Glacier retreat is considered to be one of the most obvious manifestations of recent and ongoing climate change in the majority of glacierized alpine and high-latitude regions throughout the world. Glacier retreat itself is both directly and indirectly connected to the various interrelated geomorphological/hydrological processes and changes in hydrological regimes. Various types of slope movements and the formation and evolution of lakes are observed in recently deglaciated areas. These are most commonly glacial lakes (ice-dammed, bedrock-dammed, or moraine-dammed lakes).

“Glacial lake outburst flood” (GLOF) is a phrase used to describe a sudden release of a significant amount of water retained in a glacial lake, irrespective of the cause. GLOFs are characterized by extreme peak discharges, often several times in excess of the maximum discharges of hydrometeorologically induced floods, with an exceptional erosion/transport potential; therefore, they can turn into flow-type movements (e.g., GLOF-induced debris flows). Some of the Late Pleistocene lake outburst floods are ranked among the largest reconstructed floods, with peak discharges of up to 107 m3/s and significant continental-scale geomorphic impacts. They are also considered capable of influencing global climate by releasing extremely high amounts of cold freshwater into the ocean. Lake outburst floods associated with recent (i.e., post-Little Ice Age) glacier retreat have become a widely studied topic from the perspective of the hazards and risks they pose to human society, and the possibility that they are driven by anthropogenic climate change.

Despite apparent regional differences in triggers (causes) and subsequent mechanisms of lake outburst floods, rapid slope movement into lakes, producing displacement waves leading to dam overtopping and eventually dam failure, is documented most frequently, being directly (ice avalanche) and indirectly (slope movement in recently deglaciated areas) related to glacial activity and glacier retreat. Glacier retreat and the occurrence of GLOFs are, therefore, closely tied, because glacier retreat is connected to: (a) the formation of new, and the evolution of existing, lakes; and (b) triggers of lake outburst floods (slope movements).

Keywords: glacier retreat, GLOFs, natural hazards, slope movement, climate change
Introduction

Climate change, driven by natural and anthropogenic factors (see Crowley, 2000; Hansen et al., 1998; Stoffel et al., 2015), and its consequences have become a major issue in science (IPCC, 2013). Glacier ice loss—direct evidence of changing climatic conditions—is observed in the vast majority of glacierized areas around the world, including both high-latitude (arctic) and high-altitude (mountainous) regions (Barry, 2006; Overpeck et al., 1997). Glacier ice loss (glacier retreat) is accompanied by various processes, such as the formation and evolution of glacial lakes and lake outburst floods (Clague et al., 2012; Evans & Clague, 1994; O’Connor & Costa, 1993). Glacial lakes and glacial lake outburst floods (GLOFs) are attracting substantial scientific attention, for the following reasons: (a) erosion-accumulation interactions and sediment dynamics affect various spatial and temporal scales (Maizels, 1997; Morche et al., 2007; O’Connor et al., 2015); (b) they may provide a proxy data source for palaeoenvironmental reconstructions (Bauer et al., 2004; Carrivick & Tweed, 2013; Margold et al., 2011; O’Connor & Costa, 2004); and (c) they may represent a threat to society in settled areas (Carey, 2005; Carey et al., 2015; Carrivick & Tweed, 2016; Haeberli & Whiteman, 2015; Hewitt, 2016; Reynolds, 2003). Accordingly, Emmer et al. (2016A) showed an annual nonlinear increase in the number of scientific publications focusing on GLOFs recently.

For a comprehensive reference-style overview of the relation between glacier retreat and GLOFs, especially in the context of recent (post-Little Ice Age) climate change, special attention has to be given to the causes and mechanisms of lake outburst floods from different subtypes of glacial lakes, their hydrological and geomorphological significance, and their societal impacts.

Terminology

Korup and Tweed (2007) pointed out frequent terminological disunity among lake outburst flood-related studies. Table 1 defines the basic terminology.
## Table 1. Definition of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake outburst flood (LOF)</td>
<td>Sudden release of (part of) retained water from the lake</td>
<td>Evans and Clague (1994), and Korup and Tweed (2007)</td>
</tr>
<tr>
<td>Glacial lake outburst flood (GLOF)</td>
<td>Lake outburst flood originating from any subtype of glacial lake</td>
<td>Clague and O’Connor (2015), and Richardson and Reynolds (2000A)</td>
</tr>
<tr>
<td>Glacier flood</td>
<td>GLOF originating from ice-dammed lake</td>
<td>Haeberli (1983), and Richardson and Reynolds (2000A)</td>
</tr>
<tr>
<td>Jökulhlaup</td>
<td>Volcanic activity-induced GLOF (release of water melted by volcanic activity)</td>
<td>Richardson and Reynolds (2000A)</td>
</tr>
<tr>
<td>Cause of GLOF</td>
<td>Direct trigger of GLOF (see “Causes and Mechanisms of GLOFs”)</td>
<td>Emmer and Cochachin (2013)</td>
</tr>
<tr>
<td>Mechanism of GLOF</td>
<td>The way of water release from the lake (see “CAUSES AND MECHANISMS OF GLOFS”)</td>
<td>Emmer and Cochachin (2013)</td>
</tr>
</tbody>
</table>

## Recent Glacier Retreat and Formation of Lakes

### Climate Oscillations, Glaciation Cycle and Recent Glacier Retreat: An Overview

#### The Quaternary Context

The Quaternary period (2.588 million years ago to present—BP; Gibbard et al., 2010) is characterized by numerous climate alterations: ice ages (glacial periods) and interglacial events (Hewitt, 2000). In general, colder glacial periods are characterized globally by a larger glacierized area, while during interglacial events, the ice extent is lesser. Based on
Glacier Retreat and Glacial Lake Outburst Floods (GLOFs)

marine oxygen-isotope stages (MIS), over a hundred alternations of warmer and cooler
paleoclimates occurred during the Quaternary period (see also Bintanja et al., 2005;
Lisiecki & Raymo, 2005). The last glacial period occurred from approximately 110,000 to
11,700 BP; later on, the interglacial Holocene epoch began. The Holocene epoch is also
characterized by climate conditions variable in space and time (Mayewski et al., 2004)
and by the corresponding response of glaciers (Davis et al., 2009).

