Inventory and evolution of glacial lakes since the Little Ice Age: Lessons from the case of Switzerland

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Abstract: Retreating glaciers give way to new landscapes with lakes as an important element. In this study, we combined available data on lake outlines with historical orthoimagery and glacier outlines for six time periods since the end of the Little Ice Age (LIA: 1850). We generated a glacial lake inventory for modern times (2016) and traced the evolution of glacial lakes that formed in the deglaciated area since the LIA. In this deglaciated area, a total of 1192 lakes formed over the period of almost 170 years, 987 of them still in existence in 2016. Their total water surface in 2016 was 6.22 ± 0.25 km². The largest lakes are > 0.4 km² (40 ha) in size, while the majority (> 90%) are smaller than 0.01 km². Annual increase rates in area and number peaked in 1946–1973, decreased towards the end of the 20th century, and reached a new high in the latest period 2006–2016. For a period of 43 years (1973–2016), we compared modelled overdeepenings from previous studies to actual lake genesis. For a better prioritization of formation probability, we included glacier-morphological criteria such as glacier width and visible crevassing. About 40% of the modelled overdeepened area actually got covered by lakes. The inclusion of morphological aspects clearly aided in defining a lake formation probability to be linked to each modelled overdeepening. Additional morphological variables, namely dam material and type, surface runoff, and freeboard, were compiled for a subset of larger and ice-contact lakes in 2016, constituting a basis for future hazard assessment.

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Inventory and evolution of glacial lakes since the Little Ice Age: Lessons from the case of Switzerland

Nico Mölg1,2 | Christian Huggel3 | Thilo Herold4 | Florian Storck4 | Simon Allen3 | Wilfried Haeberli3 | Yvonne Schaub3 | Daniel Odermatt1

1Surface Waters – Research and Management, Eawag, Duebendorf, Switzerland
2Enveo, Environmental Earth Observation Information Technology, Innsbruck, Austria
3Department of Geography, University of Zurich, Zurich, Switzerland
4Hydrology Division, Federal Institute of the Environment, Berne, Switzerland

Correspondence
Nico Mölg, Enveo, Environmental Earth Observation Technology GmbH, Fürstenweg 176, 6020, Innsbruck, Austria.
Email: nico.moelg@enveo.at

Abstract
Retreating glaciers give way to new landscapes with lakes as an important element. In this study, we combined available data on lake outlines with historical orthoimagery and glacier outlines for six time periods since the end of the Little Ice Age (LIA; ~1850). We generated a glacial lake inventory for modern times (2016) and traced the evolution of glacial lakes that formed in the deglaciated area since the LIA. In this deglaciated area, a total of 1192 lakes formed over the period of almost 170 years, 987 of them still in existence in 2016. Their total water surface in 2016 was 6.22 ± 0.25 km². The largest lakes are > 0.4 km² (40 ha) in size, while the majority (> 90%) are smaller than 0.01 km². Annual increase rates in area and number peaked in 1946–1973, decreased towards the end of the 20th century, and reached a new high in the latest period 2006–2016. For a period of 43 years (1973–2016), we compared modelled overdeepenings from previous studies to actual lake genesis. For a better prioritization of formation probability, we included glacier-morphological criteria such as glacier width and visible crevassing. About 40% of the modelled overdeepened area actually got covered by lakes. The inclusion of morphological aspects clearly aided in defining a lake formation probability to be linked to each modelled overdeepening. Additional morphological variables, namely dam material and type, surface runoff, and freeboard, were compiled for a subset of larger and ice-contact lakes in 2016, constituting a basis for future hazard assessment.

KEYWORDS
glacier bed overdeepening, glaciers, mountain landscape, new lakes

INTRODUCTION

The current period of atmospheric temperature rise has led to intense glacier retreat in most mountain regions worldwide since the mid-19th century (e.g., Zemp et al., 2015) and the formation of numerous (peri-)glacial lakes [e.g., Aggarwal et al., 2017; Buckel et al., 2018; Emmer et al., 2016; Federal Office for the Environment (FOEN), 2021]. Glacial lakes can form in the overdeepenings of exposed glacier beds, behind natural dams of moraines or landslides, but also behind glacier ice and even rockglacier dams (Carrivick & Tweed, 2013; Buckel et al., 2018; Costa & Schuster, 1988). A growing number of such new glacial lakes formed since the end of the Little Ice Age (LIA) around 1850 as a consequence of climatic change. In times of accelerating anthropogenic climate impacts, they represent an essential element in a newly emerging alpine landscape.

New glacial lakes can have far-reaching effects on environmental systems as well as on infrastructure and populations (Carrivick & Tweed, 2013; Schwanghart et al., 2016; Tufnell, 1984). They are often dammed by unstable or unconsolidated material and can therefore pose a hazard to downstream human activities, infrastructure and lives (Clague & Evans, 2000; Costa & Schuster, 1988; Richardson & Reynolds, 2000; Walder & Costa, 1996). Glacial lake hazards are likely...
to increase in most glaciated regions worldwide due to the growing number of such lakes, the progression of glacier retreat towards steeper terrain, and due to (increasing) destabilization of rock walls, rock glaciers, and glaciers (Deline et al., 2015; Haeberli et al., 2017). Glacial lake outburst floods (GLOFs) can strongly shape their downstream environment through erosion and sediment deposition (e.g., Carling, 2009; Cook et al., 2018; Russell et al., 2006) while existing lakes interrupt the sediment transport to downstream lakes and rivers. In contrast, glacial lakes also provide opportunities and gain importance in terms of economic value for hydropower production or as a tourist attraction site (Haeberli et al., 2016; Farinotti et al., 2016). A complete and consistent inventory of glacial lakes can hence support regional development and decision making in view of environmental, societal and economic concerns.

