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Glacial lakes in Austria - Distribution and formation since the Little Ice Age

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ABSTRACT

Glacial lakes constitute a substantial part of the legacy of vanishing mountain glaciation and act as water storage, sediment traps and sources of both natural hazards and leisure activities. For these reasons, they receive growing attention by scientists and society. However, while the evolution of glacial lakes has been studied intensively over timescales tied to remote sensing-based approaches, the longer-term perspective has been omitted due a lack of suitable data sources. We mapped and analyzed the spatial distribution of glacial lakes in the Austrian Alps. We trace the development of number and area of glacial lakes in the Austrian Alps since the Little Ice Age (LIA) based on a unique combination of a lake inventory and an extensive record of glacier retreat.

We find that bedrock-dammed lakes are the dominant lake type in the inventory. Bedrock- and moraine-dammed lakes populate the highest landscape domains located in cirques and hanging valleys. We observe lakes embedded in glacial deposits at lower locations on average below 2000 m a.s.l. In general, the distribution of glacial lakes over elevation reflects glacier erosional and depositional dynamics rather than the distribution of total area. The rate of formation of new glacial lakes (number, area) has continuously accelerated over time with present rates showing an eight-fold increase since LIA. At the same time the total glacier area decreased by two-thirds. This development coincides with a long-term trend of rising temperatures and a significant stepping up of this trend within the last 20 years in the Austrian Alps.

1. Introduction

High alpine relief is subject to an ongoing modification through glacially, periglacially and paraglacially conditioned processes, and global warming strongly affects the rates of change (Haeberli et al., 2013b). One prominent indication for global warming and changing geomorphic process rates is the rapid deglaciation of the European Alps (Haeberli and Beniston, 1998; Paul et al., 2007). The area covered by glaciers decreased by > 50% since the end of the Little Ice Age (LIA) (Fischer et al., 2015b; Zemp et al., 2006) and new landscapes developed in the ice-free zone. These developments include the formation of proglacial lakes (Frey et al., 2010; Zhang et al., 2015; Fig. 1). Glacial lakes are commonly associated with glacial meltwater impounded behind a barrier (Ashley, 2002). In a more general sense, glacial lakes are water bodies directly linked to glacier activity, either by glaciers carving depressions into the subglacial bedrock, providing deposits for impoundment or simply delivering meltwater to the lakes (U.S. Department of Agriculture, 2016). Alpine lakes generally develop in overdeepened bedrock resulting from glacial erosion (Cook and Swift, 2012) or behind dams of various materials ranging from moraine and landslide deposits to glacier ice (Carrivick and Tweed, 2013). In recent years new lakes have emerged in many mountain areas and some existing lakes are reported to be growing in both extent and volume (Carrivick and Quincey, 2014; Song et al., 2016; Wang et al., 2014). Increasing public awareness of climate change and related hazards as well as scientific interest in landscape evolution studies have put glacial lakes in the spotlight, as documented by recent review articles and a large number of case studies (Bogen et al., 2015; Carrivick and Tweed, 2013; Carrivick and Tweed, 2016; Clague and O'Connor, 2015; Cook et al., 2016; Emmer et al., 2016; Haeberli et al., 2016a; Maanya et al., 2016).

High alpine lakes significantly influence water, sediment and nutrient flux causing retention, buffering, and storage of matter (Powers et al., 2014; Schiefer and Gilbert, 2008). Glacial lakes interrupt the sediment cascade by trapping coarse sediment and, in part, suspended load. Sediment delivery to lowlands is thus reduced (Bogen et al., 2015; Geilhausen et al., 2013) impacting on downstream river systems. The stored sediment represents an important sedimentary archive enabling

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Fig. 1. Proglacial lake in the Obersulzbach valley, Austrian Alps.
(Image by J.-C. Otto, 2015.)

the reconstruction of past glacial and climatic conditions (Blass et al., 2007; Larsen et al., 2011; Leemann and Niessen, 1994). Proglacial lakes at glacier margins positively feedback on the glacier system resulting in increased ice velocities, changed mass balances and enhanced melting (Song et al., 2017; Tsutaki et al., 2011). Glacial lakes are sources of natural hazards in high mountain areas due to their potential to generate catastrophic floods, termed glacier lake outburst floods (GLOFs) (Carrivick and Tweed, 2016; O'Connor and Costa, 2004; Richardson and Reynolds, 2000). GLOFs are one of the most effective geomorphological processes in mountain environments characterized by huge amounts of deposition, very long transport distances and large boulder sizes in motion. They also impose severe damage to infrastructure and settlements and are a major risk factor in glaciated mountain regions around the globe (Clague and O'Connor, 2015).

To analyze the impact of glacial lakes on mountain environments, detailed data on lake evolution, spatial distribution and lake characteristics are required. We therefore compiled an inventory of glacial lakes for the Austrian Alps, contributing to the global picture of glacial lake distribution. Lakes were mapped manually using freely-available high-resolution image data. We further trace the development of number and area of glacial lakes in the Austrian Alps since the LIA based on a unique combination of a lake inventory and an extensive record of glacier retreat. The objectives of our study are: (1) to create an inventory of high alpine lakes in the Eastern Alps in Austria; (2) to investigate lake characteristics and distribution; (3) to assess the timing of lake formation since LIA in relation to glacier melt; and (4) to discuss conditions and influences on lake formation.

The combination of our lake inventory data and the record of glacial retreat enable reconstructing lake formation since the LIA and discussing impacts of glacial erosion and temperature change on high alpine landscape evolution. We observed a strong increase in both number of new lakes and lake area with decreasing glacier area. The increase corresponds to positive trends in mean annual air temperatures in high altitudes within the observation period. This study is part of the research project "FutureLakes" (funded by the Austrian Academy of Sciences, ÖAW) that investigates the formation of potential future lakes in Austria. The lake inventory will be used for validation of glacial lake modelling performed on past glacier extents. The inventory can also serve as a basis for assessment and monitoring of lake extents (e.g. GLOF risk assessment) and lake sedimentation and hence contributes to the estimation of sedimentation rates and lake lifetime.

2. Brief review of glacial lake formation studies

A regional assessment of lake changes or lake-related risks often relies on inventories of glacial lakes (Table 1). Most glacial lake inventories contain data on lake location, lake size, dam type and lake volume as well as other parameters depending on the focus of the compilation. They are produced by automated or manual mapping using low to medium resolution remote sensing imagery (commonly Landsat imagery with resolution ± 30 m); (Emmer et al., 2016; Nie et al., 2013; Wang et al., 2013; Worni et al., 2014; Zhang et al., 2015). Most inventories use image data from two or more time steps and not only contain a list of existing lakes but also assess lake changes. An increase in lake area and volume is reported from many parts of the globe, for example Alaska (Pelto et al., 2013), Western Greenland (Carrivick and Quincey, 2014), central Asia (Mergili et al., 2013), the Himalaya–Hindu Kush–Karakorum region (ICIMOD, 2011; Mool et al., 2001; Nie et al., 2013; Raj and Kumar, 2016; Song et al., 2016; Ukita et al., 2011; Wang et al., 2014; Wang et al., 2013; Worni et al., 2013; Xin et al., 2012; Zhang et al., 2015), Peru (Emmer et al., 2016; Vilímek et al., 2016), Bolivia (Cook et al., 2016), or Northern Patagonia (Loriaux and Casassa, 2013). Based on manual satellite image analysis Zhang et al. (2015) report > 5700 lakes (including supraglacial lakes) within a maximum distance of 10 km from existing glaciers in the Himalaya region and the Tibetan Plateau. Glacial lakes in this region cover an area of 682 ± 110 km^2 whereas glaciers cover 40,800 km^2 (Bolch et al., 2012). Between 1990 and 2010 lake number has increased by 1000 (+21%) and lake area by 23% (Zhang et al., 2015). A contrasting image is produced for the Hindu Kush-Himalaya region, where glacial lake coverage decreased in the Hindu Kush and Karakorum between 1990 and 2009 in contrast to an increase in the Himalaya (Gardelle et al., 2011). Lake formation is linked to the process conditions and landscape characteristics. For example, lakes evolving from debris covered glaciers in the Southern Tibetan Plateau region are reported to increase stronger than other types of glacial lakes for example in cirques (Song et al., 2016). Additionally, the conditions of lake formation change with climate. Emmer et al. (2016) report an upward trend in lake development in the Cordillera Blanca, Peru indicating a shift of lake formation towards higher elevations since the 1950s.

