Characteristics of glacial lake hazards and extreme flow events: advanced approaches to model processes and process chains

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Characteristics of Glacial Lake Hazards and Extreme Flow Events –
Advanced Approaches to Model Processes and Process Chains

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en cotutelle
présenté à la Faculté des Sciences de l’Université de Genève
pour obtenir le grade de Docteur ès sciences, mention sciences de l’environnement

par
Raphael Worni

de
Saanen (BE)

Thèse N° 4511

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Doctorat en co-tutelle avec l'Université de Berne
Abstract

Glaciated high-mountain regions are particularly susceptible to climate change and associated changes in hazard situations. Glacier retreat is observed in most mountain regions of the world, which has given rise to the formation of numerous new glacial lakes. Glacial lakes can be classified into several types according to their position relative to the glacier and the damming mechanism. They are often located in remote and dynamic environments and – depending on the dam and lake type – may become unstable and prone to catastrophically burst out. Sporadic glacial lake outburst floods (GLOF) can evolve into highly mobile flows, which can pose a real threat in case they reach populated regions or infrastructure where they can cause inundation or massive deposition of sediment. Extreme flow events in high mountain regions can be caused by sources other than glacial lakes: Glacier-covered volcanos have, for instance, repeatedly caused severe disasters in the past. Through volcano-glacier interactions large amounts of water can be released and highly destructive flows (lahars) can form due to sediment entrainment. Extreme flow events are often characterized by complex and interacting processes, typically resulting from cascades of processes rather than single phenomena. For instance, even unstable glacial lakes normally need a trigger to induce dam failure and a typical process chain for GLOF disasters of moraine dammed lakes would be (i) an impulse wave generation by mass flows into the lake and wave propagation over the lake; (ii) dam overtopping, dam erosion and dam breaching; and (iii) lake emptying and flood propagation. Yet, a variety of trigger mechanisms for GLOFs and other extreme flow events are common and different process cascades occur in real case events. In addition, highly dynamic and unsteady flow behavior of extreme flow events is typical, rendering risk assessments altogether a real challenge.

The aim of this thesis therefore was to improve our understanding of the onset, propagation and potential impact of extreme flow events and to provide insights into complex processes and process chains. For this purpose field- and modeling based analysis of illustrative past and potential future events was carried out. Furthermore this thesis aimed at providing a compilation of existing and state-of-the-art modeling tools to simulate various types of extreme flow events. We present advanced, dynamic modeling approaches for the simulation of moraine dam breaches and high-magnitude, water-sediment flows. In addition, we carry forward the application of modeling tools and techniques for the simulation of entire process chains. Despite certain
limitations, the modeling represented in this thesis forms one of the most complete and integral GLOF modeling approaches that has been realized so far.

The overall goal of improved process knowledge and advanced modeling techniques is eventually to improve hazard assessments of potential extreme flow events and to provide a basis for risk reduction measures. Past GLOF and lahar events in Argentina, Colombia, Switzerland and Tajikistan were studied, which provided important insights into complex processes. A crucial aspect of the analysis and retrospective modeling of past events is the calibration and testing of models. Models must be calibrated and sensitivity analyses be performed on important model input parameters before applying simulation tools to model potential future events. Scenario modeling was carried out at a volcano in Colombia, and at glacial lakes in the Indian Himalayas and the Pamir range in Tajikistan. Only by quantifying relevant flow and sediment transport processes can impacts of high-magnitude floods be understood, and results be obtained in terms of modeled inundation depths, flow extent and approximate flow travel times. This information will form the most important basis for prevention and risk reduction actions (e.g. early warning system) at downstream locations. Thereby integrated system approaches in the field and for process modeling are necessary for adequate assessment of potential hazards.
Résumé

Les régions glaciaires de haute montagne sont particulièrement sensibles aux changements climatiques et aux modifications qui en découlent en termes de risques. Dans la plupart des régions montagneuses du monde, les glaciers reculent, entraînant la formation de nombreux nouveaux lacs glaciaires. Les lacs glaciaires peuvent être répartis en plusieurs catégories en fonction de leur position par rapport au glacier et de leur mécanisme de retenue. Ils se situent souvent dans des environnements isolés et changeants et – en fonction du type de digue et de lac – ils peuvent devenir instables et enclins à des ruptures catastrophiques. Des brutales – ci-après GLOF (glacial lake outburst floods) – peuvent occasionner à terme des débits hautement variables, représentant une réelle menace du moment qu’ils atteignent des régions habitées ou des infrastructures, où ils peuvent provoquer des inondations ou le dépôt de grandes quantités de sédiments. Les épisodes d’écoulement extrêmes dans les régions de haute montagne peuvent provenir d’autres sources : par exemple, les volcans recouverts par des glaciers ont provoqué un grand nombre de catastrophes dans le passé. Les interactions entre volcan et glacier peuvent provoquer la libération de quantités d’eau importantes et la formation de flux dévastateurs enrichis par les sédiments entraînés (lahars). Bien souvent, les épisodes d’écoulement extrêmes se caractérisent par des processus complexes qui interagissent entre eux, car on a affaire à des enchaînements de processus plutôt qu’à des phénomènes isolés. Ainsi, même les lacs glaciaires instables ne subissent généralement pas de rupture sans la présence d’un élément déclencheur. Un enchaînement typique provoquant une GLOF à partir d’un lac à barrage morainique pourrait être (i) une vague déclencheuse générée par l’arrivée de flux importants dans le lac et la propagation d’une onde sur celui-ci ; (ii) de l’eau franchissant la digue, provoquant son érosion, puis sa rupture ; (iii) la vidange du lac et la survenue d’inondations. Mais il existe de nombreux mécanismes de déclenchement de GLOF et d’autres épisodes d’écoulement extrêmes et, sur le terrain, les enchaînements de processus ne sont pas toujours les mêmes. Qui plus est, les épisodes d’écoulement extrêmes se distinguent par des écoulements très dynamiques et irréguliers, si bien que l’évaluation globale des risques pose un défi majeur.

L’objectif de notre thèse est de contribuer à une meilleure compréhension du déclenchement, de la propagation et de l’impact potentiel d’épisodes d’écoulement extrêmes et de donner une idée
des processus et enchaînements de processus complexes qui interviennent. A cet effet, nous avons procédé à des analyses de terrain et à des analyses par modélisation d’évènements soit passés, soit possibles dans le futur. Un autre but était de proposer un aperçu d’outils de modélisation existants et actuels permettant de simuler différents types d’épisodes d’écoulement extrêmes. Nous présentons des approches avancées et dynamiques pour simuler la rupture de barrages morainiques et les écoulements de grande ampleur d’eau et de sédiments. Par ailleurs, des outils et techniques de modélisation nous permettent de simuler des enchaînements complets de processus. Malgré certaines restrictions, les techniques de modélisation représentées dans notre thèse représentent l’une des approches les plus complètes et intégrales de modélisation de GLOF disponibles à ce jour.

L’objectif plus général poursuivi en améliorant la connaissance des processus et les techniques de modélisation est, à terme, d’améliorer l’évaluation des risques d’épisodes potentiels d’écoulement extrêmes et de fournir une base pour des mesures de réduction des risques. L’étude d’épisodes GLOF et lahar survenus en Argentine, en Colombie, en Suisse et au Tadjikistan a contribué à notre compréhension de processus complexes. Un aspect crucial de l’analyse et de la modélisation rétrospective des épisodes passés est la calibration et la mise à l’épreuve des modèles. Ce n’est qu’après calibration du modèle et analyse de la sensibilité de paramètres importants qui y sont insérés que les outils de simulation peuvent être appliqués pour modéliser des évènements futurs potentiels. Des modélisations ont été réalisées sur un volcan en Colombie, sur des lacs glaciaires dans l’Himalaya indien et dans le massif du Pamir au Tadjikistan. La quantification de processus d’écoulement et de déplacement de sédiments est indispensable pour comprendre les effets d’inondations de grande ampleur et obtenir des résultats sous forme de modélisations de profondeurs d’inondation, d’ampleur des débits et de durées de déplacement approximatives des flux. Ces informations serviront de base pour des mesures de prévention et de réduction des risques (p.ex. systèmes d’alerte précoce) concernant les lieux en aval. Ainsi, des approches systémiques intégrées sont nécessaires autant sur le terrain que pour modéliser des processus dans le but d’évaluer correctement les risques potentiels.
# Table of contents

Abstract ................................................................................................................................................. 1

Résumé................................................................................................................................................... 3

Table of contents.................................................................................................................................... 5

1. Introduction..................................................................................................................................... 7

2. Aim and structure of the thesis ..................................................................................................... 11

3. Thematic and scientific background............................................................................................. 13
   3.1 Characteristics of extreme flow events in high mountain regions ........................................... 13
   3.2 Different triggers and types of extreme flow events ............................................................... 15
   3.3 Modeling processes and process chains of extreme flow events .......................................... 19
   3.4 Study regions ............................................................................................................................ 23

References............................................................................................................................................ 25

4. Research papers ............................................................................................................................ 31
   4.1 Numerical Modeling of Flows and Falls .................................................................................. 31
   4.2 Challenges of modeling current very large lahars at Nevado del Huila Volcano, Colombia ... 43
4.3 Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina) ................................................................................. 61

4.4 Glacial lake outburst floods in the Pamir of Tajikistan: Challenges in prediction and modelling. 75

4.5 Glacial lakes in the Indian Himalayas – from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes ......................................................... 87

4.6 Extreme flow events in mountainous regions – advanced approaches to model processes and process chains ........................................................................................................................ 103

5. Synthesis, discussion and outlook ........................................................................................................ 139

5.1 Summary and main findings ........................................................................................................... 139

5.2 Overall discussion ........................................................................................................................ 141

5.3 Conclusions and perspectives ..................................................................................................... 143

References ........................................................................................................................................ 147

Acknowledgements .......................................................................................................................... 149

Remerciements ................................................................................................................................ 151

Curriculum vitae .............................................................................................................................. 153
1. Introduction

Glaciated high-mountain regions are particularly susceptible to climate change (IPCC, 2007) and associated changes in hazard situations (Stoffel and Huggel, 2012). Changes in glacier and permafrost equilibria are shifting hazard zones beyond historical experience, while human settlements and activities have extended towards endangered zones. As a result, glacier- and permafrost-related hazards represent a growing threat to human lives and infrastructure in high mountain regions. Individual disasters have been reported to cause hundreds or even thousands of fatalities and cause damage with a global sum in the order of 100 million euros annually (GAPHAZ, 2012).

Climate-related glacier retreat is observed in most high mountain regions worldwide (e.g. Haeberli et al., 1999; Dyurgerov and Meier, 2000; Hoelzle et al., 2003; Paul et al., 2004; Bolch et al., 2012), which has given rise to the formation of numerous glacial lakes (Fig. 1). Besides being an indirect indicator of glacier change (Gardelle et al., 2011), glacial lakes can be unstable and present potential hazards to downstream locations (Costa and Schuster, 1988). Sporadic glacial lake outbursts (Fig. 2) may drain as powerful floods (Mergili et al., 2011) and are considered the most important glacier-related hazard in terms of direct damage potential (Osti and Egashira, 2009). Glacial lake outburst floods (GLOFs) have killed thousands of people in many parts of the world (Clarke, 1982; Hewitt, 1982; Clague and Evans, 1994, Watanabe and Rothacher, 1996; Clague and Evans, 2000; Richardson and Reynolds, 2000a; Huggel et al., 2004; Carey, 2005) and with ongoing glacier retreat new glacial lakes are likely to develop in the future (Frey et al., 2010). As a result, GLOF risks are receiving increased attention as a key climate change hazard (Malone, 2010).

