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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.

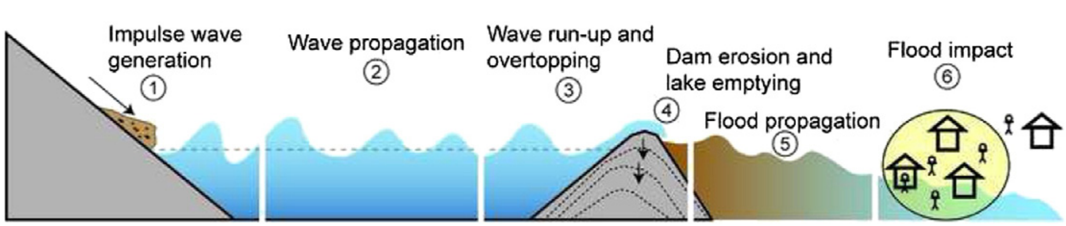

Fig. 1. Sketch of a typical GLOF process chain. (1) A landslide enters a lake, producing (2) an impact wave that (3) overtops and (4) incises the dam, resulting in (5) a flood that travels downstream and (6) eventually impacts population centers or infrastructure.

Different authors (Clague and Evans, 2000; Hancox et al., 2005; Worni et al., 2012b; O'Connor et al., 2013) have noted that dam incision starts on the steepest part of the moraine, where outflow velocities are highest, and then propagates back toward the crest. Knickpoint retreat finally results in lowering of the lake outlet and increased discharge. As the dam is incised, the breach sidewalls become steeper and fail when critical angles, related to the properties and pore water pressure of the dam material, are exceeded. Thus the breach widens as it deepens, resulting in a progressive increase in the breach cross-section and increasing outflow. When lake discharge decreases to the point that sediment is no longer transported, breach enlargement ceases.

2.3. GLOF propagation

When large amounts of water are released in mountainous terrain, sediment is normally entrained into the flow. Particle properties, fluid–particle, and particle–particle interactions govern the behavior of these flows. Consequently, the water and sediment content as well as type and size of the particles are key parameters (Pierson and Costa, 1987; Capra et al., 2004; Iverson, 2009). Glacier lake outburst floods are highly unsteady flows that are characterized by pronounced changes as they propagate downvalley. They can change from a normal flood to a hyperconcentrated flow or a granular debris flow and vice versa (Kershaw et al., 2005; Mergili et al., 2011; Manville et al., 2012; Worni et al., 2012a). Such transformations are mainly related to sediment deposition and bulking processes, which are influenced by the gradient of the flood path and to dilution of the flow by stream water (Smith and Lowe, 1991). The volumes and peak discharges of such extreme flow events can increase by a factor of three or more relative to initial values (Manville, 2004; Mergili et al., 2011) owing to sediment entrainment along the flow path. Sediment is mainly entrained on steep slopes and deposited on shallow slopes (e.g., Iverson et al., 2011). The hydrographs of GLOFs attenuate (i.e., flatten and lengthen) as the flows propagate downstream (Cronin et al., 1999; Worni et al., 2012a).

Glacier lake outburst floods are dominantly non-Newtonian flows (e.g., hyperconcentrated flows or debris flows) for which yield strength and viscosity are important parameters and viscosity is dependent on the strain rate (Pierson and Scott, 1985). In the case of debris flows, yield strength alone can suspend coarse gravel particles; whereas gravel can be suspended only by fluid forces in hyperconcentrated flows (Jakob et al., 2005).

3. Modeling process components and chains of GLOFs

A large number of models are available to simulate different types of flows and mass movements, but it is beyond the scope of this study to provide a full perspective. Therefore, we consider a selection of models that can be applied to characterize the initial phase of a typical GLOF process chain (impact wave modeling and dam breach modeling), and then present some widely applicable flow models that can be used to simulate water–sediment flows. We then present an approach to model an entire GLOF process chain from the onset to downstream flow impact.

3.1. Impact wave modeling

Many analytical and numerical models exist to characterize tsunami waves triggered by submarine or subaerial landslides (Falappi and Gallati, 2007; Heller et al., 2008a,b; Biscarini, 2010; Ataie-Ashthiani and Yavari-Ramshe, 2011; L'Heureux et al., 2011). Analytical methods are based on empirical studies and general computational guidelines for landslide-generated impulse waves (e.g., Heller et al., 2008a). Numerical models (e.g., 2D-BING; L'Heureux et al., 2011) generally apply Boussinesq formulations (e.g. Madsen et al., 1997), linear and nonlinear two-dimensional shallow-water equations (SWEs) and potential flow equations (Ataie-Ashthiani and Yavari-Ramshe, 2011). Shallow-water equations, however, are only valid if the height of the waves is much less than the water depth and if wavelength is much longer than water depth. Therefore, many shallow-water wave models are not capable of reproducing tsunami inundation for waves of the type considered here (Watts et al., 2000, 2003). In order to include nonlinear effects of waves (e.g., steepening of waves as they propagate toward the shore, followed by possible wave breaking), Boussinesq models, which allow the horizontal water velocity to vary with depth, must be used in impact wave simulations (Waythomas et al., 2006; L'Heureux et al., 2011).

The 2D-BING model uses a flexible box with prescribed velocity progression and propagation in a one-dimensional channel to represent the landslide that generates the impulse waves. Mass movement models can be applied to evaluate the required landslide parameters, such as velocity progression, for the 2D-BING model. The LS3D tsunami model is a two-dimensional, fourth-order Boussinesq-type numerical model that is used to simulate landslide-generated waves in reservoirs (Ataie-Ashthiani and Yavari-Ramshe, 2011). The model considers all relevant processes – specifically wave generation, wave propagation, dam overtopping, and wave runup – and laboratory test model results are in good agreement with experimental data (for more detailed information refer to Ataie-Ashthiani and Yavari-Ramshe, 2011). Waythomas et al. (2006) applied the Boussinesq model FUNWAVE (Wei et al., 1995) to simulate tsunami generation by cold volcanic mass flows. FUNWAVE models the fluid mechanics of breaking waves and simulates shoreline inundation. It accounts for wave nonlinearity and handles frequency dispersion in a manner that correctly simulates deep-water waves. The tsunami source from TOPICS (Tsunami Open and Progressive Initial Conditions System; Watts et al., 2000) is used as an initial condition for the FUNWAVE calculations. The Geowave model (Watts et al., 2000, 2003) couples TOPICS and FUNWAVE and has been applied successfully to evaluate tsunamis generated by debris flows in reservoirs (Walder et al., 2006).

3.2. Dam breach modeling

Different approaches and mathematical models exist to simulate earthen dam breach processes and breach outflow (Singh and Scarlators, 1988; Powledge et al., 1989a,b; Tingsanchali and Chinnarasri, 2001). Singh (1996) described a number of dam breach models, including BRDAM, Lou model, BREACH, DAMBRK, and BEED. More recently, earthen dam breaches have been studied in detail within the CADAM (EU Concerted Action on DAm break Modeling) and IMPACT (Investigation of extreMe flood Processes And unCertainTy) projects (Wang and Bowles, 2006).

Empirical dam break models are used to predict breach formation time, breach geometry, and peak outflow discharges based on analyses of real dam failures (Singh, 1996; Wahl, 2010). Parametric models such as HEC-RAS (2013) and NWS DAMBRK (Fread, 1982) provide outflow hydrographs based on breach geometry and breach development time provided by the user. In contrast, physical models apply geotechnical considerations, erosion rates, and hydraulic principles to simulate breach development. The best-known model of this type is BREACH (Fread, 1991), which predicts the development of a breach and the resulting discharge based on hydraulic, sediment transport, and soil mechanical principles.

Many physical dam break models require sensitive input parameters, such as the shape of the breach and its enlargement over time that are commonly based on assumption rather than physical evidence (Pickert et al., 2011; Worni et al., 2012b). In this respect, new erosion-based dynamic models are an improvement because they reproduce the breaching process with good accuracy (Balmforth et al., 2008; Faeh et al., 2012). Models such as BASEMENT (Faeh et al., 2012) and HR-BREACH (Mohamed et al., 2002; Morris et al., 2008) use physical input parameters to solve balancing equations for water flow in combination with transport formulas to simulate embankment failures. BASEMENT is a two-dimensional dynamic model (Faeh et al., 2012; Volz et al., 2012) used to simulate breaching of noncohesive earthen dam structures. The program solves the SWE for water flow calculations, and sediment transport laws are used to determine incision of dam structures due to overtopping flow. The complex process of lateral breach widening owing to collapse of the sidewalls is considered with a geometrical three-dimensional bank failure operator (Worni et al., 2012b). The program simulates water and sediment flows as a two-phase system with separate unstructured meshes for the water and sediment phases.

Most state-of-the-art dam breach models apply the SWE to simulate overtopping flow and related dam erosion. Technically, however, SWEs are not valid on steep slopes, which are typical topographic conditions. The error owing to inadequate physics of the model is usually small, and given other uncertainties in modeling real-case dam failures, it is acceptable for most dam breach simulations.

3.3. Flow modeling

Diverse models, ranging from simple empirical models to physically based dynamic models, simulate the downstream propagation of water and sediment flows. Unlike empirical models, sophisticated physical models can handle complex flow behavior governed by fluid and particle interactions, turbulent flow, and changing flow regimes. Physical flow models generally involve (i) a set of terms that describe conservation of mass and momentum, (ii) a method to quantify flow resistance, (iii) a numerical approach to solve partial differential equations, and (iv) a description of the channel and floodplain geometry (Manville et al., 2012). Hydraulic models solve equations for continuity (conservation of mass or volume) and momentum to calculate the propagation of water flows.