Table 1
Glacial lake inventories worldwide with no claim to completeness.

Mountain range	State	n lakes	Min. lake size [m^2]	Method	Topic	Reference
This study	**Austria**	**1410**	**1000**	**Digital mapping**	**Lake changes**	**–**
Eastern Alps/Tyrol	Austria	1024	250	Digital mapping	GLOF risk	Emmer et al. (2015)
Cordillera Blanca	Peru	882	> 100 m (length + width) + > 20 m (width)	Digital mapping	GLOF risk	Emmer et al. (2016)
Cordillera Oriental	Bolivia	~250	–	Digital mapping	GLOF risk	Cook et al. (2016)
Sikkim Himalaya	India	320	–	Remote sensing-based	GLOF risk	Govindha Raj et al. (2013)
East Himalaya	Bhutan	2674	100,000	Remote sensing-based	GLOF risk	Mool et al. (2001)
Central Himalaya	Nepal	1466	1000	Remote sensing-based	GLOF risk	ICIMOD (2011)
Central Himalaya	Nepal	1314	8100	Remote sensing-based	Lake changes	Nie et al. (2013)
Uttarakhand Himalaya	India	362	20,000	Remote sensing-based	GLOF risk	Raj and Kumar (2016)
Bhutan Himalaya	Bhutan	203	3600	Remote sensing-based	Lake changes	Gardelle et al. (2011)
Everest region	Nepal	583	3600	Remote sensing-based	Lake changes	Gardelle et al. (2011)
West Nepal	Nepal	116	3600	Remote sensing-based	Lake changes	Gardelle et al. (2011)
Garhwal	India	233	3600	Remote sensing-based	Lake changes	Gardelle et al. (2011)
Spiti Lahaul	India	35	3600	Remote sensing-based	Lake changes	Gardelle et al. (2011)
Karakorum	Pakistan	422	3600	Remote sensing-based	Lake changes	Gardelle et al. (2011)
Hindu Kush	Pakistan	102	3600	Remote sensing-based	Lake changes	Gardelle et al. (2011)
Tibetian Plateu	China	312	4000	Digital mapping	Lake changes	Wang et al. (2013)
Indian Himalaya	India	251	10,000	Remote sensing-based	GLOF risk	Worni et al. (2013)
Teesta basin (Sikkim)	India	143	100,000	Remote sensing-based	GLOF risk	Aggarwal et al. (2016)
Bhutan Himalaya	Bhutan	336	–	Remote sensing-based	Lake detection	Ukita et al. (2011)
Northern Patagonia Icefield	Chile	137	–	Digital mapping	Lake changes	Loriaux and Casassa (2013)
Poiqu River basin	China	119	10,000	Digital mapping	Lake changes	Wang et al. (2014)
Koshi River Basin	Nepal + China	1203	–	–	Lake changes	Shijin and Tao (2014)
Southeastern Tibetan Plateau	China	1396	4500	Digital mapping	Lake changes	Song et al. (2016)
Chinese Himalaya	China	1680	3400	Remote sensing-based	Lake changes	Xin et al. (2012)
Pamir	Tajikistan	1642	2500	Digital mapping	Lake changes	Mergili et al. (2013)
Stelvio National Park	Italy	116	–	Digital mapping	Lake changes	Salerno et al. (2012)
Western Greenland	Greenland	823		Remote sensing-based	Lake changes	Carrivick and Quincey (2014)

Analyzing small ponds in the Stelvio National Park (Italian Alps) between 1954 and 2007, Salerno et al. (2014) found an increase in pond size and lake formation corresponding to observed positive temperature trends since the early 1990s. They also report a correlation between basin aspect and lake evolution with lakes disappearing in southward facing watersheds.

The vast majority of studies on glacial lake formation focus on the Himalaya-Hindukush region (Table 1). A closer look to other glaciated mountain regions is required to complete the global picture of glacial lakes and their impacts on environment and society, especially in the context of possible changes in the future. The increased formation of new lakes, for example induced by climate change, systematically increases flood risks in down-valley zones of mountain regions (Frey et al., 2010). This is induced for example by an upward shift of new lakes, bringing them closer to the zone of destabilized rock faces with degrading permafrost conditions. From a society perspective, glacial lakes have a local and regional relevance for energy production (hydropower) and for water resource management (Terrier et al., 2011). From a tourism perspective, glacial lakes have an idyllic and esthetic function and serve as attractors for high mountain recreation activities (Haeberli et al., 2016a).

3. Study area

The study area (12,882 km^2) comprises the main part of the eastern Alps with a minimum elevation of 1700 m a.s.l., limited by the national border of Austria. Highest peak is the Großglockner (3798 m a.s.l.). Numerous catchments are covered by glaciers of which several have been monitored since > 150 years (glacier inventories, length changes, mass balances, etc. (WGMS, 2017)). Fig. 2 shows the extent of the study area (green shapes) and the glacier extent (941 km^2) of the LIA maximum ice advance (Fischer et al., 2015a). The analysis of lake formation is performed for the latter area.

4. Material and methods

This study follows a two-step approach (Fig. 3): First we created a lake inventory using freely available orthophotos and a digital elevation model (DEM). The lake inventory serves as basis for discussing the distribution of lakes and gives insights into lake formation conditions. Second, a formation period was assigned to all lakes based on different glacier extents since the LIA. This step required the compilation and delineation of glacier extents at different times (see below). Combining the lake inventory data with different glacier extents allowed for the assessment of dynamics and changes of lake formation. This analysis is restricted to the post-LIA period due to lack of previous glacier extents.

4.1. Creating the lake inventory

We started with an existing data set of 1024 proglacial lakes (> 250 m^2, 2000 m a.s.l.) produced by Emmer et al. (2015) for the western part of Austria (6139 km^2). This data set was filtered for lake size > 1000 m^2 and expanded to the entire Austrian territory above 1700 m a.s.l. (12,882 km^2). This threshold represents the lowest limit of the Little Ice Age (LIA) glacier extent in Austria (Fischer et al., 2015b) with an existing lake. Lake mapping was performed using freely available satellite images and orthophotos from various sources (Google Earth, Esri World Imagery, Orthofoto Österreich, Geoland Austria) from different years (2009–2015, image resolution: 60 cm for Google Earth and Esri World Imagery to 35 cm for Orthofoto Österreich) and DEM data (resolution 10 m, data from data.gv.at). We set a minimum lake area of 1000 m^2 for mapping to exclude smaller lakes that potentially only persist periodically or intermittently for example after heavy rainfall or snowmelt. For a faster localization of lakes, a classification of DEM cells with a slope between 0° and 1° was performed to detect flat areas. With this preparatory step mapping was significantly accelerated and lakes could be found where snow or shadows on some scenes would prevent identification. The lake boundaries were manually mapped by one expert and crosschecked by two peers. Eventually all mapped lakes