The Little Ice Age (LIA) and post-LIA Glacier Retreat

The last of the cooler periods in the Holocene (the Little Ice Age, LIA) occurred from
1400 to 1700 AD, with the greatest cooling over the extratropical Northern Hemisphere
(Mann et al., 2009). Post-LIA climate change, glacier ice loss, and glacier retreat have
been documented in most high-altitude (mountainous) and high-latitude (arctic) regions
(Barry, 2006; Overpeck et al., 1997). It was shown by Zemp et al. (2006) that Alpine glaci­
ers lost 35% of their area between 1850 and the 1970s and almost 50% between 1850
and 2000. An estimated two thirds of glacier ice were lost from Alpine glaciers during
this period. Numerous studies focus on estimation of recent glacier changes in a regional
context, for example in the Alps (Paul et al., 2004), the Andes (Vuille et al., 2008), and the
Himalayas (Bolch et al., 2012).

Formation and Evolution of Glacial Lakes

Glacier ice loss and retreat (see the section “CLIMATE OSCILLATIONS, GLACIATION CY­
CLE AND RECENT GLACIER RETREAT: AN OVERVIEW”) are often accompanied by the
formation and evolution of various subtypes of glacial lakes (Benn et al., 2012; Carrivick
& Tweed, 2013; Heckmann et al., 2016; Hutchinson, 1957; Kalff, 2002; Komori, 2008). The
subtypes include ice-dammed lakes, moraine-dammed lakes, and bedrock-dammed lakes.
Emmer et al. (2015A) showed that, from a long-term perspective, moraine- and bedrock-
dammed lakes evolve in relation to glacier retreat from the proglacial phase (direct con­
tact with the mother glacier tongue), through the glacier-detached phase (no direct con­
tact, some glaciers in the catchment), to the nonglacial phase (no glaciers in the catch­
ment). In general, these phases have a relation to the hazardousness of a given lake—lake
outburst floods. Lake outburst floods (see the section “GLACIAL LAKE OUTBURST
FLOODS”) are considered to be a specific evolutionary pattern that may occur never,
once, or repeatedly during the evolution of the lake (Carrivick & Tweed, 2016; Duissail­
lant et al., 2010; Kropáček et al., 2015), while various subtypes of glacial lakes (see Fig­
ure 1) are susceptible to different causes and subsequent mechanisms of lake outbursts
(see “CAUSES AND MECHANISMS OF GLOFS”). Carrivick and Tweed (2016) showed
that the majority of recorded GLOFs (70%) originated from ice-dammed lakes.
Ice-Dammed Lakes

Ice-dammed lakes are all situated on glaciers (supraglacial lakes; see Figure 1A), within glaciers (englacial lakes), underneath glaciers (subglacial lakes), or at the margins of glaciers (Benn & Evans, 1998). Formation of ice-dammed lakes was shown to be related to changing climatic conditions, glacier ice loss (Carrivick & Tweed, 2013), and surge-type glacier activity. Surge-type glaciers are characterized by periodic large flow accelerations, usually accompanied by terminus advance (Harrison et al., 2015), possibly leading to the blocking of a valley and lake formation: that is, blocking of a main valley by a surging glacier situated in a side valley, or blocking of a side valley by a surging glacier situated in the main valley (Costa & Schuster, 1988). Repeated surging-induced formation of ice-dammed lakes and subsequent outburst flooding has been documented (Anacona et al., 2015A; Haemming et al., 2014).

Moraine-Dammed Lakes

Moraine-dammed lakes are those retained by moraines (see Figure 1B), irrespective of the moraine type. Costa and Schuster (1988) showed that moraine-dammed lakes may
form in various topographical positions relative to damming moraines. Moraine-dammed lakes are typically found in mountainous areas, where they can reach a volume of up to $10^9$ m$^3$ (Kalff, 2002). It was shown that moraine-dammed lakes typically form in the initial phases of glacier retreat, when glaciers are retreating from their maximum positions delimited by moraines, e.g., LIA-moraine-dammed lakes dammed by moraines formed during the Little Ice Age (see “THE LITTLE ICE AGE (LIA) AND POST-LIA GLACIER RETREAT”; Clague & Evans, 2000; Emmer et al., 2015A). In some cases, moraine-dammed lakes may also form due to the melting of buried (dead) ice, e.g., the formation and evolution of Lake Imja in the 1980s and 1990s (Watanabe et al., 1995). Moraine-dammed lakes are susceptible both to dam overtopping and dam failure (see “CAUSES AND MECHANISMS OF GLOFS”) and the majority of GLOFs occur in the early (proglacial) phases of lake evolution, when lakes are exposed to calving processes and impact (displacement) waves (Clague & Evans, 2000; Emmer & Cochachin, 2013).

**Bedrock-Dammed Lakes**

Bedrock-dammed glacial lakes (embedded lakes; see Figure 1C) occupy depressions excavated by glacial activity (Kalff, 2002). Bedrock dams are composed of solid rocks and are considered stable (Huggel, 2004; Mergili & Schneider, 2011). Therefore, dam overtopping is the only mechanism of lake outburst floods from this glacial lake subtype (see “CAUSES AND MECHANISMS OF GLOFS”). In the observed post-LIA patterns of glacier retreat, the formation of moraine-dammed lakes dominates in the initial phases (retreat of the glaciers from their maximum extent, i.e., LIA moraines), while the formation of bedrock-dammed lakes dominates in later stages (LIA cirques located further upstream and bedrock overdeepenings; see Figure 2). Like moraine-dammed lakes, bedrock-dammed lakes are most susceptible to producing outburst floods in the young proglacial phase, when they are exposed to calving processes (Emmer et al., 2015A; see “FUTURE PERSPECTIVES”).
Future perspectives