Here, we present three dynamic flow models that are applied in the case studies later in the paper. Other models have been applied in the past to model GLOFs (Table 1), but they are partly based on the same principles as the models applied in this study. In the case of two-dimensional models such as BASEMENT, IBER (IBER, 2010), and FLO-2D (O'Brien et al., 1993), the SWEs are general constitutive flow equations that are solved using an explicit finite-volume or finite-element method on structured or unstructured meshes. In hydraulic models, flow resistance is generally described by the empirical Strickler or Manning coefficients (Manville et al., 2012). Sediment transport can be included in hydraulic models by solving empirical sediment transport formulas (e.g., Meyer-Peter and Müller, 1948) that quantify erosion and deposition using a two-phase system and without changing rheology.

Single-phase rheological models are suitable for modeling the behavior of the more sediment-laden flows at the end of the flow continuum (Manville et al., 2012). Different rheological models are applied in dynamic modeling, including Newtownian, Voellmy, Mohr–Coulomb, and Bingham models (Hungr, 1995). The FLO-2D program applies a quadratic rheological model that combines Bingham shear stresses (sum of yield stress and viscous stress) and turbulent-dispersive shear stresses to define the inertial flow regime (FLO-2D, 2013). The user specifies the sediment concentration of a flow and flow rheological parameters, which together define the flow rheology and flow behavior. Flow resistance terms are combined with the hydraulic model, and a water–sediment hydrograph is routed across a DEM. Expressions for mass and momentum conservation of sediment and water are solved numerically (Manville et al., 2012).

The RAMMS (Christen et al., 2010) model is used to simulate a variety of rapid mass movements, such as snow avalanches, rockfalls, ice-rock avalanches, and debris flows. In contrast to FLO-2D, it can compute material entrained by mass flows. Frictional resistance is described using a Voellmy approach that incorporates a parameter for the dry Coulomb friction μ and a turbulent friction ξ. The latter is dependent on the square of the velocity, and both parameters depend on the properties of the flowing material and the surface roughness (Bartelt et al., 1999). In contrast to simple empirical modeling approaches, dynamic modeling requires substantial computer power and depends on inputs that may be difficult to obtain (Fig. 2).

3.4. Integrated modeling of a typical GLOF process chain

In the context of this study, we used the phrase *integrated modeling* to refer to the combination of models from different fields and process types to provide a more complete representation of reality (Geidl, 2007). Hydrologic modeling and hydraulic modeling are combined, for example, in the FLO-2D program; and coupled climate-hydrologic models include regional climate models to calculate at the basin scale the hydrologic response to a storm event (Yu et al., 2000). However, no systematic integrated modeling approach yet exists for many types of extreme flow events such as GLOFs, which are characterized by cascades of processes. Erosion-based dam breach models apply hydraulic

Table 1
Different dynamic flow models that have been used to model lake outburst floods.

Program	Dimension/governing equation	Relevant processes	Case study site	Reference
HEC-RAS (2013)	1-D (St. Venant)	Water flow, sediment transport	Vatnajökull Iceland	Alho et al. (2005, 2007); Alho and Aaltonen (2008)
HEC-RAS	1-D (St. Venant)	Water flow, sediment transport	Wisconsin (US)	Clark et al. (2008)
HEC-RAS	1-D (St. Venant)	Water flow, sediment transport	Mt. Everest region (Nepal)	Osti and Egashira (2009)
HEC-RAS	1-D (St. Venant)	Water flow, sediment transport	Southeastern Tibet	Wang et al. (2012)
HEC-RAS	1-D (St. Venant)	Water flow, sediment transport	Sagarmatha region (Nepal)	Bajracharya et al. (2007)
NWS-FLDWAV (2013)	1-D (St. Venant)	Water flow, debris flow	Sagarmatha region (Nepal)	Bajracharya et al. (2007)
TELEMAC-2D (2013)	1-D/2-D (St. Venant/SWE)	Water flow, sediment transport	Vatnajökull Iceland	Alho and Aaltonen (2008)
DASSFLOW (2013)	St. Venant/SWE	Water flow	Val d'Hérens, Switzerland	Bohorquez and Darby (2008)
SOBEK (2013)	1-D/2-D (St. Venant/SWE)	Water flow, sediment transport	Vatnajökull Iceland	Carrivick (2006)
Delft3D (2013)	3-D/2-D (Boussinesq assumption/SWE)	Water flow, sediment transport	Mt. Ruapehu (crater lake) New Zealand	Carrivick et al. (2009, 2010)
FLO-2D (2013)	1-D/2-D (St. Venant/SWE)	Water flow, sediment transport, debris flow, dam breach	Tajikistan	Mergili et al. (2011)
RAMMS Christen et al. (2010)	2-D (SWE, Voellmy approach)	Debris flows	Tajikistan	Mergili et al. (2011)
IBER IBER (2010)	2-D (SWE)	Water flow, sediment transport,	Andes, Peru	Schneider et al. (2014)
BASEMENT Faeh et al. (2012)	1-D/2-D (St. Venant/SWE)	Water flow, sediment transport, dam breach	Mt. Tronador, Argentina	Worni et al. (2012b)
BASEMENT	1-D/2-D (St. Venant/SWE)	Water flow, sediment transport, dam breach	Indian Himalaya	Worni et al. (2012c)

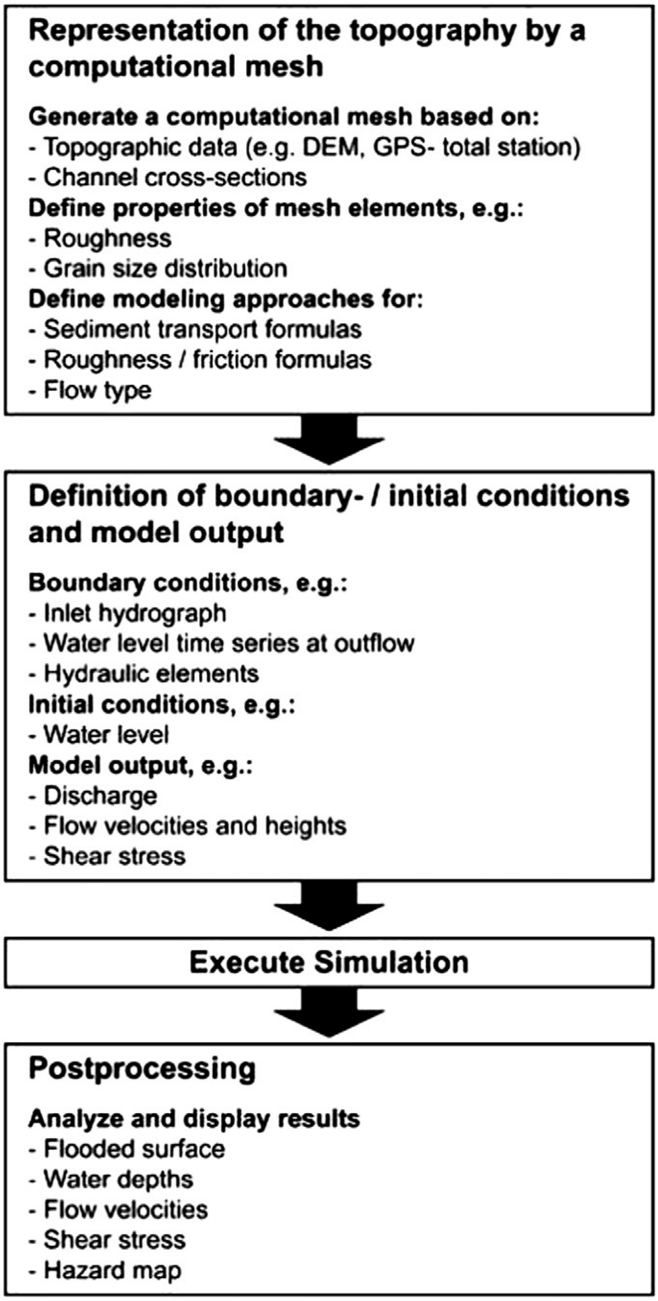

Fig. 2. Typical work flow for dynamic modeling of extreme flow events and related processes.
Based on BASEMENT User Manual; Faeh et al. (2012).

principles and therefore can simulate flow propagation following dam breaching. Dam overtopping flows can erode the dam, eventually leading to dam failure and the initiation of the flood wave. Such programs calculate dam erosion rates based on the bottom shear stress exerted by the hydraulic flow on the dam material. The water–sediment flow, which is calculated as a two-phase system, is then propagated farther downstream. In such simulations, however, the trigger mechanism for the dam breach (e.g., a mass movement into the lake) is not included in the model. We therefore adapted the simulation setup of BASEMENT to model GLOF scenarios triggered by dam breaches. Below and in Fig. 1 we describe three different modeling components within a single BASEMENT model run (Worni et al., 2012c):

- Impulse wave modeling. BASEMENT does not simulate the propagation of dense mass movements, therefore a sudden entry of water into a lake from a steep mountain slope was chosen to represent the impact (Faeh, 2005). The momentum of the rapid high-discharge flow was transferred to the lake water. Despite the different immersion processes of water and solids, realistic impulse waves were created. SWE was used to simulate impulse wave generation, propagation, and runup at the shore.
- Dam breach modeling. Impulse waves overtopped the dam, initiating breaching. The properties of the dam material and the shear stress of the water flow control incision rates. Vertical breach incision led to a steepening of the breach sidewalls, which collapsed when critical failure angles were exceeded. Breach expansion ceased when the outflow decreased below the threshold for bedload transport.
- Modeling flood propagation. Water and sediment flow through the breach was propagated downstream based on hydrodynamic and sediment transport laws. Inundation depths, flow velocities, bottom shear stresses, and changes in bed elevation were determined for each cell of the computational mesh.