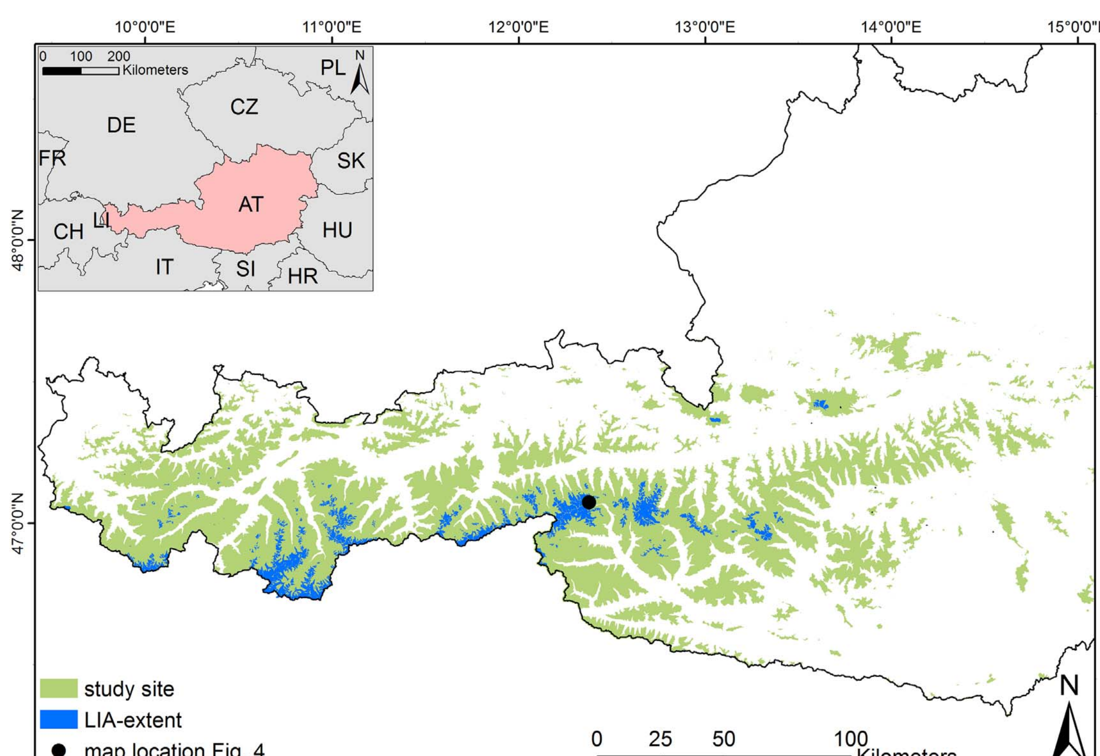

Fig. 2. Map of Western Austria indicating the study area and the extent of the LIA maximum ice advance (Fischer et al., 2015a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

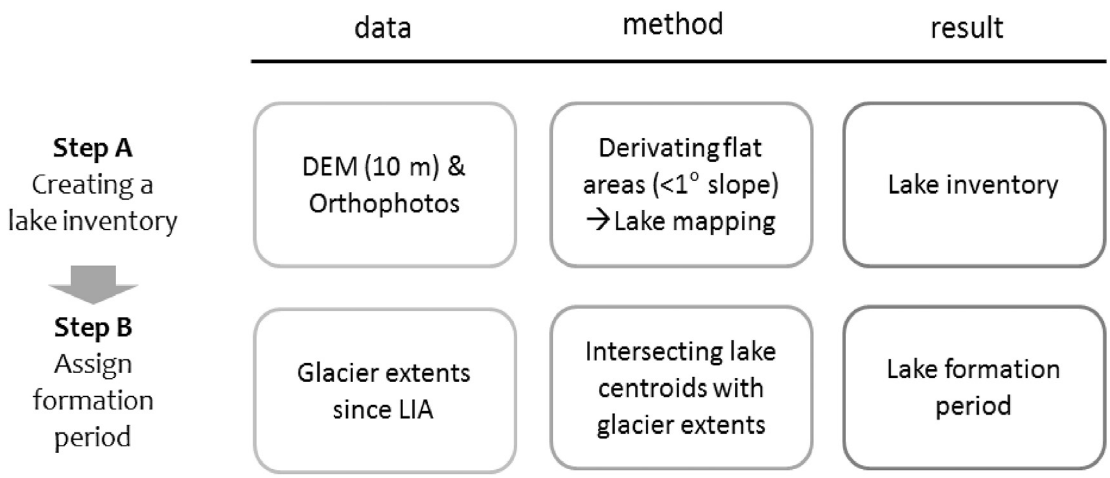

Fig. 3. Data and workflow.

were approved by each of the three experts to avoid varying and highly subjective mapping results.

All mapped lakes are provided with basic attributes aiming at a wide applicability of the inventory to different research topics and usage (download of the entire database is available at: https://doi.pangaea.de/10.1594/PANGAEA.885931).

Attribute include:

- Name (if available)
- dam material (see below)
- damming process
- damming form
- surface area [m^2]
- elevation [m a.s.l.]
- lake formation period (see below) date of image acquisition
- glacier water supply
- direct glacier contact.

All lakes were classified according to their damming material (bedrock, debris, ice), the process that deposited the debris material and the related landform (Table 2). The classification follows the three geomorphological principle components (form, process, material) and enables to characterize and represent all types of lakes detected in the study area. It differs from previously published classifications (e.g. Carrivick and Tweed, 2013; ICIMOD, 2011; Iturrizaga, 2014). We consider this nested classification beneficial to provide easy access to all information that characterizes the different lakes in the inventory. By this we intend to enable a widespread usage of the inventory for different applications, e.g. hazard analysis, hydrological and ecological monitoring or hydropower site assessment.

Most bedrock-dammed lakes originate from glacial erosion, mainly quarrying and abrasion, leading to the formation of glacier-bed overdeepenings. Typically, the overdeepened bedrock is formed in trunk valleys, cirques or confluence zones of glaciers (Cook and Swift, 2012; Haeberli et al., 2016b). Bedrock ridges that retain water are often located at the lower end of cirques or hanging valleys.

Debris-dammed lakes exist due to glacial, gravitative and periglacial processes. We split the class of glacial debris-dammed lakes in glacial impoundments behind terminal/lateral moraine dams and lakes embedded in glacial deposits. Dams resulting from gravitative processes include forms like debris cones or landslide deposits. Rock glaciers act as periglacial-debris dams.

Ice-dammed lakes are located between a glacier and a lateral or terminal moraine or bedrock. Because of the permanent change of the glacier, these lakes have a shorter lifespan than lakes impounded by more persistent material such as bedrock.

Table 2
Lake classification with respect to dam characteristics (material and form) and formation processes.

Material	Process	Form
Bedrock		
Debris	Glacial	Moraine-dammed
		Embedded in glacial deposits
	Gravitative	Debris cone
		Landslide deposit
	Periglacial	Rock glaciers
Ice	Glacial	

4.2. Assigning period of lake formation

In Austria glacier inventories exist that contain high resolution outlines of glacier extent at four different stages in time since LIA (Fischer et al., 2015b). These datasets allow comparing lakes mapped on modern aerial imagery with glacier extents at different points in time. In this way, the time of the formation of lakes located within the LIA glacier extent can be derived with a temporal accuracy depending on the temporal resolution of the glacial extent datasets. Thus, we extended the glacial extent datasets with additional time slices to narrow down lake formation periods and also to update existing data (Table 3). Fischer et al. (2015a) published four glacier inventories (GI's) representing the ice extent at the LIA maximum around 1850 (GI LIA), at 1969 (GI 1), at 1998 (GI 2), and 2006 (GI 3). Glacier extent for GIs 1 and 2 is based on orthoimage interpretation (Lambrecht and Kuhn, 2007). GI 3 and GI LIA were produced using combined hillshade visualization of high resolution LIDAR-DEM data (resolution 1 m) and additional orthoimagery (Fischer et al., 2015b). The reconstruction of the GI LIA glacier extent is based on mapping of frontal and lateral moraines (Fischer et al., 2015b). We added two more time slices: (a) glacier extent of the 1920ies; and (b) glacier extent of 2015. Many glaciers in Austria advanced in the 1920ies forming terminal moraines

Table 3
Periods of lake formation and glacier inventory data applied.