Many studies on new glacial lakes focus on the Himalaya-Karakoram-Hindu-Kush (e.g., Zhang et al., 2015) and the Andes (e.g., Emmer et al., 2016), whereas in the European Alps only one region (Austria) has been systematically inventoried on a national scale (Buckel et al., 2018; Emmer et al., 2015). Switzerland has a rich history of glacier monitoring activities, including some of the world’s longest time series of glacier length changes, and an extensive mass balance monitoring programme since the 1960s (World Glacier Monitoring Service (WGMS)). In contrast to the retreating glaciers, little research has dealt with the appearing landscape including glacial lakes (Haeberli et al., 2016). Some individual cases linked to GLOFs in Switzerland in modern times were investigated, for example at Lac de Mauvoisin in 1818 (Tufnell, 1984; Woodward, 2014), and the Sirvolte lakes in 1993 or the Weingarten lake in 2001 (Huggel et al., 2002, 2004).

In this study, we reconstruct more than 150 years of glacial lake formation history based on countrywide glacier boundaries from several reference periods since the mid-19th century, and historic orthomosaics acquired by the Swiss Federal Office of Topography (Swisstopo). This systematic inventory of glacial lakes and their evolution are related to causal environmental conditions, and compared to previously modelled glacial overdeepenings for the period 1973–2016 (Linsbauer et al., 2012) in view of further prediction strategies.

Based on the described necessities, the objectives of this study are to (1) generate a comprehensive glacial lake inventory of Switzerland for the year 2016, (2) analyse lake evolution since the LIA and link it to glacier retreat and climatic conditions, and (3) assess the adequacy of modelled glacier bed overdeepenings to anticipate locations with possible future lake formation.

2 | STUDY SCOPE

This study focuses on the perimeter in the Swiss Alps that was deglaciated between ~1850 (end of LIA) and 2016, which encompasses 743 km² along an elevation range from 930 m to almost 4000 m (Figure 1). Between these dates, the glacier area decreased from 1783 km² (~4.3% of the country surface; Maisch et al., 2000; Paul, 2003) to 1040 km² (~2.5% of the country surface; Swisstopo, 2020a). At the end of the LIA, many glaciers reached a peak extent, often leaving behind more or less distinct terminal moraines from which they have almost continuously retreated until today, with the exceptions of intermittent favourable climatic phases that partly caused glacier readvances in the 1910s/1920s and in the 1970s/1980s (Bauder et al., 2007; Huss et al., 2008).

Within the extent of the glacierized area in 1850 we analysed peri-glacial lakes, that is lakes that were located either in the pro-glacial area (maximum distance roughly 3 km to today’s glacier tongue), or at or close to the glacier margin above the terminus. Supra-glacial lakes were disregarded due to their temporary nature and small size. Lakes still in touch with the glacier at a specific date are called ice-contact lakes at the respective time; their formation is potentially incomplete at the date of observation. After separation from the glacier, lakes become either stable in area or shrink due to sedimentary infill or sudden release (GLOF).

3 | DATA AND METHODS

Our analyses are based on lake and glacier boundaries from previous studies and national cartographic records by Swisstopo, which we complemented with lake and glacier boundaries derived from Swisstopo’s national orthophoto mosaics (Swisstopo, 2020b; Table 1). These datasets were combined to generate a time series of lake boundaries from 1900 to 2016 within the deglaciated area, similar to the study by Viani et al. (2017) for north-western Italy. Lake boundaries were either manually mapped or inferred by combining glacier and lake boundaries of present and subsequent points in time, respectively, as explained in Section 3.2. To establish a basis for future hazard assessment, several additional lake variables were retrieved using the orthophoto mosaic from 2014 to 2016 (hereafter referred to as ‘2016’; spatial resolution 0.25 m; Swisstopo, 2020a) and the corresponding national digital elevation model (DEM; SwissAlti3d, spatial resolution and vertical accuracy 2 m; Swisstopo, 2020b).

3.1 | Datasets previously available

Lake boundaries in vector format (minimum lake size 200 m², i.e., 0.0002 km²) are available from Swisstopo based on aerial imagery for the years 2006 and 2016 (Swisstopo, 2020c). We updated about one-third of these lake boundaries to fit the orthophotos from 2014 to 2016 and added a number of missing, smaller lakes to the 2006 dataset.

Glacier boundaries for the end of the LIA (~1850) were generated by Paul (2003) and Maisch et al. (2000) and are available in vector format at the Global Land Ice Measurement from Space (GLIMS) data browser (GLIMS, 2020; Raup et al., 2007). Freudiger et al. (2018) extracted and provided glacier boundaries from the georeferenced Siegfried maps, dating from roughly around 1900 (with up to several years earlier or later; for details, see Freudiger et al., 2018). Additionally, we used the vectorized (Maisch et al., 2000) glacier boundaries for the 1973 Swiss Glacier Inventory (Müller et al., 1976), also available from GLIMS.

To interpret the results with regard to climatic trends, we used homogenized temperature time series of five alpine weather stations in Switzerland with long-term measurements, namely Col du Grand Saint-Bernard (2472 m), Châteaux-d’Oex (1028 m), Engelberg (1036 m), Säntis (2501 m), and Segl-Maria (1804 m), provided by Meteoswiss (2020).
Datasets produced in this study

We manually mapped complementary lake and glacier boundaries using Swisstopo’s monochromatic orthophoto mosaics for 1946 and 1979–1985 (hereafter termed ‘1980s’; Swisstopo, 2020d; Swisstopo, 2020e). These orthophotos have a spatial resolution of 1 m (1946) and 0.5 m (1980s) and were generated using the same DEM and set of ground control points. Thus, their geolocation is in high agreement and geolocation errors on flat and small surfaces (such as lakes) are minimal. The mapping was restricted to locations of subsequent lake formation.