4. Illustrative GLOF modeling case studies

Past GLOF events and hazards posed by existing glacial lakes have been analyzed in many places around the world, but comparably little research has been done on mass impacts in glacial lakes (Schneider et al., 2014), moraine dam breaching resulting from overtopping caused by such impacts (Bajracharya et al., 2007; Xin et al., 2008; Osti and Egashira, 2009; Worni et al., 2012a, b), and outburst floods (see Table 1 for an extensive overview). In line with the previous two sections, modeling case studies from all around the world were selected, which are representative for the simulation of identified different process components: (i) mass movements impacting glacial lake, (ii) moraine dam breaching, and (iii) outburst flow propagation. In addition, an approach is presented to model the entire process chain (i–iii) at one stretch, consistent with what has been outlined in the previous section. We distinguish between retrospective and scenario-based modeling. This section should thus provide a comprehensive synthesis of state-of-the-art work in the field and leading edge modeling of individual GLOF process components as well as complete process chains.

In the case of retrospective modeling, past events are reproduced through model simulations. Retrospective modeling contributes to an improved understanding of process and also is useful for calibrating and validating models, both of which are indispensable for scenario modeling. Scenario modeling is used to evaluate potential future events for hazard assessments and risk reduction. It requires definition of input parameters and initial and boundary conditions, which are based on assumptions and scenario definition; in contrast, in retrospective modeling, input parameters and initial and boundary conditions are mainly based on field observations and measurements.

4.1. Mass movement into a lake and impulse wave generation

As outlined in Section 2.1, different kinds of models exist to simulate impact waves into water bodies, and a large number of tsunami model applications have been published. For glacial lakes, however, such models have very rarely been applied although they can provide important information on dam overtopping waves and resulting hydrographs. Direct observations of impact waves into glacial lakes are extremely rare, and thus, the process has to be reconstructed based on observations in the field after-the-fact. Another typical limitation for modeling is the lack of topographic and bathymetric data required as input to models. One of the very few well-documented cases of impact wave generation into a glacial lake comes from Peru in 2010. This site is selected here because it represents a model case of avalanche impact into a glacial lake with generation of displacement wave, dam overtopping, and outburst flood.

4.1.1. Ice-rock avalanche impacts Lake 513

The comparatively good documentation of the Lake 513 case facilitated the development of a new model chain simulating the cascading mass movement and impact processes. A main challenge was to couple a mass movement model with a hydrodynamic model to derive a realistic dam overtopping hydrograph.

Lake 513 in the Cordillera Blanca, Peru, is a bedrock-dammed glacial lake that formed after glacier 513 started to retreat in the 1980s. On 11 April 2010 an ice and rock avalanche with a total volume of 0.2-0.4 $\times$ 10^6 m^3 detached from the steep southwest slope of Mount Hualcán (6104 m asl). The avalanche traveled over glacier 513 and impacted Lake 513 (Fig. 3), generating a wave that overtopped the 19-m-high freeboard of the dam by ~5 m. The wave overtopping the rock dam was clearly smaller than 1×10^6 m^3, but running down steep Hualcán Canyon, significant volumes of sediment were entrained and a debris flow formed. After deposing most of the sediment load on the flat Pampa de Chonquil, a hyperconcentrated flow continued down the Chucchun River, again severely eroding the valley floor and transformed into a debris flow. The flow reached the outskirts of the city of Carhuaz (ca. 25,000 inhabitants) but caused no casualties (Carey et al., 2012).

To retrospectively model the impact wave, several challenges at the interface of RAMMS and IBER had to be addressed. The modeled ice avalanche (using RAMMS) had to be calibrated based on estimated initial failure volume, travel distance, and a range of reasonable values of friction parameters. Modeled avalanche flow velocity, height, width, and duration were used to generate the hydrograph that represented the main interface and input for IBER and the impact wave model. A further calibration point of the coupled model experiment was the overtopping wave dimensions at dam crest. The final model fit resulted in an avalanche block release volume of 350,000 m^3 and the RAMMS friction values of $\mu = 0.12$ and $\xi = 1000$ m/s^2. Field observations suggested that erosion during the avalanche flow over the glacier and therefore ice entrainment had to be included in the simulation. The modeling resulted in an impact of 550,000 m^3 of mostly ice and some rock in the lake, lasting for 30 s with a maximum avalanche mass flux corresponding to 49,000 m^3/s after 20 s.

Despite the assumptions made for the interface between RAMMS and IBER, modeling results agreed well with field-based assumptions on the characteristics of the impact wave. The highest peak discharge of the overtopping wave was reached 50 s after the impact and overtopping lasted 10 s (Fig. 4A). The wave reached a height of about 5 m at the dam's crest and a total outflow volume of ca. 20,000 m^3 was calculated (Fig. 4B).

The coupled model experiment at Lake 513 can be considered a model case for the development of model chains simulating cascading mass movement and lake outburst trigger processes. The models that can simulate the different processes are not designed to be coupled, and therefore the development of an interface and multiple calibration phase needs to be undertaken. Schneider et al. (2014) continued the model chain farther downstream using RAMMS to simulate the outburst flood and debris flow and, based on that, generated a hazard map for the city of Carhuaz.

4.2. Dam failure

A small number of researchers have used numerical models to simulate moraine dam breaching and lake drainage. Bajracharya et al. (2007) validated BREACH on the 1985 Dig Tsho event to model a potential dam breach event at Imja Lake in Nepal. Xin et al. (2008) and Shrestha et al. (2012) also applied BREACH to simulate moraine dam breaching in Nepal and Tibet. Osti and Egashira (2009) simulated the outflow hydrograph of the Tam Pokhari GLOF using HEC-RAS. Here we use BASEMENT to dynamically model breach evolution of a moraine dam in Patagonia.

4.2.1. Retrospective dam breach modeling at Ventisquero Negro Lake, Argentina

This case illustrates one of the first studies where a dynamic two-dimensional model approach was applied to a moraine dam breach process and therefore is informative for research in other regions.

The end moraine impounding proglacial Ventisquero Negro Lake (41°12′19″ S., 71°49′55″ W.; 1000 m asl) in the Patagonian Andes, Argentina, breached catastrophically on 21 May 2009 and devastated the valley below the dam (Fig. 5). The breach was triggered by an increase in lake level caused by heavy precipitation and by blockage of

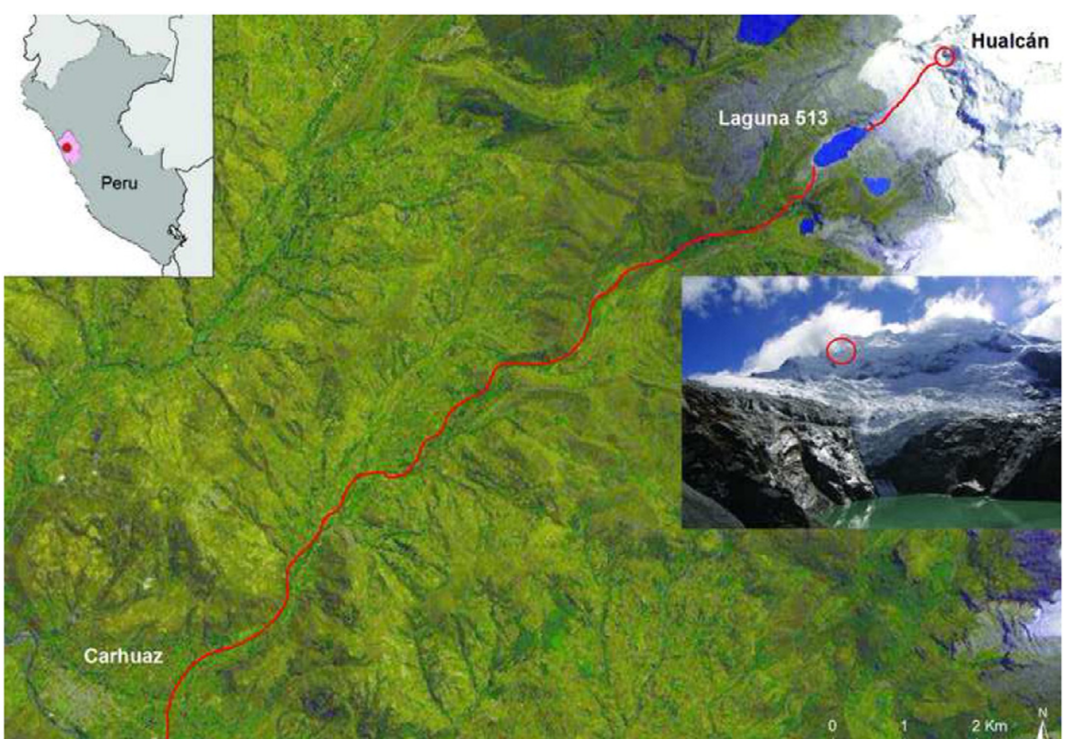

Fig. 3. The flow path of the ice avalanche from Mount Hualcán, which impacted Laguna 513 and triggered an outburst flood above Carhuaz, Cordillera Blanca Peru, on 11 April 2010.

