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Review

Coupling glacial lake impact, dam breach, and flood processes: A modeling perspective

Raphael Worni [a,b], Christian Huggel [a,d], John J. Clague [c], Yvonne Schaub [d], Markus Stoffel [a,b,*]

[a] Institute for Environmental Sciences, University of Geneva, Switzerland
[b] Institute of Geological Sciences, University of Bern, Switzerland
[c] Department of Geography, University of Zurich, Switzerland
[d] Department of Earth Sciences, Simon Fraser University, British Columbia, Canada

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ABSTRACT

Glacial lake outburst floods (GLOFs) are highly mobile mixtures of water and sediment that occur suddenly and are capable of traveling tens to hundreds of kilometers with peak discharges and volumes several orders of magnitude larger than those of normal floods. They travel along existing river channels, in some instances into populated downstream regions, and thus pose a risk to people and infrastructure. Many recent events involve process chains, such as mass movements impacting glacial lakes and triggering dam breaches with subsequent outburst floods. A concern is that effects of climate change and associated increased instability of high mountain slopes may exacerbate such process chains and associated extreme flows. Modeling tools can be used to assess the hazard of potential future GLOFs, and process modeling can provide insights into complex processes that are difficult to observe in nature. A number of numerical models have been developed and applied to simulate different types of extreme flows, but such modeling faces challenges stemming from a lack of process understanding and difficulties in measuring extreme flows for calibration purposes. Here we review the state of knowledge of key aspects of modeling GLOFs, with a focus on process cascades. Analysis and simulation of the onset, propagation, and potential impact of GLOFs are based on illustrative case studies. Numerical models are presently available for simulating impact waves in lakes, dam failures, and flow propagation but have been used only to a limited extent for integrated simulations of process cascades. We present a spectrum of case studies from Patagonia, the European Alps, central Asia, and the Himalayas in which we simulate single processes and process chains of past and potential future events. We conclude that process understanding and process chain modeling need to be strengthened and that research efforts should focus on a more integrative treatment of processes in numerical models.

1. Introduction

Glacier thinning and retreat over the past century has led to the formation and growth of lakes at the margins of glaciers and moraines in all high mountain regions of the world (IPCC, 2012). Sudden draining of these lakes has caused disasters in the Andes (Lliboutry et al., 1977; Reynolds et al., 1998; Carey, 2005; Hegglin and Huggel, 2008), Caucasus and central Asia (Aizen et al., 1997; Narama et al., 2006), the Himalayas (Vuichard and Zimmermann, 1987; Richardson and Reynolds, 2000a; Xin et al., 2008), Iceland (Björnsson, 2002; Russell et al., 2006), North America (Post and Mayo, 1971; Mathews and Clague, 1993; Clague and Evans, 2000; Geertsema and Clague, 2005; Kershaw et al., 2005), and the European Alps (Haeberli, 1983; Haeberli et al., 2001). The formation of new glacial lakes in a warming climate is paralleled by slope destabilization in many regions (Stoffel and Huggel, 2012). Debuttressing of rock slopes adjacent to downwasting glaciers is an important cause of many alpine rock slope failures (Evans and Clague, 1994; Ballantyne, 2002; Geertsema et al., 2006) and has recently resulted in a number of large rock falls, rockslides, and ice avalanches (Fischer et al., 2010; Huggel et al., 2012b). Evidence is also increasing that permafrost thaw and related processes have destabilized alpine slopes and caused failures in unprecedented numbers in recent decades (Gruber and Haeberli, 2007; Krautblatter et al., 2012). An increase in high mountain rock slope failures has recently been detected at local and regional scales in the Alps (Huggel et al., 2012a). The coincident development of new and expanding glacial lakes and the decreasing stability of steep bedrock slopes increase the possibility that landslides and ice avalanches will impact lakes, potentially triggering very large downstream floods. Many lake outburst floods in the recent past have resulted from such linked processes (Clague and Evans, 2000; Kershaw et al., 2005; Carey et al., 2012).

* Corresponding author at: Dendrolab.ch, Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland. Tel.: +41 31 631 87 73; fax: +41 31 631 48 43.
E-mail addresses: markus.stoffel@dendrolab.ch (R. Worni), christian.huggel@geo.uzh.ch (C. Huggel), jclague@sfu.ca (J.J. Clague), yvonne.schaub@geo.uzh.ch (Y. Schaub), markus.stoffel@dendrolab.ch (M. Stoffel).

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The term GLOF (glacial lake outburst flood) has been extensively used in literature. Usually, this term has not been used in a very process-specific and technical sense but rather to describe the event as such, or only the flow process. Here we refer to GLOF as the event comprising a series of different, often cascading processes. We provide further technical specification in case that any particular component of the process cascade (e.g., the dam failure process) is addressed.

Outburst floods from glacier- and moraine-dammed lakes are highly mobile mixtures of water and sediment, capable of traveling tens of kilometers to more than 100 km at velocities exceeding tens of kilometers per hour. They are a serious threat because of their sudden onset, high-magnitude discharge, long runout distance, and their tendency to flow along existing river channels where humans and property are concentrated (Carrivick, 2010; Manville et al., 2012; Cui et al., 2013). These events are highly dynamic processes—their volume and peak discharge can increase by a factor of three or more relative to initial values owing to erosion and entrainment of sediment (Manville, 2004; Mergili et al., 2011). Sediment can be entrained from periglacial environments exposed after glacier retreat (Haeberli et al., 1989; Chiarle et al., 2007), from channels in areas of thick unconsolidated deposits (Lugon and Stoffel, 2010; Stoffel and Huggel, 2012), or through erosion of landslide debris in channels of rivers and torrents (Cui et al., 2013; Savi et al., 2013). Process cascades are characteristic of GLOFs — rock slope failures, ice avalanches, or mass movements from moraines may impact glacial lakes and produce displacement waves that overtop and breach the dam, generating extreme floods, debris floods, or debris flows (Haeberli et al., 2010).

