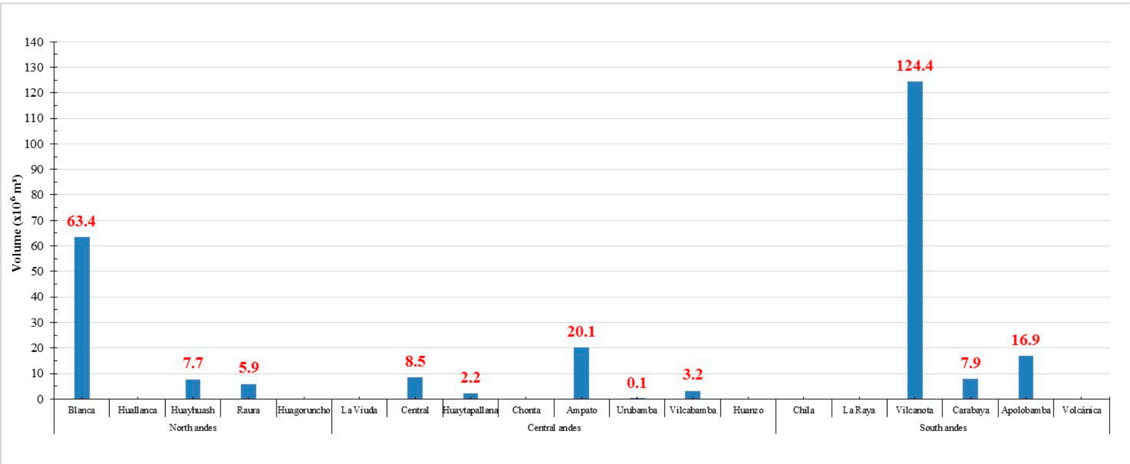

Figure 12. Estimated volumes of possible future lakes from the GlabTop model run for 11 cordilleras.

Table 3. Number of future lakes by earliest possible initial time of formation (acceleration scenario).

Classification	Number
Underway or imminent	133
First half of the century	43
Mid-century or later	25
Total	**201**

Most of the new lakes will form in bedrock depressions and, hence, have stable dams. However, most of them will also form in the immediate neighbourhood of de-buttressed lateral moraine/rock slopes and extremely steep bedrock peaks above 5000 m a.s.l. with warming hanging glaciers and degrading permafrost. This rapidly changing and destabilizing high-mountain environment causes the long-term probability of large rock or ice avalanches into such lakes to increase. Risks from impact and flood waves even for humans and their infrastructure at considerable distances downstream are, therefore, also systematically increasing [3].

4.2. Perspectives and Possible Improvements

The added value of the inventory is the availability of a scientific knowledge base for long-term planning and adaptation to climate change. Such planning is necessary in view of options for sustainable use of water resources but especially also for risk reduction. Integrative-holistic system consideration relating to the emerging new landscapes with their heavily disturbed geo- and ecosystems especially helps with making the best use of possible options and synergies concerning flood protection, hydropower production, water supply and/or landscape protection [2]. The now-available knowledge base about possible future lakes, however, is still far from being perfect and must be understood as a first-order approximation. While the general position and approximate size of glacier-bed overdeepenings is quite robustly estimated, especially from morphological indicators, numerical modelling of detailed morphometries, and depths/volumes have considerable uncertainty (cf. [12]) and can probably best provide reasonable orders of magnitude. Moreover, ill-defined slope calculations for glacier surfaces at glacier margins can in cases produce uncertainties or even artifacts. A further uncertainty relates to the question whether and to what level lakes will indeed form in the anticipated bed overdeepenings. Especially the existence of breaches or deep narrow gorges in the damming part of still ice-covered overdeepnenigs have a strong influence on potential lake levels and volumes, but can so far not be predicted by any model or empirical rule. The likely timing of possible lake formation is another highly uncertain aspect. As an example, extrapolating past horizontal and vertical changes in the position of the lowest point on the glacier can lead to strongly differing results. This reflects the non-linearity of glacier retreat over undulating terrain. Information on the earliest time of lake formation is therefore calculated with numbers but finally semi-quantitatively expressed with words. Uncertainties especially also relate to heavily debris-covered glaciers where lakes may not form due to high permeability in elevated moraine beds or where lakes may become rapidly filled with sediments. Despite such limitations, the possibility of compiling realistic inventories of potential future lakes marks an important progress in the emerging research field of modeling future landscapes and environmental conditions in de-glaciating mountain ranges.