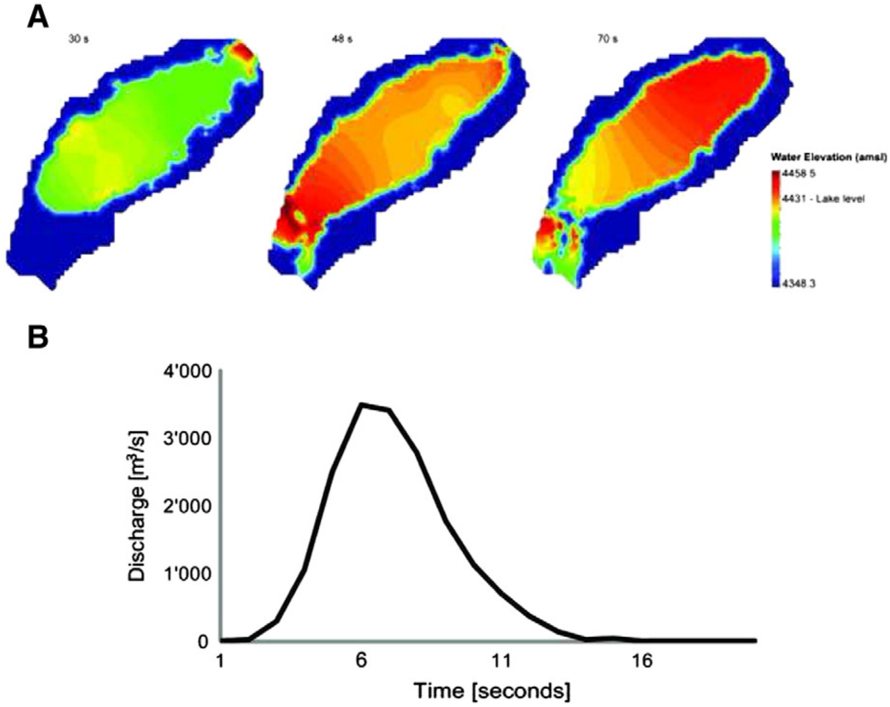

Fig. 4. (A) Results of impact wave modeling by IBER at the end of the impact (30 s), at the maximum of the dam overtopping wave (48 s), and after overtopping has finished (70 s). The avalanche impact is from top right, and the colors refer to absolute lake levels above sea level. (B) The outburst hydrograph on the top of the dam, as modeled by IBER.

the lake outlet by ice blocks. Ice at the outlet was probably washed away suddenly, and the outflow exceeded the critical bottom shear stress required to initiate dam erosion. Once erosion had started, the hydrostatic lake pressure was the driving force for continued lake outflow and breaching (Worni et al., 2012b).

Moraine breaching was simulated with BASEMENT by setting the level of the lake above the outlet, thus creating a high initial outflow and initiating dam erosion. The program evaluates surface erosion based on the bottom shear stress exerted by the flow on the dam material. When outflow discharges and velocities reach threshold values, sediment is eroded and the breach enlarges. Fig. 6 shows the evolution of bottom shear stress as lake discharge increases. The model indicated that the steepest section of the downstream face of the moraine initially experiences the greatest erosion (Fig. 7, 30 min). The breach then migrates backward toward the outlet, the lake outlet is lowered, and increased discharge and erosion lead to progressive breach enlargement (Fig. 7, 50 min). Flow velocities increase owing to the increased outflow, leading to a simultaneous increase in bottom shear stress to a maximum of 5100 N m^{-2} (Fig. 7, 70 min). Outflow and erosion then decrease as the rate of lake-level lowering decreases (Fig. 7, 120 min). Breach enlargement ceases about 120 min after the start of the model run (Worni et al., 2012b).

Model results were validated by comparing modeled and measured breach and deposit geometry (Fig. 8). Modeled and measured breach

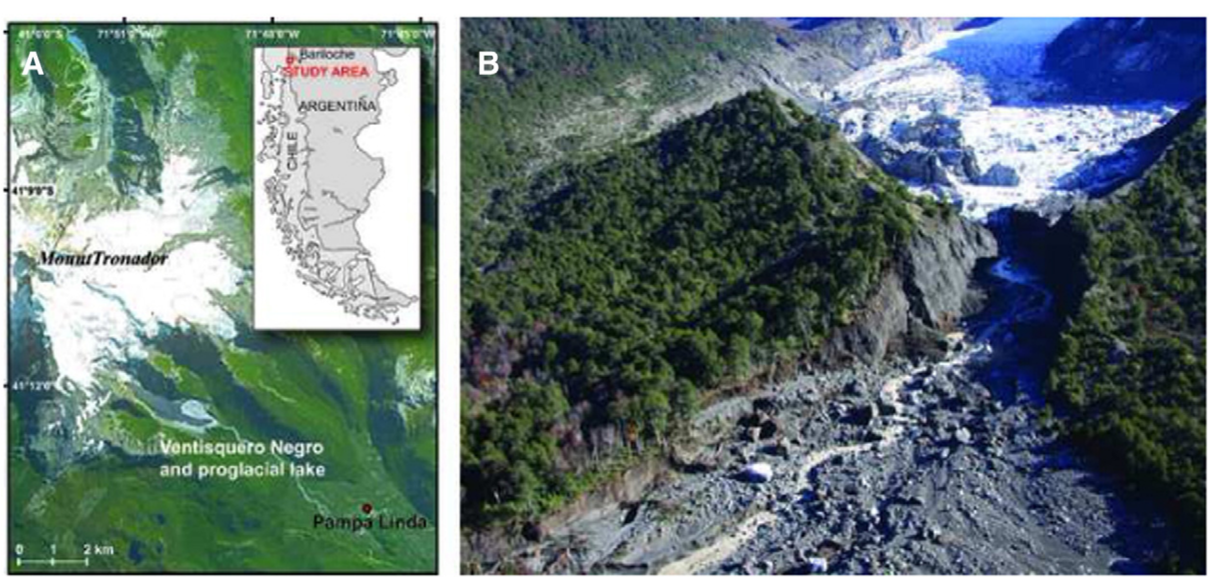

Fig. 5. (A) Overview of Mount Tronador and Ventisquero Negro Lake in the Patagonian Andes near Bariloche, Argentina, prior to the lake outburst in May 2009. Satellite image from Google Earth. (B) Breached moraine of the Ventisquero Negro glacial lake.
Photo from Club Andino Bariloche.

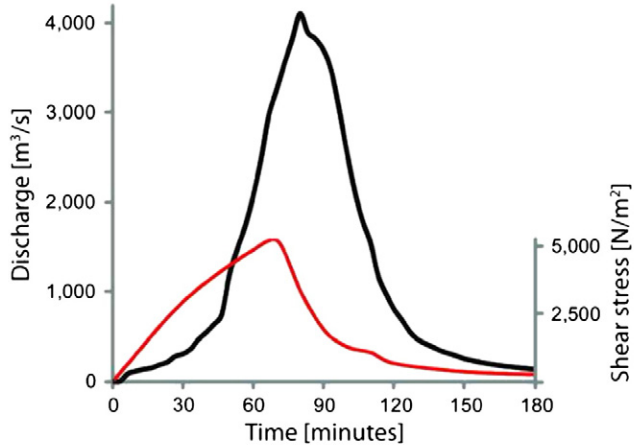

Fig. 6. Outflow hydrograph (black line) and bottom shear stress (red line) over the period of lake outflow as modeled by BASEMENT.

depths agree well, with a mean deviation of 2.5 m. Satellite imagery reveals a longitudinally curved breach, whereas the modeled breach is straight although similar in extent. No discharge measurements exist for this event, thus we could only evaluate the hydrograph indirectly. We assume that a good match in real and modeled final breach geometry implies a reasonable reproduction of breach expansion rate and hence of the model lake outflow hydrograph.

This case study allowed us to model input parameters (Worni et al., 2012b) and test dynamic, erosion-based dam breach modeling. Model results provided insights into complex dam breach mechanisms that are difficult to observe in nature (e.g., bottom shear stress evolution). In addition, they showed that high lake levels and enhanced discharge can initiate dam breaching.

4.3. Downstream flood propagation

The propagation of GLOFs has been simulated using dynamic modeling approaches. Table 1 lists studies that have used hydraulic and debris flow models to calculate flow depths, velocities and extents, sediment transport, and other properties of GLOFs. Here we present two studies, one of a past GLOF and another of a possible future GLOF that are based on hydrodynamic and debris flow models. The first study illustrates the challenges involved in modeling sediment transport; the second study applies different models to outburst scenarios to simulate different flow types.

4.3.1. Retrospective GLOF modeling at the lower Grindelwald glacial lake, Switzerland

The 2008 GLOF at Grindelwald, Switzerland, has been used to calibrate and validate dynamic flow models because accurate data are available on the topography of the valley below the glacier (a 2-m DEM), pre-flood river cross-sections every 100 m, and the flood event itself. On 30 May 2008, a supraglacial lake on lower Grindelwald Glacier (46°35′41″ N., 8°3′26″ E.; 1380 m asl) in Switzerland drained suddenly beneath the glacier (Fig. 9). About 570,000 m^3 of the 800,000 m^3 water in the lake were released in 3 h, and the flood had a maximum peak discharge of 111 $m^3\ s^{-1}$ (Fig. 10). The floodwaters discharged into a deep and narrow gorge (Gletscherschlucht), where significant amounts of sediment were entrained into the flow. Below the outlet of the gorge, the GLOF inundated the Weisse Lütschine River floodplain at Aspi (Fig. 11). The highly turbulent flow caused more flooding and river bank erosion farther downstream. Flooding was exacerbated by significant accretion in the river channel during the event, which reduced the channel cross-sectional area.