In consideration of the serious hazard potential emanating from GLOFs and other large-magnitude water-driven processes such as lahars (refer to chapter 3.2), it is of great importance to improve the understanding of processes involved and their dynamics. However, due to the difficulty of directly measuring large-magnitude flows, there is an unsurprising lack of quantitative information. Studies of well characterized past events can provide an important basis for enhancing knowledge on flow physics and flow parameters under real case conditions (Worni et al., 2012a). Yet, worldwide, few such case studies exist where recent extreme flow events with
volumes of tens to hundreds of millions of cubic meters could be observed (Major and Newhall, 1989; Carrivick, 2006). In an attempt to close this critical gap, key aspects and important processes of extreme flow events are analyzed in this thesis based on field studies and advanced modeling approaches. Particularly dynamic models have been demonstrated to be a valuable tool to reconstruct past events and to assess potential hazards emanating from different types of flow events. Such data facilitates the planning and dimensioning of accurate mitigation and adaptation measures such as early warning systems, and help the justification of decisions aimed at preventing infrastructure and populated areas from being possibly at risk (Worni et al., in press).
**Fig. 1:** The Trift Glacier in Switzerland illustrates how glacier retreat caused by climate warming can lead to the formation of a proglacial lake within a few decades. In most mountain regions of the world such an image of retreating glaciers is reality (from Stoffel and Huggel, 2012).

**Fig. 2:** A moraine dammed glacial lake in the Patagonian Andes (Argentina) before (left) and after (right) dam failure and catastrophic lake drainage. This case illustrates typical instability of (moraine dammed) glacial lakes. (Photographs by Bran Luckmann (left) and Club Andino Bariloche (right)).
2. Aim and structure of the thesis

This thesis was realized within the EU Framework Programme 7 project “HighNoon” (2009 – 2012; http://www.eu-highnoon.org), realized jointly between European, Indian, and Japanese partner institutions. The principal aim of the HighNoon project was to assess the impact of Himalayan glacier retreat and possible changes in the Indian summer monsoon on the spatial and temporal distribution of water resources in northern India. In addition, the project aimed at providing recommendations for appropriate strategies to cope with hydrological extreme events (Moors and Siderius, 2012). The research on glacial lakes and glacial lake hazards in the Indian Himalayas, presented in this thesis, covers one aspect of hydrological extremes. Yet, the focus of this thesis is not limited to glacial lakes and glacial lake hazards in the Indian Himalayas, but also includes other extreme flow processes and study sites outside the Indian Himalayas. The overall goal was to improve the process understanding of a variety of extreme flow events and to carry forward the application of modeling tools and techniques for the simulation of different processes involved in extreme flow events.

In order to improve knowledge of the complex nature of large-magnitude, water-driven flows, past events were analyzed in the field, which provided insights into the functioning and dynamics of critical processes and process chains. The retrospective modeling of past events allowed quantification of critical parameters, as well as calibration and testing of modeling tools, with the aim to apply the newly gained process understanding for scenario modeling of potential future events. This thesis is therefore structured in five chapters:

Chapter 1 and 2 provide a synopsis of the thesis; chapter 3 reviews the thematic and scientific background and includes a presentation of the study sites. The research papers that form the core of this thesis are contained in chapter 4. They provide (i) an overview of existing and novel modeling techniques for the simulation of extreme flow events; (ii) present case studies of past events in order calibrate and test different modeling tools with the aim of improving process understanding; and (iii) deal with field and modeling based assessments of potential future risks of extreme flow events. The research papers are presented in the following order:

Chapter 4.1: Numerical Modeling of Flows and Falls.
Chapter 4.2: Challenges of modeling current very large lahars at Nevado del Huila Volcano, Colombia.

Chapter 4.3: Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina).

Chapter 4.4: Glacial lake outburst floods in the Pamir of Tajikistan: Challenges in prediction and modelling.

Chapter 4.5: Glacial lakes in the Indian Himalayas – from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes.

Chapter 4.6: Extreme flow events in mountainous regions – advanced approaches to model processes and process chains.

A synthesis and general discussion of the methods applied and findings is finally given in chapter 5.
3. Thematic and scientific background

3.1 Characteristics of extreme flow events in high mountain regions

In the context of this thesis, extreme flow events are referred to processes of water-sediment flows in high mountain regions. They can be described by hydraulic principles and mechanisms of sediment transport, and encompass different flow types such as lahars and GLOFs (refer to chapter 3.2). In the following, some key definitions and characteristics of extreme flow events are given:

- Extreme flow events in high mountain environments can be attributed by extraordinary mobility, flow transformations or chain reactions implying high hazard potentials if they are reaching populated areas (Schneider, 2011).
- Classification of extreme flow events can be done e.g. according to the water content, material properties, velocity of movement, failure mechanism, and volume (Hungr, 2005).
- Extreme flow events are characterized by dynamic and interconnected behavior and processes cannot be treated discretely, but integral systems and process chains must be considered (Worni et al., in review).
- Extreme events are, almost by definition, of particular importance to human society. Consequently, the importance of understanding potential extreme events is first order. (IPCC, 2007).
- Extreme events are occurrences that are notable, rare, unique, profound, or otherwise significant in terms of their impacts, effects, or outcomes. When extreme events occur at the interface between natural and human systems, they are often called “disasters” (Sarewitz and Pielke, 2001).

When large amounts of water are released in mountain terrains, sediment and debris is normally entrained into the flow, where particle properties, fluid–particle and particle–particle interactions govern the flow behavior. Thereby the water and sediment content as well as type and size distribution of the particles are key parameters (Pierson and Costa, 1987; Capra et al., 2004;
Iverson, 2009). Water-sediment flows can be roughly divided into Newtonian and non-
Newtonian flows. Newtonian flows are pure water or low sediment concentration stream flows
whose shear stress is linear to the strain rate. Non-Newtonian flows are e.g. hyperconcentrated
flows or debris flows for which yield strength and viscosity become flow-dominant parameters
whereby viscosity is dependent on the strain rate (Pierson and Scott, 1985). Debris flows are
poorly sorted cohesive or noncohesive sediment-laden mixtures with a sediment concentration of
ca. 60% or more by volume (Lavigne and Thouret, 2002). Hyperconcentrated flows have
sediment concentrations in the range of 20% to 60% by volume and flows with a sediment
concentration below 20% by volume normally have Newtonian flow behavior. Yet, these
boundaries strongly depend on the particle-size distribution of solids and clay-mineral content
and vary for different mixtures. In addition, hyperconcentrated flows are not only defined by
sediment concentration but also by the concentration of suspended fines which must be sufficient
to impart yield strength to the fluid and to maintain high fluid viscosity (Jakob and Hungr, 2005).
Commonly such flows transport large quantities of sand-sized material in full suspension and
some gravel as bedload. Deposition occurs progressively and not “en masse”, as it is commonly
assumed for debris flows (Smith and Lowe, 1991; Major and Iverson, 1999; Lavigne and
Thouret, 2002; Pierson, 2005). In the case of debris flows, yield strength alone can suspend
course gravel particles, whereas gravel can be suspended only by fluid forces in
hyperconcentrated flows (Jakob et al., 2005). Debris flows are $10^4$-$10^5$ times more viscous than
water and the yield strength must be typically exceeded before flow is possible but then they can
achieve velocities double those of water floods (Manville et al., 2012).

The flow type of past events can be reconstructed in the field: Debris flows commonly develop
lateral levees composed of coarse blocks and steep, lobate snouts at the flow front. Deposits can
have framework-supported larger clasts, exhibiting a wide range of grain sizes, are poorly sorted
and lack any stratification. Hyperconcentrated flows deposit sandy sediments including lenses of
gravel and wood on the surface. Cross-bedding and ripple lamination are absent while outsize
cobbles and boulders are, in contrast, present. The sand- and granule-grade deposits exhibit a
faint horizontal stratification, and strata are graded to normal graded (Worni et al., 2012a).

Extreme flow events are highly unsteady flows, often characterized by pronounced changes
during the flow, converting from normal runoff to a hyperconcentrated flow and granular debris
flows and vice versa (Mergili et al., 2011; Worni et al., 2012a; Manville et al., 2012). Such
transformations are mainly related to sediment deposition and bulking processes or the dilution
of a flow by stream water (Smith and Lowe, 1991). Transitional flow between a debris and
hyperconcentrated flow deposits mainly poorly graded and sorted sandy material, and some
boulders on top of the deposits. The volumes and peak discharges of extreme flow events can
increase by a factor of three or more relative to initial values (Manville, 2004; Mergili et al.,
2011) due 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). Hydrograph attenuation (i.e.
flattening and lengthening) is typically observed as flows propagate downstream (Cronin et al.,
1999; Worni et al., 2012a).
3.2 Different triggers and types of extreme flow events

Different types of extreme flow events exist in mountain regions, with the most common being flash floods, glacial lake outburst floods (GLOF) or lahars. Such extreme flow events normally have shorter timescales and consequently more pointed hydrographs than regular floods. Although the flow behavior of different extreme flow events may differ, they are still comparable as in each case large amount of water and in most cases entrained material is mobilized, flowing downstream due to gravitational forces. The source or trigger mechanism of a flow serves as a main criterion to distinguish between flow types. Flash floods are often associated with meteorological extreme events such as cloud bursts, however are sometimes also related to other triggers such as dam break floods. In this thesis, only GLOFs and lahars are taken into consideration.

Glacial lakes and glacial lake outburst floods

GLOFs (also called Jökulhlaups) are triggered by a partial or complete dam failure of a glacial lake. Glacial lakes can be proglacial, englacial, subglacial, supraglacial, ice marginal or periglacial. Lakes of the last type are not in contact with active glaciers, but are often associated with dead glacier ice or ground ice in permafrost. Lake dams can consist of weak or strong bedrock, competent glacier ice, highly fractured or crevassed ice produced by glacier surges or ice avalanches, dead and sometimes buried glacier ice, moraines (frozen, unfrozen, consolidated, loose) or material deposited by mass movements, including rock or ice avalanches, landslides, debris flows and creeping permafrost (such as rock glaciers; Haeberli et al., 2010). Depending on the glacial lake and dam type different outburst floods can result. Costa (1988) describes typical outburst flood hydrographs of moraine dammed and ice dammed lakes. While the outburst hydrographs of moraine dammed lakes normally have steep rising and steep falling limbs with outburst durations of minutes to hours, the outburst hydrographs of ice dam breaches often have a progressive rising limb and a very steep falling limb where the outburst can last from hours to days.