Post-LIA glacier ice loss and retreat has been documented in the most of the mountain ranges worldwide (see “THE LITTLE ICE AGE (LIA) AND POST-LIA GLACIER RETREAT”) and this trend is expected to continue or even accelerate in the 21st century (Zemp et al., 2015). Glacier bed overdeepenings are modeled in order to identify locations that will host new, potentially hazardous lakes in future (Allen et al., 2016A; Haeberli et al., 2016A, 2016B; Linsbauer et al., 2016) in order to enhance GLOF risk management (see “HAZARD IDENTIFICATION, DELIMITATION OF POTENTIALLY AFFECTED AREAS AND ELEMENTS AT RISK”). Existing lakes change their susceptibility to outburst flood triggered by ice avalanche/calving processes in reaction to ongoing glacier retreat. The volume of water in them may also significantly change over time. Emmer et al. (2015A) showed that glacial lakes are generally most susceptible to producing an outburst flood at the end of their proglacial phase (Phase I) when they are exposed to calving processes and ice avalanches and lake volume is high, while they are less susceptible during the glacier-detached phase (Phase II), when susceptibility is decreased by fewer glaciers in the catchment and there is only residual susceptibility from other causes (e.g., impact waves from slope movements as a consequence of permafrost degradation), as expected in the stable nonglacial phase (Phase III; see Figure 3).
Glacial Lake Outburst Floods (GLOFs)

Glacial lake outburst flood (GLOF) is a set phrase used to describe a sudden release of water (or parts thereof) retained in the glacial lake, irrespective of glacial lake subtype, cause, or mechanism (Benn & Evans, 1998; Clague & Evans, 2000; Clague & O’Connor, 2015). GLOFs are complex processes with various possible causes and mechanisms of origin (see “CAUSES AND MECHANISMS OF GLOFS”) and have significant hydrological (see “HYDROLOGICAL SIGNIFICANCE”), geomorphological (see “GEOMORPHOLOGICAL SIGNIFICANCE”), and possibly even societal impacts (see “SOCIETAL IMPACTS”).

Causes and Mechanisms of GLOFs

A GLOF may have diverse causes and subsequent mechanisms (how water is released). Specific causes are related to specific mechanisms and not all their combinations are realistic scenarios. Moreover, specific subtypes of glacial lakes (see “FORMATION AND EVOLUTION OF GLACIAL LAKES”) are susceptible to specific causes and subsequent mechanisms of outburst floods. Numerous studies have investigated the causes of lake outburst floods for specific lake subtypes and regions (see Table 2); however, systematic investigation of the causes and mechanisms of GLOF, as well as database construction, are required (see Emmer et al., 2016A; Wirt et al., 2014) in order to better understand the complex processes and, in turn, provide more effective hazard and risk management (see “GLOF RISK MANAGEMENT”).

Figure 3. General evolution of a glacial lake in time. Change of lake volume, susceptibility to outburst flood caused by ice avalanche or calving processes, hazard, and glacier extent in the catchment are shown. Three phases are distinguished: Phase I—proglacial phase (direct contact with the glacier); Phase II—glacier-detached phase (no direct contact, some glaciers in the catchment); and Phase III—nonglacial (no glaciers in the catchment). Decrease in lake volume in Phases II and III represent lake infill by sediment, leading to lake extinction at the end of Phase III. Nonzero susceptibility to outburst flood in Phase III reflects triggers not related to presence of glaciers, e.g., slope movements from slopes with degraded permafrost. Modified from Emmer et al. (2015A).
Table 2. Examples of Studies Focusing on Analysis of the Causes and Mechanisms of Glacial Lake Outburst Floods (based partly on Emmer et al., 2016A)

<table>
<thead>
<tr>
<th>Study</th>
<th>Lake type*</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anacona et al. (2015A)</td>
<td>MDL, IDL</td>
<td>Chilean and Argentinean Andes</td>
</tr>
<tr>
<td>Clague and Evans (2000)</td>
<td>MDL</td>
<td>Canadian Cordillera</td>
</tr>
<tr>
<td>Emmer and Cochachin (2013)</td>
<td>MDL</td>
<td>Cordillera Blanca (Peru), Himalaya, North American Cordillera</td>
</tr>
<tr>
<td>Ding and Liu (1992)</td>
<td>MDL, IDL</td>
<td>Tibet, Himalaya</td>
</tr>
<tr>
<td>Haeberli (1983)</td>
<td>IDL</td>
<td>Swiss Alps</td>
</tr>
<tr>
<td>Harrison et al. (2006)</td>
<td>MDL</td>
<td>Patagonian Andes</td>
</tr>
<tr>
<td>Hewitt (1982)</td>
<td>IDL</td>
<td>Karakoram</td>
</tr>
<tr>
<td>Ives et al. (2010)</td>
<td>MDL</td>
<td>Hindu Kush-Himalaya region</td>
</tr>
<tr>
<td>O’Connor et al. (2001)</td>
<td>MDL</td>
<td>North American Cordillera</td>
</tr>
<tr>
<td>Richard and Gay (2004)</td>
<td>All</td>
<td>Europe (GLACIORISK project)</td>
</tr>
<tr>
<td>Walder and Costa (1996)</td>
<td>IDL</td>
<td>Global inventory</td>
</tr>
<tr>
<td>Xu et al. (2015)</td>
<td>IDL</td>
<td>Northern Norway</td>
</tr>
</tbody>
</table>

Notes: MDL= moraine-dammed lakes; BDL= bedrock-dammed lakes; IDL= ice-dammed lakes.
(* ) While great attention is paid to moraine-dammed and ice-dammed lakes, bedrock-dammed lakes are often neglected.

Based on a literature review (Clague & Evans, 2000; Costa & Schuster, 1988; Emmer & Cochachin, 2013; Grabs & Hanisch, 1993; Mergili & Schneider, 2011; Richardson & Reynolds, 2000A; Zapata, 2002), the following direct causes of glacial lake outburst floods (C1–C7; see Table 3 and Figure 4) were documented:

(C1) Rapid slope movement into the lake  
(C2) Heavy rainfall/snowmelt  
(C3) Cascading processes (flood from a lake situated upstream)  
(C4) Earthquake  
(C5) Melting of ice incorporated in dam/forming the dam (including volcanic activity-triggered jökulhlaups)  
(C6) Blocking of subsurface outflow tunnels (applies only to lakes without surface outflow or lakes with a combination of surface and subsurface outflow)  
(C7) Long-term dam degradation.