We inferred lake extents for dates or regions where direct lake mapping was not possible (1900, 1973, snow-covered lakes in 1946 and 1980s), by using available or mapped glacier boundaries and the lake boundary of the next available date (Figure 2). This means that lake boundaries for a specific date \( t_1 \) were either (1) taken from existing datasets, (2) mapped directly from orthophotos, or (3) inferred from the subsequent date \( t_2 \) based on whether they were located completely or partly inside or outside the glacier polygon of date \( t_1 \) (Figure 2).
3.3 | Lake morphology and hazard assessment variables

We define several morphological variables to describe the glacial lakes, their evolution, and their hazard potential. For each date and individual lake identifier (ID), the respective centre location and size were retrieved directly from the polygons. Additional information that was attached to each lake include the host Canton, the host mountain zone, a flag for ice-contact lakes in 2016, the lake level (lowest polygon elevation as extracted from the DEM), and the maximum formation time (starting at the end of the observation period before the lake appeared and ending in the last observation period with an increase in lake area).

Variables, which are considered relevant for hazard assessment include dam material and type, lake outflow, freeboard, and surrounding steepness. This information was derived from the 2016 orthophotos and for a subset of 225 lakes of relevant size (> 0.5 ha) or smaller ice-contact lakes, which have the potential to grow larger than the threshold size.

Both dam material and type are important for hazard assessment; for example, a debris dam is potentially prone to breaching, whereas a rock dam is stable and can only be overtopped. Dam material is also relevant for the assessment of ecological and hydropower potentials. Dam material was defined visually from the 2016 orthophotos. The dam material categories included ‘debris’, ‘rock’, and ‘ice’, but also all possible mixed combinations since an accurate mapping from orthophotos is not always feasible. Dam type (‘moraine’, ‘embedded’) was assessed for all debris dams and defines, whether a lake is dammed by a moraine or located inside the subglacial till. ‘Embedded’ applied when the topography downstream of the lake was relatively flat (< 15° average for 300 m below the lake; cf. Aggarwal et al., 2017; Buckel et al., 2018; Petrov et al., 2017).

Lake surface outflow (categories yes/no) was also defined visually from the 2016 orthophotos. When a channelized riverbed was clearly visible, a surface outflow was assigned, even if a stream itself was not discernible in the image.

A freeboard of 0 m was assigned to all lakes with an outflow. In case of no outflow, the freeboard was defined as the elevation difference between the lake surface and the lowest point along the crest of the dam, independent of the crest-to-lake distance. This distance can reach high values of up to 200 m but was mostly smaller than 100 m. The freeboard was defined manually using the DEM and the respective hillshade. Freeboard was not defined for artificially dammed (regulated) and ice-dammed (en-/sub-glacial drainage) lakes.

3.4 | Mapping uncertainties

Manually mapped lake extents from multi-spectral remote sensing data are generally subject to relatively low uncertainty (e.g., Petrov et al., 2017). The uncertainty in lake area is linked to the image pixel size, which defines the smallest lake area that can be discerned based on a potential mapping accuracy. The vector data used in this study is based on very high-resolution aerial imagery, expert analyses at Swisstopo and Eawag, and thorough quality control at Swisstopo. The spatial uncertainty in Swisstopo vector data for 2006 and 2016 is estimated to be ±1 m (Swisstopo, personal communication). For the datasets in this study, we performed a multiple digitizing exercise, where 12 lakes were digitized three times with a time difference of at least 2 days (similar to Paul et al., 2013), for the imagery of 2016 and 1946.

The repeated digitization of 2016 orthophotos suggests a maximum overall uncertainty of < 1 m for the lake outlines based on the 2006 and 2016 data, with a maximum area difference of 5% (±2.5%) at a small lake. We therefore adopt the – more conservative – ±1 m uncertainty estimate by Swisstopo for the data of 2006 and 2016. For a small, round lake of 100 m diameter, such uncertainty of ±1 m adds up to approximately ±5% in terms of lake area, and less with increasing lake size. The repeated digitization of 1946 orthophotos indicated a maximum uncertainty of ±4 m. This significant increase in uncertainty is due to the lower spatial resolution (1 m), greyscale quality and suboptimal seasonal observation conditions, involving often snow- and ice-covered lakeshores.

Based on these contrasting outcomes, we estimate ±1.5 m and ±2 m maximum uncertainty for the 1980s and 1973 lake outlines, respectively, which are based on monochromatic, high-resolution images. For the 1900 lake outlines, we estimate ±5 m uncertainty.

3.5 | Anticipation of lake formation

The location of possible future glacial lakes can be estimated by (1) calculations of glacier thickness (Farinotti et al., 2017; Linsbauer et al., 2012) or (2) a combination of slope threshold and (visually defined) glacier-morphological criteria (Frey et al., 2010; Magnin et al., 2020). Both methods (thickness method, visual method, summarized below) indicate glacier bed overdeepenings but do not hint at the likelihood of lake formation inside an overdeepening.