In this thesis we mainly deal with moraine dammed glacial lakes and moraine dam breaches, reason why such breach mechanisms are outlined in more detail. Not all existing moraine dammed glacial lakes are unstable and most lakes will not burst out catastrophically (Huggel et al., 2004). Lake outburst probability is a function of the susceptibility of the dam to fail and the potential of external trigger processes (Richardson and Reynolds, 2000a). The stability of a dam depends primarily on its geometry, internal structure, and material properties (Costa and Schuster, 1988; Korup and Tweed, 2007). The stability of a dam can change with time, as for instance melting of stagnant ice within moraine dams can contribute to a weakening of overall dam structure (Clague and Evans, 2000; Richardson and Reynolds, 2000b; Worni et al., 2012b). However, even unstable glacial lakes normally need a trigger to induce dam failure: Dams fail...
when the material strength is exceeded by driving forces that comprise, among others, the weight of the impounded water mass, seepage forces, earthquakes and shear stresses from overtopping flow or displacement waves (Korup and Tweed, 2007; Massey et al., 2010). Overtopping flows can be caused by heavy rainfall or a sudden influx of water from upstream sources; displacement waves are, in contrast, triggered by mass movements entering the lake, such as snow and ice avalanches, rockfalls, debris flows or landslides (Costa and Schuster, 1988; Clague and Evans, 2000; Huggel et al., 2004). Once the lake overflows water will typically induce dam erosion, forming an initial breach, that leads to greater outflow and increasing hydrodynamic forces which cause progressive breach enlargement (Singh, 1996). Thereby critical shear forces are exerted on the dam material by the flow 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 glacial lake. The peak discharge, the volume of released lake water, the amount of entrained sediment and material (also trees) and the downstream terrain are critical parameters that control flow behavior. Each location is unique and individual floods will differ from one other; therefore, in order to assess flood parameters and magnitudes field survey and modeling tools must be applied.

In order to assess the hazard potential of glacial lakes, there is a need for a multi-level approach including (i) basic lake detection, (ii) first classification of detected lakes based on high-resolution imagery, and (iii) local-scale hazard assessment of individual lakes based on field evidence and modeling (Huggel et al., 2002).

(i) Glacial lake detection

Glacial lakes can be mapped semi-automatically over large areas using the normalized difference water index (NDWI; equation 1), applied on the spectral bands TM1 (for blue wave length) and TM4 (for near infrared wave length) of Landsat ETM+ satellite images (Huggel et al., 2002).

\[
\text{NDWI} = \frac{TM4 - TM1}{TM4 + TM1}
\]  

(1)

Typical NDWI values for lake surfaces range between –0.60 and –0.85. However, as a result of spectral reflection, self-shadowed areas can be misclassified as lakes and therefore an optical validation is required to get the final lake mask (Huggel et al., 2002). For glacial lake mapping, glacier outlines are required as well in order to consider only lakes in direct or close glacier proximity.
Fig. 3: Spectral band 1 (TM1) and 4 (TM4) of a Landsat ETM+ satellite image, showing North Sikkim, India. On the normalized difference water index (NDWI) image, water bodies and shadowed areas appear black. By choosing adequate threshold values to separate water from shadow and after manual post processing, lakes can be identified and mapped.

(ii) **First assessment and classification of detected lakes**

Based on satellite images and digital elevation models (DEM) a first classification and assessment of the detected glacial lakes is possible. Thereby high resolution imagery in Google Earth gain more and more importance as it provides freely available images over large areas in often good quality. Thereby parameters such as dam types, dam geometry, lake areas, lake drainage, lake environment in respect to possible trigger mechanisms, dam freeboard, and downstream terrain can be assessed. At this level it should not be concluded on the prevalent hazard situations, as in most cases data basis is to scarce for a serious evaluation. However, a rough lake classification helps to prioritize lakes that need further investigations such as field surveys and/or modeling. Glacial lake inventories with a classification of detected lakes are also useful for non-specialist local authorities to quickly identify sites where more detailed and comprehensive studies should be directed (Allen et al., 2009).

(iii) **Hazard assessment of critical glacial lakes**

Glacial lakes are often located in remote areas and depending on their accessibility field survey can be more or less extensive. In case that heavy equipment can be transported to the lake, geophysical sounding techniques, notably electrical resistivity and seismic refraction techniques,
can help to define dam characteristics and stability (Haeberli et al., 2010). A boat and sonar equipment is required to measure lake bathymetry for lake volume calculations. The lake volume is an important parameter to estimate potential lake outburst magnitudes. Alternatively, empirical relationships have been developed which correlate lake area with lake volume (e.g., Huggel et al., 2002). If heavy equipment cannot be transported to a critical lake, qualitative methods can be applied in the field to gather relevant data and parameters and to assess hazard potential (Costa and Schuster, 1988; Yamada and Sharma, 1992; Clague and Evans, 2000; Huggel et al., 2004; McKillop and Clague, 2007). Crucial parameter include dam type, dam geometry (dam width to dam height ratio), distal dam flank steepness, material properties of the dam, grain size distributions, dam material’s repose angle, freeboard or morphology of glaciated and non-glaciated lake environment (potential for mass movements to impact the lake). With respect to lake outburst scenario modeling, which is important for the assessment of hazard situations, model input parameters must be obtained in the field. Process modeling is addressed in more detail in chapter 3.3.

**Volcanos and lahars**

The Indonesian term ‘lahar’ defines debris and hyperconcentrated flows of volcanic origin differing from normal streamflow (Smith and Lowe, 1991; Coussot and Meunier, 1996; Canuti et al., 2002; Lavigne and Thouret, 2002). Lahars often exhibit higher concentrations of fines (Verstappen, 1992; Vallance, 2000), which makes them more mobile than their non-volcanic counterparts (Legros, 2002; Dufresne et al., 2010).

Most lahars are triggered by rainfalls, which occur weeks to years after an eruption, mobilizing eruptive deposits on the volcano flanks (Lavigne and Thouret, 2002). Alternatively, on glacier and/or snow-covered volcanos, volcano-ice/snow interactions can destabilize potentially frozen steep debris (Evans and Clague, 1988; Iverson, 1997) and glaciers (Huggel et al., 2007) or rapidly melt large volumes of ice and snow (Pierson et al., 1990; Thouret et al., 2007; Julio-Miranda et al., 2008). Another trigger of lahar was observed in 1994 after a rainy period at Nevado del Huila Volcano (Colombia). An earthquake at the base of the volcano triggered shallow landslides from the steep, water saturated volcano flanks, evolving into a highly mobile lahar (Worni et al., 2012a).

Lahars have occurred in many settings around the world (Verstappen 1992; Lavigne and Thouret, 2002; Thouret et al., 2007; Worni et al., 2012a) and they are typically highly destructive. As historical events have shown, even small volcanic eruptions may produce large-scale water-sediment floods when interacting with snow and ice. This was the case at the world’s largest historic volcano-glacier disaster at Nevado del Ruiz Volcano in the Colombian Andes. In 1985, this glaciated volcano produced a small Plinian eruption during which a density current entrained snow and ice, resulting in rapid melt. The estimated volume of ice, firm, and snow lost during the eruption was 60 million m$^3$, corresponding to a water equivalent of approximately 43
million m\(^3\) (Thouret, 1990). Only 11–12 million m\(^3\) of released water formed the deadly set of lahars that claimed more than 23,000 lives in the town of Armero (Pierson et al., 1990). Lahars can occur without or almost no preannouncement, e.g. in cases of rainfall or earthquake triggered events; but they can also be forecasted to a certain extent by monitoring volcanic activity. In contrast to GLOFs, which are normally single events (at least for moraine dam breaches), lahars can occur repeatedly from the same volcano. Hence, by knowing the volcano’s history and by monitoring volcanic activity, lahar alert systems can be installed so as to protect people located in the vicinity of a volcano. In Colombia, for instance, active volcanoes are monitored by seismographs, web cams, geophones and helicopter surveys to assess the prevalent volcanic activity and to estimate the potential of lahar formation. Four levels of volcanic activities are distinguished: (i) stable, (ii) changing volcanic activities, (iii) volcanic eruption probable within days or weeks and (iv) volcanic eruption is about to happen. Each level is assigned with possible scenarios for which the involved authorities and population are aware of potentially required actions. Lahar modeling can provide important data to compile hazard maps, define places for evacuation (save heavens) and estimate lahar travel times. The latter is important for early warning, which requires information on approximate evacuation times in case of a lahar alert. More details on lahar modeling are provided in the next chapter.

3.3 Modeling processes and process chains of extreme flow events

Modeling processes or process chains of extreme flow events is a valuable tool to improve (i) the knowledge of complex processes and (ii) to assess potential magnitudes and hazards of potential future events. Within this thesis different modeling tools have been used for the simulation of extreme flow events, and one modeling tool was applied for the simulation of earthen dam breaches. In the following, general characteristics are provided for the different modeling approaches used. More detailed descriptions can be found in the research papers (chapter 4.1-4.6)

A large variety of modeling approaches and a vast number of programs exist to simulate the propagation of water and sediment flows, ranging from simple empirical models to physically-based dynamic models. Empirical models are founded on statistical analyses of field measurements from past flow events on which base average behavior of future flows are predicted (Manville et al., 2012). Physical flow models generally consist of (i) a set of terms that describe conservation of mass and momentum; (ii) a description of the channel and floodplain geometry; (iii) a method to quantify flow resistance; and (iv) a numerical approach to solve partial differential equations (Manville et al., 2012). In contrast to empirical models, sophisticated models can handle complex flow behaviors governed by fluid and particle interactions, turbulent flow or changing flow regimes. Nevertheless, no modeling approach exists today which covers the complex nature of extreme flow events fully (e.g. constantly changing...
flow rheology) and thus a careful selection of the most adequate models is crucial for a certain problem.

Similar as for flow models, different approaches and mathematical models exist to simulate earthen dam breach processes and breach outflow (Singh and Scarlatos, 1988; Sing, 1996; Tingsanchali and Chinnarasri, 2001). Empirical dam break models are used to predict breach formation time, breach geometry and peak outflow discharge, based on the analysis of real dam failures (Singh, 1996; Wahl, 2010). In contrast, physical models apply geotechnical considerations, erosion rates and hydraulic principles to take account of breach development. However, many physical dam break models still require critical input parameters regarding the shape of the breach and its enlargement over time, which are often based on assumptions rather than on physical evidence (Pickert et al., 2011; Worni et al., 2012b). New erosion-based, dynamic models represent an improvement in this respect (Balmforth et al., 2008; Faeh et al., 2012), and constitute a promising approach to capture the breaching processes with reasonable accuracy. These models solve balancing equations for water flow in combination with empirical transport formulas to simulate embankment failures, thereby using clear physical input parameters (Worni et al., in review).

An innovative approach in modeling natural disasters, which are characterized by cascades of processes rather than single phenomena (Haeberli et al., 2010), are integrated modeling approaches. Integrated modeling means that models from different fields are merged, thus yielding an integrated system description and a more complete representation of reality (Geidl, 2007). In a multi-hazard analysis, all relevant hazards in a defined region are considered and possible interactions and cascading effects between hazardous processes are taken into account (Delmonaco et al., 2006).

In Table 1a/b different models are presented that were applied to model extreme flow events and moraine dam breaches at different case studies in this thesis (chapter 4). This selection covers a range of representative models; however, it is not meant to be a holistic discourse of existing model types.
Table 1a: Physically-based, dynamic models that were applied to model extreme flow events and moraine dam breaches. The table also indicates the dimensions in which the programs are running, references the research papers in chapter 4 in which the programs appear and lists the modeled processes. Only BASEMENT was applied for modeling single processes and entire process chains.