5. Discussion

The first-order approaches presented here provide perspectives for adaptation planning related to increased lake formation, allowing the start of planning concerning options for sustainable use or hazard anticipation and risk reduction (cf. [2]). More sophisticated procedures can be applied in case of locally- or regionally-enhanced interest. Ground-penetrating radio-echo (GPR-) soundings can provide more reliable and exact local data on ice depths, overdeepening geometries, and perhaps even about the presence/absence of deep cuts in the damming part of the landforms. Such information is crucial for achieving better estimates of future lake geometries. In connection with hydropower or water supply projects, focused local investigations can help in the establishment of plans for dam construction and artificial closure of breaches or gorges. A suitable strategy concerning hazard and risk assessments is to apply simple/fast approaches for a first overview of regional hazard zones. In combination with spatial information on human infrastructure, a rough first-order assessment of possible high-risk zones can be made.

The example illustrated in Figure 13 shows the possible path of an outburst flood from one of the anticipated new lakes. The simulation uses the modified single flow (MSF) approach [41] (no volumes, triggering mechanisms, or flow velocities involved) with an empirical value for a minimal overall slope of 11° [42]. The MSF model is a robust, first-order assessment tool that is able to reproduce flood or debris flow dynamics through confined channels, as well as over relatively shallow/convex terrain where spreading flow can otherwise deviate from the line of steepest descent. The simulation of a potential outburst flood above the town of Caraz reveals the necessity to carefully interpret the results of automated procedures. The modelled future lake at a down-wasting debris-covered glacier tongue is rather unlikely to form or to grow to a large water body, and any outburst flood would dissipate along the flat and highly-permeable fore-field or be retained by marked late-glacial moraines further down-valley. A debris flow could only form in the steep part below these moraines, and may come to a halt early or, otherwise, could reach agricultural terrain but not the town of Caraz.

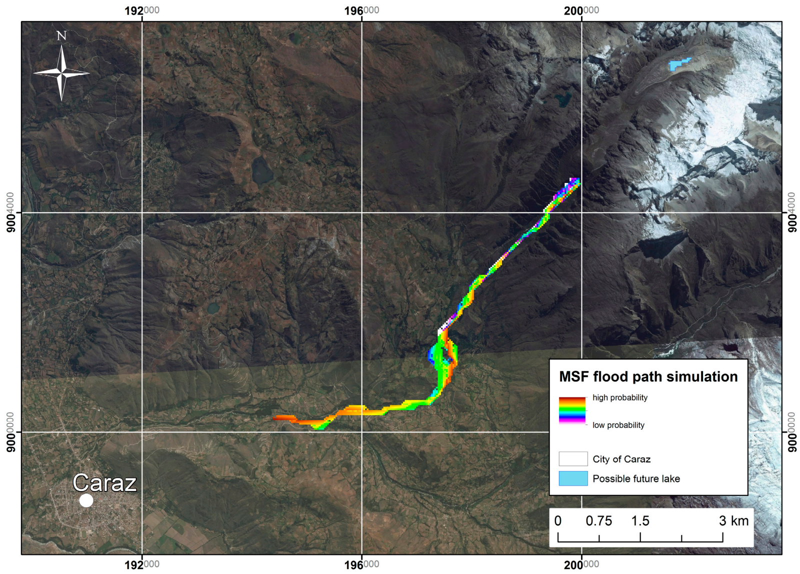

Figure 13. Model run of an outburst flood from a possible future lake (about 380,000 m^3; upper right corner of the image) using the modified single flow (MSF) approach. The color scheme indicates probability levels of pixels to be affected. See text for discussion.