The thickness method: Linsbauer et al. (2012) calculated glacier ice thicknesses for the Swiss Alps based on the Swiss Glacier Inventory from 1973 using the model GlabTop. GlabTop relates ice thickness to glacier surface slope via basal shear stresses by assuming a general relation with mass turn-over (Haeberli & Hoelzle, 1995; James & Carrivick, 2016; Linsbauer et al., 2012). By subtracting distributed ice thickness from a DEM, Linsbauer et al. (2012) estimated the location and volume of potential overdeepenings. However, the calculation of ice thickness is associated with an uncertainty of ~30% (Farinotti et al., 2017), which strongly affects estimates on the potential volume of an overdeepening, whereas its location is more robust (Viani et al., 2020).

The visual method: Starting from a conceptual idea by Frey et al. (2010), recent studies analysed glacial lake formation by combining low surface slopes (< 10°) with visual aspects of glacier morphology, that is a reduction of glacier width, a step in slope, and a visible rock step or surface crevasses below low gradient areas (Colonia et al., 2017; Magnin et al., 2020; Viani et al., 2020). Starting from the GlabTop overdeepenings, Magnin et al. (2020) attributed each overdeepening polygon with a probability category, which resulted from merging the varying intensities of the morphological criteria. They then compared the overdeepenings with and without the inclusion of morphological criteria to lakes that formed within a 10-year period in the Mont Blanc massive. They found that more lakes had formed in areas with higher probability values based on the visual method, but also that lakes had formed in areas where no overdeepenings were predicted by GlabTop.
In this study we used the approach by Magnin et al. (2020) and compared the lakes that formed during a period of ~43 years (1973–2016) over the Swiss Alps to the predicted overdeepenings from GlabTop in order to assess GlabTop’s accuracy and potential to estimate future lake formation. The GlabTop overdeepenings > 0.5 ha were weighted according to the visual glacier-morphological aspects (Table 2), which we extracted from the 1980s orthophotos and the Swisstopo DEM 25 Level 1 that had mainly been generated from the same data (Swisstopo, 2020f). For a detailed discussion of the chosen criteria please refer to Magnin et al. (2020).

For each lake, the values of the different criteria were summed up and classified according to the share that was reached from the potential maximum:

- < 10% = 0.
- 10 to < 30% = 1.
- 30 to < 50% = 2.
- 50 to < 70% = 3.
- 70 to < 90% = 4.
- > 90% = 5.

These categories zero to five can be seen as a representation of lake formation probability (Magnin et al., 2020).

### RESULTS

#### 4.1 Lake inventory 2016

In total, we identified 1192 lakes that formed in the area that has become deglaciated since the LIA (Figure 3). Of these, 987 still existed in 2016. Twenty-four additional, purely artificial, lakes (reservoirs) with an area of around 8.5 km² were disregarded in our further analysis apart from the generation of hazard parameters.
glacial lake; Bortelseewji; Griessee, all in Valais) that formed naturally were artificially dammed and enlarged for hydropower production.

The lakes are well distributed over the whole glaciated area of Switzerland (Figure 3). Most lake area formed in the mountain zones with the most extensive LIA glaciation: most lake area formed in the southwest (1.92 ± 0.08 km$^2$), followed by the central northern Alps (1.33 ± 0.04 km$^2$) and south-eastern Switzerland (1.18 ± 0.05 km$^2$).

In the northwest, almost 1.2% of the deglaciated area was transformed into lake area, while the central Northern Alps showed with 0.5% the lowest value.

The total lake area in 2016, combining natural and artificially enlarged lakes, adds up to 6.22 ± 0.25 km$^2$. More than 90% of all lakes are smaller than 1 ha (Figure 4a–c). The medium elevation of lake formation is roughly 2600 m above sea level (a.s.l.), ranging from 1215 m to 3427 m in 2016 (Figure 4d). In 2016, 169 lakes were larger than 0.005 km$^2$ (0.5 ha), 26 of these were ice-contact lakes. Ice-contact lakes are well distributed over the whole Swiss Alps, with a similar spatial distribution as the total lake area, showing that lakes form even in areas where only small glaciers are left.

4.2 | Additional variables

Hazard related variables in 2016 were assessed for a total of 225 lakes with an area of 5.35 ± 0.13 km$^2$, corresponding to ~86% of the total natural lake area in 2016. The subset included 82 ice-contact lakes covering 0.93 ± 0.03 km. Of these, 56 lakes smaller than the threshold size of 0.5 ha were included because of their potential to further grow.

4.2.1 | Dam material

One hundred and eight lakes are dammed by glacial debris, another 31 lakes by a mix of debris with either rock or ice or both (Figure 5a). Thirty-four of the debris-dammed lakes are located behind a moraine, the rest is located in relatively flat areas (‘embedded’). Forty-eight lakes are dammed by bedrock, 12 by ice. No landslide-dammed lakes were found.

The average elevation varied between different dam materials for the subset of the 2016 lakes (Figure 5b). Lakes behind debris dams were on average located at an elevation of 2611 m, rock dammed lakes at 2610 m and ice-dammed lakes at 2675 m when excluding one lake at the tongue of Grindelwaldgletscher at 1800 m. Most ice-dammed lakes and those from the mixed category that are potentially ice-dammed are located somewhat higher (> 2700 m) since they have to be in touch with the glacier and are typically located higher than the glacier terminus. Rock-dammed lakes were on average the largest lakes (0.037 km$^2$), whereas debris-dammed, ice-dammed, or mixed-dammed lakes were similarly sized (0.019 km$^2$, 0.019 km$^2$, 0.016 km$^2$).
4.2.2 | Outflow and freeboard

One hundred and thirty lakes had a surface outflow, for 95 lakes this was not the case. Ice-dammed lakes typically have a sub- or en-glacial outflow that cannot be determined from orthoimagery and thus no freeboard was estimated. For lakes with a visible outflow, a freeboard height of 0 m was assigned. Almost all rock-dammed lakes belonged to this category. Of the 95 lakes without a surface outflow, 21 had a freeboard of less than 1 m. Thirty-one of the remaining lakes without an outflow were either dammed by ice or an artificial dam, while the remaining 43 had an average freeboard height of 4.16 m, with a maximum height of 70 m (Table 3).