Period	Based on
Before ~1850	GI LIA
~1850–1920	GI LIA, 1920s data
1920–1969	1920s data, GI 1
1969–1998	GI 1, GI 2
1998–2006	GI 2, GI 3
2006–2015	GI 3, GI 4

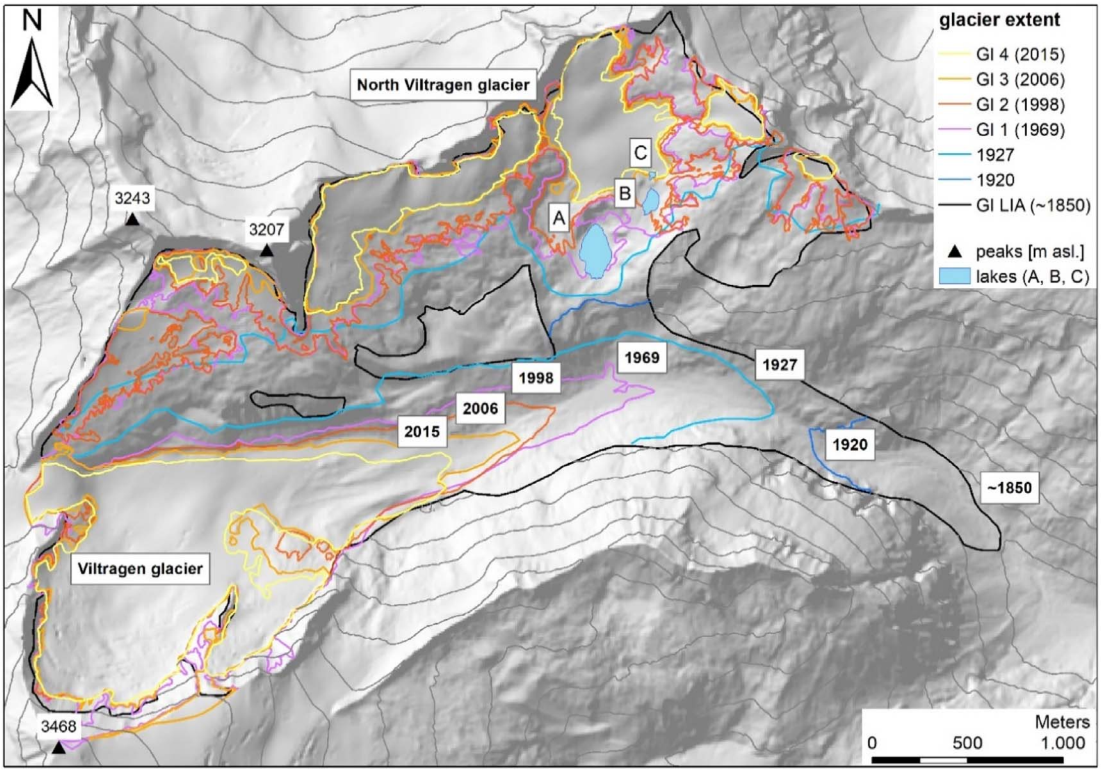

Fig. 4. Illustration of the formation period assessment: Colored lines represent the glacier extent at the different inventory times. The 1920ies data is represented by a contour line based on the point information provided by Gross (1987). The 1927 extent was digitized from a historical map (ÖAV map 36, Venedigergruppe). Three lakes have developed at three different formation periods: A (1969–1998), B (1998–2006), C (2006–2015). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
(DEM data from data.gv.at; glacier shapes ~1850, 1969, 1998 and 2006 from Fischer et al. (2015a).)

that can be identified in the field, on orthoimages, or on DEMs. Gross (1987) mapped the position of the lowest altitudes of the 1920ies moraines for selected glaciers in the Austrian Alps. We complemented this data set with glacier extents marked on historical maps published between 1896 and 1955 by the Austrian Alpine Club. These maps contain information on the date of glacier mapping with most glaciers mapped in the 1930ies. A total of 27 historical maps where rectified and georeferenced and compared to data by Gross (1987). We used these maps to (a) verify the altitudes provided by Gross (1987) and (b) to assess the formation period of missing lakes. This additional time slice subdivides the long time period between the GI LIA and GI 1 (1969) data set. Additionally, the current glacier extent was mapped using Google Earth imagery from 2015 (GI 4).

To link mapped lakes within the LIA extent to a formation period, the intersection of lakes and glacier polygons from the different inventories was evaluated using GIS. We assigned the formation period to each lake by its position between the youngest complete intersection with the glacier extents (lake polygon fully covered by glacier polygon) to the oldest incomplete intersection (lake polygon not or only partly covered by glacier polygon) (Fig. 4). In contrast to the GI data by Fischer et al. (2015a), the 1920ies data set contains point information only. In order to intersect the lake polygons with these data, we calculated a contour line for the 1920ies altitudinal limit. We classified the lakes according to their position above or below this contour line into the period either before or after the 1920ies advance. A lower limit of the 1920ies glacier extent for 78% of the glaciers listed in GI LIA could be established by this procedure. 19 lakes could not be attributed to either GI LIA or the 1920ies period. We distributed these lakes according to their relative position to one of each class, but are aware of a potential uncertainty produced (see Section 5.3). Different parameters, like the number and area of new lakes and new lakes per year in specific formation period, describe the lake formation since LIA.

We discovered some inconsistencies between the different inventories by Fischer et al. (2015b). First, the original survey that produced GI 1 did not include a number of mountain ranges compared to GI LIA, GI 2 and GI 3 (Lambrecht and Kuhn, 2007), resulting in a total of 74 glaciers missing in GI 1. We used historical topographic maps with known glacier extent to close this gap for assigning the formation period of the related lakes.

5. Results

5.1. Lake distribution and characteristics

The lake inventory contains 1410 lakes above 1700 m a.s.l. in Austria covering a total area of 17.1 km^2. The lakes spread from the border to Switzerland in the West to the Seckauer Tauern, close to Leoben, Styria, in the East. Lake density, i.e. the lake area (in m^2) in relation to the surface area above 1700 m (in km^2), varies significantly between the mountain ranges (Fig. 5). Highest lake density is observed in the Schladminger Tauern, the Ankogel group and the Venediger group. Lower densities can be identified in the Tuxer/Zillertaler Alps or the Stubaier Alps, for example.