To do a systematic overview analysis with simple assessment of hazard potentials and vulnerabilities/exposures related to the possible new lakes would already be a major undertaking but could provide information about "hot spots" of risk cf. [43,44]. A corresponding priority list could then be derived for further and more detailed investigations such as field measurements and more complex modelling of potentially dangerous processes and process chains. In critical cases, the assessment of hazard potentials and risks can be done with sophisticated model chains [45–48]. Such further steps and improvements necessitate better data, especially higher-resolution DEMs, and continued monitoring, mainly with high-resolution remote sensing, of glacier changes, corresponding acceleration trends, and the detailed formation of new lakes.

6. Conclusions

Techniques and data are now available to compile inventories of glacier-bed overdeepenings and corresponding sites of possible future lake formation in still-glacierized mountain regions. A corresponding inventory was prepared for the Peruvian Andes where about 71% of the existing and rapidly retreating tropical glaciers exist in South America. Work for this inventory shows that:

- The combination of GIS-based terrain analysis, visual inspection of glacier morphologies, and distributed numerical modelling of glacier-bed topographies is optimal for reaching realistic assessments including definition of probability/confidence levels.
- The most robust predictions concern the location and approximate area of glacier-bed overdeepenings; estimated morphometries relating to their exact shape, depth or volume are less certain, providing orders of magnitude rather than clearly defined values.
- Additional uncertainties relate to lake formation and lake geometries in such overdeepened parts of glacier beds becoming exposed by ice retreat. Such uncertainties especially concern the possible

existence of deep/narrow breaches or gorges in the damming material (bedrock or moraine), the permeability of glacier beds or the rapid infilling of sediments.

- The volume of 260 million m^3 in 201 modelled bed overdeepenings represents only 0.5 to 1% of the presently still existing glacier volume; this small ratio results from the fact that most flat glacier parts have already disappeared in the investigated mountains leaving mostly small and steeply inclined glaciers.
- With further glacier shrinking and even vanishing, the rate of lake formation can be expected to be on the decline; most of the anticipated future lakes are likely to come into existence within the next few decades.

This inventory of possible future lakes for the Peruvian Andes constitutes an important knowledge base for planning and climate change adaptation. It enables early anticipation of risks and options, including consideration of related potential for synergies but also conflicts. It should thereby be taken into account that these risks (especially from impact/flood waves) and options (especially in view of irrigation, hydropower, or landscape protection) concern an emerging high-mountain landscape with geo- and ecosystems in strong and long-term disequilibrium.

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References

1. Zemp, M.; Frey, H.; Gärtner-Roer, I.; Nussbaumer, S.U.; Hoelzle, M.; Paul, F.; Haeberli, W.; Denzinger, F.; Ahlstrøm, A.P.; Anderson, B.; et al. Historically unprecedented global glacier changes in the early 21st century. *J. Glaciol.* **2015**, *61*, 1–17. [CrossRef]
2. Haeberli, W.; Bütler, M.; Huggel, C.; Lehmann, T.; Schaub, Y.; Schleiss, A. New lakes in deglaciating high-mountain regions—Opportunities and risks. *Clim. Chang.* **2016**, *139*, 201–214. [CrossRef]
3. Haeberli, W.; Schaub, Y.; Huggel, C. Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology* **2016**. [CrossRef]
4. Salzmann, N.; Kääb, A.; Huggel, C.; Allgöwer, B.; Haeberli, W. Assessment of the hazard potential of ice avalanches using remote sensing and GIS-modelling. *Nor. Geogr. Tidsskr.* **2004**, *58*, 74–84. [CrossRef]
5. Linsbauer, A.; Paul, F.; Haeberli, W. Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. *J. Geophys. Res.* **2012**, *117*, F03007. [CrossRef]
6. Clarke, G.; Anslow, F.; Jarosch, A.; Radic, V.; Menounos, B.; Bolch, T.; Berthier, E. Ice volume and subglacial topography for western Canadian glaciers from mass balance fields, thinning rates, and a bed stress model. *J. Clim.* **2013**, *26*, 4282–4303. [CrossRef]
7. Huss, M.; Farinotti, D. Distributed ice thickness and volume of all glaciers around the globe. *J. Geophys. Res.* **2012**, *117*, F04010. [CrossRef]
8. Cook, S.J.; Swift, D.A. Subglacial basins: Their origin and importance in glacial systems and landscapes. *Earth Sci. Rev.* **2012**, *115*, 332–372. [CrossRef]