4.3 | Lake changes and climate

The increase in lake area and number with reference to our assessment periods is relatively constant (Figure 6a). However, increase in average annual lake area and number over the last 10 years are several times higher than in previous decades, with a smaller peak in lake formation occurring in the third quarter of the 20th century (Figure 6b).

Average lake size of all lakes increased from 0.0045 km$^2$ in 1900 to 0.0063 km$^2$ in 1973 and stayed roughly stable since then. In contrast, the median lake size was almost stable over the whole time series (roughly 0.001 km$^2$).

The medium elevation at which new lakes formed was around 2600 m a.s.l. and did not show a significant trend over time. Accordingly, the elevation range from 2500 to 3000 m experienced the strongest increase in lake area in all periods (Figure 7). Analogue to the overall small growth in lake area, the period 1973–1982 showed the lowest values in all elevations. The average of the new annual lake area coincided well with the hypsometry of the lost glacier area over the full time period.

The average temperature evolution of five high-mountain weather observation stations (1000–2500 m) in Switzerland with long-term measurements (Meteoswiss, 2020) was compared to the evolution of lake area and glacier mass balance (relative to the long-term average; Figure 8). The increase in temperature in the 1940s is reflected by negative glacier mass balance, which led to the lake formation increase in the period 1946–1973. In contrast, temperature decrease and increased summer precipitation in the decades after the 1960s led to more stable and partly positive glacier mass balance and thus lower lake formation rates. The temperature rise in the 1990s and 2010s again strongly pushed lake area formation. The analysis furthermore revealed that lake formation shows a delay in response to warming and negative glacier mass balance. For the strong warming since the mid-1980s the main signal of lake formation and growth is only visible about 20 years later.

Lakes were assigned to categories describing their changes in size, they were either ‘increasing’, ‘stable’, or ‘decreasing’. The analysis included all lakes that existed in either the start or the end date of a period. Generally, decreasing lakes were growing in number

| TABLE 3 Freeboard statistics for the lake subset from 2016 |
|-----------------------------------------------|
| Surface outflow (fb = 0) | 130 |
| No surface outflow: | 95 |
| Artificially dammed | 15 |
| Ice-dammed | 16 |
| Zero freeboard | 21 |
| Freeboard (visible so): | 43 |
| Average = 4.16 m |
| Median = 1 m |
| Maximum = 70 m |

Fb, freeboard; so, surface outflow.

FIGURE 6 Increase in total (a) and annual (b) lake area and number over time [Color figure can be viewed at wileyonlinelibrary.com]
somewhat over time, whereas in the period 1973–1982 the majority of the lakes were stable (Figure 9).

From the resulting > 300 lakes that were found to shrink (by more than the associated uncertainty) or disappear at some point in time, we could not retrieve a clear signal hinting to the lifetime of a lake. This was true also for smaller subsets when only considering larger lakes (i.e., > 0.001 km$^2$ and > 0.01 km$^2$). One hundred and eighty-seven lakes were found to disappear or shrink below the threshold size of 0.0002 km$^2$ during the study period, but the temporal resolution hampers a clear detection of the major responsible process(es). The time series shows, however, that a time frame of decades rather than centuries is sufficient for many lakes to strongly decrease in size or even disappear. Only one lake (small neighbouring lake of Fälbdachsee in Valais) was found to have re-grown after a period of shrinking, which might be due to a seasonal nature.

4.4 | Comparing mapped lakes to calculated overdeepenings

One hundred and sixty-six lakes larger than 1 ha with a total area of 9.02 km$^2$ were the maximum to be expected according to the calculated overdeepenings by Linsbauer et al. (2012) for the period 1973–2016. Over the same period, we mapped the formation of 216 lakes (> 1 ha: 56) with a total area of 4.18 km$^2$ (> 1 ha: 3.7 km$^2$, corresponding to 40% of the maximum area). Ninety of the mapped lakes overlapped with the expected ones, with a total area of 3.61 km$^2$. The directly overlapping areas were mostly found where large lakes formed (e.g., Lej da Vadret, Triftgletscher, Gauligletscher, Rhonegletscher, Unterer Grindelwaldgletscher, Paluegletscher, Glacier de Moiry, Stockhorngletscher).

About one-third of the overdeepened area without water in 2016 was found around lakes that did form, but generally not up to their maximum extent according to the calculated overdeepening (Figure 10a). In other locations, no lakes formed at all (about two-thirds). However, most of these areas were located on low-sloping surfaces, often with braided rivers and small, seasonal ponds. Conversely, the largest ‘unpredicted’ lake that formed is the partly supraglacial lake on Glacier de la Plaine Morte. This lake is at least partially ice-dammed and potentially not located in an overdeepening. More large, unpredicted lake area was found at Chüeboden gletscher (Figure 10b), where almost no overdeepening was modelled, and at Lej da Vadret, which already existed as a proglacial lake in 1973 (Figure 10c). At 13 (~30%) of the lakes > 1 ha no overdeepening had been modelled, in contrast to another 35 locations, where at least partly overdeepened areas were modelled.

We then performed an additional analysis using the morphological criteria from Table 2 to assess lake formation probability. The evaluation of the overdeepened areas > 0.5 ha from GlabTop using
morphological criteria resulted in 121 classified overdeepenings. At their location or their direct vicinity (< 100 m) a total number of 41 lakes formed between 1973 and 2016. The higher the probability class, the more likely the lake formation (Figure 11), thereby supporting the findings by Magnin et al. (2020). All of the considered morphological aspects were equally important, that is no criterion seemed to be a single major driver leading to lake formation, which once more justifies the application of the visual approach.