Figure 4. Causes of GLOFs. Part (A) shows causes (C1) to (C3), which are relevant for all glacial lake subtypes (see “FORMATION AND EVOLUTION OF GLACIAL LAKES”); part (B) shows a longitudinal section of the dam and causes (C4) to (C7), which are relevant only for specific glacial lake subtypes (see Table 3). Based on Clague and Evans (2000), Costa and Schuster (1988), Emmer and Cochachin (2013), Grabs and Hanisch (1993), Mergili and Schneider (2011), Richardson and Reynolds (2000A), and Zapata (2002).
Table 3. Causes (C4) to (C7) and Relevant Specific Glacial Lake Subtypes

<table>
<thead>
<tr>
<th>Cause</th>
<th>Relevant glacial lake subtype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake (C4)</td>
<td>MDL, IDL</td>
</tr>
<tr>
<td>Melting of ice incorporated in dam/forming the dam (C5)</td>
<td>IDL, Ice-cored MDL</td>
</tr>
<tr>
<td>Blocking of subsurface outflow tunnels (C6)</td>
<td>IDL, MDL with subsurface outflow tunnels</td>
</tr>
<tr>
<td>Long-term dam degradation (C7)</td>
<td>MDL, IDL</td>
</tr>
</tbody>
</table>

Note: MDL = moraine-dammed lakes; IDL = ice-dammed lakes.

In terms of mechanisms of GLOFs (how water is released; see Figure 5), two are distinguished:

(M1) Dam overtopping by a displacement wave (major part of released water flows over the dam without significant damage to the dam itself). Dam overtopping is a possible mechanism for all glacial lake subtypes and the only possible mechanism for bedrock-dammed lakes.

(M2) Dam failure (a major part of the water is released by failure of the dam, including: direct rupture of the dam, incision and breaching, and piping and seepage). Dam failure is possible only for moraine- and ice-dammed lakes.

Obviously, not all direct causes (C1-C7) are tied to both mechanisms (M1-M2) of GLOFs (see Table 4). Moreover, different mechanisms involve different glacial lake subtypes. While dam overtopping is the only possible GLOF mechanism for bedrock-dammed lakes, dam failure is possible for only moraine- and ice-dammed lakes. In some specific cases, dam overtopping is followed by dam failure (dam overtopping-induced dam failure; Kershaw et al., 2005). An example is the two-phase outburst flood from the moraine-dammed Queen Bess Lake in British Columbia, Canada. An ice avalanche into the lake caused dam overtopping (first phase) and increased discharge later on caused erosion of the surface outflow channel, its incision, and consequently dam failure (second phase). The majority of the flood volume was released during the overtopping phase (Kershaw et al., 2005).
Figure 5. Schematic mechanisms of GLOFs. Part (A) shows mechanism M1—dam overtopping; part (B) shows mechanism M2—dam failure (subtype incision and breaching; B); part (C) shows mechanism M2—dam failure (subtype direct rupture; R); and part (D) shows mechanism M2—dam failure (subtype piping and seepage; P). Direct rupture is a fast dynamic process, on the order of seconds to minutes, while piping and seepage are a gradual process, taking hours to days.
<table>
<thead>
<tr>
<th>Causes</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dam overtopping</td>
</tr>
<tr>
<td>Rapid slope movement into the lake (C1)</td>
<td>D</td>
</tr>
<tr>
<td>Earthquake (C2)</td>
<td>N/A</td>
</tr>
<tr>
<td>Heavy rainfall/snowmelt (C3)</td>
<td>O</td>
</tr>
<tr>
<td>Melting of ice incorporated in/ forming the dam (C4)</td>
<td>O</td>
</tr>
<tr>
<td>Cascading processes (C5)</td>
<td>D</td>
</tr>
<tr>
<td>Blocking of subsurface outflow tunnels (C6)</td>
<td>O</td>
</tr>
<tr>
<td>Long term dam degradation (C7)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Notes: Dam overtopping: N/A = nonrealistic scenario for the given cause; D = dam overtopping by displacement wave(s); O = dam overtopping by new lake outflow(s) (not in the form of displacement wave). Dam failure: R = direct rupture; B = incision and breaching; P = piping and seepage.

**Rapid Slope Movement into the Lake (C1)**

When they hit the lake, various types of fast slope movements (slides, falls, avalanches, and flows; see Figure 6) may cause a lake outburst flood. Fast slope movement into the lake produces displacement wave(s) (Richardson & Reynolds, 2000A) which, in turn, may: overtop the dam (all glacial lake subtypes) or cause direct rupture of the dam (moraine and ice dams). Various types of fast slope movements (especially ice avalanches) were shown to be the most frequent documented cause of GLOFs from moraine- and bedrock-dammed lakes in the Himalayas and Andes (Aanacona et al., 2015A; Emmer & Cochachin, 2013; Richardson & Reynolds, 2000A).

By analyzing 2002 GLOFs from Lake Safuna Alta, Cordillera Blanca, Peru, Hubbard et al. (2005) showed that displacement waves may overflow the dam despite tens of meters of...
Glacier Retreat and Glacial Lake Outburst Floods (GLOFs)

dam freeboard (80 m in this case). Numerous examples of rapid slope movements causing GLOFs have been documented from all around the world (Emmer & Cochachin, 2013). In the face of climate change (see “RECENT GLACIER RETREAT AND FORMATION OF LAKES”), slope movements are considered to have increased in high mountain regions (see Dietrich & Krautblatter, 2016; Haeberli et al., 2016A; Huggel et al., 2012; Stoffel & Huggel, 2012). These are slope movements directly related to glacier ice loss—ice avalanches and ice/rock avalanches (see Alean, 1985; Richardson & Reynolds, 2000A; see Figure 3A); diverse types of slope movements associated with permafrost degradation (Haeberli, 2013; Haeberli et al., 2016A); landslides in recently deglaciated moraine slopes that have lost the support of the glacier, which subsequently downwasted and retreated (Klimeš et al., 2016; see Figure 3B); and debutressing-induced rockfall/rockslide (Cossart et al., 2008; Evans & Clague, 1994; McColl, 2012).

**Figure 6.** Examples of potential slope movements, which may trigger glacial lake outburst floods. Part (A) shows an example of a small-magnitude ice avalanche from Palcaraju massif, Cordillera Blanca, Peru (6,274 m a.s.l.) on June 5, 2012. Part (B) shows a displaced block of moraine hanging above the lake (Lake Palcacocha, Cordillera Blanca, Peru). Note the persons for the scale (in circle). All photos: Author.