Modeling GLOF processes or process chains is important for (i) improving knowledge of complex surface processes and (ii) assessing the hazard and risk of potential future events. Several researchers have attempted to model GLOF processes and process cascades (Bajracharya et al., 2007; Osti and Egashira, 2009; Worni et al., 2012a,b; Westoby et al., 2014). Hydraulic models reasonably simulate the actual flow physics and have yielded useful results for water floods. Modeling sediment transport and sediment-laden flows has been more problematic because it is based on empirical equations and geotechnical simplifications and because critical input parameters are typically difficult to derive.

In this paper, we first review the current state of knowledge of the main physical processes and cascades of processes involved in GLOF events, from the impact of a mass of rock or ice on a glacier- or moraine-dammed lake, through dam breaching, to flow propagation. We then revise state-of-the-art modeling for each of these processes from a theoretical point of view and discuss emerging methods for simulating coupled process cascades. Finally, we draw on a diverse sample of illustrative case studies from around the world, each representing one or more process components involved in GLOFs, that collectively highlight the potential and limitations of current GLOF modeling.

2. Process components and chains of glacial lake outburst floods

Outburst floods from glacier- and moraine-dammed lakes must be systematically analyzed in the context of the cascade of the processes that are involved. Even unstable glacial lake dams require a trigger event to initiate partial or complete dam failure and lake drainage. Different trigger mechanisms and process cascades can cause devastating outburst floods. The initiation phase of process chains can differ; for example, a mass of rock or ice impacts a lake, an extreme precipitation event causes overtopping of the dam, or an upstream GLOF enters the lake (Clague and Evans, 2000; Westoby et al., 2014). The processes, however, generally converge toward large sediment-laden flows. A typical process chain of GLOFs is (i) impulse-wave generation by mass flows or rock or ice impact, (ii) dam overtopping and breaching, and (iii) lake emptying and flood propagation (Fig. 1).

2.1. Mass movements into glacial lakes

Landslides, rock falls, snow and ice avalanches, and glacier calving generate impulse waves in glacier- or moraine-dammed lakes (Heller and Hager, 2011). The region from the lake shoreline to the area where the subaerial mass flow or fall stops on the lake bottom is the splash zone (Walder et al., 2006; Waythomas et al., 2006). This zone is dominated by complex wave dynamics and chaotic water behavior (Fritz et al., 2004; Waythomas et al., 2006). The impulse waves generated by the impact involve nonlinear and intermediate- to shallow-water waves that are dispersive and differ depending on the wave type, the amount of fluid transported, the runup height, or wave force on a structure (Heller and Hager, 2011). Heller and Hager (2011) distinguish (i) Stokes-like waves, (ii) conoidal-like waves, (iii) solitary-like waves, and (iv) bore-like waves. The main factors that influence wave type are the slide Froude number, thickness, mass, and impact angle. The amount of fluid transport of the different wave types thereby increases from small to large for wave types (i)–(iv), respectively.

Beyond the splash zone is the near-field zone in which a well-defined wave evolves and radiates out into the water body (Waythomas et al., 2006; Di Risio et al., 2011). The far-field zone is the region beyond the near-field, where directional energy disperses, refracts, and diffracts depending on the water body configuration and waves features. Finally, waves reach the edge of the water body and runup and flood coastal areas or overtop reservoir dams (Waythomas et al., 2006; Di Risio et al., 2011).

2.2. Breaching of moraine dams

The stability of a moraine dam depends primarily on its geometry, internal structure, material properties, and particle size distribution (Costa and Schuster, 1988; Richardson and Reynolds, 2000b; Korup and Tweed, 2007). A moraine dam can fail when the material strength of the dam is exceeded by driving forces that include shear stresses from the overtopping flow or displacement waves (Korup and Tweed, 2007; Massey et al., 2010). Overtopping flows are the most common trigger for moraine-dam breaching (Richardson and Reynolds, 2000a). The overflow initiates dam erosion that leads to greater outflow and increasing hydrodynamic forces that progressively enlarge the breach (Singh, 1996). Critical shear forces are exerted on the dam material by the outflow, and the eroded sediments are transported downstream as bedload. This process is irreversible and will ultimately lead to a partial or complete emptying of the lake.

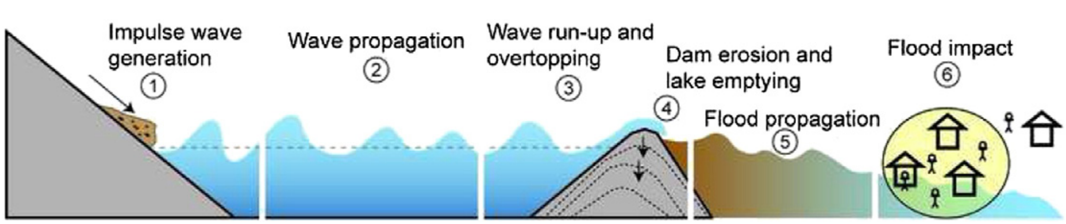

Fig. 1. Sketch of a typical GLOF process chain. (1) A landslide enters a lake, producing (2) an impact wave that (3) overtops and (4) incises the dam, resulting in (5) a flood that travels downstream and (6) eventually impacts population centers or infrastructure.