Lake area varies between 1000 m^2 and 320,000 m^2. The largest lake of the inventory the “Tappenkarsee” (320,000 m^2) is located in the Radstätter Tauern, Salzburg. Bedrock-dammed lakes have a mean as well as a maximum area significantly higher than glacial debris-dammed and ice-dammed lakes. Bedrock-dammed lakes comprise about 67% of the total lake surface in the study area, compared to 32.8% for debris-dammed lakes. The group of glacial debris-dammed lakes is sub-classified into 150 moraine-dammed lakes and 450 lakes embedded in glacial debris. Moraine-dammed lakes are located at higher altitude with a larger mean area compared to lakes embedded in glacial debris. Rock glaciers dam 15 lakes at a mean elevation around

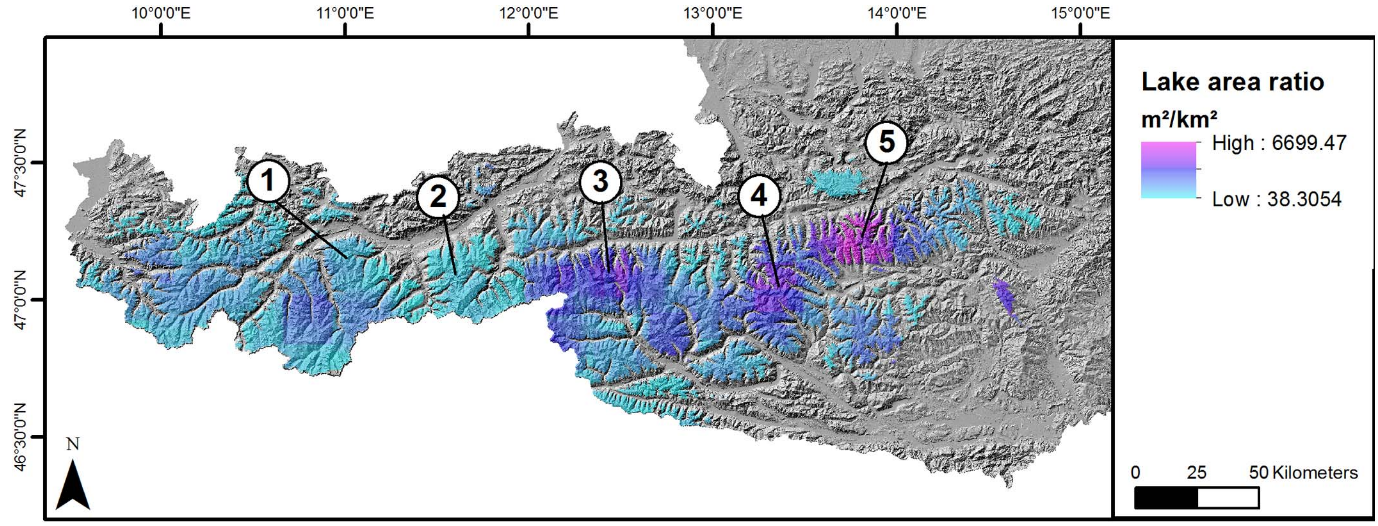

Fig. 5. Lake density [j1] [j2] (m^2/km^2) derived from dividing lake area above 1700 m a.s.l. by terrain area above 1700 m a.s.l.; calculation based on a moving window with a size of 20 × 20 km. Numbers label mountain ranges mentioned in the text: (1) Stubaier Alps, (2) Tuxer and Zillertaler Alps, (3) Venediger group, (4) Ankogel group, (5) Schladminger Tauern. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Lake characteristics classified by dam material, dam formation process und dam form, entire lake database. Percentage of lakes corresponds to the entire number of lake in the database (1410 = 100%).

Class	Number (percentage) of lakes	Sum area [km^2]	Mean area [m^2] (min.–max.)	Mean elevation [m a.s.l.] (min.–max.)	Number (percentage) of lakes fed by glaciers	Number (percentage) of ice contact lakes
Dam material						
Bedrock	777 (55.1)	11.51	14,816 (1013–322,461)	2395 (1712–3123)	80 (5.7)	30 (2.1)
Debris	627 (44.5)	5.61	8947 (1012–133,935)	2345 (1700–3225)	78 (5.5)	32 (2.3)
Ice	6 (0.4)	0.04	6406 (1081–24,573)	2776 (2519–3191)	6 (0.4)	6 (0.4)
Sum	1410 (100)	17.16	–	–	164 (11.6)	68 (4.8)
Process						
Glacial deposition	600 (42.6)	5.19	8663 (1012–133,936)	2351 (1700–3225)	78 (5.5)	32 (2.3)
Gravitative	12 (0.9)	0.32	26,966 (2858–85,211)	1931 (1825–2107)	0 (–)	0 (–)
Periglacial	15 (1.1)	0.09	5899 (1170–13,434)	2443 (1977–2745)	0 (–)	0 (–)
Ice damming	6 (0.4)	0.04	6406 (1081–24,573)	2776 (2519–3191)	6 (0.4)	6 (0.4)
Sum	633 (44.9)	5.64	–	–	84 (5.9)	38 (2.7)
Form						
Moraine dammed	150 (10.6)	1.47	9796 (1012–133,935)	2530 (1833–3225)	42 (3)	20 (1,4)
Embedded in glacial deposits	450 (31.9)	3.72	8285 (1012–124,351)	2291 (1700–3015)	36 (26)	12 (0,9)
Debris cones	6 (0.4)	0.10	17,729 (3801–42,578)	1931 (1950–2107)	0 (–)	0 (–)
Landslide deposits	6 (0.4)	0.22	36,203 (3948–85,211)	1932 (1825–1993)	0 (–)	0 (–)
Rock glacier	15 (1.1)	0.09	5899 (1170–13,434)	2443 (1977–2745)	0 (–)	0 (–)
Sum	627 (44.5)	5.6	–	–	78 (5.5)	32 (2,3)

2450 m a.s.l. The wide elevation range of rock glacier-dammed lakes (min. 1977 m to max. 2745 m a.s.l.) indicate that all types of rock glaciers (active, inactive and relict) dam lakes in the study region. The lowest mean altitude is observed for gravitative debris-dammed lakes, indicating the distribution and relevance of mass movement deposits in lower valley locations (Table 4).

Glacier meltwater feeds 164 lakes; however, none of the gravitative debris-dammed lakes have a recent glacier in the upstream catchment. 68 lakes are currently in contact with glaciers. Lake depth for 61 lakes was gathered from published resources and is only available for older lakes (prior to 1999) (Fugger (1890–1911); Lindlbauer (2014); Schabetsberger et al. (1996); Seitlinger (1999)). Mean lake depth varies between 0.2 m and 56.8 m.

The distributions of high alpine lake area and lake number over elevation clearly deviate from the distribution of total area (Fig. 6). While total area diminishes continuously with increasing elevation, both lake number and area peak around 2500 m a.s.l. Formation process-related aspects such as local glacial erosional and depositional dynamics have a major control on the occurrence of high alpine lakes and hypsometry as a measure of overall terrain state plays only an indirect role. The highest lake is located in the Pitztal, Ötztaler Alps, Tirol, at 3225 m a.s.l.

The altitudinal distribution also varies with lake type (Fig. 7A), representing both damming conditions and formation period. Bedrock-dammed lakes have the largest share in total number of lakes, especially at elevations between 2000 m a.s.l and 2700 m a.s.l. At elevations below 2000 m a.s.l., debris-dammed lakes are more frequent than bedrock-dammed lakes. Ice-dammed lakes are located in the highest parts of the study area. The number of moraine-dammed lakes increases with elevation and until 2600 m a.s.l. Lakes dammed by landslide deposits and debris cones occur at elevations below 2100 m a.s.l. only. Rock glaciers act as dams at elevations between 1900 m a.s.l. and 2700 m a.s.l.