5 | DISCUSSION

5.1 | Lake inventory and lake evolution

Together with the glacial lakes dataset of Austria (Buckel et al., 2018), our time series with seven dates spanning almost 170 years represents one of the longest, nationally (almost) complete, glacial lake characterizations published. We argue that, in order to better understand processes governing lake formation, growth and contraction, a long-term time series is of great value.

Over the full time period (end of LIA - 2016), approximately 740 km² became deglaciated. Within this perimeter, Switzerland hosted 987 naturally formed glacial lakes in 2016, with a total area of 6.22 km². The rate of lake formation was highly non-linear, with a strong increase in the mid-20th century and an almost stable period from 1973 to the 1980s. It was again followed by a period of lake increase, with an exceptionally strong increase in the most recent decade from 2006 to 2016, overlapping with a time period (1990–2018) in which glacial lake area has strongly increased globally (Shugar et al., 2020). Interestingly, Shugar et al. (2020) suggest that much of the increase in Switzerland took place prior to 2004, with lake volumes (estimated from areas) remaining constant or even slightly decreasing since then. This is clearly contradicted by the results presented here, and demonstrates the importance of high quality, manually corrected lake inventories for validating automated approaches, and for assessing temporal trends. A similarly sudden increase in lake number and area over the most recent decade was also reported for Austria by Buckel et al. (2018), while the increase in the Cordillera Blanca in the Peruvian Andes was almost linear since the mid-20th century (Emmer et al., 2020). Overall, the average increase in total lake area of around 0.11 km²/yr measured from 1948 to 2017 in the Cordillera Blanca (Emmer et al., 2020) is almost double the rate of around 0.069 km²/yr measured in Switzerland since 1946. The period of strong increase in glacial lake number and area from the 1990s onwards has typically been linked with extensive glacier retreat (Chen et al., 2021; Shugar et al., 2020; Zhang et al., 2019).

In contrast, periods of little glacier change also led to decelerated lake formation or even lake area decrease (Gardelle et al., 2011). In Switzerland, the stable situation in glacier extent in the period 1973–1980s led to a comparatively small increase in lake number (Figure 6), and most of the new lake area emerged at existing lakes. Thus, the area increase per lake was with 595 m²/yr larger by a factor of 1.5 to 5 compared to all other periods. Only 29 new lakes appeared in that decade, which hosted less than 30% of the total area increase, whereas the majority of the new lake area can be assigned to 61 growing lakes that existed before 1973. Previous observations showed that ice-contact lakes negatively affect glacier mass balance (mechanical calving and increased melt at the lake-glacier interface; e.g., Clague & Evans, 2000; King et al., 2018), suggesting that glaciers in contact with pro-glacial lakes preferentially continued to retreat, even during this climatically favourable period with less negative mass balance. From the evolution of glaciers and climate during the 20th century a similar behaviour can be expected throughout the Alps; indeed, the disappearance of lakes due to advancing glaciers was observed in western Italy by Viani et al. (2017). A comparatively small lake area increase was also reported for Austria (Buckel et al., 2018), although the observed period (1969–1998) covered much more than the expected favourable period (roughly late 1960s to mid-1980s). After the period 1973–1980s air temperatures started to increase strongly, and glacier mass balance turned negative (Figure 8). This climatic change signal, however, was not yet visible in lake changes: for the period 1980s–2006, the annual growth in lake area decreased with reference to the previous time period. The climatic and glacier mass balance signal was only clearly taking effect on glacial lakes in the most recent period from 2006 to 2016 when lake area and number strongly increased. Glacial lake formation and growth is primarily related to glacier length and area changes which are a delayed response to temperature and mass balance changes (Johansson et al., 1989). Our findings are thus also in line with the study from the Cordillera Blanca where Emmer et al. (2020) defined a limnological response time, that is the period between the beginning of warming and the formation of a lake.

The elevation of lake formation did not increase over time, unlike expected from the intense glacier retreat at lower elevations, in contrast to lakes in the Aosta region (Viani et al., 2020). However, in the latest period substantially more lake area formed at higher elevations (Figure 7), and the average elevation was only compensated by the comparably large lakes that formed at the downwasting tongue of Untertal Grindelwaldgletscher, at elevations well below 1500 m. Due to almost complete deglaciation, lake formation in this elevation zone is now completed, and the average elevation of newly emerging lakes in the future is expected to rise. Similar to Switzerland, lake formation in Austria has peaked at an elevation of 2600 m (somewhat lower than the 2776 m found for lakes in western Italy; Viani et al., 2020), whereas the lowest lakes are located substantially higher in elevation (~1800 m compared to ~900 m in Switzerland).
During the mapping process, we noticed that several lakes also formed outside of the mapping perimeter, for example dammed by rock glaciers that developed out of terminal moraines, and at the distal side of lateral moraines. On the one hand, this highlights the advantage of an extended investigation perimeter as done in other studies (e.g., Gardelle et al., 2011; Mal et al., 2020). On the other hand, a larger perimeter shows the necessity to apply accurate and robust automatic mapping methods.

In our study area we did not find lakes that formed as a consequence of gravitational processes such as landslides or debris cones (that might be conditioned by glaciation, e.g., availability of debris). Possibly, such situations exist in connection to former glaciation stages (Last Glacial Maximum), but mainly outside of our study area. This was mentioned also in Buckel et al. (2018), who found these types of lakes only in the lowest ranges of their study region (around 1700 m).