9. Haeberli, W.; Linsbauer, A.; Cochachin, A.; Salazar, C.; Fischer, U.H. On the morphological characteristics of overdeepenings in high-mountain glacier beds. *Earth Surf. Process. Landf.* **2016**, *41*, 1980–1990. [CrossRef]
10. Morlighem, M.; Rignot, E.; Mouginot, J.; Wu, X.; Seroussi, H.; Larour, E.; Paden, J. High-resolution bed topography mapping of Russell Glacier, Greenland, inferred from Operation IceBridge data. *J. Glaciol.* **2013**, *59*, 1015–1023. [CrossRef]
11. Patton, H.; Swift, D.A.; Clark, C.D.; Livingstone, S.J.; Cook, S.J. Distribution and characteristics of overdeepenings beneath the Greenland and Antarctic ice sheets: Implications for overdeepening origin and evolution. *Quat. Sci. Rev.* **2016**, *148*, 128–145. [CrossRef]
12. Patton, H.; Swift, D.A.; Clark, C.D.; Livingstone, S.J.; Cook, S.J.; Hubbard, A. Automated mapping of glacial overdeepenings beneath contemporary ice sheets: Approaches and potential applications. *Geomorphology* **2015**, *232*, 209–223. [CrossRef]
13. Frey, H.; Haeberli, W.; Linsbauer, A.; Huggel, C.; Paul, F. A multi level strategy for anticipating future glacier lake formation and associated hazard potentials. *Nat. Hazards Earth Syst. Sci.* **2010**, *10*, 339–352. [CrossRef]
14. Linsbauer, A.; Frey, H.; Haeberli, W.; Machguth, H.; Azam, M.F.; Allen, S. Modelling glacier-bed overdeepenings and possible future lakes for the glacier areas in the Himalaya-Karakoram region. *Ann. Glaciol.* **2016**, *57*, 119–130. [CrossRef]
15. UGRH. *Inventario. de Glaciares. del Perú*, 1st ed.; Autoridad Nacional del Agua: Lima, Perú, 2014; p. 56.
16. Carey, M. *Shadow of Melting Glaciers. Climate Change and Andean Society*; Oxford University Press: Oxford, UK, 2010; p. 240.
17. Carey, M.; Huggel, C.; Bury, J.; Portocarrero, C.; Haeberli, W. An integrated socio-environmental framework for glacier hazard management and climate change adaptation: Lessons from Lake 513, Cordillera Blanca, Peru. *Clim. Chang.* **2012**, *112*, 733–767. [CrossRef]
18. Intergovernmental Panel of Climate Change (IPCC). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
19. Colonia, D.; Torres, J.; Haeberli, W.; Schauwecker, S. *Metodología Para la Identificación de Posibles Lagunas Glaciares Futuras en Zonas Tropicales: Andes del Perú. Boletín N° 2*; Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña (INAIGEM), Ministerio del Ambiente (MINAM): Huaraz, Peru, 2016; pp. 37–46.