Heavy Rainfall/Snowmelt (C2)

Increased water inflow into a lake caused by heavy rainfall or intense snowmelt (or a combination thereof) causes increased discharge (outflow) from the lake. In the case of moraine-dammed lakes (and possibly also ice-dammed lakes), increased discharge may lead to increased erosion and incision of the outflow channel into the dam body, which in turn may lead to increased discharge and dam failure (positive feedback; Yamada, 1998). Several GLOFs from British Columbia in Canada and the Cascade Range in the United States are attributed to heavy rainfall, such as the GLOF from Tide Lake in the 1920s (Clague & Evans, 2000) and that from the lake beneath Deller glacier (O’Connor et al., 2001). The 2013 GLOF from Lake Chorabari, Garhwal Himalaya, India (Kedarnath disaster) was also caused by heavy rainfall (Allen et al., 2016B; Dobhal et al., 2013; see also “SOCIETAL IMPACTS”). Heavy rainfall may also act as an indirect trigger of GLOFs when rainfall triggers slope movement into the lake (Emmer & Cochachin, 2013).

Cascading Processes (Flood from a Lake Situated Upstream; C3)

Within individual valleys, glacial lakes are often grouped into cascading systems (Hutchinson, 1957; Kalff, 2002). GLOFs originating in upstream lakes may, in turn, cause GLOFs in lakes downstream. Downstream lakes may amplify the intensity and magnitude of a flood further downstream (increase the flood volume by releasing retained water), or they may mitigate the intensity and magnitude of the flood (reduce the flood volume by...
retention capacity; see Emmer & Juřicová, in print). These complex chain process interactions, which are predicted to increase their frequency in future, have recently attracted significant scientific attention (Haeberli et al., 2016B; Mergili et al., FORTHCOMING; Westoby et al., 2014; Worni et al., 2014).

**Earthquake (C4)**

The direct mechanism of earthquake-triggered lake outburst floods is dam rupture (moraine or ice dam), or earthquake-induced piping and subsequent dam failure (moraine dams; Lliboutry et al., 1977). A limited number of earthquake-triggered lake outburst floods are documented in the literature (Emmer & Cochachin, 2013). A well-known example of an earthquake-triggered lake outburst flood is the GLOF from Lake Safuna Alta, Cordillera Blanca, Peru. A heavy earthquake on May 31, 1970, changed the internal structure of the dam and piping occurred (Lliboutry et al., 1977). The lake water level decreased by 38 m, with release of a major part of the $4.9 \times 10^6$ m$^3$ of water retained in the lake at that time. Another example is the Late Pleistocene earthquake-triggered moraine dam failure and outburst flood from Lake Zurich, Switzerland; however, in this case, it is not clear whether the lake outburst flood was caused directly by an earthquake or indirectly by earthquake-triggered slope movement(s) into the lake (for more details, see Strasser et al., 2003). Besides earthquake-triggered slope movements into the lake, another possibility for indirect earthquake-triggered lake outburst floods is earthquake-induced blockage of outflow tunnels, subsequent water level increase, and failure due to the increased hydrostatic pressure or overtopping. The Gorkha earthquake in Nepal in 2015 ($M = 7.8$), however, documented that not every strong earthquake in high mountain areas necessarily leads to lake outburst floods (Kargel et al., 2016). Earthquake-triggered GLOFs are, actually, quite rare compared to GLOFs with other documented triggers (see Emmer & Cochachin, 2013).

**Melting of Ice Incorporated in Dam/Forming the Dam (Including Volcanic Activity-Triggered Jökulhlaups; C5)**

The C5 trigger occurs in ice-dammed lakes, possibly in moraine-dammed lakes if the dam contains an ice lens (so called “buried” or “dead” ice; e.g., Kruger & Kjaer, 2000; Schomacker, 2008), and in lakes dammed in an arid permafrost environment (e.g., lakes dammed by rock glaciers). Permafrost thawing and degradation may, therefore, play an important role in lake evolution and also in the occurrence of outburst flood due to permafrost degradation-induced slope movements (Haeberli, 2013; Haeberli et al., 2016A; see “RAPID SLOPE MOVEMENT INTO THE LAKE (C1)”). Walder and Costa (1996) showed that flooding from ice-dammed lakes is associated with drainage through a tunnel incised into the basal ice, ice-marginal drainage with mechanical failure of part of the ice dam, or a combination of the two. A specific type of outburst flood related to volcanic activity is called jökulhlaup (volcanic activity-induced lake outburst flood, see Table 1; Bjornsson, 2001; Tweed & Russel, 1999). In the case of a lake dammed by an ice-cored moraine, the melting of the ice cores may lead to structural disintegration of the dam body and piping, or dam subsidence, with formation of new surface outflow(s), and incision and breaching (see Richardson & Reynolds, 2000B).
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Blocking of Subsurface Outflow Tunnels (C6)
Emmer and Cochachin (2013) showed that glacial lakes with subsurface outflow (only possible for moraine- or ice-dammed lakes) are susceptible to blocking of the outflow tunnels by: (a) sediment brought into the lake by its tributaries, (b) slope movements (e.g., slopes on the inner slopes of moraine dams), (c) freezing of outflow channels (O’Connor et al., 2001), and (d) change in the internal structure of the dam caused by an earthquake (Lliboutry et al., 1977). If the subsurface outflow tunnel(s) are blocked, the level of the lake starts to rise, which may, in turn, lead to dam rupture triggered by increased hydrostatic pressure (Richardson & Reynolds, 2000A), or dam overtopping, incision, and failure. An example of failure caused by blocking of subsurface outflow tunnels is the moraine dam failure event at Lake Zhangzhanbo in Tibet on July 11, 1981 (Ding & Liu, 1992; Yamada, 1998).