During the study period, many lakes strongly decreased in size and even disappeared. Some of these observations can clearly be attributed to reported cases of GLOFs (e.g., Lakes Weingarten and Sirwolte, glacial lake at Grubengletscher; Haeberli et al., 2001; Huggel et al., 2002, 2004). These cases highlight the value of a high-resolution database for intensely used regions such as the Alps, because even small lakes can lead to events with a strong impact.

For Austria, a comparable area became exposed due to glacier retreat over the same time period (613 km² LIA – 2015), where Buckel et al. (2018) found a total lake area of 2.93 km². This means that in Switzerland almost twice as much of the deglaciated area became occupied by lakes (~0.9%) compared to Austria (0.5%). Larger glacier tongues with thicker ice and higher velocities have the potential to produce larger overdeepenings (e.g., Patton et al., 2016), which might lead to the formation of larger lakes. The geological setting defines – among others – the erodibility of the mountain slopes by glaciers (e.g., Harbor, 2013), where higher values lead to faster sediment infill into the lakes. Potentially, the higher share of igneous rocks in the Swiss Alps compared to Austria led to overall less eroded material to fill up the deglaciated overdeepenings. Viani et al. (2017) did not provide the deglaciated area but found a total lake area of 1.39 km² in the active glacier forefields of western Italy, with a considerably smaller glacier coverage in this region (Smiraglia et al., 2015). Overall, existing numbers on lake formation in different Alpine regions rank on a similar level.

In other mountain ranges, for example the Himalaya, central Andes, or Southern Alps of New Zealand, many lakes are larger than the largest Alpine lakes by an order of magnitude (e.g., Aggarwal et al., 2017; Emmer et al., 2016; Robertson et al., 2012). The reasons may be found in the generally larger size of glaciers and glacier valleys and the higher rates of erosion due to larger elevation differences, higher uplift rates, and greater precipitation amounts (Fitzsimons & Veit, 2001; Nikonov, 1989), which has overall led to the formation of large terminal moraines and associated lakes. Also, most of the lakes in the Himalaya and Cordillera Blanca, Peru, are moraine-dammed, whereas in the Alps this is only the case for on average 11–23% (this study, Aggarwal et al., 2017; Buckel et al., 2018; Viani et al., 2017; Viani et al., 2020).

5.2 | Predicting glacial lakes

Due to the considerable uncertainties in ice thickness estimates, our comparison of modelled and observed lakes was restricted to lakes larger than 0.05 km² for the period 1973 to 2016. The comparison suggested that most of the large lakes could be expected with high certainty based on the overdeepening calculations. On the one hand, concerning individual lakes, the overdeepening calculations using GlabTop seem to overestimate potential lake scenarios both in number and area, which was confirmed in previous studies (Magnin et al., 2020; Viani et al., 2020). On the other hand, expected and actual lake location match well in most cases of larger lakes (in line with findings by Magnin et al. (2020) and Viani et al. (2020)), whereas smaller lakes often were either not expected or did not form. The inclusion of morphological criteria would add a formation probability to each modelled overdeepening (as found also by Magnin et al., 2020) that could strongly support prioritizing cases for further investigation (e.g., ground penetrating radar measurements for better estimating the overdeepened area). When starting from the GlabTop calculations, we ignore lake formation probability in other locations. We observed lake formation of mainly small lakes in the forefield of small cirque glaciers, behind moraines of neighbouring glaciers, or above small rock steps in larger flat forefields. Magnin et al. (2020) also observed lake formation outside of GlabTop overdeepenings but noted that these locations had a low formation probability also applying the visual method.

In their comparison of modelled overdeepenings to actual lakes, Magnin et al. (2020) and Viani et al. (2020) found an accordance of ~60% and ~45%, respectively. These numbers are to some extent dependent on the size threshold (1 ha in Magnin et al., 2020; 0.5 ha in Viani et al., 2020) but are in a similar range as found in our study (34%, 0.5 ha).

In our study we did not consider the volume of the overdeepenings. The reasons are the uncertainties associated with ice thickness calculations (Farinotti et al., 2017), making it difficult to estimate lake volume (Magnin et al., 2020; Viani et al., 2020). For a better estimate in the case of large modelled overdeepenings, it is therefore advised to additionally perform in situ measurements, for example using ground penetrating radar (Viani et al., 2020). However, even with this information, the possibility of a narrow drainage channel in the glacier bed and the infill of sediments into the basin during glacier retreat might lead to much smaller water volumes and introduce uncertainties that persist until the formation of a lake.

5.3 | Lake sedimentation

The long time period covered in this study with six intervals revealed that in some periods many lakes decreased in size (Figure 9). As soon as a lake starts to form, sediments are transported into the lake basin and contribute to its volume reduction (Leonard & Reasoner, 1999; Loso et al., 2004). Sediment fluxes are supposed to be highest immediately after deglaciation due to an oversteepened environment and paraglacial slope readjustment (Ballantyne, 2002; Hallet et al., 1996; Leonard & Reasoner, 1999; Loso et al., 2004). In shallow lakes, these processes can relatively quickly lead to a reduction in lake area.

Examples from our study suggest a relatively short lifetime for some of the lakes. For example, the glacial lake at Huetifirn in the Canton of Uri decreased by about 20% in area between 1985 (0.067 ± 0.001 km²) and 2016 (0.053 ± 0.001 km²; Figure 12). In the case of multiple lakes within a glacier forefield, the upper lake(s) act as
a retention basin, substantially reducing the sediment influx for the lower lake. For an improved understanding of sedimentation into alpine lakes it is necessary to investigate lake bathymetry multi-temporally as well as the sedimentation rate itself over longer time periods. Projected changes in rainfall, as well as altered rates of periglacial slope adjustment and permafrost degradation under a warmer climate also imply that rates of sedimentation in the future may differ from what has been observed in the past.