5.2. Characteristics of lakes in the LIA-extent

Lakes within the LIA extent, representing the current active glacier forefields, cover an area of 2.93 km^2. Compared to the area exposed by glaciers (613 km^2) since the LIA maximum ice extent, this amounts to

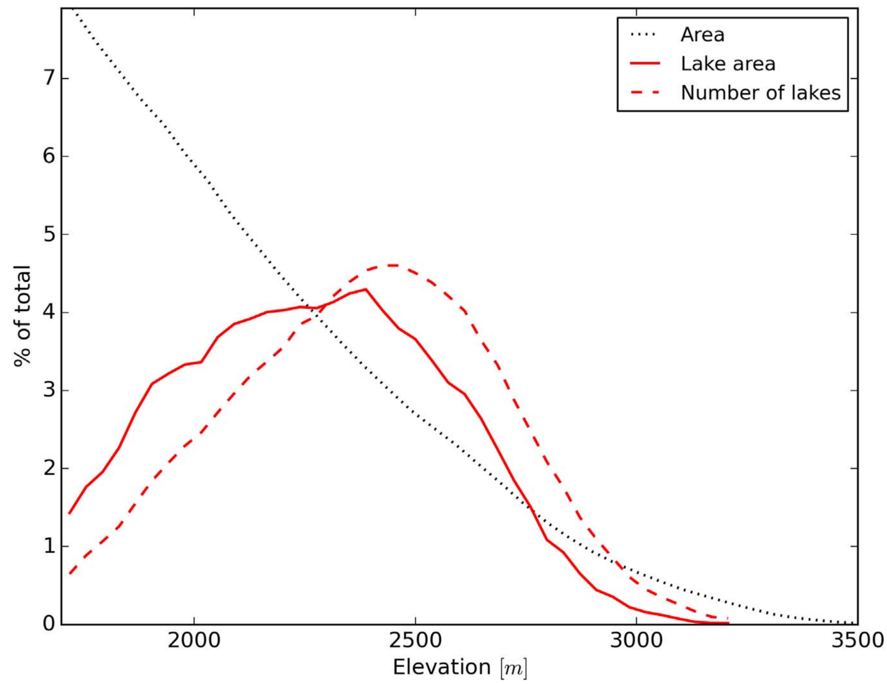

Fig. 6. Relative distribution of lake number, lake area and total area over elevation.

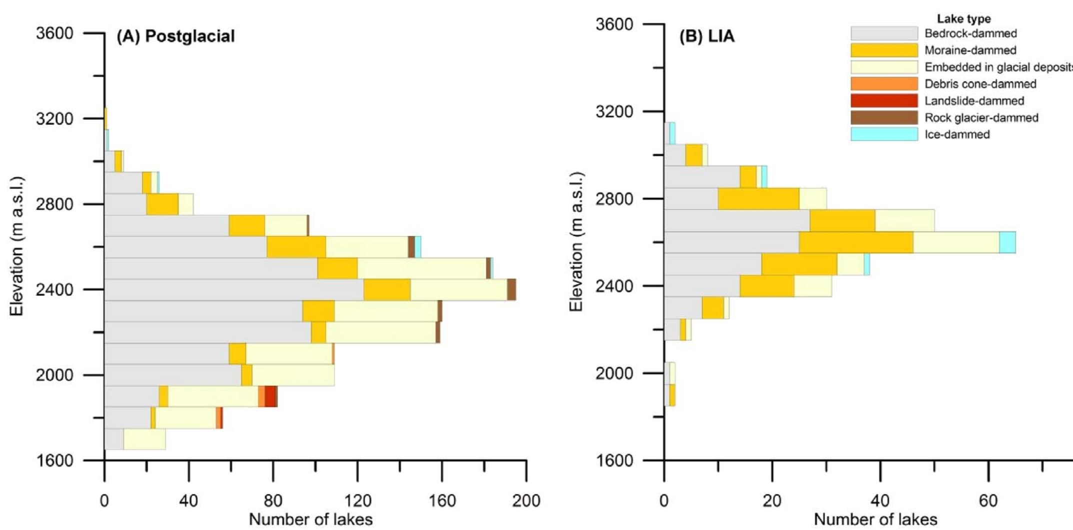

Fig. 7. (A) The distribution of all dam types over elevation. The material type "debris" splits into the different depositional landforms involved. (B): The distribution of dam types over elevation within the LIA extent. Data is binned into 100 altitude levels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

0.5% of this new land surface. 18.7% of the mapped lakes have formed since the LIA. These formed on average at higher altitudes compared to the Postglacial lakes (Table 5). Accordingly, post-LIA lake types show a different distribution with more (50.3%) and on average larger debris dammed lakes compared to less (47.3%) and on average smaller bedrock dammed lakes. By nature, all ice-dammed lakes are within the LIA extent, representing the most recent events of lake formation. We don't observe lakes blocked by landslide deposits or rock glaciers within the glacier forefields. Lake distribution over elevation reveals a distinct concentration of lakes between 2.300 and 2.800 m a.s.l., representing the mean elevation of glacier forefields in the study area (Fig. 7B). Only few lakes are located below 2.300 and above 2.900 m. While bedrock-dammed lakes show a widespread altitudinal distribution, moraine-dammed lakes and those embedded within glacial deposits are less frequent in higher regions (≥2800 m a.s.l).

5.3. Lake formation since LIA

On average 1.6 lakes per year (17,758 m^2/year) emerged since LIA (1850) until 2015. The rate of lake formation changed significantly within the last 165 years. The per-year average of both number and area of new lakes increased from the oldest (1850–1920) to the most recent (2006–2015) period. The mean number of new lakes per year increased by a factor of eight since the oldest period analyzed (Fig. 8). This trend accelerated after 1969 with more lakes evolving between 1998 and 2015 than in the period between LIA and 1969. New lake area per year increases by a factor of 10 in the study period. Especially, within the past 20 years the area of new lakes has doubled from 37,470 m^2/year from 1998 to 2006 to 78,534 m^2 from 2006 to 2015 (Table 6).

This accelerating trend corresponds to the increasing ice loss since

Table 5
Characteristics of glacial lakes within the LIA extent classified by dam material, dam formation process und dam form. Percentage of lakes corresponds to total number of lakes (264 = 100%) within LIA extent.

Class	Number (percentage) of lakes	Sum area [km²]	Mean area [m²] (min.–max.)	Mean elevation [m a.s.l.] (min.–max.)	Number (percentage) of lakes fed by glaciers	Number (percentage) of ice contact lakes
Dam material						
Bedrock	125 (47.3)	1.66	13,297 (1048–252,550)	2660 (1902–3123)	54 (20.5)	28 (10.6)
Debris	133 (50.4)	1.23	9245 (1012–133,935)	2647 (1995–3029)	64 (24.2)	27 (10.2)
Ice	6 (2.3)	0.04	6406 (1081–24,573)	2776 (2519–3191)	6 (2.3)	6 (2.3)
Sum	264 (100)	2.93	–	–	124 (47)	61 (23.1)
Process						
Glacial deposition	133 (50.4)	1.23	9245 (1012–133,935)	2647 (1995–3029)	64 (24.2)	27 (10.2)
Gravitative	–	–	–	–	–	–
Periglacial	–	–	–	–	–	–
Ice damming	6 (2.3)	0.04	6406 (1081–24,573)	2776 (2519–3191)	6 (2.3)	6 (2.3)
Sum	139 (52.7)	1.27	–	–	70 (26.5)	33 (12.5)
Form						
Moraine dammed	84 (31.8)	0.93	11,092 (1012–133,935)	2649 (1995–3029)	38 (14.4)	17 (6.4)
Till-embedded	49 (18.6)	0.30	6078 (1012–63,955)	2643 (2007–3015)	26 (9.8)	10 (3.8)
Debris cones	–	–	–	–	–	–
Landslide deposits	–	–	–	–	–	–
Rock glacier	–	–	–	–	–	–
Sum	123 (50.4)	1.23	–	–	64 (24.2)	27 (6.4)

1998. The deglaciation record shows an apparent similar trend of ice loss until the GI 2 (1998), which however blends the ice retreat and minor ice re-advances and halts during this time that have not been recorded for all glaciers. This trend changes after 1998, revealing a stronger decrease of glacier area afterwards (Fig. 9). The year 1998 also marks the point in time when more terrain has been released from ice compared to the total area still covered by glaciers in the Eastern Alps. All together almost two-thirds of Austria's glacier area at LIA disappeared until 2015 (941 km^2 compared to 328 km^2).