<table>
<thead>
<tr>
<th>Program</th>
<th>Processes*</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASEMENT</td>
<td>1-D/2-D Water-sediment flow; dam breach, impulse waves</td>
<td>BASEMENT is a fluid dynamics and sediment transport model for the analysis of water-sediment flow propagation and breaching processes of non-cohesive earthen dam structures (Faeh et al., 2012). The two-dimensional program simulates water and sediment flows in a two phase system with separate unstructured meshes for the water and sediment phase. For the hydrodynamic calculations the program solves the shallow water equations with an explicit Finite-Volume method and the application of an exact Riemann solver. Erosion and sediment transport of single and multiple grain classes caused by water flow are calculated with empirical sediment transport equations. Hence, sediment transport laws are used to calculate the vertical incision in earthen dam structures due to overtopping flow. The lateral breach widening due to slope collapses of the side walls are considered with a geometrical 3-D bank failure operator. It is based on different critical failure angles, and if one of the failure angles is exceeded due to vertical dam erosion, gravitational bank failure occurs.</td>
</tr>
<tr>
<td>FLO-2D</td>
<td>1-D/2-D Water-sediment flow, hyperconc. flow, debris flow</td>
<td>FLO-2D is a commercial hydraulic flood-routing model for channel and unconfined overland flow (O’Brien, 2001). It is a finite difference model using the dynamic wave momentum equation to describe the fluid, which consists of the continuity equation and the equation of motion. When modeling flows for the more sediment-laden, debris-flow end of flow continuum, the FLO-2D program applies a quadratic rheological model, combining Bingham shear stresses (sum of yield stress and viscous stress) and turbulent-dispersive shear stresses that define the inertial flow regime (O’Brien, 2001). The sediment concentration of a flow and flow rheological parameters are specified by the user, which together define the flow rheology and flow behavior. The 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 both sediment and water are solved numerically (Manville et al., 2012).</td>
</tr>
<tr>
<td>RAMMS</td>
<td>2-D Debris flow</td>
<td>RAMMS (Christen et al., 2010) is a model to simulate various types of rapid mass movements (e.g. snow avalanche, ice-rock avalanche, debris flow). The core of the program is an efficient second-order numerical solution of the depth-averaged equations of motion (the shallow water equations) for granular flows. Frictional resistance is described by using a Voellmy approach which incorporates a parameter for the dry Coulomb friction µ and a velocity squared dependent turbulent friction ξ, which are depending on the properties of the flowing material and the surface roughness (Bartelt et al., 1999). The RAMMS DEBRIS FLOW module was developed to simulate the runout of muddy and debris-laden flows in complex terrain and provides the option to use an input hydrograph or a block release to start the model (RAMMS, 2012).</td>
</tr>
<tr>
<td>HEC-RAS</td>
<td>1-D Water flow</td>
<td>The U.S. Army Corps of Engineers’ River Analysis System (HEC-RAS) solves the full 1D St Venant equations and allows performing one-dimensional steady and unsteady flow, as well as movable boundary sediment transport computations. HEC-RAS is an integrated system of software, designed to perform hydraulic calculations for a full network of natural and constructed channels and for interactive use in a multi-tasking, multi-user network environment (Brunner, 2002).</td>
</tr>
</tbody>
</table>

* as modeled in this thesis (some programs are capable to model more processes)
**Table 1b:** Semi-empirical models that were applied to model extreme flow events. The table also indicates the dimensions in which the programs are running, references the research papers in chapter 4 in which the programs appear and lists the modeled processes.

<table>
<thead>
<tr>
<th>Program</th>
<th>Processes*</th>
<th>Description</th>
</tr>
</thead>
</table>
| **LAHARZ**  
2-D  
Chapter 4.2, 4.6 | Water-sediment flow (lahar) | The LAHARZ flow model is a semi-empirical program developed by Iverson et al. (1998) that calculates flow extent and run-out distances of lahars in valleys. It links the valley cross-sectional area \((A)\) and the planimetric area inundated by lahars \((B)\) with total lahar volume \((V)\). The equations \(A=0.05V^{2/3}\) and \(B=200V^{2/3}\) form the basis of the program, where the proportionality rules \(A \propto V^{2/3}\) and \(B \propto V^{2/3}\) have a physical basis and two proportionality factors \(C\) and \(c\) in the equations \(A=CV^{2/3}\) and \(B=cV^{2/3}\) are calibrated based on 27 past lahars and non-volcanic debris flows. The LAHARZ program runs in an ArcGIS environment. |
| **MSF**  
2-D  
Chapter 1 | Water-sediment flow | The modified single flow (MSF) model can be applied to model mass flows and hydrological extreme events. The downslope-moving mass is controlled by gravitational forces, following the given topography. To simulate the downslope flow, a hydrological flow-routing algorithm is applied, which transfers flow sequentially to lower areas. A probability function defines that the more the flow diverts from the steepest descent direction the greater is the resistance and, accordingly, the lower the probability that this area is affected. The travel distance of the modeled mass flow is controlled by an empirical approach applying a minimum average slope (Huggel et al., 2003). |
| **Flow-R**  
2-D  
Chapter 1 | Debris flow | The Flow-R model was developed for susceptibility assessment of debris flows at a regional scale. It provides a quick assessment of the potential source areas and aims to delimit the zone tending to be in the path of the flow propagation. The spreading area estimations are based on a probabilistic spreading by means of flow direction algorithms on the one hand, and, on the other hand, on a basic energy balance, which allows defining the maximal runout distance (Horton et al., 2008). The slope-angle-concept (the friction model is used to assess the energy balance) is extended with an option of velocity maximum threshold, making modeling nonlinear. The turbulent models are also included in Flow-R. |

* as modeled in this thesis (some programs are capable to model more processes)
3.4 Study regions

In this thesis we have analyzed and modeled different past and potential future extreme flow events in Argentina, Colombia, India, Switzerland and Tajikistan. In the following each case study site is shortly described.

**Nevado del Huila Volcano** (2°56’5”N; 76°1’39”W) is located in the south west of Colombia and forms the highest summit of the Colombian Andes with 5364 m asl (Pulgarín et al., 2004). No historic eruptions are known before 2007 when eruptive activity from Nevado del Huila was first reported. The volcano has an elliptical form with approximate basal axes of 16 km in the north–south and 11 km in the east–west directions. In 2007 the glaciers on Nevado del Huila covered an area of about 10.7 km². In 1994, 2007 and 2008, lahars were triggered from Nevado del Huila, with volumes of up to 320 million m³ and runout distances of up to 160 km, killing up to 1000 people and causing severe damage to infrastructure (Worni et al., 2012a).

**Mount Tronador** (41° 10’ S, 71° 52’ W; 3480 m asl) is the highest mountain in the Nahuel Huapi National Park and straddles the border between Chile and Argentina in northern Patagonia. The upper part of the mountain is covered by a continuous ice cap, with eleven outlet glaciers. The total glacier area is about 64 km² and the largest glaciers reach down to 950 m asl (Villalba et al., 1997). The recession of the valley glacier Ventisquero Negro on the Argentinian side of the mountain resulted in the formation of a proglacial, moraine dammed lake. The lake grew rapidly after the 1990s and the maximum lake extent was 47 ha before its moraine breached in May 2009, producing a devastating GLOF (Worni et al., 2012b).

**Spong Togpo lake** (34°03’02’’N; 76°43’04’’E; 5100 m asl) is a moraine dammed glacial lake in the Zanskar mountain range in the Ladakh region (Jammu and Kashmir), in the northwestern Indian Himalayas. No past events are known for this site, but in case of a moraine dam breach, a GLOF could hit the downstream village of Honupatta.

**Gopang Gath lake** (32°31’38’’N; 77°13’03’’E; 4100 m asl) is a large, moraine dammed glacial lake above the Chandra Valley (Himachal Pradesh, India) in the Great Himalayan mountain ranges. It is surrounded by highly dynamic glaciated and non-glaciated mountain slopes, which are sources of potential mass movements impacting the lake. The downstream village Sissu might be at risk in case of a lake outburst flood.

**Shako Cho lake** (27°58’29’’N; 88°36’58’’E; 5000 m asl) is a large proglacial lake that is dammed by a sharp moraine dam consisting of unconsolidated material. The lake is located in North Sikkim, India, at the foot of the 1000 m high, glaciated and steep south face of Mount Kangchengyao (6889 m asl). A breach of the unstable moraine dam would lead to disastrous flooding in the downstream villages of Thangu and Lamayuru (Worni et al., in press).
Lake Khavraz (38°34′10″N; 72°36′31″E; 4000 m asl) in Khavrazdara, Tajikistan, is a periglacial lake of ca. 2 km² with an estimated volume of 40 million m³ and is dammed by an active rock glacier. Khavrazdara is a northern tributary of the Barhang Valley in the highly glaciated Pamir mountain range. In the case of a degradation of the rock glacier tongue, a breach of the dam followed by a flood wave down the valley is possible, which would threaten the village of Pasor. Lake Khavraz represents the most important study site within a joint venture glacial lake hazard project in Tajikistan (TajHaz; http://www.baunat.boku.ac.at/15600.html). However, outburst flood modeling was also performed for four other glacial lakes in the Pamir (Mergili et al., 2011).

On the lower Grindelwald-glacier in Grindelwald, Switzerland (46°35′41″N; 8°3′26″E; 1380 m asl), a supraglacial lake drained catastrophically on 30 May 2008. An estimated 570,000 m³ of water were released subglacially within 3 hours, with a maximal peak discharge of 100-110 m³ s⁻¹. The highly turbulent water-sediment flow caused flooding and river bank erosion. Due to annual lake filling and drainage, a tunnel was accomplished in 2010 in order to drain the water in a controlled manner.

Fig. 4: Case study sites where past and potential future extreme flow events were analyzed and modeled within this thesis.
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4. Research papers

4.1 Numerical Modeling of Flows and Falls

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doi:10.1016/B978-0-08-088523-0.00177-5.
7.35 Numerical Modeling of Flows and Falls

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7.35.1 Introduction

7.35.2 Basic Model Principles

7.35.2.1 The Energy-Line Method

7.35.2.2 Dynamic Mass Movement Modeling

7.35.2.3 Dynamic Flood Modeling

7.35.3 Modeling of Flows

7.35.3.1 Energy-Line-Based Models

7.35.3.2 Dynamic Modeling of Large-Scale Flows

7.35.4 Modeling of Rockfall

7.35.5 Future Challenges in Mass Movement Modeling

Acknowledgment

References

Glossary

Debris flow  Poorly sorted cohesive or noncohesive sediment-laden mixtures with a sediment concentration ~60% or more by volume. Yield strength alone can suspend coarse gravel particles and deposition commonly occurs en masse.

Glacier lake outburst floods (GLOFs)  These occur when a lake in a glaciated environment, dammed by glacier ice or a moraine, bursts out due to a dam breach or ice-barrier failure.

Hyperconcentrated flows  Non-Newtonian fluids with sediment concentrations in the range of 20–60% by volume. Gravel can be suspended only by fluid forces in hyperconcentrated flows.

Lahar  Debris flows or hyperconcentrated flows from volcanoes that can be related or unrelated to volcanic activities. Commonly lahars occur on the slopes of a volcano.

Rockfall  These occur when one or several rocks on a steep slope become dislodged and fall down the slope. A rockfall trajectory basically consists of the four processes: sliding, free falling, bouncing, and rolling.

Abstract

A wide range of programs used to model mass movements currently exist. In this chapter, we provide an overview by presenting a selection of approaches used for modeling flows (e.g., debris flows and hyperconcentrated flows) and falls (e.g., rockfall). Mass-movement models support the study of geomorphic landscape changes, and, probably more importantly, they are often used for natural hazard assessments in mountain areas. As a first approach, the energy-line principle is widely applied, but not all flow and fall processes can be simulated with this rather simple method. Therefore, dynamic, process-based models have been developed, each one adapted to specific mass-movement problems. The energy-line principle is explained and models based thereon as well as modeling problems presented. Then, models and modeling approaches are introduced, which are used to describe mass flows with equations of motion and continuity. Rockfall is often modeled by trajectory models, which are explained theoretically and illustrated with an applied example. This state-of-the-art chapter on numerical modeling of flows and falls is followed by a discussion on future challenges in mass-movement modeling.