5.4 | Mapping challenges

The mapping was based on end-of-summer images (August, September), during the most favourable snow and ice conditions of the year. Nevertheless, mapping in high alpine areas is challenged by seasonal snow and ice cover. Consequently, it cannot be excluded that (small) frozen lakes have been wrongly classified as glacier or seasonal snow and were missed in the mapping process.

The main uncertainty results from the mapping itself and depends on the resolution of the imagery. Using the uncertainty of ±1 m for the polygons of 1982, 2006, and 2016 gives a total area uncertainty of ~2%. Further uncertainties arise from seasonal water level variations of a lake. Not much is known about such variations in small alpine lakes, but changes of 0.3 m at relatively flat shores can already produce lake area changes in the range of the assumed mapping uncertainty of ±1 m. Since no information on water level changes and on lakeshore slope are available, it is not possible to assess the magnitude of this uncertainty. Older orthophotos from 1946 likely have a less exact geolocation due to lower photograph quality. The related uncertainty is typically higher on steep slopes than in the flat areas of glacier tongues and lakes. Another challenge of the 1946 imagery is the extensive coverage of seasonal snow: 213 (mostly small) of 373 lakes were partly or fully snow-covered (images acquired mostly in July and August). Based on the assumption that a potential basin gets water-filled once it becomes exposed, we copied the lake boundaries from 1973 and adjusted them with the glacier boundaries from 1946, analogue to 1900 and 1973, and assumed a higher mapping uncertainty of ±4 m to account for these difficulties.

Possible variations in growth and contraction of lakes between dates with orthophotos and glacier outlines could not be captured. In these periods, also potential changes at the outflow of existing lakes, such as the increase or lowering of outflow elevation or the change of outflow position, had to be disregarded.

With the advent of several high-resolution satellite sensors over the last few years, some studies continued earlier efforts to investigate the possibility to automatically map glacial lakes based on such satellite imagery (e.g., Zhang et al., 2020; Wangchuk & Bolch, 2020; Qayyum et al., 2020). In this context, the high accuracy of our 2016 outlines makes them a useful reference dataset for any such attempts, which face major challenges such as high elevated lakes with seasonal snow cover, lakes of varying turbidity or cast shadow.

6 | CONCLUSIONS AND PERSPECTIVES

Our study represents one of the most complete inventories of glacial lakes in space and time since the LIA. Generating such a database was only possible due to the availability of high-quality data over longer time periods over entire Switzerland, which is not the standard in many other, especially larger and developing, countries. Whereas most contemporary studies have been limited to the high-resolution satellite era (c. 1990 onwards), the analysis of such a comprehensive dataset allowed us to better understand dynamics and magnitude of lake formation, growth, and decline. Such time series of lake evolution are especially important to disentangle the relation between climate, glacier change, and lake formation. Additionally, this study lays the groundwork for a national assessment of both, potentially hazardous lakes and such that provide economic opportunities. Although there are individual examples of technical interventions at lake sites in Switzerland (Haebeler et al., 2001), a national risk mitigation strategy is still missing (Faulkner, 2001; Haebeler et al., 2016). Using aerial imagery with spatial resolutions between 0.25 and 1 m as basic data enables maximum accuracy and completeness, both critical given that even small discharge peaks can potentially lead to damage and fatalities (Haebeler, 1983; Petrov et al., 2017; Byers et al., 2019). It also represents an outstanding reference dataset for the validation of global scale glacial lake mapping using multispectral satellites such as Landsat-8 or Sentinel-2 (e.g., Pekel et al., 2016; Shugar et al., 2020).

In view of lake and water resource management and hazard prevention, one important question to know in advance is where glacial lakes might appear and the water volume they might contain (e.g., Haebeler et al., 2016). In a second step it would be beneficial to reliably estimate the lifetime of these lakes (e.g., Emmer et al., 2020).

Our study provides a baseline for such investigations as it yields an overview of new glacial lakes as well as insights into their formation timing and parts of their life cycle. Our results showed a dynamic variability of many lakes in the order of decades, since 15–20% were found to disappear during the study period since the end of the LIA. For some lakes, a larger set of images exists that could be exploited for in-depth studies of their areal development and – by combining image analysis, DEM generation, and modelling approaches – to analyse aspects such as sediment transfer into the lake basin. Periodic measurements of lake bathymetry constitute one possibility to quantitatively estimate sediment inputs and potential lake lifetimes.

FIGURE 12 Sedimentation over a period of 31 years for a large glacial lake at Huefifirn [Color figure can be viewed at wileyonlinelibrary.com]
The large number of lakes and their location in an often unstable and steep topographic context shows the need for a deeper analysis of their hazard potential (Magnin et al., 2020). Such an assessment can then constitute a starting point for a comprehensive adaptation strategy, for example by pointing out specific lakes for regular change monitoring. A regular monitoring approach could assist in the early detection of glacial-lake related hazards.

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CONFLICT OF INTEREST

None.

DATA AVAILABILITY STATEMENT

Most of the database has been submitted to Pangaea, where the submission is being processed. Some parts of the database fall under the copyright of the Swiss national institute for topography and were therefore only provided as point shapefiles instead of polygons. All the necessary information to reconstruct the study are provided.

ORCID

Nico Mölg https://orcid.org/0000-0001-6223-2366
Florian Storck https://orcid.org/0000-0002-2706-3808

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