6. Discussion

6.1. Patterns of lake formation in Austria

The peculiar distribution of high-alpine lake area and lake number over elevation in Austria is a result of local process-dependent influences, particularly glacial erosional and depositional dynamics. The hypsometry of glaciated landscapes with extended cirque areas above the ELA and pronounced glacial troughs further down, as described by Anderson et al. (2006) and Brocklehurst and Whipple (2004), largely explains the distributions of lake area and lake number over elevation as shown by our assessment of genetic lake types. High-alpine lakes either form as the result of long-term bedrock erosion causing over-deepening, due to sediment deposition by glacier advance (moraine-dammed) or retreat (embedded in glacial deposits), due to melting processes within or beneath the glacier, or by non-glacial processes after glacier retreat. We argue that the altitudinal distribution of different lake types indicates a regional distribution of these different ways of lake formation and process dynamics. The pattern of glacial lakes further reflects different phases and locations of erosion and

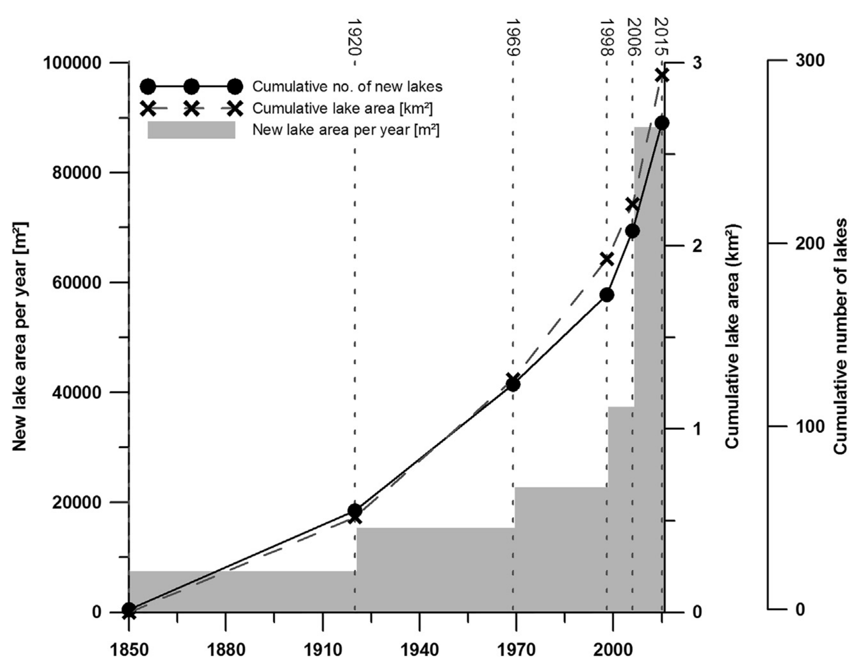

Fig. 8. Number and area of new lakes since LIA (black lines) and the average new lake area per year (gray bars). Dashed vertical lines mark the respective end of each formation period. (Data from this study and Fischer et al. (2015a).)

Table 6
Formation of new glacial lakes over different time periods.

	1850–1920	1920–1969	1969–1998	1998–2006	2006–2015
n lakes	54	68	49	34	59
New lakes per year	0.8	1.4	1.7	4.3	6.5
Total lake area [km^2]	0.52	0.75	0.66	0.30	0.71
New lake area per year [m^2/year]	7423	15,356	22,660	37,470	78,534
Deglaciated area [km^2]	376.3[a]		94.2	55.2	87.5

[a] Glacier extent not available for the separate periods (cf. Material and methods).

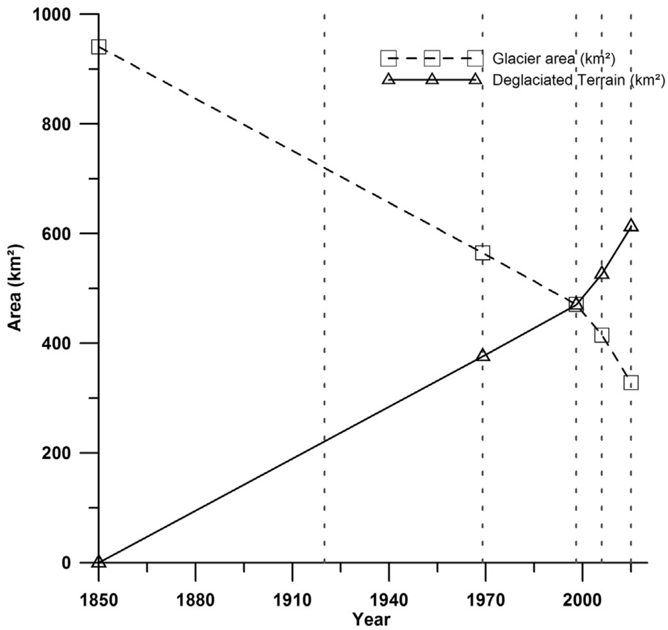

Fig. 9. Comparing glacier area reduction (dashed line) and terrain exposed (solid line) by glacier melt between 1850 and 2015 in Austria. Dashed vertical lines mark the respective end of each formation period.
(Data from Fischer et al. (2015a) and own data.)

deposition by glacier and glacially conditioned processes. We observe a general upward shift of all lake types that are directly glacier-conditioned (bedrock-dammed, moraine-dammed, embedded lakes, ice-dammed) between Postglacial lakes and post-LIA lakes (Fig. 7A/B). This reflects the altitudinal distribution of current glacier forefields and subrecent lake formation within. The Postglacial lake distribution also includes locations that have most probably been free of ice during most of the Holocene, for example in cirques and valleys east of the current glacier occurrence (see below). The number of moraine-dammed lakes at lower elevations (below 2000 m) is significantly reduced (Fig. 7A), indicating the low number of distinct moraine walls outside the current glacier forefields. Moraine formations due to ice re-advance or stagnation occurred for example at the maximum ice extent of the LIA around 1850, at the end of the 19th century or in the 1920ies and during several Lateglacial periods (e.g. Younger Dryas). However, moraine heights and sizes vary significantly between the terminal moraines produced by Lateglacial and LIA maximum advances and the smaller moraines produced by post-LIA glacier advances. We explain the low number of moraine-dammed lakes in lower elevation by the possibility that older moraine dams, e.g. Younger Dryas age have been already eroded, or have been deposited below 1700 m, our lower limit of analysis.

In contrast, bedrock-dammed lakes formed at higher altitudes. Anderson et al. (2006) describe this upper zone as knobby terrain characterized by gentle slopes, exposed bedrock and little deposition after ice retreat. Here, glacial erosion led to a large number of spatially limited bedrock depressions (Robl et al., 2015). While this pattern is less pronounced for the Postglacial lakes, within the LIA extent bedrock-dammed lakes prevail at higher elevations (> 2.800 m) corroborating this general observation. Larger ice volumes causing higher ice velocities and erosive power may lead to substantial overdeepening where glaciers coalesce (Cook and Swift, 2012), also producing favorable locations for lakes. Further down the valleys, U-shaped cross sections formed during glacial presence. After and during ice retreat these U-shaped valleys are filled with glaciofluvial and fluvial sediments. Previously carved bedrock depressions are mostly buried by sedimentary deposits (van der Beek and Bourbon, 2008). We interpret the prevalence of embedded lakes at elevations below 2.000 m as a representation of sedimentary filled valley locations. Similarly, these embedded lakes are formed also within the LIA glacier extent. Here lake formation is also related to kettle hole generation due to delayed melting of dead ice and also by burying of bedrock depressions with sediments exported from the glacier system.