The sediment in the flow did not significantly alter its rheology, therefore the hydraulic model BASEMENT was applied to retrospectively model the event. The objective was to provide insights into flood and sediment transport processes and to test the ability of BASEMENT to simulate a GLOF. High-precision data were available to model the event: pre-flood river cross profiles every 100 m, a digital terrain model with 2-m resolution, and accurate flood hydrographs. Areas that were flooded were mapped after the outburst event based on a field reconnaissance. Flood modeling was done downstream of Gletscherschlucht because discharge measurements were available at the end of the gorge. The simulation reproduced the inundation on the east side of the river, but the model predicted significant flooding on the west side of the river, which did not occur (Fig. 11). Differences in modeled and actual sediment deposition explain this discrepancy. Although a variety of sediment transport

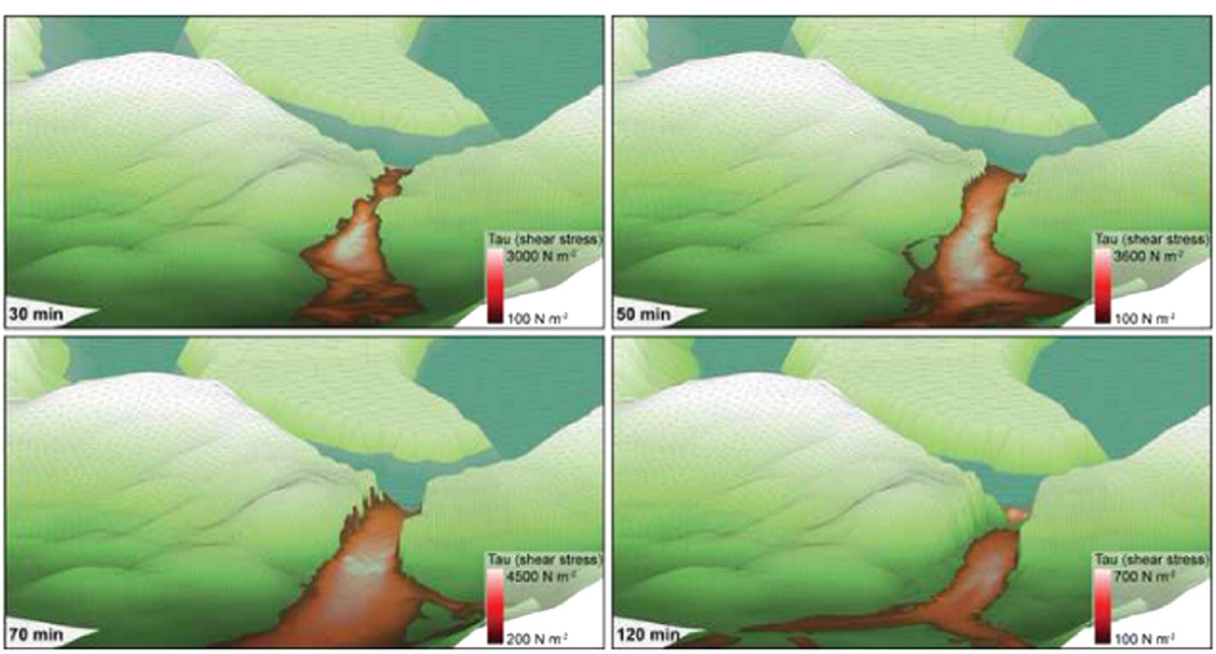

Fig. 7. Dam breach simulation at Ventisquero Negro glacial lake using BASEMENT. The schematic shows the temporal evolution of the breach and bottom shear stress evolution at 30, 50, 70, and 120 min.

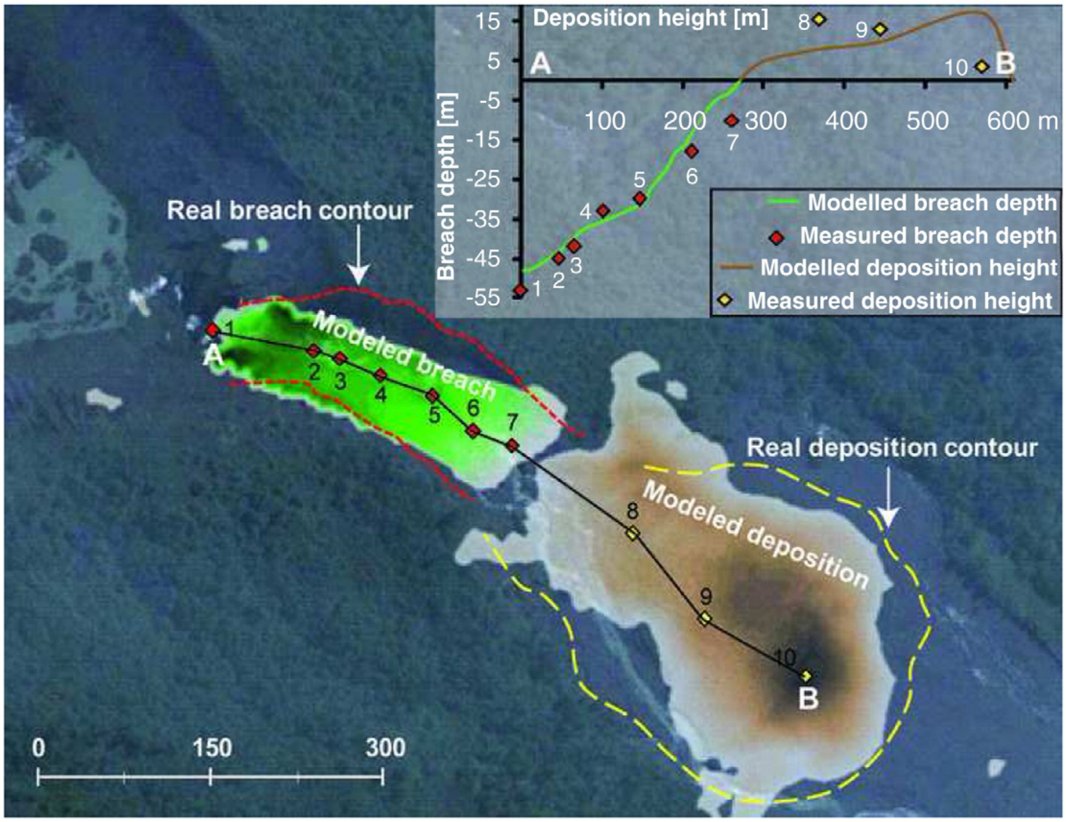

Fig. 8. Validation of model results based on a comparison of measured and modeled breach and deposit geometries. BASEMENT calculated breach depths and extent (green), and the depths and extent of outburst flood deposits (brown) that were similar to those observed in the field.

conditions were tested, the model consistently predicted too much accretion in the river channel, with the consequence that the water overflowed westward. This example shows that accurate simulation of sediment transport is challenging and model output remains questionable even when input data are precise.

4.3.2. Modeling lake outburst flood scenarios in Khavrazdara, Tajikistan

In this example, a large set of dynamic flow modeling results were combined to deal with uncertainties in how a lake might outburst. Such an extensive modeling effort is unique in studies of GLOFs.

Periglacial Lake Khavraz (38°34′10″ N., 72°36′31″ E.; 4000 m asl) in Khavrazdara, Tajikistan, has an area of about 2 km^2 and is dammed by an active rock glacier. Fieldwork revealed that, in the event of dam failure, the downstream village of Pasor would be at risk (Mergili et al., 2011). The FLO-2D and RAMMS models were applied to retrospectively simulate a GLOF event in Dasht, Tajikistan, in 2002. Mergili et al. (2011) then used the results of the 2002 GLOF to calibrate FLO-2D and RAMMS and apply it to Lake Khavraz outburst scenarios.

The purpose of back-calculating the Dasht 2002 GLOF event was to calibrate and validate the models for this type of event. In RAMMS, the friction parameters needed to be calibrated such that the flow reached the floodplain. Friction parameters of $\mu = 0.14$ and $\xi = 1300$ proved to be the best values for reconstructing the event. The simulated travel time from the onset of the flow to the village of Dasht corresponded reasonably with local reports, and also the inundation extent was accurately reproduced by the model (Fig. 12) (Mergili et al., 2011). For a hyperconcentrated flow scenario modeled with FLO-2D, viscosity ($\eta = 279$ poises) and yield stress ($\tau = 798$ dyn/cm^2) parameters were chosen based on the Dasht event to achieve a good match between observed and modeled deposition on the debris flow fan (Fig. 12; Mergili et al., 2011).

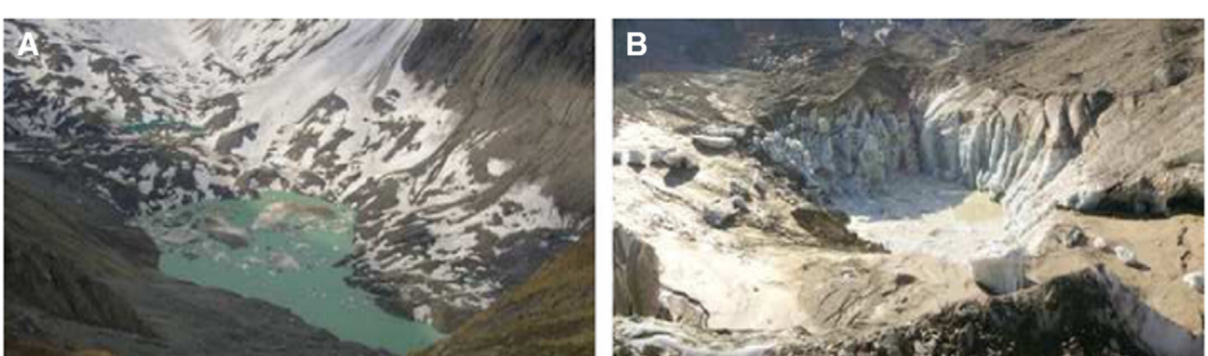

Fig. 9. Supraglacial lake on Lower Grindelwald Glacier (A) before and (B) after lake drainage. (The photo in A was taken in 2009, after the lake had refilled). Photographs from www.gletschersee.ch.