Long-Term Dam Degradation (C7)
Spontaneous moraine (icy) dam failure without any evident (dynamic) cause may be explained as a co-action of long-term degrading processes (i.e., dam self-destruction; Yamada, 1998; Emmer & Cochachin, 2013), such as successive changes in the internal structure of the dam leading to piping and failure or hydrostatic pressure. Several GLOFs from the Hindu-Kush Himalaya region have been attributed to this cause (Ives et al., 2010; Yamada, 1998), such as the GLOF from Lake Lugge Tsho, Bhutan Himalaya, in 1994, which was caused by increased hydrostatic pressure induced by basal ice melting that resulted in deepening of the lake (Watanabe & Rothacher, 1996).

Hydrological Significance
GLOFs represent extreme hydrological processes in terms of flood volume (V), peak discharge (Q_max), and the ratio of peak discharge to mean flow rate (Clague & O’Connor, 2015). The flood volume has exceeded thousands of cubic kilometers in reconstructed paleo-GLOFs, such as the 3,000 km³ outburst of the ice-dammed Lake Vitim in Siberia (Margold et al., 2011). Floods with volumes on the order of several km³ have recently occurred, such as the 3.2 km³ jökulhlaup from the subglacial Lake Grímsvötn in Iceland in 1997 (Gudmundsson et al., 1997), or the 0.23 km³ outburst from the moraine-dammed Laguna del Cerro Largo (Chile) in 1989 (Hauser, 1993), which is considered to be the largest documented GLOF originating from a moraine-dammed lake (Clague & Evans, 2000).

In terms of peak discharge, documented/reconstructed GLOFs are ranked among the world’s largest floods (O’Connor & Costa, 2004). Examples are Late Pleistocene GLOFs from ice-dammed lakes, such as the GLOF from Lake Kuray (Altai, Russia), with a peak discharge of 1.8 · 10^7 m³ s⁻¹ (Baker et al., 1993), or the GLOF from Lake Missoula (United States), with a peak discharge of 1.7 · 10^7 m³ s⁻¹ (O’Connor & Baker, 1992). An outburst flood from Lake Agassiz with a discharge of 1.2 · 10^6 m³ s⁻¹ (Smith & Fischer, 1993) is considered to be one of the largest floods in the Holocene (O’Connor & Costa, 2004). Peak discharges from recent (post-LIA) GLOFs have been documented up to 10^5 m³ s⁻¹ in
some cases (Walder & O’Connor, 1997) and up to $3 \cdot 10^5 \text{ m}^3 \text{s}^{-1}$ in the case of recent jökulhlaups (e.g., Katla jökulhlaup in 1918; Tomasson, 1996). Peak discharge is often estimated using lake-volume-based empirical equations (Costa, 1985; Huggel et al., 2004); it is, however, also strongly influenced by the mechanism of the outburst flood (Haeberli, 1983), the topography, and the distance from the lake (Costa, 1985; Schwanghart et al., 2016), which directly influences downstream hazard of GLOF (see “GLOF RISK MANAGEMENT”).

GLOFs are also characterized by an extremely high ratio of peak discharge to mean flow rate (Clague & Evans, 2000; Smith et al., 2014), which may be many times greater than the peak discharge of “normal” rainfall/snowmelt-induced floods. Cenderelli and Wohl (2001) showed that the peak discharges of lake outburst floods in the Mt. Everest region were up to 60 times greater than seasonal high-flow floods. Due to the extreme peak discharges, GLOFs are also characterized by extremely high erosion and transportation potential (see “GEOMORPHOLOGICAL SIGNIFICANCE”). Lake outburst floods may, therefore, easily transform into flow-type movement, such as debris flows (O’Connor et al., 2001) with a density of approximately $1.5 \text{ t/m}^3$ (Yamada, 1998) and an extraordinary damage potential (see “SOCIETAL IMPACTS”).

Possible Impacts of Major GLOFs on the Circulation of the Oceans and Global Climate

Major paleolake outburst floods from ice-dammed lakes into oceans are considered able to change circulation patterns and, in turn, influence the global climate (Barber et al., 1999; Bond et al., 1992; Clarke et al., 2004; Hemming, 2004). It has been shown that a sudden release of an extremely large amount of cold freshwater into the ocean (a so-called Heinrich event; Hemming, 2004) correlated well with global-scale climate changes in the Late Pleistocene and Holocene. A well-known example is the major outburst flood from the ice-dammed Lake Agassiz into the Labrador Sea, 8,200 BP (Bauer et al., 2004; Clarke et al., 2004), which reduced the salinity of the surface layer of the northern Atlantic Ocean and subsequently altered ocean circulation. This event is considered to have initiated the most abrupt cold event in the Holocene (Barber et al., 1999; Clark et al., 2001; Teller et al., 2002).

Geomorphological Significance

Reflecting hydrological significance of GLOFs, it was shown by Evans and Clague (1994), Costa and O’Connor (1995), Richardson (2010), and Clague et al. (2012) that GLOFs are among the most significant geomorphological processes in high mountain areas during periods of glacier ice loss. Geomorphological impacts are directly tied to the stream power of floods (Benito, 1997; Desloges & Church, 1992; Krapesch et al., 2011). Baker et al. (1993) estimated that the stream power per unit area of the Late Pleistocene flood in Altay, Russia, was $10^5 \text{ W m}^{-2}$ for subcritical flow and $10^6 \text{ W/m}^2$ for supercritical flow. Cenderelli and Wohl (2003) estimated that the stream power of the recent Himalayan GLOFs was up to $5 \cdot 10^4 \text{ W m}^{-2}$. GLOFs, therefore, have significant potential to influence erosion-accumulation interactions and sediment dynamics on various spatial scales (Cen-
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derelli & Wohl, 2003; Morche & Schmidt, 2012). Late Pleistocene outburst floods from ice-dammed lakes (such as Lake Missoula; Baker & Bunker, 1985) have had significant continental-scale geomorphic impacts (Mangerud et al., 2004), which are identifiable in the field even after tens of thousands of years (Baker et al., 1993).

Recent (post-LIA) GLOFs are characterized by a reach of up to hundreds of kilometers in some cases, with rapidly decreasing geomorphological impacts with increasing distance from the lake and strong attenuation of peak discharge (Anacona et al., 2015B; Cenderelli & Wohl, 2003; Hewitt, 2016; Richardson & Reynolds, 2000A). Erosional symptoms and landforms related to GLOFs are typically bank and depth erosion of the stream/river channel, meander shift, and, in some cases, replacement of existing channels and formation of new ones (accompanied by the formation of abandoned channels) or formation of erosional terraces (Robitaille & Dubois, 1995; Thorndycraft et al., 2016; see Figure 7). Failed moraine dams are also considered to be specific landforms associated with GLOFs (Clague & Evans, 2000).