7.35.1 Introduction

Currently, a wide range of models with different computational and physical approaches exist for the simulation of flows (e.g., debris flows and hyperconcentrated flows) and
falls (e.g., rockfall). This chapter assembles a selection of approaches and programs that exist in this modeling field, aiming to identify possibilities and limitations in reproducing such highly dynamic processes. Modeling flows and falls are not new, but the scientific domain and the applications emerging from it are rapidly evolving because of constantly increasing computing power, program code development, and landscape modeling possibilities (e.g., availability of high-resolution digital terrain models). Mass-motion models play an important role in understanding and quantifying geomorphological changes in a landscape (e.g., Carrivick, 2006); but, more importantly, today they are often used as a basis for hazard mapping and risk assessment in mountainous areas (e.g., Hürlimann et al., 2008).

Conceptual mass-motion models were already elaborated in the beginning of the twentieth century. Heim (1932), for example, developed the so-called energy-line principle. This is an easy approach to assess the runout distance of many types of moving masses, by joining the top of the collapse to the toe of the moving mass by a straight line with a given angle. Nowadays, this principle is still commonly used in mass-motion modeling, albeit in a two-dimensional (2D), spatially continuous form. This is mostly being done by modeling an energy cone-like shape from each potential mass movement source in a rasterized digital terrain model (DTM).

Besides such rather simple approaches, highly detailed, dynamic models have been developed, each one adapted to specific mass-motion problems. Complex models may be able to reproduce more precisely the physical behavior of flows or falls, however, normally require a more sophisticated model structure. Furthermore, an appropriate process description is questionable, if the required model input parameters are afflicted with major uncertainties. Thus, regardless if conceptual or physically dynamic models are applied to simulate a certain mass-motion problem, model calibration on past events is crucial (Carrivick et al., 2009; Sheridan et al., 2005; Worni et al., in press). The back-calculation of a past event not only is valuable for program calibration, but also provides insights in flow and fall processes, which are normally difficult to observe in nature.

In the following, we present a selective overview of existing mass-motion modeling techniques, from simple to complex models. However, regarding the significant number of commercial and noncommercial program codes, this overview is far from being exhaustive. The core consists of three sections, which correspond to three basic modeling principles. These are then applied to model flows, ranging between pure water and sediment-laden flows, and falls. Each modeling approach is illustrated with an example and the chapter closes with a discussion of future challenges in mass movement modeling.

### 7.35.2 Basic Model Principles

#### 7.35.2.1 The Energy-Line Method

The assessment of runout distances of mass-motion processes, such as landslides, debris flows, and rockfalls, is challenging (Hung, 1995) due to complex rheological properties and behaviors between the interface and the substratum. The energy-line principle (Heim, 1932) is still widely applied for the modeling of mass movements, which can be described by a friction coefficient $\mu$ and a basal angle of friction $\phi_b$, $\mu = \tan \phi_b$ (Figure 1). The loss of energy by friction depends on the normal force $N$ and is related to the weight $m \cdot g$ ($m$ = mass; $g$ = terrestrial acceleration) by the following equation:

$$\frac{E_f}{E_i} = \tan \phi_b$$

As a consequence, the energy loss by friction $dE_i$ is given by

$$dE_i = m \cdot g \cdot \tan \phi_b \cdot dx$$

After integration, $E_i$ is given by

$$E_i = \int m \cdot g \cdot \tan \phi_b \cdot dx = m \cdot g \cdot x \cdot \tan \phi$$

The energy loss depends only on the horizontal travel distance $x$. Starting from this point, it is possible to find along a profile the point where the kinetic energy is totally consumed by friction assuming a constant $\phi_b$ between the ground material and the moving mass (Heim, 1932; Scheidegger, 1973; Hsu ¨ , 1975; Evans and Hung, 1993). Assuming that $H_c$ is the altitude of the center of mass of the starting zone, $h(x)$ the altitude of the topography at the distance $x$ from the start zone, $v(x)$ the center of mass velocity at the position $x$, the energy balance at point $x$ can be written as follows (Figure 1):

$$(H_c - h(x)) \cdot mg = \frac{1}{2} m v^2(x) \cdot m g x \cdot \mu$$

This means that the potential energy (left term in eqn [4]) is transformed either in kinetic energy (first right term in eqn [4]) or consumed by friction. Let us write

$$\Delta h(x) = (H_c - h(x) - x \cdot \tan \phi)$$

The difference between the
topography altitude at \( x \) and the energy lost by friction at this point, the kinetic energy is given by

\[
\frac{1}{2} m v^2(x) = \Delta h(x)
\]  

The latter corresponds to the energy line making an angle of \( \phi_b \) with the horizontal and joining the center of the mass of the starting material to the center of the transported mass. Once \( \Delta h(x) \) is equal to zero, the block is stopped because all the potential energy has been consumed by friction after the horizontal travel distance \( L_c \). Graphically, this is represented by the point where the energy line crosses the topography taking into account the height of the center of the mass. To obtain a spatially continuous map, this can be done in a raster-based program, which basically rotates the energy line \( 360^\circ \) about a vertical axis at its source. Then it detects if a DTM cell is located below the energy-line level, that is, within the cone, meaning in the runout zone. The velocity at a point \( x \) of the path can then be calculated by

\[
v(x) = \sqrt{2g \Delta h(x)}
\]

This result does not take into account the mass, which means that only the travel propagation can be estimated but no mass balance can be obtained. Such an approach can include additional dissipative terms, for example, caused by turbulence. It is expressed in the momentum equation by a constant multiplying of the squared velocity. These are known as the Voellmy model (Voellmy, 1955) or the Perla–Cheng–McClung (cf. Perla et al., 1980) model (see Chapter 2.2 Fundamental Principles and Techniques of Landscape Evolution Modeling (00025)).

One important observation made by Heim (1932) is that the angle of reach decreases for large volumes. Scheidegger (1973) has shown that

\[
\tan \phi_b = \mu = 4.21 \times V^{-0.157}
\]

Corominas (1996) stated that all mass movements, including debris flows, possess a volume effect. One of the explanations for this is that the low basal dispersive stress either decreases the basal friction angle or modifies the normal stress, leading to an apparent decrease of the basal friction angle (Bagnold, 1954; Hsü, 1975; Davies, 1982; Melosh, 1987).

### 7.35.2.2 Dynamic Mass Movement Modeling

Since the late 1980s, all sorts of mass movements were modeled using computers (Savage and Hutter, 1989) and more complex models were developed, especially taking into account the propagation in two or three dimensions. Currently, many models exist that are able to predict propagations, and most of them depend on complex rheological laws with multiple parameters (cf. Hungr, 1995; Imran et al., 2001).

Such dynamic models can be applied to flow-like mass movements, such as debris flows, rock avalanches, snow avalanches, and others. Different rheological models can be implemented, such as frictional, plastic, Newtonian, Voellmy, and Bingham (cf. Hungr, 1995; Mika McKinnon, 2008).

Widely used models with the frictional resistance based on Voellmy (1955) were successfully tested, for example, by Evans et al. (2009). In many models, however, one of the simplest laws, the friction law base or the Mohr–Coulomb law is used. It yields good results with a comparably small effort (Pirulli and Mangeney, 2008), whereas, by contrast, most other model approaches rely on extensive parameter calibration and/or detailed knowledge of the rheology. Yet, friction law-based models are not able to reproduce the full physical behavior of mass-movement processes, because, for instance, they do not reproduce adequately all output parameters, such as velocity.

Savage and Hutter (1989) developed a 2D model averaging the vertical deformation of the moving mass in a Lagrangian scheme in finite differences. Depth-averaged equations of motion are applied and the granular mass is treated as a frictional Coulomb-like continuum with a Coulomb-like basal friction law. The recent use of finite difference, finite element, or smoothed particles methods allowed great progress in terms of modeling. Crosta et al. (2004) and Hungr and McDougall (2009) succeeded in reproducing the deposit shape of past events, but are still not able to predict it without calibration.

Available programs for dynamic mass movement modeling are, among others, DAN-W/DAN3D (Hungr, 1995; Hungr and McDougall, 2009), for modeling debris flows and avalanches, flow slides and rock avalanches; TITAN2D for debris and rock avalanches (Pitman et al., 2003); or RAMMS for a range of mass movements including snow avalanches, alpine debris flows, and rock and ice avalanches (Allen et al., 2009; Christen et al., 2010).

Other than for avalanche and landslide rocks, rockfall is typically simulated by trajectory models. In contrast to rock avalanche modeling, where the motion of the avalanche is described, trajectory models simulate the individual paths of falling rocks. A rockfall trajectory basically consists of the four main processes: sliding, free falling, bouncing, and rolling (Broili 1973). Sliding normally occurs at the initial stage of rockfall and is not an important process, and also rolling is of little importance, as in nature instead of rolling usually short bounces occur. Free falling and bouncing (impact) are the predominant states of a rockfall, of which the latter is a highly complex process and still poorly understood (Azzoni et al., 1995; Guzzetti et al., 2002). During the elastic or inelastic impact, energy is lost and the direction of motion changes (Guzzetti et al., 2002). Although all these processes can be described with physical laws, predicting the trajectory of a rockfall is difficult and fraught with uncertainties. Different modeling approaches exist and, in the following, a method is presented that captures the four above described processes.

Generally, the trajectory of a boulder is calculated from the DTM, and depends mainly on the (1) starting point, (2) the topography and properties of the slope, (3) the geometry, shape, and mechanics of the boulder, and (4) the applied bouncing and rolling principles. After rockfall initiation, the rock moves along the steepest slope and follows, driven by gravity, a parabolic trajectory (free falling) until it hits the ground (Guzzetti et al., 2002). Potential energy is transformed into kinetic energy. Free fall occurs generally due to a sharp variation in the slope angle or after an impact with the slope. At the impact location, the new direction and velocity of the aerial trajectory must be computed by applying *inter alia*...
momentum conservation laws. Whether the rock bounces or rolls after the impact depends on a previously assessed threshold value for velocity, above which the rock bounces and below which it rolls/slides. To describe the rolling and sliding phase, friction laws are applied. Regarding the intrinsic nature of rockfall processes, it is problematic to apply deterministic models. Instead, all possible trajectories are calculated by adjusting the relevant parameters within a reasonable range (Azzoni et al., 1995).

### 7.35.2.3 Dynamic Flood Modeling

The range of models that are able to simulate rapid mass flows with varying content of water and sediment is considerable. The model domain is normally represented by unstructured meshes of variable size or a system of square grid elements in order to simulate 2D flow on irregular terrain. Hydraulic models are generally based on the solution of depth-integrated equations of mass conservation and momentum. Normally, the Saint Venant equation (1D) or the shallow water equations (2D) are numerically solved applying, for example, an explicit finite-volume or finite-difference routing scheme (O’Brien et al., 1993; McDougall and Hungr, 2004; Christen et al., 2010). This set of equations describes accurately the behavior of the water level and flow velocities. As turbulence cannot be resolved, this can be accounted for by a friction factor in the closure condition, which relates flow velocity with shear stress. The primary variables of the shallow water equations (see eqns [8] and [9]; conservative form) are the water depth \( h \) and the specific discharges \( q = hu, r = hv \) in the coordinate directions.

\[
\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0 \tag{8}
\]

\[
\frac{\partial}{\partial t} \left( hu \right) + \frac{\partial}{\partial x} \left( hu^2 + \frac{1}{2} gh^2 \right) + \frac{\partial}{\partial y} \left( hvh \right) = -gh \frac{\partial \tau_x}{\partial x} + \frac{\tau_y}{\rho} \tag{9}
\]

where \( u \) is the velocity in \( x \)-direction, \( v \) the velocity in \( y \)-direction, \( g \) the acceleration due to gravity, \( \rho \) the pressure, \( \tau_x \) is the bottom elevation, and \( \tau_x \), \( \tau_y \) bed shear stress in \( x \)- and \( y \)-direction.