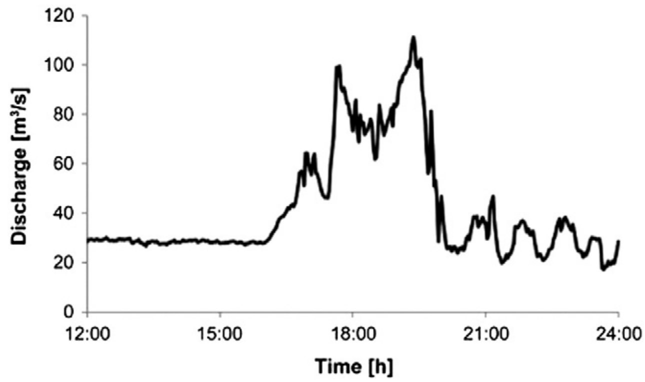

Fig. 10. Measured discharge at the outlet of Gletscherschlucht on 30 May 2008 during the GLOF at Grindelwald. Two peaks of 100 m^3/s and 111 m^3/s were separated by 100 min. Data from BVE OIK I.

The two programs predict different inundation depths: RAMMS generally predicted lower depths than FLO-2D. However, RAMMS and FLO-2D model different processes, and the range of possible scenario GLOFs at Khavrazdara requires the use of both approaches.

Mergili et al. (2011) used RAMMS to simulate debris flows and FLO-2D to simulate floods and hyperconcentrated flows for four lake outburst scenarios. The result was a set of 12 model outputs that provided a range of flooding possibilities in Pasor. Small and large outburst scenarios for three different flow simulations are shown in Fig. 13. All 12 model outputs indicate that zone *A* in Fig. 13 would be inundated. In contrast, none of the model results indicates that the cultivated and populated areas south of the river (zone *B*) would be affected, therefore the probability of flooding in that area is low. Six model outputs indicate partial inundation of the populated area west of the river (zone *C*), thus the probability of flooding in that area is uncertain. The possibility of an outburst flood depends on the susceptibility of the dam to breaching, which can only be evaluated by geotechnical investigation, but modeled inundation depths and flow arrival times are important data for mitigation and evacuation planning.

4.4. Modeling typical GLOF process chains

The GLOF process cascades, from lake impact to overtopping and breaching of the dam and flood propagation, have been dynamically modeled by Faeh (2005), Worni et al. (2012c), and Schneider et al. (2014). Existing modeling tools are not explicitly designed for such process cascades, thus compromises must be made. The following case study of a potential GLOF illustrates a feasible approach to dynamically model such process cascades with BASEMENT.

4.4.1. Modeling a potential outburst of Shako Cho glacial lake, India

This case illustrates a glacial lake in the Himalayas, whose high hazard potential has not been adequately been recognized in the past. The dynamic modeling of a potential process cascade leading to lake failure and severe flooding presented here is innovative and at the same time is an important contribution to assess the hazard potential of this lake.

Proglacial Shako Cho Lake (27°58′29″ N., 88°36′58″ E.; 5000 m asl) in Sikkim, India, has an area of 0.575 km^2 and is dammed by a sharp-crested end moraine consisting of loose granular sediment. A steep, 1000-m-high mountain face behind Shako Cho Lake is a potential source of ice-rock avalanches that could enter the lake and trigger a displacement wave that would overtop and breach the moraine dam (Fig. 14). Based on potential lake impacts and the geometry and composition of the moraine dam, Worni et al. (2012c) concluded that the lake has a high outburst potential and poses a considerable threat to downstream villages.

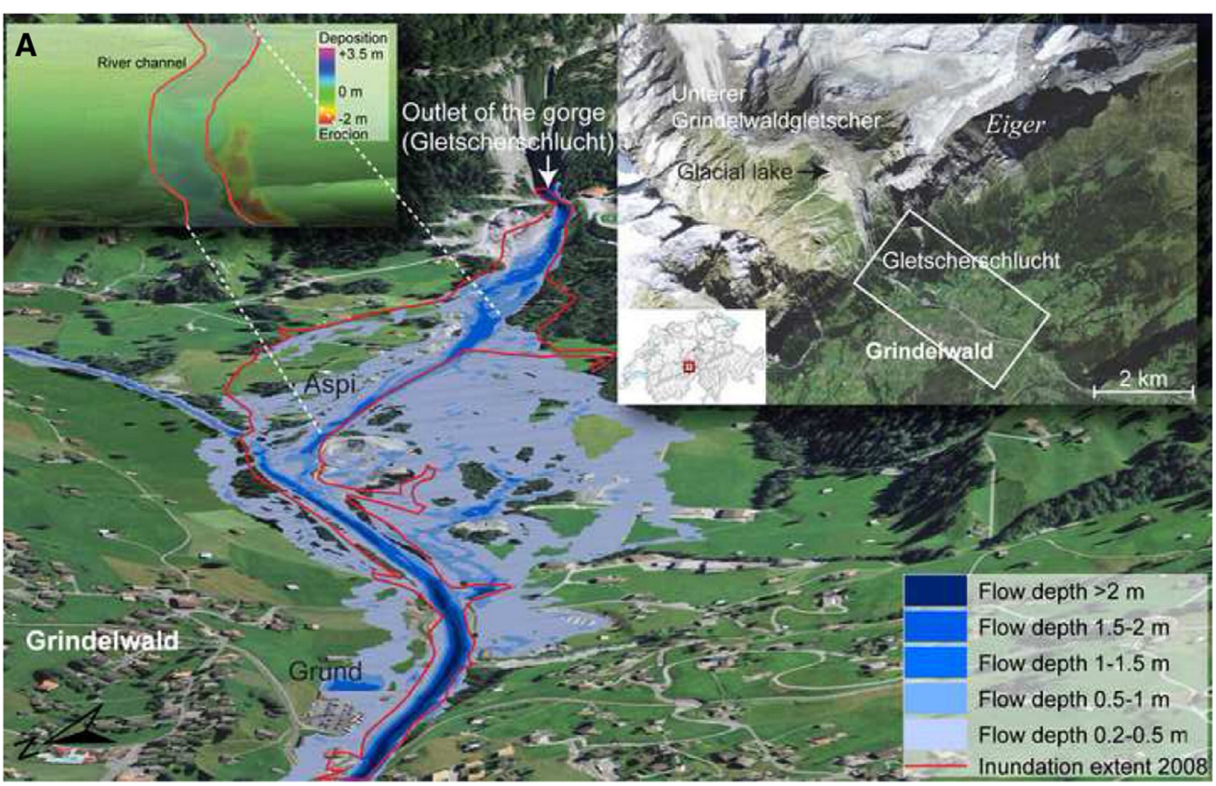

Fig. 11. Results of flood and sediment transport modeling of a GLOF at Grindelwald, Switzerland, in May 2008 using BASEMENT. Modeled flooded areas are shown in blue; the actual inundation extent is delineated by the red line. Modeled deposition and erosion are illustrated in the inset.
Data from BVE (OIK I), BAFU and swisstopo.

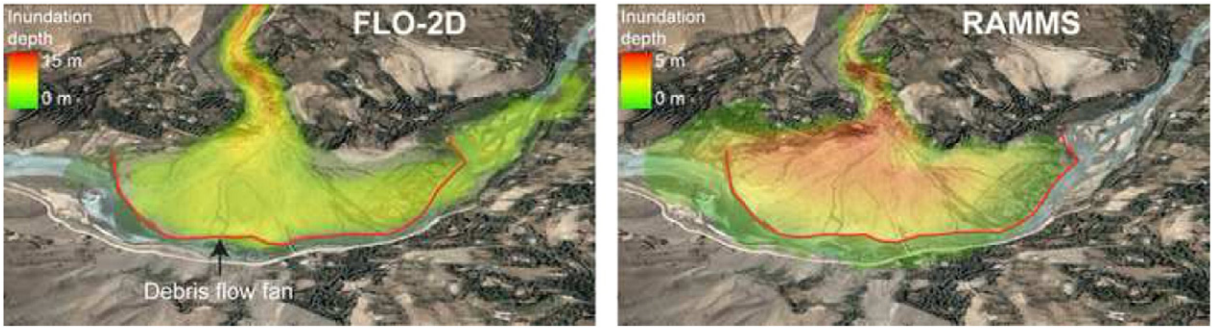

Fig. 12. FLO-2D and RAMMS model calibration and validation based on the 2002 GLOF in Dasht, Tajikistan. Both models produce a debris flow pattern (red line) similar to the real one.