Richardson and Reynolds (2000A) showed that recent GLOFs are capable of transporting boulders with diameters of up to several meters and an estimated mass of 200 tons. Entrainment in the order of $10^8$ m$^3$ has been documented, as in the 1996 Grimsvötn (Iceland) GLOF, while the mean specific sediment yield may reach $10^7$ t/km$^2$/yr for a short time (Korup, 2012; Stefánsvötn & Gislason, 2005). Korup (2012) further showed that extreme specific sediment yields (> $10^7$ t/km$^2$/yr) in mountain environments are typically linked to extreme events, such as volcanic eruptions, mass movements, or lake outburst floods. Accumulational landforms vary from interchannel sand bars and bank boulder accumulation to outwash fans covering large piedmont areas (Bernard et al., 2006; Robitaille & Dubois, 1995; see Figure 8). By analyzing the 2012 GLOF from lake No. 513 (Peru), Vilímek et al. (2015) showed that the geomorphological consequences of GLOFs vary significantly across the longitudinal valley profile, reflecting general topographical conditions and the amount and grain size of sediment available for entrainment.
Figure 8. Examples of accumulation landforms related to glacial lake outburst floods in the Santa Cruz valley, Cordillera Blanca, Peru (see Emmer et al., 2014; Mergili et al., FORTHCOMING). Part (A) shows an outwash plain downstream from the steep part of the valley (see Figure 4A); the affected area is approximately 600 m wide. Part (B) shows a fine-grained accumulation in the flat part of the valley further downstream; the maximum accumulation thickness was up to 2 m. Note the person for scale. All photos: Author.

Societal Impacts

Carrivick and Tweed (2016) compiled a world inventory of the societal impacts (deaths and property and infrastructure destruction and disruption) of documented GLOFs (1,348 individual events from 332 sites). It was shown that, for 36% of the sites, a GLOF had some societal effects, and the overall number of fatalities exceed 12,000, of which most were in South America (Peru) and Central Asia (Nepal and India). It was further shown that high-magnitude GLOFs are quite rare, but may have disastrous consequences if they occur in settled areas. Two examples of significant post-LIA GLOFs are the Lake Palcacocha moraine dam failure in 1941 (Cordillera Blanca, Peru) and the Lake Chorabari moraine dam failure (Kedarnath GLOF disaster) in 2013 (Garhwal Himalaya, India). According to Carrivick and Tweed (2016), these two events are responsible for 88% of the fatalities caused by documented GLOFs.

Lake Palcacocha (December 13, 1941)

Lake Palcacocha (9°23′52″ S, 77°22′52″ W) is situated at the head of the Cojup valley, beneath the southern slopes of the Palcaraju massif (6,274 m a.s.l.) and western slopes of the Pucarana massif (6,156 m a.s.l.), Cordillera Blanca, Peru (see Figure 9). Dam failure occurred at 6:45 a.m. on December 13, 1941 (Zapata, 2002). Oppenheim (1946) mentioned two alternative causes: seepage-induced dam failure, and an ice avalanche into the lake initiating breaching; however, no direct evidence for either of these potential causes was recorded. The pre-failure lake water level elevation was 4,610 m a.s.l., which decreased by 47 m during the event (i.e., 47 m breach depth). Material eroded from the dam formed a 300-m wide and 1,080-m long fan (see Figure 9B and 9C).

The volume of released water was estimated to be between $8 \cdot 10^6$ m$^3$ (Evans & Clague, 1994) and $10 \cdot 10^6$ m$^3$ (Vilímek et al., 2005). The outburst flood following the failure of the Lake Palcacocha dam subsequently caused failure of the dam on landslide-dammed Lake Yircacocha situated in the valley 8.2 km downstream, increasing the overall flood...
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The volume of water released from Lake Palcacocha was estimated to be $0.43 \times 10^6 \text{ m}^3$. The resulting flood wave caused intense entrainment of loose sediment, transforming the outburst flood into debris flow movement (Das et al., 2015), which traveled downstream to the village of Kedarnath, situated 1,500 m from the lake (300 m vertical difference).
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Besides the numerous fatalities (Das et al., 2015), the event had significant impacts in the village of Kedarnath, an important holy site. The northwest part of the village was directly affected by the GLOF-induced debris flow and suffered the heaviest damage; 138 of the 259 structures were obliterated and 56 structures were damaged. Only one quarter of the village was not affected. In addition, indirect economic losses due to decreased tourism were registered.

GLOF Risk Management

In the basic concept of natural hazards and risks, the risk of a GLOF is explained as a result of: hazard of GLOF (probability of the occurrence of the flood described by specific characteristics, such as flood volume, peak discharge, spatial extent, etc.), and the vulnerability of elements in potentially affected areas. This concept has been modified in various ways in relation to GLOFs or GLOF-induced debris flows, by Ciurean et al. (2016), Emmer et al. (2014), Fuchs (2008), Hegglin and Huggel (2008), Huggel et al. (2004), Richardson (2010), and Shrestha (2010). Effective GLOF risk management includes two general steps: hazard identification and delimitation of potentially affected areas, including identification of elements at risk; and risk minimization by hazard reduction and vulnerability reduction.