The definition of boundary conditions, such as, for example, an input hydrograph, whose downstream flow is simulated, is required for modeling. For many applications of predictive modeling studies, the definition of the initial condition is a major difficulty and introduces important uncertainties in the model results and in subsequent hazard assessments. More recently, efforts have been directed to consider entrainment of material along the flow path (McDougall and Hungr, 2005; Fagents and Baloga, 2006). Corresponding model results demonstrate the important influence of entrainment on flow characteristics and runout and thus confirm observation from field studies (Mangeney et al., 2007; Allen et al., 2009). When modeling sediment-laden flows, a number of different approaches have been proposed for the implementation of the flow rheology. When the sediment concentration and suspended fines of the flow exceed a critical value (about 20% by volume; after Lavigne and Thouret (2002)), rheological parameters become relevant and must be accounted for.

Commercially available hydraulic models are, for example, Delft2D/3D for flood and outburst flood modeling (e.g., Carrivick, 2006) and FLO-2D for the simulation of floods and debris flows (O’Brien et al., 1993). In these 2D models for channel and unconfined overland flow, the flood hydrograph is routed using the full dynamic approximation to the momentum equation. FLO-2D runs on either a water-flow routine or a mud/debris flow routine, where parametrized rheological flow characteristics have to be determined. Mudflows are routed as a fluid continuum, where a quadratic rheologic model predicts viscous and yields stresses as a function of sediment concentration. Sediment concentration must be defined by the model user. Dilution effects, mudflow cessation, and the remobilization of deposits are simulated, where sediment concentration changes in a grid element.

### 7.35.3 Modeling of Flows

#### 7.35.3.1 Energy-Line-Based Models

A model that has been widely applied to mass flows and hydrological extreme events is the modified single flow (MSF) model developed by Huggel et al. (2003). In this model, the downslope-moving mass is largely controlled by gravitational forces, following the given topography. To simulate the downslope flow, a hydrological flow-routing algorithm is applied, which transfers flow sequentially to lower areas. In such model types, typically single or multiple flow direction concepts are used (O’Callaghan and Mark, 1984; Quinn et al., 1991; Tarboton, 1997) to determine the direction and extension of flow. The central flow line of the flow is assumed to follow the direction of steepest descent as calculated by a single-flow direction algorithm. A modification of the algorithm allows lateral flow spreading (diverging flow) as observed in nature. Such models have been developed and applied not only to glacial lake outburst floods (Huggel et al., 2003), alpine and volcanic debris flows (Huggel et al., 2008; Schneider et al., 2008), but also to rock, ice, and snow avalanches (Noetzli et al., 2006; Gruber, 2007; Huggel et al., 2007).

A probability function defines that the more the flow diverges from the steepest descent direction the greater is the resistance and, accordingly, the lower the probability that this area is affected. In the model result, a color range represents the different probabilities. The travel distance of the modeled mass flow is controlled by an empirical approach applying a minimum average slope (e.g., Haebeli, 1981; Rickenmann and Zimmermann, 1993), below which the flow stops. An advantage of such models is the limited amount of required input information, the fast computation, its integration in geographic information system (GIS) environments, and the potential application over large areas. The level of resulting information usually corresponds best with the objectives of rapid first-order assessments.
Among various flow direction algorithms, the one defined by Holmgren (1994) is often chosen as it can reproduce the behavior of almost every other algorithm because of its exponent. In combination with this algorithm, a notion of inertia influences the spreading (Gamma, 2000). Basic energy-line algorithms are used to assess the runout distance. This constraint defines if a cell can be reached by the debris flow or if the actual energy of the flow portion is insufficient. The slope-angle-concept, friction model is used to assess the energy balance, which is extended with an option of velocity maximum threshold, making it nonlinear. This permits taking into account the maximum velocity of debris flow as the limit, inducing internal energy dissipation. The turbulent models are also included in Flow-R.

As a concrete example of the model Flow-R, the catchment north of Guido’s curve is presented. This area is located along National Road 7 in Argentina, in the Frontal Cordillera of the Mendoza Province, and presents signs of debris flow activity (Figure 3). The erosion of highly altered granite produces abundant sandy material that can be mobilized. In January 2005, this material combined with heavy rainfall triggered debris flows that hit a car. Even if there are few data and information, the 2005 event was adequately simulated with a calibration based on field survey. The study of the levees in the curves and of the fan deposits allowed estimating on the debris flow velocities and the friction loss angle.

7.35.3.2 Dynamic Modeling of Large-Scale Flows

Dynamic models such as FLO-2D, DAN-W/DAN3D, or RAMMS have been extensively used for modeling floods and debris flows (e.g., Mikos et al., 2006). However, still very few modeling studies exist for very large events such as volcanic debris flows (lahars) or GLOF events, which are related to the rare and extreme nature of these processes, making direct field monitoring difficult, if not impossible. From field observations of flow deposits, we know that GLOFs can change their flow rheology and dynamics over relatively short distances, which makes accurate modeling difficult. For large GLOF events, such as those that occur from moraine-dammed glacier lakes in the Himalayas or the Andes, we see that the dam breach process involves incorporation of large amounts of sediment into the flow. Depending on the topography of the flow trajectory, initial debris flows may relatively soon transform into a hyperconcentrated flood that then may travel for tens of kilometers. Flow transformations along the trajectory are probably best modeled by applying separate model runs on different flow sections, as current models are typically unable to change flow rheology parameters in one run. More research is needed to better understand how and when such flow transformations occur.

The example shown in Figure 4 is a FLO-2D and RAMMS model output of a potential GLOF in Tajikistan. The characteristics and magnitude of the GLOF depend on the type of outburst and dam breach at the lake. Several outburst scenarios were defined considering different volumes of water outflow. Based on that, possible initial flow hydrographs were estimated and different flow rheologies were modeled with both programs. Figure 4 shows modeled inundation depths of two different flow models applied to the same lake outburst scenario. FLO-2D routes the hypothetic lake outflow hydrograph downstream calculating inundation depths and flow velocities. The sediment concentration in the flow (bulking factor) and flow rheologies are defined in the initial conditions. RAMMS just requires the initial lake outburst volume...

Figure 4  FLO-2D and RAMMS model output of a hypothetical outburst of Khavrazdara Lake in Tajikistan. In the biggest scenario a water volume of 30 000 000 m³ was released from the lake in about 2 h (black hydrograph), and was bulked to 48 000 000 m³ (green hydrograph) because of material entrainment (for FLO-2D modeling). RAMMS modeled a start volume of 30 000 000 m³, which was continuously bulked on the flow path. Maximum inundation depths of 60 m and 70 m were calculated with FLO-2D and RAMMS, respectively. Model results indicated that the flood reaches the populated cone after 90 min.
Figure 5 In 2009, a moraine dammed glacier lake burst out catastrophically in the Patagonian Andes. This event was retrospectively modeled with the dam breach model BASEMENT; achieving good match between model results and reality. The main model output was the outflow hydrograph.

Trajectory models can first be grouped according to their spatial domain defined by two axes. This can be a model that calculates along a user-defined slope profile that is defined by a distance axis \((x \text{ or } y)\) and an altitude axis \((z)\). Such a profile often follows the line of the steepest descent. The majority of the rockfall trajectory models belong to this group (Ritchie, 1963; Bozzolo and Pamini, 1986; Pfeiffer and Bowen, 1989; Spang and Sönser, 1995). The second type of 2D models calculate rockfall trajectories in a spatial domain defined by two distance axes \(x\) and \(y\); for example, a raster with elevation values or a map with contour lines. Such models generally calculate the rockfall velocity and runout distance with a sliding block approach (cf. van Dijke and van Westen, 1990). As such, these models do not provide information on rebound heights.

The second group of trajectory models can be defined as 2.5D, or also called ‘quasi-3D’, models. The key characteristic of such models is that the direction of the rockfall trajectory in the \(x,y\) domain is independent from the kinematics of the falling rock and its trajectory in the vertical plane. In fact, in these models, the calculation of the horizontal fall direction (in the \(x,y\) domain) could be separated completely from the calculation of the rockfall kinematics and the rebound positions and heights. This means that these models actually carry out two separate 2D calculations. The first one determines the position of a slope profile in an \(x,y\) domain and the second one is a 2D rockfall simulation along the previously defined slope profile. Examples of such models are those that calculate rockfall kinematics along a slope profile that follows the steepest descent as defined on the basis of a digital terrain data, as was done in the model Rocky3 (Dorren and Seijmonsbergen, 2003).

The last group of rockfall trajectory models calculates the rockfall trajectory in a 3D space \((x, y, z)\) during each calculation step. As such, there is an interdependence between the direction of the rockfall trajectory in the \(x,y\) domain, the kinematics of the falling rock, its rebound positions and heights and, if included, impacts on trees. Examples of such models are EBOUL-LMR (Descouedres and Zimmermann, 1987), STONE (Guzzetti et al., 2002), Rotomap (Scioldo, 2006), DDA (Yang et al., 2004), STAR3D (Dimnet, 2002), Rockyfor3D (Dorren et al., 2006), HY-STONE (Agliardi et al., 2009), and PICUS-ROCKnROLL (Rammer et al., 2010). The
The second main characteristic that can be used to describe a rockfall trajectory model is the general underlying calculation principle of the rockfall kinematics. Most of the rockfall trajectory models use a normal ($r_n$) and a tangential coefficient of restitution ($r_t$) for calculating the rebound of the simulated rock on the slope surface (cf. Chau et al., 2002) and a friction coefficient for rolling. Details on these coefficients are among others presented in Guzzetti et al. (2002). An overview of typical values for the coefficients of restitution can be found in Scioldo (2006). The models that use these kinds of coefficients generally apply a probabilistic approach for choosing the parameter values used for the actual rebound calculation. This is done to account for the enormous variability in the real values of these parameters because of the terrain, the rock shape, and the kinematics of the rock during the rebound. A more objective method as compared to the direct estimation of the $r_i$ in the field is described by Dorren et al. (2006). Bourrier et al. (2009) presented a new rebound model that linked the impact angle and the translational and rotational velocity before and after the rebound based on multidimensional stochastic functions, which provided promising results for rocky slopes. Models are also available that use deterministic approaches for calculating the rockfall rebound. These models use mostly a discrete element method (cf. Cundall, 1971), such as the discontinuous deformation analysis (Yang et al., 2004) or the percussion theory (Dimnet, 2002). The parabolic freefalls are mostly calculated with standard algorithms for a uniform accelerated parabolic movement.

A final main characteristic that allows distinguishing between different rockfall trajectory models is the representation of the simulated rock in the model. This can be done first by a lumped mass, which means that the rock is represented as a single, dimensionless point. The second approach is the rigid body, meaning that the rock is represented by a real geometrical form, which is characteristically a sphere, cube, cylinder, or ellipsoid. In general, this approach is used by the deterministic models mentioned above. The last approach is the hybrid approach, meaning a lumped mass approach for simulating freefall and a rigid body approach for simulating rolling, impact, and rebound (Guzzetti et al., 2002).