To assess the potential consequences of a dam breach, we modeled the following process chain using BASEMENT: (i) lake impact; (ii) wave overtopping and dam erosion; and (iii) lake outburst and flood propagation. The impact scenario illustrated in Fig. 15 is based on the minimum momentum flux required to cause dam failure. This impact transferred the energy of about 2.55×10^{10} N·s to the lake, equal to

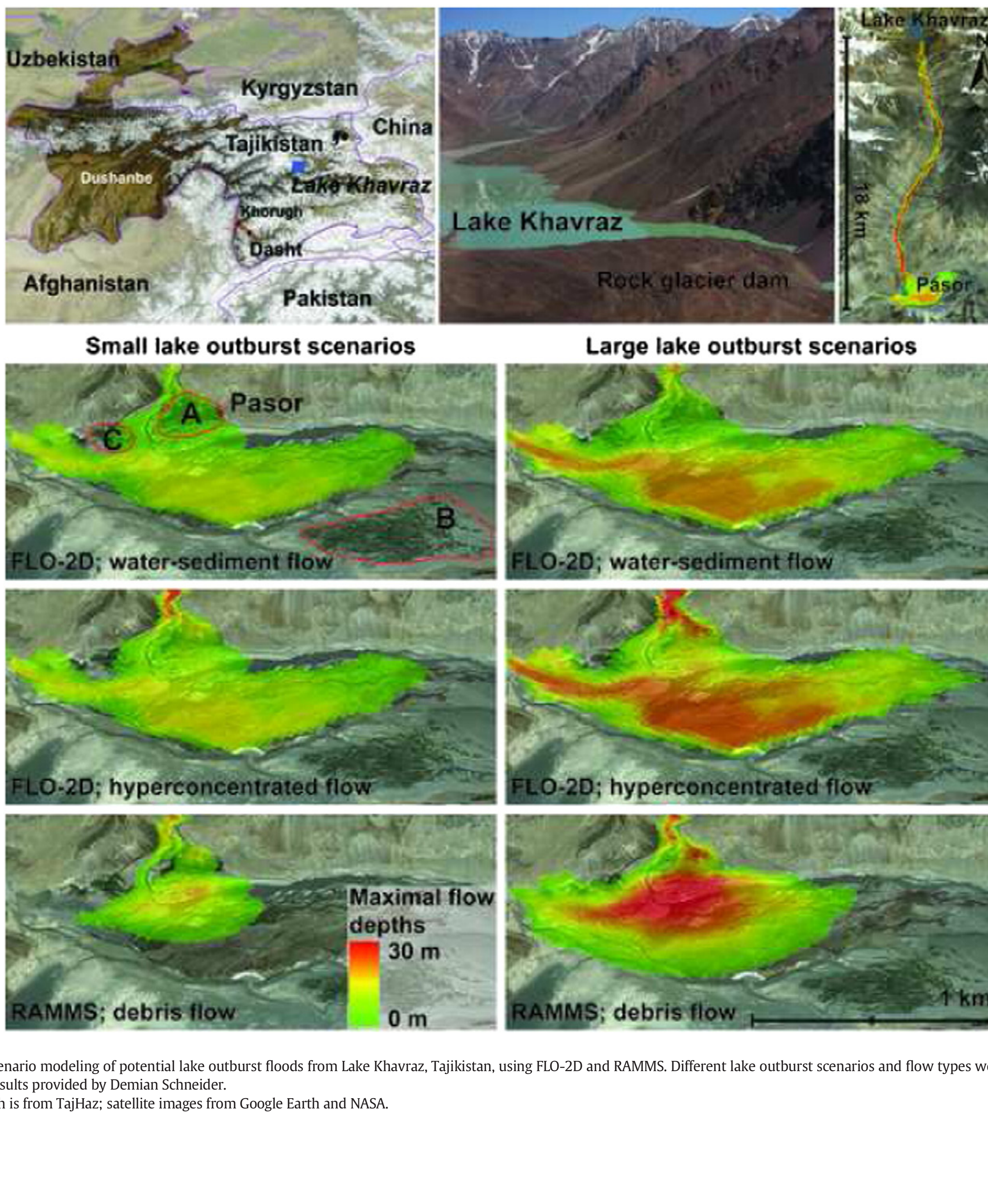

Fig. 13. Scenario modeling of potential lake outburst floods from Lake Khavraz, Tajikistan, using FLO-2D and RAMMS. Different lake outburst scenarios and flow types were modeled. RAMMS results provided by Demian Schneider.
Photograph is from TajHaz; satellite images from Google Earth and NASA.

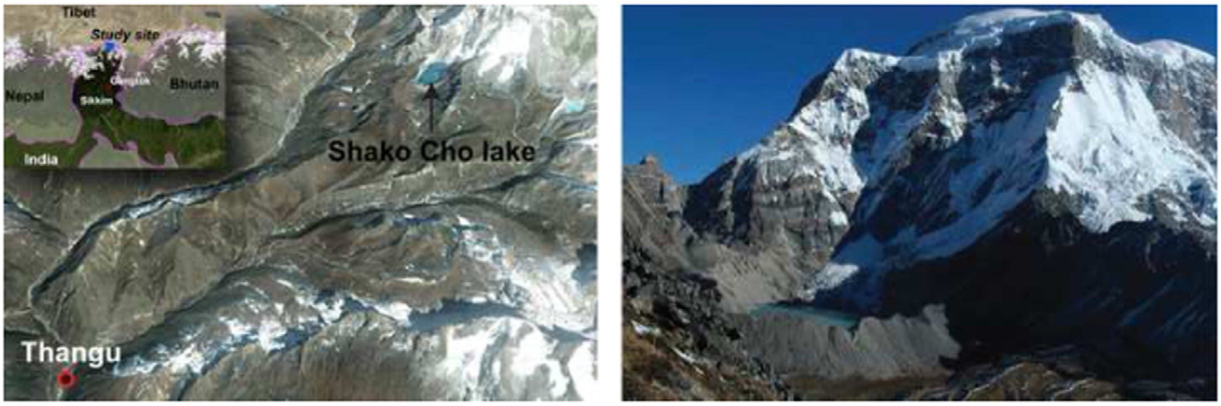

Fig. 14. Shako Cho glacial lake above the village of Thangu in Sikkim, India. The lake is 1.3 km long, and the distance from the lake to the village of Thangu is 12 km. Photograph obtained from a mountaineer; satellite images from Google Earth and NASA.

ca. 700,000–900,000 m^3 of ice entering the lake at 30–40 m s^{-1} (Worni et al., 2012c). The overtopping waves initiated lake outflow that eroded a 10-m-deep breach in the dam. The impact in the lake occurred 30 s after the start of the program; the first wave overtopped the dam at 100 s; a second overtopping occurred at 250 s; and steady lake outflow was achieved after 800 s (Fig. 15). The most rapid breach enlargement coincided with maximum lake outflow between 1200 and 2400 s (20–40 min). Breach expansion ceased at about 7200 s (120 min). In this simulation, about 16×10^6 m^3 water drained in 180 min, with a maximum discharge of ca. 6100 m^3 s^{-1} (Fig. 16). The flood wave would reach Thangu village, 12 km below the lake, with maximum flow velocities of 15 m s^{-1} and maximum flow depths of 12 m about 50 min after lake impact. The villages of Thangu and Yathang, 3.5 km below Thangu, would be impacted by the GLOF, with damage especially severe in Thangu. For a more detailed description of the glacial lake setting and model setup also refer to Worni et al. (2012c).

5. Discussion

Glacier lake outburst floods (GLOFs) may pose significant hazards tens of kilometers downstream from their sources. Yet few observations or quantitative data on GLOFS exist, and the hydraulics of these high-magnitude flows and the mechanisms of erosion, sediment transport, and deposition are understood in only a limited way and remain largely unquantified (Carrivick, 2006). An improved understanding of GLOFs can be obtained by retrospectively characterizing events using state-of-the-art numerical modeling techniques that quantify relevant flow and sediment transport processes (Carrivick et al., 2009). Advanced approaches to simulate entire process chains are essential for future hazard assessments.

Our discussion draws from the previous case studies and focuses on important aspects of retrospective and scenario-based modeling. We consider the possibility of fully coupled modeling of GLOF-related process cascades.

5.1. Retrospective modeling

The characterization of GLOFs and choice of model input parameters are challenging, yet important tasks. Retrospective modeling provides key insights into complex processes that are otherwise difficult to analyze. Moraine-breach modeling at Ventisquero Negro and GLOF modeling at Grindelwald enabled an analysis of erosion and sedimentation

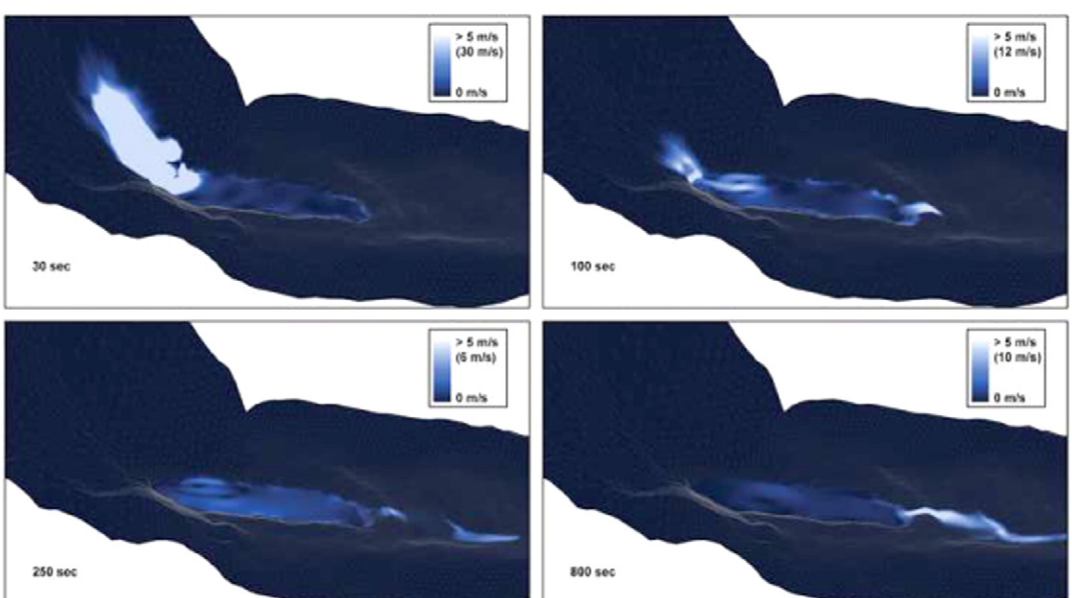

Fig. 15. Example of results of impulse wave modeling of Shako Cho glacial lake with BASEMENT. A landslide impact produced waves that overtopped and breached the moraine dam. The four panels show flood velocities (values in brackets are maximum velocities).