Lakes formed behind deposits of non-glacial origin such as debris cones or landslides likely reflect the impact of paraglacial processes on lake formation. These processes are conditioned by glaciation for example by deposition of debris available for gravitative processes such as debris flows (Ballantyne, 2002). Landslides are often the result of stress release within slopes previously covered by glacier ice masses in the valleys (McColl, 2012). Consequently, these lakes are formed at lower locations, and with significant distance to the current glaciers (Fig. 7A). Lakes formed behind rock glacier deposits are most probably less affected by glaciation, too. However, they indicate locations, where glaciers have not been present for most of the Postglacial enabling rock glaciers to evolve and grow down to locations where they blocked the flow of water. Recent studies show that many rock glaciers formed immediate after the Younger Dryas ice advance mostly from glacial deposits (Moran et al., 2016). We don't observe these kinds of paraglacial lakes within the LIA-extent (Fig. 7B).

Regional maxima in lake density may be explained by regional differences in lake number and/or size (Fig. 5). Such differences can be attributed to lake formation processes, or a greater persistence of lakes for example due to reduced sedimentation rates. In case of the Schladminger Tauern, for example, glaciers have not been present during the LIA. Cirques and valleys most probably have been ice-free throughout most of the Postglacial. Though we have found no published information on the timing of ice cover in this area, we can confirm this assumption by comparing the altitudinal distribution of cirques and peaks of this region with the potential equilibrium line altitude (ELA) e.g. during the Younger Dryas. Cirque floors in the Schladminger Tauern for example are located at altitudes between 1.700 and 2.100 m. The surrounding ridges and peaks spread between 2.400 and 2.700 and do not reach above 2.860 m. Assuming that the ELA at the Younger Dryas was located around 200 m below the current/LIA level at approximately 2.700–3.100 m for the Eastern Alps (Gross et al., 1978; Zemp et al., 2007), we can conclude that even at the times of the Younger Dryas glacier stage, not much accumulation space was available for the generation of cirque glaciers. This implies significant lower sediment production rates in the cirques and valleys during most of the Postglacial and reduced sediment delivery compared to higher parts of the study area, where glaciers have been present over more extensive and more recent time periods. Lake density may thus indicate the variability of lake lifetime, if similar lake formation and siltation processes are assumed throughout the mountain ranges.

6.2. Evolution of lake formation since LIA

The formation of glacial lakes is closely linked to glacier retreat and changing climatic conditions. However, the linkages between glacier mass balance change and hence glacier size and variations in climate are highly complex when looking at individual glaciers and vary widely across the globe (e.g. Haeberli et al., 2013a; Vincent et al., 2017). The dynamic response of glaciers to climate change is controlled by variable topographic conditions that evoke local climate fluctuations, and by dust and debris cover feeding back on accumulation and ablation rates as well as ice flow dynamics (Haeberli et al., 2013a; Oerlemans, 2010; Oerlemans et al., 2009; Scherler et al., 2011). Abermann et al. (2011) analyzed glacier distribution and extent using GI 1 and GI 2 data in relation to regional climate conditions, mainly precipitation and temperature, in the Austrian Alps. They stress the dominant impact of glacier size on glacier distribution, which relates to ice flow dynamics, and the high variability of local topography that reduces a correlation between regional climatic controls and ice distribution. However, they conclude that the observed ice loss between the glacier inventories is mainly related to continuous positive temperature anomalies since 1981 in contrast to weaker correlation to precipitation changes (Abermann et al., 2011). Mean annual air temperature in mountain regions of Austria has increased by almost 2 °C since 1880, compared to 0,85 °C globally (Böhm, 2012). About 50% of this increase occurred since 1980 (APCC, 2014). This trend corresponds well with our observed pattern of lake evolution with increasing lake formation trend since 1998 and stronger increase within the past 20 years. We thus suggest that temperature increase is a vital control of lake formation in the Austrian Alps. Topographic configuration of the deglaciated terrain either supports or counteracts lake formation trends depending on the location of future glacier melt. Once the ice has disappeared from valley and cirque floors, the formation of new lakes is stopped.

6.3. Uncertainties

6.3.1. Mapping

Some mapping uncertainties have already been mentioned in Section 4 - Mapping accuracy significantly depends on image quality, image resolution and the person in charge (Salerno et al., 2012; Zhang et al., 2015). We chose a minimum image resolution of 35-60 cm to enable high accuracy. Additionally, we tried to minimize negative effects of shadows and snow and cloud cover by employing three different sets of orthophotos for the analysis. Additionally, also using a DEM classification method to detect flat areas reduced the change of missing lakes in shadow areas or underneath snow or clouds. For mapping of the 2015 glacier extent, only summer images with limited snow cover were chosen. Summing up these effects, we conclude that the accuracy of lake boundaries is < 2 m. Temporary lakes are mostly ruled out due to the lower size limit ($> 1000\,m^2$) and artificial lakes have been omitted by visual detection of artificial dams and barrages.

6.3.2. Number of new glacial lakes

In the formation period from LIA to 1969 we detected 122 new glacial lakes. By introducing the 1920ies glacier extent, 19 lakes could not be assigned to the formation period before or after the 1920ies marker since the location of the 1920ies ice advance was unclear (see above). We consider the impact of the 19 lakes insignificant with respect to the trend of lake formation. Adding the 19 lakes to the first formation period leads to a rise from 0.8 to 1.0 in the number of new lakes per year. If the 19 lakes are added to the second formation period, the number of new lakes per year rises from 1.4 to 1.7. In comparison to the increasing trend in the two younger formation periods (4.6; 7.4 new lakes per year), the change in number of new lakes per year can be neglected.

The observation period between LIA maximum ice extent and today has not been a phase of constant ice melt. In contrast, several small re-advances have been observed within the past 165 years (Fischer et al., 2016; Gross, 1987), for example in 1890, 1920, 1980. Re-advances have been highly variable between glaciers and not always left significant terminal moraines as ground truth. We acknowledge that these glacier advances could have overrun previously formed lakes within the glacier forefield and thus eliminated lakes that now miss out in our inventory. Since our analysis is based on image data from the most recent years, we cannot track these events and thus cannot remove these uncertainties. Looking at typical distances of ice advances of several meters to few tens of meters we consider that only smaller lakes might have disappeared during these events. Mapping lakes larger than $1000\,m^2$ reduces the chance of missing data here as well.

Sedimentation could influence the number of mapped glacial lakes that formed since LIA more significantly. We discovered several flat areas within the glacier forefield in the DEM analysis during the mapping process that may be indicative of such filled up lakes. Lake filling and lifetime depend on sedimentation rates, lake size and lake depth. Since no data on sedimentation rates of recently formed lakes is available, we cannot estimate how fast these sedimentation processes operate and how long proglacial lakes exist. From visual image interpretation only it is also impossible to decide whether flat zones in proglacial areas are filled-up lakes or glaciofluvial deposits (e.g. sandur plains). It is also unclear if subglacial depressions are already filled up with sediment while still underneath the ice. These uncertainties should be kept in mind for further research on lake formation and need to be addressed in succeeding studies.

7. Conclusion and future work

The distribution of glacial lakes over elevation reflects glacier erosional and depositional dynamics rather than the distribution of total area. We analyzed the formation of glacial lakes in the Austrian Alps combining a detailed lake inventory with an extensive record of glacier retreat since LIA. From LIA to 2015 264 new glacial lakes developed as a result of glacier retreat and rising temperatures. The accelerated development of new glacial lakes and lake area correlates with an accelerating decrease of glacier area from 941 km^2 to 328 km^2 until 2015. Furthermore, rates of lake formation have been subject to constant acceleration throughout the entire observation period, even though uncertainties exist due to potential vanished lakes through siltation processes. This observation is in concordance with glacier retreat and can be related to increasing positive temperature trends within the last 35 years. We consider the lake inventory a valuable database for further analysis ranging from applications in hazard research and hydrology to hydropower generation and other fields.

Acknowledgements

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