A few rockfall trajectory models (e.g., Dorren et al., 2006; Rammer et al., 2010) explicitly take into account the mitigating effect of existing forest cover. This means that these models incorporate the spatial distribution of different stand densities, stem diameter distributions, and even tree species. They enable rockfall hazard zoning to take into consideration the mitigation effect of forests, which is non-neglectable, even in the case of rock avalanches. Its efficacy depends logically on the length of the forested slope in the transit zone and the forest characteristics, such as stem density and diameter distribution. Recent data describing the energy dissipative effect of trees is published in Dorren and Berger (2006) and Jonsson (2007). Until the beginning of this century, the energy dissipative capacity of trees was seriously underestimated, that is, adult coniferous trees were thought to dissipate up to 8 kJ instead of more than 200 kJ.

### 7.35.5 Future Challenges in Mass Movement Modeling

The overview of numerical models presented in this chapter showed that detailed models for specific mass-movement problems have been developed, partly using the same underlying laws and principles. Currently, these 2D and 3D models have successfully demonstrated their ability to back-analyze past events and assess possible future events. Nevertheless, a calibration of the parameters is normally essential in order to achieve good results.

Future challenges are to develop (1) more complete descriptions of the physical processes active during mass movements and to link them to true, physical properties measurable in the field, and (2) smaller mesh sizes and more cells, representing the model domain, increasing the model quality as the topography in computation is more accurately reproduced. This requires, however, high-resolution DTM$s$, which are the base for mesh creation, and high computing power. If we succeed in that, simulation models will gain accuracy. Nevertheless, when modeling future scenarios, scenario definition often bears the biggest uncertainties. The definition of scenarios, which are the model’s initial conditions, imply, for example, estimation of released water amount, water content in a sliding mass, block sizes and shapes of falling rocks, or the volume of erodible material in a channel or a natural dam.
These uncertainties cannot simply be reduced by increasing the computing power, input parameter quality, or physical knowledge. An approach in modern natural hazard assessments is therefore to use an integral modeling technique, meaning to reproduce as many as possible involved or precedent process elements of an event. GLOF modeling is in this regard an illustrative example: To assess the hazard situation for downstream areas flood modeling tools are required, whose results are strongly influenced by the upper boundary condition (input hydrograph). In order to evaluate this aspect with a sophisticated approach, the lake outflow hydrograph can be computed by a dam-breaching model instead of a simple estimate. Ideally, further processes, such as the trigger mechanisms (e.g., rockfall impacting the lake) leading to dam-breaching initiation, should be included in the modeling process. Such an integral modeling approach would highly reduce arbitrary assumptions and account for important cascading processes that typically produce the largest catastrophes. However, besides time consuming and costly, highly complex natural processes can never be completely reproduced in models. This is why expert knowledge and field-based assessments, supported by model results, will always be required in hazard assessments and the planning of mitigation measures.

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References

Biographical Sketch

Raphael Worni is an environmental scientist (ETH Zurich), working now at the Institute for Geology at the University of Bern. He is doing a PhD on hazard assessment of glacial lakes and related glacial lake outburst floods in the Indian Himalayas.
4.2 Challenges of modeling current very large lahars at Nevado del Huila Volcano, Colombia

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Challenges of modeling current very large lahars at Nevado del Huila Volcano, Colombia

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Abstract Nevado del Huila, a glacier-covered volcano in the South of Colombia’s Cordillera Central, had not experienced any historical eruptions before 2007. In 2007 and 2008, the volcano erupted with phreatic and phreatomagmatic events which produced lahars with flow volumes of up to about 300 million m$^3$ causing severe damage to infrastructure and loss of lives. The magnitude of these lahars and the prevailing potential for similar or even larger events, poses significant hazards to local people and makes appropriate modeling a real challenge. In this study, we analyze the recent lahars to better understand the main processes and then model possible scenarios for future events. We used lahar inundation depths, travel duration, and flow deposits to constrain the dimensions of the 2007 event and applied LAHARZ and FLO-2D for lahar modeling. Measured hydrographs, geophone seismic sensor data and calculated peak discharges served as input data for the reconstruction of flow hydrographs and for calibration of the models. For model validation, results were compared with field data collected along the Páez and Simbola Rivers. Based on the results of the 2007 lahar simulation, we modeled lahar scenarios with volumes between 300 million and 1 billion m$^3$. The approach presented here represents a feasible solution for modeling high-magnitude flows like lahars and allows an assessment of potential future events and related consequences for population centers downstream of Nevado del Huila.

Keywords Lahar · Nevado del Huila Volcano · Hydrograph reconstruction · Model calibration/validation · Lahar modeling · FLO-2D · LAHARZ

Introduction

Ice- and snow-covered volcanoes may produce large and devastating water-sediment flows (lahars) because of possible interactions between volcanic activity and the subsequent and rapid melting of snow and ice (Major and Newhall 1989). Lahars have occurred in many settings and they are typically highly destructive.

As historical events have shown, even small volcanic eruptions may produce large-scale water-sediment floods when interacting with snow and ice. This was the case at the world’s largest historic volcano-glacier disaster at Nevado del Ruiz Volcano in the Colombian Andes. In 1985, this glaciated volcano produced a small Plinian eruption during which a density current entrained snow and ice, resulting in rapid melt. The estimated volume of ice, firn, and snow lost during the eruption was 60 million m$^3$, corresponding to a water equivalent of approximately 43 million m$^3$ (Thouret 1990). Only 11–12 million m$^3$ of released
water formed the deadly set of lahars that claimed more than 23,000 lives in the town of Armero (Pierson et al. 1990).

In consideration of the serious hazard potential emanating from large-magnitude water-driven processes such as lahars and outburst floods, it is of great importance to improve the understanding of processes involved and their dynamics. However, due to the difficulty of directly measuring large-magnitude mass flows, there is an unsurprising lack of quantitative information. Studies of well-characterized events are an important basis for enhancing knowledge on flow physics and flow parameters. Flow parameters and dynamics of real flows need to be included in numerical modeling, which provides a valuable tool for a quantitative prediction of large-scale floods. For example, Carrivick (2006) analyzed fluvial landforms, which are seen as records of hydraulic processes at a specific place and time during a flood. Cross-sectional geometry, hydraulic roughness, deposited products, and the altitude of scour lines are important indicators to identify flow mechanism (Baker 2000; Carrivick 2006). Geophone recordings (Arattano 1999; Van Westen and Daag 2005) and gauging stations can help to reconstruct the flow hydrograph. With such information, a simple modeling approach can link cross-sectional areas, run-out distance or velocities of the flow with its total volume using semi-empirical relationships (Iverson et al. 1998; Pierson 1998; Berti and Simoni 2007; Muñoz-Salinas et al. 2007). More sophisticated models assume that flows propagate as kinematic waves (Weir 1982; Vignaux and Weir 1990) and calculations are based on the fully dynamic wave momentum equation (O’Brien et al. 1993).

Even though the precise physical behavior of large sediment-laden flows may not be completely predictable, the application of existing simulation programs can be meaningful and helpful. Flow parameters need to be defined and calibrated for these models, and perhaps even more importantly, models have to be fully validated with adequate field studies (Carrivick et al. 2009). Worldwide, few study sites exist where recent lahars with volumes of tens to hundreds of millions of cubic meters could be observed (Major and Newhall 1989). This is not only true for lahars but also for other comparable water-sediment flows caused by failures of natural or artificial dams (Cenderelli and Wohl 2003; Pulgarín et al. 2004; Capra 2007).

In 1994, 2007, and 2008, Nevado del Huila volcano produced lahars with volumes of up to 320 million m³ and run-out distances of up to 160 km, killing up to 1,000 people and causing severe damage to infrastructure. The remoteness, limited accessibility and armed conflicts in the area have made investigations on Nevado del Huila and the affected drainage basins difficult. Nevertheless, this volcano offers a unique opportunity to gain knowledge about complex and interactive roles of ground-water release and glacier melting that led to formation of these lahars. An improved understanding of ongoing processes and potential future hazards will further improve the planning and implementation of prevention measures that could protect local people and their assets.

The purpose of this paper is to (1) reconstruct flow dynamics of recent lahars at Nevado del Huila, including hydrographs and a number of flow parameters and to (2) use these data for simulations of past (retrospective modeling) and (3) potential future events (scenario-based modeling) with the two-dimensional flow model FLO-2D and the semi-empirical model LAHARZ. We are aware of several uncertainties that can neither be avoided nor necessarily be overcome with such an approach. Nevertheless, the objective is to constrain interpretations of the dimensions of the different flow parameters to a level acceptable and useful in hazard assessment and mitigation.

**Study site**

The Nevado del Huila Volcano

Nevado del Huila is a stratovolcano with predominantly effusive activity. No historic eruptions are known before 2007 when eruptive activity from Nevado del Huila was first reported. The volcano has an elliptical form with approximate basal axes of 16 km in the north–south and 11 km in the east–west directions. The steep flanks have average slopes ranging from 13° to 27° and the four glaciated peaks, named North, Crest, Central and South are aligned on a longitudinal axis, with Central peak forming the highest summit of the Colombian Andes at 5,364 masl (Pulgarín et al. 2004). Although the glacier area on Nevado del Huila has shrunk from 19.1 km² in 1965 (Pulgarín et al. 1996) to a surface of about 10.7 km² in 2007, the estimated volume of the glacier is still 450 million m³, corresponding to a water equivalent of ~400 million m³. Following the 2007 and 2008 eruptions, the glacier area was further reduced.

Runoff from Nevado del Huila drains into the Páez (western slopes) and Simbola (eastern slopes) Rivers, which merge 2 km above Belalcázar, the biggest town in the valley (3,500 inhabitants). Belalcázar is located 46 km downstream from the volcano summit. Other important riverine villages are Tóez, Talaga, Ricaurte and Paicol. Some 120 km downstream from the volcano (Central peak), the Páez River discharges into the Magdalena River and 30 km further downstream into the Betania reservoir (Fig. 1).

Recent lahars at Nevado del Huila Volcano

On 6 June 1994, after a period of heavy rainfall, a tectonic earthquake at the base of Nevado del Huila triggered over
3,000 shallow landslides, which coalesced into a massive lahar flowing down the Páez River (Martínez et al. 1995). Almost 1,000 people were killed and 28,000 persons were directly affected by the disaster. In the communities of Irlanda and Tóez, devastation was especially high, as they were buried almost completely with lahar deposits (Ávila et al. 1995; Scott et al. 2001). Based on calculations of Calderón et al. (1997), this lahar had a volume of about 320 million m$^3$ and a travel distance of 150 km, which emphasizes the enormous dimension of the event.

In February 2007, Nevado del Huila attracted much attention because of a significant increase in seismicity. For the first time in historical times, two comparatively small phreatic eruptions (VEI=2) were recorded, on 19 February and 18 April 2007. Lahars were produced, traveled down the Páez and Simbola Rivers and joined above Belalcázar. Only the second and bigger lahar traveled as far as the Betania reservoir, and it caused severe damage to infrastructure. No lives were claimed thanks to early warning systems that were in place. Each eruptive event was accompanied by the formation of large fissures in the summit region, with lengths of up to 2 km, widths of 50–80 m; continued strong fumarolic activity followed the eruptions (Fig. 2). Although the origin of the lahars is not completely understood, it is clear that water was expelled directly from the newly opened fissures, because the volume of water involved cannot be explained by melting of snow and ice alone. It is suspected that the expelled water came from hydrothermal water reservoirs (Pulgarín et al. 2007).