20. Rabatel, A.; Francou, B.; Soruco, A.; Gomez, J.; Cáceres, B.; Ceballos, J.-L.; Basantes, R.; Vuille, M.; Sicart, J.-E.; Huggel, C.; et al. Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. *Cryosphere* **2013**, *7*, 81–102. [CrossRef]
21. Kaser, G.; Osmaston, H. *Tropical Glaciers*; Cambridge University Press: New York, NY, USA, 2002.
22. Salzmann, N.; Huggel, C.; Rohrer, M.; Silverio, W.; Mark, B.G.; Burns, P.; Portocarrero, C. Glacier changes and climate trends derived from multiple sources in the data scarce Cordillera Vilcanota region, southern Peruvian Andes. *Cryosphere* **2013**, *7*, 103–118. [CrossRef]
23. Hanshaw, M.N.; Bookhagen, B. Glacial areas, lake areas, and snow lines from 1975 to 2012: Status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru. *Cryosphere* **2014**, *8*, 359–376. [CrossRef]
24. Schauwecker, S.; Rohrer, M.; Acuña, D.; Cochachin, A.; Dávila, L.; Frey, H.; Giráldez, C.; Gómez, J.; Huggel, C.; Jacques-Coper, M.; et al. Climate trends and glacier retreat in the Cordillera Blanca, Peru, revisited. *Glob. Planet. Chang.* **2014**, *119*, 85–97. [CrossRef]
25. Cochachin, A.; Haeberli, W. Cambio climático y glaciares-Glaciers and climate change. In *Perú: País de Montaña–los Desafíos Frente al Cambio Climático (Peru: Mountain Country–Facing the Challenges of Climate Change)*; Lima COP20/CMP10; Ministerio del Ambiente (MINAM): Lima, Peru, 2014; pp. 53–55.
26. Emmer, A.; Klimeš, J.; Mergili, M.; Vilímek, V.; Cochachin, A. 882 Lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods. *Catena* **2016**, *147*, 269–279. [CrossRef]
27. Portocarrero, C.A. *The Glacial Lake Handbook: Reducing Risk from Dangerous Glacial Lakes in the Cordillera Blanca, Peru*; Technical Report; United States Agency for International Development; Global Climate Change Office; Climate Change Resilient Development Project: Washington, DC, USA, 2014.
28. Linsbauer, A.; Paul, F.; Hoelzle, M.; Frey, H.; Haeberli, W. The Swiss Alps without glaciers—A GIS-based modelling approach for reconstruction of glacier beds. In Proceedings of the Geomorphometry 2009, Zurich, Switzerland, 31 August–2 September 2009; pp. 243–247.

