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Spatiotemporal patterns of high-mountain lakes and related hazards in western Austria

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ABSTRACT

Climate-induced environmental changes are triggering the dynamic evolution of high-mountain lakes worldwide, a phenomenon that has to be monitored in terms of lake outburst hazards. We analyzed the spatial distribution and recent temporal development of high-mountain lakes in a study area of 6139 km^2, covering the central European Alps over most of the province of Tyrol and part of the province of Salzburg in western Austria. We identified 1024 natural lakes. While eight lakes are ice-dammed, one-third of all lakes are located in the immediate vicinity of recent glacier tongues, half of them impounded by moraines, half by bedrock. Two-thirds of all lakes are apparently related to LIA or earlier glaciations. One landslide-dammed lake was identified in the study area.

The evolution of nine selected (pro)glacial lakes was analyzed in detail, using multitemporal remotely sensed images and field reconnaissance. Considerable glacier retreat led to significant lake growth at four localities, two lakes experienced stagnant or slightly negative areal trends, one lake experienced a more significant negative areal trend, and two lakes drained completely during the investigation period. We further (i) analyzed the susceptibility of selected lakes to glacial lake outburst floods (GLOFs), using two different methods; (ii) identified potential triggers and mechanisms of GLOFs; (iii) calculated possible flood magnitudes for predefined flood scenarios for a subset of the lakes; and (iv) delineated potentially impacted areas.

We distinguished three phases of development of bedrock-dammed lakes: (a) a proglacial, (b) a glacier-detached, and (c) a nonglacial phase. The dynamics — and also the susceptibility of a lake to GLOFs — decrease substantially from (a) to (c). Lakes in the stages (a) and (b) are less prominent in our study area, compared to other glacierized high-mountain regions, leading us to the conclusion that (i) the current threat to the population by GLOFs is lower but (ii) the future development of emerging lakes has to be monitored carefully.

1. Introduction

Glacier retreat is considered the most obvious evidence for ongoing climate change (Haeberli et al., 2007). Glacier retreat itself is part of a complex and multiscale framework of current high-mountain environmental evolution processes. One of these processes is the life cycle of high-mountain lakes in terms of formation, evolution, and disappearance (emptying or lake basin filling by sediments). High-mountain areas are considered to be among the most active regions of the world from the perspective of lake formation, evolution, and emptying (e.g., Costa and Schuster, 1988; Korup and Tweed, 2007). Particularly the number of glacial lakes has been reported to have increased in the majority of glacierized high-mountain areas all around the globe (e.g., Mergili et al., 2013; Emmer et al., 2014). This increase has been attributed to glacier retreat since the end of the Little Ice Age (LIA; e.g., Zemp et al., 2006; Haeberli et al., 2007), directly leading to the formation of different types of glacial lakes (e.g., Frey et al., 2010; Schaub et al., 2013; Emmer et al., 2014). The evolution of high-mountain lakes reflects climatic fluctuations resulting in a changeable geoenvironment (e.g., Evans and Clague, 1994; Haeberli et al., 2007; Korup and Clague, 2009; Carrvick and Tweed, 2013). On the other hand, such lakes may pose a threat to society in the case of sudden drainage (e.g., Carey, 2005; Clague et al., 2012). Rapid and highly dynamic flows from glacial lakes are referred to as glacial lake outburst floods (GLOFs) (Richardson and Reynolds, 2000) or as GLOF-induced debris flows (O'Connor et al., 2001). Reported GLOFs have claimed thousands of lives worldwide during documented history and caused considerable damage (e.g., Vuichard and Zimmermann, 1987; Clague and Evans, 2000; Zapata, 2002; Clague and O'Connor, 2015).