Hazard Identification and Delimitation of Potentially Affected Areas and Elements at Risk

The first step in GLOF risk management is reliable identification of hazardous lakes, i.e., lakes susceptible to producing lake outburst floods (Haeberli & Whiteman, 2015; Kääb et al., 2005). Unlike “classical” hydrometeorologically induced floods, GLOFs are rarely repeated events and their occurrence usually cannot be derived from return periods; furthermore, the hazard changes over time, reflecting the evolution of a given lake (see “FUTURE PERSPECTIVES”). To identify hazardous lakes, a number of predominantly remotely sensed data-based methods were developed for diverse environments. Reflecting the different dominant causes of GLOFs in different environments (Emmer & Cochachin, 2013), regionally based methods seem to provide the most plausible solution. Examples are methods designed for the Hindu Kush-Himalaya region (Ives et al., 2010; Rounce et al., 2016; Wang et al., 2011; Wang & Jiao, 2015), Tien Shan (Bolch et al., 2011; Zaginaev et al., 2016), the Cordillera Blanca, Peru (Emmer & Vilímek, 2014; Reynolds, 2003), British Columbia (McKillop & Clague, 2007A,B), and the Swiss Alps (Huggel et al., 2002, 2004). All the methods are based on assessment of selected characteristics indicating increased likelihood of lake outburst floods (see Emmer & Vilímek, 2013, 2014), which might be grouped according to: dam characteristics (e.g., dam type, dam freeboard, dam geometry), lake characteristics (e.g., lake area, lake volume), and characteristics of lake surrounding (e.g., characteristics of the glaciers and characteristics of slopes facing the lake, such as presence and condition of permafrost).
Delimitation of potentially affected areas and subsequent identification of elements at risk are usually based on various modeling approaches, use of digital elevation models, and predefined scenarios of triggering events (e.g., slope movement of a given volume into the lake), as well as validation on previous GLOFs (Anacona et al., 2015; Carey et al., 2012; Kropáček et al., 2015; Pitman et al., 2013; Somos-Valenzuela et al., 2016; Westoby et al., 2015; Worni et al., 2014; Zhang & Liu, 2015). Once hazardous lakes are identified and potentially affected areas are delimited, elements at risk are revealed. Naturally, these approaches usually have a degree of uncertainty as well as potential drawbacks (Mergili, 2016; Westoby et al., 2014); however, they prove to be useful tools in GLOF risk management (Anacona et al., 2015B; Huggel et al., 2004; Kääb et al., 2005). Consequently, GLOF risk mitigation is generally feasible through the application of hazard and vulnerability reduction.

Hazard and Vulnerability Reduction

GLOF hazard and vulnerability reduction (risk mitigation) is a highly challenging task, because GLOFs may have exceptional peak discharge and stream power (see “HYDROLOGICAL SIGNIFICANCE”), as well as erosion and transport potential (see “GEOMORPHOLOGICAL SIGNIFICANCE”). Diverse structural GLOF hazard mitigation measures have been applied at selected lakes around the world: in the Swiss Alps (Haeberli et al., 2001; Lichtenhahn, 1971), Scandinavia (Grabs & Hanisch, 1993), Hindu Kush-Himalaya region (Ives, 1986; Kattelmann, 2003; Richardson, 2010), and the Cordillera Blanca, Peru (Carey, 2005; Emmer et al., 2016B; Portocarrero, 2014; Reynolds et al., 1998). Measures aimed at the prevention or mitigation of the magnitude of the flood (dam remediation; e.g., artificial dams, tunnels, open cuts, concrete outflows; see Emmer et al., 2016B) and measures aimed at diverting the flood wave from vulnerable areas (downstream flood-protection measures, such as flood-protection walls; see Figure 10A) are generally distinguished. Vulnerability in areas potentially affected by GLOFs (or GLOF-induced debris flows) is reduced by diverse measures, which are generally divided into structural measures (e.g., construction improvements increasing the resilience of elements at risk) and nonstructural measures, such as early warning systems (see Figure 10B), information campaigns, insurance, etc. (Ciurean et al., 2016; Fuchs, 2008; Hegglin & Huggel, 2008; Shrestha, 2010). The increased vulnerability of communities in high mountains areas (e.g., Andes, Hindu Kush-Himalaya region) is often linked to low adaptive capacity (Berkes, 2007; Carey et al., 2015; Cutter et al., 2008; Hewitt, 2016).
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Conclusions and Hindsight

Glacier ice loss and retreat driven by climate change have become a broadly studied topic in different environments throughout the world because glacier retreat is frequently accompanied by the formation and evolution of lakes, most commonly glacial lakes (ice-dammed lakes, moraine-dammed lakes, and bedrock-dammed lakes). A significant number of glacial lakes have formed within areas that have become deglaciated since the end of the Little Ice Age—the period of the last significant glacier advance. Such lakes are commonly dynamically evolving entities, generally with relatively short longevity (Costa & Schuster, 1988). GLOFs are a specific evolutionary pattern of a glacial lake; they involve the sudden release of (a part of) the retained water from a lake, irrespective of the cause, mechanism, and glacial lake subtype involved (Korup & Tweed, 2007).

GLOFs are highly complex phenomena, which may be triggered by diverse processes (causes): (C1) rapid slope movement into the lake; (C2) heavy rainfall/snowmelt; (C3) cascading processes (flood from a lake situated upstream); (C4) earthquake; (C5) melting of ice incorporated in the dam/forming the dam (including volcanic activity-triggered jökulhlaups); (C6) blocking of subsurface outflow tunnels (only in the case of lakes with subsurface outflow); (C7) long-term dam degradation (Clague & Evans, 2000). Causes (C1) and (C5) are both directly or indirectly linked to glacier retreat. Causal processes are potentially followed by two diverse mechanisms of water release (lake outburst flood)—dam overtopping by a displacement wave (where the majority of the released water flows over the dam without damaging it) and dam failure (where the majority of the water is released by failure of the dam, including direct rupture of the dam, incision and breaching, piping and seepage). Specific causes are linked to specific mechanisms, and, moreover, specific glacial lake subtypes, and even triggering events of relatively small magnitudes may lead to significant and destructive processes.

GLOFs are characterized by hydrological significance—peak discharges of GLOFs can be far higher than those of hydrometeorologically induced floods, resulting in exceptional erosion and transport potentials; therefore, they often transform into flow-type movement (e.g., debris flow) if erodible material is available. The documented major GLOFs also caused significant geomorphological changes. Due to these characteristics, GLOFs clearly may also have catastrophic societal impacts, if they affect settled areas. Fatal GLOFs...
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have been documented in the Andes and in the Hindu Kush-Himalaya region (Carrivick & Tweed, 2016). With ongoing climate change, the risk of GLOFs has been predicted to increase, due to the formation and evolution of different subtypes of new, potentially hazardous, glacial lakes, often hand in hand with both the increasing vulnerability of the elements at risk and low adaptive capacity.

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