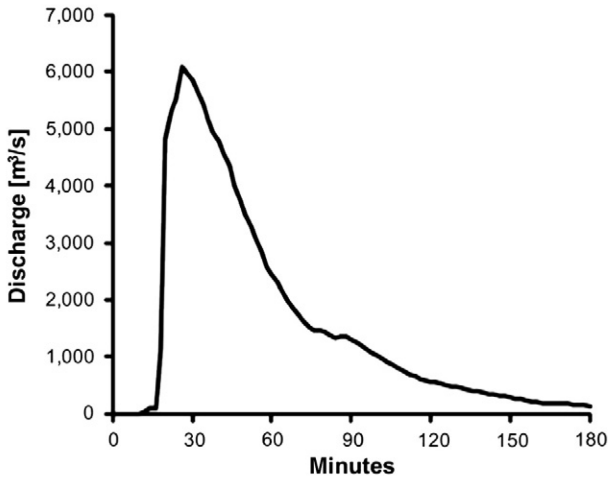

Fig. 16. Hydrograph of the Shako Cho glacial lake outburst calculated by BASEMENT.

processes and facilitated interpretation of field observations and event reconstruction.

Empirical models depend on parameter calibration, whereas physical models represent processes using physical principles such as mass and momentum conservation. However, even sophisticated physical models have large uncertainties when applied to real events, thus model calibration is essential (Walder and Costa, 1996; Tingsanchali and Chinnarasri, 2001). Although model calibration is common in the laboratory (e.g. Balmforth et al., 2008), it has limited application in nature. Ideally, models have to be fully calibrated and validated with high-quality field data (Carrivick et al., 2009). However, the number of well-documented, extreme flow events is limited and compromises must be made. For example, in the case of the GLOF scenario modeling at Khavrazdara, rheologic input parameters required by FLO-2D were chosen using a past GLOF event from the same region. Sediment transport and dam breach parameters required by BASEMENT were estimated from the Ventisquero Negro moraine dam failure and then applied to dam breach scenarios in the Indian Himalayas.

Critical issues in model calibration are the selection of suitable tuning parameters and the definition of an acceptable range of parameter adjustments. A sensitivity analysis may identify sensitive input parameters used in model calibration, but the modeler must justify deviations of standard parameter values. In addition, uncertainties in model calibration must be accounted for in subsequent scenario modeling.

5.2. Scenario modeling

The choice of scenarios can be arbitrary and partly based on assumptions, but this key element in deterministic modeling of natural hazards must be carefully evaluated. For example, the choice of a scenario involving a particular mass flow into a lake may require a morphological, geotechnical, or glaciological investigation. Yet, determination of the trigger and size of the rock or ice failure and forecasting when such an event will occur remain problematic (Haeberli et al., 2010). To minimize uncertainties, it is essential that the remaining model input parameters be based on physical principles and field measurements. Credible scenario modeling requires a previous field survey to provide appropriate input data.

An alternative to choosing and modeling a single scenario is modeling a range of realistic initial conditions. This approach was used to model the GLOF scenarios at Shako Cho glacial lake in the Indian Himalayas. In addition to different initial conditions, a range of input parameters (e.g. dam composition), topographic inputs (DEMs), and flow types (water–sediment flows and debris flows) can be used in modeling, as was done at Khavrazdara, Tajikistan. Successful modeling of different flow types may require a probabilistic approach that uses different tools to correctly simulate different flow rheologies. The result is a set of model outputs representing a realistic range of potential extreme flow events. A realistic range of model outputs is required to estimate the magnitudes, maximum velocities, and travel times of extreme flows (Mergili et al., 2011). Presently, however, studies are lacking that systematically evaluate the effect of different, and to some degree arbitrary, scenarios on model results and hence on related hazard assessments.

5.3. Process chain modeling

Many natural disasters have resulted from cascades of processes rather than single phenomena (Haeberli et al., 2010), therefore an integrated system approach must be applied to fully understand them (Huggel et al., 2004). All relevant hazards in a region must be considered and possible interactions and cascades taken into account (Delmonaco et al., 2006). Different software tools, such as HAZUS (FEMA, 2008), RiskScape (Reese et al., 2007), and CAPRA (CEPREDENAC et al., 2011), consider sequences of hazardous processes and facilitate multihazard analyses. Kappes and Glade (2011), for example, applied the MultiRISK tool (Kappes, 2011) to investigate the risk of river damming by landslides and subsequent catastrophic dam breaching in the Barcelonnette watershed in France. Zones susceptible to shallow landslides were modeled and overlaid on water courses in a GIS to identify zones prone to damming.

Although the focus of most multihazard simulations is risk reduction, important advances recently have been made in physically based, dynamic process model development to simulate complex processes of extreme flow events (Bajracharya et al., 2007; Procter et al., 2010; Worni et al., 2012a,b). Little work, however, has been done on modeling cascades of processes, and there are few program codes for dynamic, integrated modeling.

We envision three feasible approaches for dynamic, integrated modeling of process chains in natural hazards. First, specific processes within a process chain are individually modeled, and model outputs of one process are used at each subsequent step as model input. For example, earthen dam breaches can be initiated by overtopping flow triggered by hydrologic extreme events or mass impacts in a lake. Tsunami or hydrologic models can provide initial conditions for dam breach modeling, in the form of a hydrograph of water overflowing the dam. Dam breach triggers (such as piping, melt of internal ice, and earthquakes) are also plausible (Clague and Evans, 2000), but in such cases other models than erosion-based dam breach models must be applied (e.g. Shrestha et al., 2012). The dam breach model calculates a lake outflow hydrograph, which serves as initial conditions of a downstream flow model. The advantage of such an approach is that the most appropriate model can be applied at each step in the modeling exercise. A disadvantage is that model outputs may not exactly fit the required input for the succeeding model. For example, a hydrograph of a dam-overtopping flow derived from a tsunami model does not represent the real motion of waves at the dam, and its use in an erosion-based dam breach model is inaccurate.

Second, existing models are adapted to simulate process chains within a single model run. With such an approach, not all processes may be represented in a state-of-the-art manner, but transitions between different processes are smoother and more realistic. A practical advantage of this approach is that only one program is used, with savings in cost and time. The use of BASEMENT to model a typical GLOF process chain has yielded promising results (Xin et al., 2008; Osti and Egashira, 2009) and can be considered one of the most complete and integral GLOF modeling approaches currently available.

Third, given that the two approaches outlined above are only approximations of real integrated modeling, the most appropriate models could be combined into a single integrated model to simulate process chains of extreme flow events. For this purpose, program codes of existing models would have to be modified and interfaces would be needed in a new model. Few models offer such solutions, although a variant of the BREACH model has been implemented in FLO-2D.

Presently, the performance of multihazard simulations and dynamic process chain modeling must be evaluated in a series of steps; therefore the modeling is inherently time-consuming, data requirements are large, and computing power is intensive. Uncertainties in the process cascade grow along the process chain (Haeberli et al., 2010), rendering model results more sensitive to errors. When attempting to model a process chain, interpretation of the results is thus as important as the modeling itself.

6. Conclusions and perspectives

Glaciated high-mountain regions are particularly susceptible to climate change and associated changes in hazardous processes (IPCC, 2012). Changes in temperature, precipitation, glacier cover, or permafrost owing to recent and continuing atmospheric warming are shifting hazard zones beyond their historical limits, and empirical knowledge must be complemented by improved process understanding and modeling. Despite a large body of literature on glacial lake hazards, studies that model GLOF processes and especially GLOF process chains are rare. Yet past events may provide important calibration models that simulate potential GLOF scenarios. We provide a comprehensive perspective on this issue by reviewing modeling approaches that have been used to retrospectively assess past GLOFs and to model possible future events.

A growing scientific community is analyzing mass impacts into reservoirs, lakes, and the sea. Yet few modeling studies have been done on overtopping displacement waves generated by rock or ice avalanches in glacial lakes.

Several dam-break models exist for simulation earthen dam failures, but the application of erosion-based, dynamic dam-break models to real events is still in its infancy. Advances in this field of study are essential for properly assessing hazards posed by existing glacial lakes. Of particular note, accurate simulation of horizontal breach enlargement owing to sidewall collapse has not been achieved. In addition, dam overtopping impact waves should be included in future dam-break modeling.

Combined dam breach and hydraulic models, conventional hydraulic models, or debris flow models can be used to simulate flow propagation downstream of a failed dam. The hydraulics of water floods are well understood, and model results based on the one-dimensional St. Venant equations or two-dimensional SWE can therefore be considered as reliable. However, when sufficient amounts of sediments are entrained into a flow, process descriptions are based in part on empirical relations. Therefore, simulations of hyperconcentrated flows and debris flows are generally less accurate than simulations of pure water flows. Yet, sediment transport cannot be neglected—flow transformations with changes in flow rheologies are common in outburst events and pose important challenges to modeling. A limitation in modeling GLOF process chains is that numerical models have been developed by different scientific and engineering communities for specific processes such as impact wave generation, dam breaching, and flow propagation. The challenge is to couple models that were not designed for a GLOF process chain. In this paper, we have reviewed process-specific models and their applications and have suggested new ways of simulating coupled processes, specifically: (i) coupling of different models designed for different processes by developing numerical model interfaces; and (ii) dynamic modeling of process chains as a continuum. Although a physically based process continuum approach is preferable to one involving coupling of different models, both approaches have their strengths and limitations. Understanding of each GLOF process component is crucial for advancing modeling of process coupling, in particular through documentation and analysis of past events.

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