29. Haeberli, W.; Hoelzle, M. Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: A pilot study with the European Alps. *Ann. Glaciol.* **1995**, *21*, 206–212. [CrossRef]
30. Farinotti, D.; Brinkerhoff, D.J.; Clarke, G.K.C.; Fürst, J.J.; Frey, H.; Gantayat, P.; Gillet-Chaulet, F.; Girard, C.; Huss, M.; Leclercq, P.W.; et al. How accurate are estimates of glacier ice thickness? Results from ITMIX, the Ice Thickness Models Intercomparison eXperiment. *Cryosphere Discuss.* **2017**, *11*, 949–970. [CrossRef]
31. Paul, F.; Linsbauer, A. Modeling of glacier bed topography from glacier outlines, central branch lines, and a DEM. *Int. J. Geogr. Inf. Sci.* **2012**, *26*, 1173–1190. [CrossRef]
32. Chisolm, R.E. Climate Change Impacts and Water Security in the Cordillera Blanca, Peru. Ph.D. Thesis, University of Texas at Austin, Austion, TX, USA, 2016.
33. Zemp, M.; Kääb, A.; Hoelzle, M.; Haeberli, W. GIS-based modelling of the glacial sediment balance. *Z. für Geomorphol.* **2005**, *138*, 113–129.
34. Haeberli, W.; Fisch, W. Electrical resistivity soundings of glacier beds: A test study on Grubengletscher, Wallis, Swiss Alps. *J. Glaciol.* **1984**, *30*, 373–376. [CrossRef]
35. Linsbauer, A.; Frank, P.; Machguth, H.; Haeberli, W. Comparing three different methods to model scenarios of future glacier change in the Swiss Alps. *Ann. Glaciol.* **2013**, *54*, 241–253. [CrossRef]
36. Jóhannesson, T.; Raymond, C.; Waddington, E. Time-scale for adjustment of glaciers to changes in mass balance. *J. Glaciol.* **1989**, *35*, 355–369.
37. Braithwaite, R.J.; Müller, F. On the parameterization of glacier equilibrium line altitude. In *Riederalp Workshop 1978-World Glacier Inventory*; IAHS Publication: Washington, DC, USA, 1980; pp. 263–271.
38. Braithwaite, R.J.; Raper, S.C.B. Estimating equilibrium-line altitude (ELA) from glacier inventory data. *Ann. Glaciol.* **2009**, *50*, 127–132. [CrossRef]
39. Machguth, H.; Haeberli, W.; Paul, F. Mass-balance parameters derived from a synthetic network of mass-balance glaciers. *J. Glaciol.* **2012**, *58*, 965–979. [CrossRef]
40. Torres, J.; Colonia, D.; Haeberli, W.; Giráldez, C.; Frey, H.; Huggel, C. Thicknesses and volumes of glaciers in the Andes of Peru estimated with satellite data and digital terrain information. *Geophys. Res. Abstr.* **2014**, *16*, EGU2014-13759.
41. Huggel, C.; Kääb, A.; Haeberli, W.; Krummenacher, B. Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: Evaluation and application in the Swiss Alps. *Nat. Hazards Earth Syst. Sci.* **2003**, *3*, 647–662. [CrossRef]
42. Huggel, C.; Haeberli, W.; Kääb, A.; Bieri, D.; Richardson, S. An assessment procedure for glacial hazards in the Swiss Alps. *Can. Geotech. J.* **2004**, *41*, 1068–1083. [CrossRef]
43. Allen, S.K.; Linsbauer, A.; Randhawa, S.S.; Huggel, C.; Rana, P.; Kumari, A. Glacial lake outburst flood risk in Himachal Pradesh, India: An integrative and anticipatory approach considering current and future threats. *Nat. Hazards* **2016**, *84*, 1741–1763. [CrossRef]
44. Maanya, U.S.; Kulkarni, A.V.; Tiwari, A.; Bhar, E.D.; Srinivasan, J. Identification of potential glacial lake sites and mapping maximum extent of existing glacier lakes in Drang Drung and Samudra Tapu glaciers, Indian Himalaya. *Curr. Sci.* **2016**, *111*, 553–560. [CrossRef]
45. Schneider, D.; Huggel, C.; Cochachin, A.; Guillén, S.; García, J. Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru. *Adv. Geosci.* **2014**, *35*, 145–155. [CrossRef]
46. Worni, R.; Huggel, C.; Clague, J.J.; Schaub, Y.; Stoffel, M. Coupling glacial lake impact, dam breach, and flood processes: A modeling perspective. *Geomorphology* **2014**, *224*, 161–176. [CrossRef]
47. Schaub, Y.; Huggel, C.; Cochaching, A. Ice-avalanche scenario elaboration and uncertainty propagation in numerical simulation of rock-/ice-avalanche-induced impact waves at Mount Hualcán and Lake 513, Peru. *Landslides* **2016**, *13*, 1445–1459. [CrossRef]
48. Somos-Valenzuela, M.A.; Chisolm, R.E.; Rivas, D.S.; Portocarrero, C.; McKinney, D.C. Modeling glacial lake outburst flood process chain: The case of Lake Palcacocha and Huaraz, Peru. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 2519–2543. [CrossRef]