The number of previous studies related to the evolution of high-mountain lakes and related hazards reflects the scientific significance

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of this issue. Glacial lakes and the hazards they pose have been recently described in the Himalayas (e.g., Quincey et al., 2007; Benn et al., 2012; Raj et al., 2013; Worni et al., 2013; Westoby et al., 2014a), the Pamir (e.g., Mergili and Schneider, 2011; Gruber and Mergili, 2013; Mergili et al., 2013), the Tien Shan (Janský et al., 2010; Narama et al., 2010; Bolch et al., 2011; Engel et al., 2012; Wang et al., 2013), the Hindukush-Karakoram (Iturrizaga, 2005; Ives et al., 2010; Ashraf et al., 2014; Haemming et al., 2014), the tropical Andes (e.g., Vilímek et al., 2005; Carey et al., 2012; Emmer and Vilímek, 2013), the Patagonian Andes (e.g., Harrison et al., 2006; Dussaillant et al., 2010; Loriaux and Casassa, 2012; Anacona et al., 2014, 2015), the North American Cordillera (e.g., Geertsema and Clague, 2005; Kershaw et al., 2005; McKillop and Clague, 2007a, 2007b), and the Swiss Alps (e.g., Haeberli et al., 2000; Huggel et al., 2002, 2004; Paul et al., 2007; Nussbaumer et al., 2014).

Surprisingly, this topic has not been studied broadly in Austria before (see Section 2). Consequently, the objectives of the present study are:

- to prepare an inventory of high-mountain lakes in the study area;
- to classify the lakes meaningfully for the analysis of lake outburst susceptibility;
- to identify and to analyze dynamically evolving lakes within the study area;
- to identify local properties and characteristics associated with lake formation;
- to analyze the susceptibility of selected lakes to GLOFs and to identify potential triggers of such events;
- to estimate overtopping duration and peak discharge at the dam for different flood scenarios;
- to delineate possible impact areas of potential GLOFs from selected lakes; and
- to discuss the patterns of lake characteristics and development with regard to the possible future evolution of the studied lakes as well as to highlight long-term patterns of lake formation in the context of post-LIA glacier retreat.

2. Study area and previous work

The study area encompasses most of the central Alps of western Austria, including the southern and eastern parts of the province of Tyrol and the western part of the province of Salzburg. It includes seven catchments and has a total area of 6139 km^2 (Fig. 1). The highest peak is Großglockner (3798 m asl). Parts of the catchments' headwaters are glacierized. The Austrian Glacier Inventory of 2006 (Abermann et al., 2012; Stocker-Waldhuber et al., 2012) shows 745 entries for the study area, with a total glacier area of 336 km^2. However, glaciers have thinned and retreated since the end of the LIA. The rate of ice loss has increased in the last decades (e.g., Zemp et al., 2006; Haeberli et al., 2007; Lambrecht and Kuhn, 2007; Paul et al., 2007; Kellerer-Pirklbauer et al., 2008; Abermann et al., 2009, 2012; Stocker-Waldhuber et al., 2012), undoubtedly resulting from climate change (Gobiet et al., 2014). The total glacier area in the province of Tyrol shrank by 8% in the period 1998–2006 (Abermann et al., 2012).

While a number of recent GLOFs have been reported from the Swiss part of the Alps (Haeberli, 1983; Würmli et al., 2013; Vilímek et al., 2014a), most GLOFs reported from Austria occurred several decades or even centuries ago. Costa and Schuster (1988), Clague and Evans (2000) and O'Connor et al. (2001) mentioned two events: 1874 at Madatschferner Lake and 1890 at Galrittferner Lake. More information was compiled within the Glaciorisk European Project (2001–2003): Richter (1892) mentioned repeated GLOFs in the Ötztal Valley from 1600 to 1848. At least seven of these GLOFs were induced by surges of the Vernagtferner Glacier which dammed Rofen Valley and caused flooding of the Ötztal Valley. However, some GLOFs were also reported in the twentieth century (Kinzl, 1949; Patzelt and Nicolussi, 1991), of which probably the most catastrophic one occurred in 1932: an icefall from the Hochalmkees Glacier impacted Lake Preiml, producing an outburst flood resulting in three deaths (Fresacher, 1934). Recently, research has been conducted in Hohe Tauern, namely Obersulzbach and Unterer Eisboden by Geilhausen et al. (2012), Wiesenegger et al. (2013), and Koehler et al. (2014). Koehler et al. (2014) and Koehler (2014) also used a GIS-based approach to identify localities with a potential for future lake formation. However, no systematic inventory of lakes or analysis of the long-term evolution of lakes has yet been published for the Austrian Alps.

3. Materials and methods

3.1. Work flow

The work flow of the present study is illustrated in Fig. 2.

Fig. 1. The study area.