On November 20, 2008, Nevado del Huila produced a phreatomagmatic eruption that generated yet another lahar. A crater with an approximate diameter of 400 m and a dome were formed. Due to the threat of a possible collapse of the dome, detailed monitoring was performed by seismic surveillance, aerial inspections and a web-linked camera (webcam). Pictures show that the glacier on the west flank was fractured heavily during the eruption. The resulting lahar was extremely large, with an approximate volume of 300 million m$^3$, and left destruction in its path, similar to that in 1994 (Fig. 3). However, due to the advanced early warning system and the sensitized population, not more than ten victims were claimed. The following analysis and modeling will primarily focus on the 2007 events, with some consideration on the 2008 event.

Data

Earth observation data

For flood modeling, we used a geo-referenced and interpolated Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) with a 30-m resolution, representing the topography in 2000. Absolute and relative 90% vertical accuracies are ±16 and ±6 m, respectively (Rabus et al. 2003).

Quickbird and ASTER satellite images and aerial photographs were available to study eruptive effects, volcano-
glacier interactions and lahar processes. The ASTER image, with a 30-m resolution, was acquired on 23 February 2007, 4 days after the first eruption of Nevado del Huila, whereas the Quickbird image was taken on 7 February 2007, showing the glaciers on Nevado del Huila prior to the eruption at 0.62-m resolution. Aerial photographs from helicopter and plane flights over the volcano were also available for 2007 and 2008.

Discharge measurements and geophone records

Discharge measurements at the Páez River were taken by the Colombian Institute of Hydrology, Meteorology and Environmental Studies. The gauging stations give relations between river stage and discharge, defined and calibrated on the basis of velocity and cross-section measurements. The only discharge data existing for the April 2007 lahar were from hourly measurements near Paicol, 105 km downstream of Nevado del Huila. According to stage measurements during the April 2007 lahar, the peak discharge at Paicol was $2,500 \text{ m}^3 \text{s}^{-1}$ and the flow volume of 17.4 million m$^3$.

Tremors caused by tectonic and volcanic activities or large debris flows produce seismic waves that travel through the subsurface. Geophones register these waves and transform them into electrical signals. Along the upper sections of the Páez and Simbola rivers, six geophones were installed to register ground shaking caused by lahars. Records from the geophones located at Tóez (Páez River) and Pueblo Nuevo (Simbola River) could be used in this study for the April 2007 lahar (Figs. 4 and 5).

Field data collection

Following the April 2007 eruption the Colombian Institute of Geology and Mining (INGEOMINAS) started extensive field data collection in the Páez and Simbola valleys. Lahar inundation depths at 60 locations (Fig. 5) over a distance of...
about 70 km were estimated based on flow trim lines. Preflood river cross-section profiles, measured with a theodolite, were available for seven locations between Avirama and Guadualejo. Together with the measured lahar inundation depths, wetted cross-sectional areas were calculated for these locations. For hydrograph reconstructions, cross-sectional areas at the geophone locations at Tóez and Pueblo Nuevo were estimated with reference points at bridges (Table 1).

The strongest seismic signal associated with the eruption of Nevado del Huila was registered at Central peak at 2:58 a.m. on 18 April 2007. This marks most probably the location and time of the release of large amounts of water, which then formed the lahar. Travel times to different locations downstream are based on geophone records, eyewitness reports and a river gauge. Together with according flow distances, measured from satellite images, flow velocities were calculated (Table 1).

After the April 2007 lahar, nine samples of deposited fine material (<0.1 mm) were taken at different locations along the flow path and analyzed by wet-sieving. Average D16, D50 and D84 were 0.018, 0.042 and 0.081 mm, respectively, and the clay content averaged 3.5%. The grain size distribution of the fine fraction did not change significantly over the flow path.
Reconstruction of flow hydrographs of the April 2007 lahar

The mean wetted cross-sectional area between Avirama and Guaduales was 575 m$^2$ for the April 2007 lahar, and flow velocities of 12.5 ms$^{-1}$ were calculated based on eyewitness reports stating that the lahar covered the distance between Avirama and Guaduales (12 km) in 16 min. The multiplication of wetted cross-sectional area by flow velocity consequently yields a peak discharge of $\sim 7,200$ m$^3$s$^{-1}$. A qualitative river profile analysis in the Páez and Simbola valleys above Belalcázar revealed wetted cross-sectional areas of 800–1,000 and 400–500 m$^2$, respectively. Flow velocities at the Tóez and Pueblo Nuevo geophone locations were 15 and 14 ms$^{-1}$, respectively, based on recorded travel times from Central Peak to the locations of the geophones. This yields maximum discharge values of $\sim 13,500$ m$^3$s$^{-1}$ at Tóez (Páez River) and $\sim 6,300$ m$^3$s$^{-1}$ at Pueblo Nuevo (Simbola River) (Table 1).

The output graphs from the Tóez and Pueblo Nuevo geophones (Fig. 4) were used to reconstruct the flow hydrographs for the respective river sections. To calculate a hydrograph from geophone recordings peak discharge at the geophone location was first evaluated, and the y-axes of the geophone recordings were then normalized to values between 0 and 1 (by dividing all vibration amplitudes by the maximum value). The normalized numbers were then multiplied by the previously defined peak discharge. This leads to a hydrograph with the same shape and x-axis values as the geophone recordings, but with discharge values instead of a vibration amplitude. By implementing peak discharges of 13,500 and 6,300 m$^3$s$^{-1}$ into the geophone recordings from Tóez and Pueblo Nuevo, we derived flow hydrographs of the April 2007 lahar (Fig. 6).

Expansible geophone recordings were not available for the river segments below the confluence of the Páez and Simbola Rivers. A different approach was therefore used to reconstruct the hydrograph in this section: The hydraulic program FLO-2D modeled the flows of the Tóez and Pueblo Nuevo hydrographs simultaneously river downstream to produce a single hydrograph for the river downstream of Belalcázar. The program accounts for floodwave attenuation and is able to reproduce a superimposing hydrograph, i.e. a flowing together of the floods from two valleys. However, in the present case, FLO-2D overestimates peak discharge and flow volume in the output hydrograph, because the program does...
not account sufficiently for deposition in the uppermost river sections. As a consequence, similar to the hydrograph reconstruction based on the geophone data, we accepted the form and time axis of the FLO-2D output hydrograph, but adapted discharge to a maximum of 7,200 m$^3$ s$^{-1}$ (Fig. 6). Local flow volumes which are determined from the hydrograph integrals are indicated in Table 1.

**Flow type and flow rheology**

Water and sediment content together control lahar behavior in a valley (Capra et al. 2004). Transformations between debris and hyperconcentrated flows, as occurred during the April 2007 lahar, are mainly related to sediment deposition and bulking processes or the dilution of a debris flow by stream water (Smith and Lowe 1991).

Debris flows are poorly sorted cohesive or noncohesive sediment-laden mixtures with a sediment concentration 60% or more by volume (Lavigne and Thouret 2002). Hyperconcentrated flows have sediment concentrations in the range of 20% to 60% by volume. These boundaries depend on the particle-size distribution of solids and vary for different mixtures. In addition, hyperconcentrated flows are not only defined by sediment concentration but also by the concentration of suspended fines which must be sufficient to impart yield strength to the fluid and to maintain high fluid viscosity (Jakob and Hungr 2005). Like debris flows, hyperconcentrated flows can be described as non-Newtonian fluids, where yield strength alone can suspend coarse gravel particles, whereas gravel can be suspended only by fluid forces in hyperconcentrated flows (Jakob et al. 2005).

The sections in the Páez and Simbola valleys where the lahar flowed as a debris flow are indicated by the presence of lateral levees composed of coarse blocks (Fig. 7a), and steep, lobate snouts at the flow front. Deposits have framework-supported larger clasts, and exhibit a wide range of grain sizes (i.e. from clay to boulders), are poorly sorted and lack any stratification (Fig. 7b). A sediment concentration of >60% by volume was assumed for these river sections.

In areas where a transformation from debris to hyperconcentrated flows and vice versa was observed, deposits contain mainly poorly graded and sorted sandy material, and some boulders on top of the deposits (Fig. 7c, d). Such transitional flows are inferred to have a sediment concentration of ∼50% by volume.

Hyperconcentrated flows deposited sandy sediments including lenses of gravel and wood on the surface. Cross-bedding and ripple lamination are absent while outsize cobbles and boulders are, in contrast, present. The sand- and granule-grade deposits exhibit a faint horizontal stratification, and strata are ungraded to normal graded (Fig. 7e, f). Here an average sediment concentration of ∼40% by volume is inferred.

In the river sections above Belalcázar lahar deposits suggest a continuous transformation from debris flows to hyperconcentrated flows and vice versa. Debris flows covered smaller distances in each case, in between the hyperconcentrated flow phases. With increasing distance from the source, the lahar moved predominantly as a hyperconcentrated flow and downstream of Belalcázar debris flow deposits are no longer present. In the river section below, Paicol sediment concentration may have dropped below ∼20%, meaning that the flow was a Newtonian stream flood.

At sediment concentrations above ∼20% the flow was treated as a non-Newtonian fluid, where yield strength and viscosity become important parameters (Pierosn and Scott 1985). O’Brien and Julien (1988) analyzed sediments <0.072 mm from natural debris flow deposits in the Colorado Rocky Mountains and identified viscosity and yield stress of these flows. They assumed that viscosity ($\eta$) and yield stress ($\tau$) depend on empirical coefficients and on sediment concentration:

$$\eta = \alpha_1 e^{\beta_1 C_V}$$  \hfill (1)

$$\tau = \alpha_2 e^{\beta_2 C_V}$$  \hfill (2)

where $\alpha_1$, $\alpha_2$, $\beta_1$ and $\beta_2$ are the empirical coefficients obtained by regression analysis and $C_V$ is the volumetric sediment concentration in the flow. The lahar deposits at Nevado del Hulla showed a similar grain size distribution of fine materials as one of the debris flows reported by O’Brien and Julien (1988), and are thus supposed to have the same empirical coefficients $\alpha$ and $\beta$ (Table 2). With average sediment concentrations of 50% and 40% for upper and lower river sections, according to Eqs. 1 and 2 viscosity is 144 and 77 mPa s, respectively, and yield stress is 35.8 and 6.6 Pa, respectively.

**Dynamic lahar modeling**

Modeling the motion of very large lahars is a challenge, using existing possibilities and software packages. No explicit and all-embracing modeling approach exists, as lahars represent highly variable and complex phenomena. Nevertheless, if limitations and uncertainties involved in lahar modeling are appropriately accounted for, risk reduction efforts can be greatly supported by modeling.

We applied the physically based model FLO-2D (O’Brien et al. 1993) and the semi-empirical simulation
program LAHARZ (Iverson et al. 1998) with three main objectives: (1) to define model parameter values, (2) to calibrate and validate the models on the basis of the April 2007 lahar (retrospective modeling) and (3) to model possible future lahars (“Scenario modeling”) based on the previously defined model setup. In the retrospective modeling, flow volumes and peak discharges of the April 2007 lahar (Table 1) were used as model input; in the scenario-based modeling, volumes between 300 million and 1 billion m$^3$ and peak discharges between 80,000 and 270,000 m$^3$/s were modeled. LAHARZ modeled the lahars from the base of the volcano to the Betania reservoir (see Fig. 5) and FLO-2D from Tóez/Pueblo Nuevo to Paicol.

FLO-2D modeling

For dynamic lahar modeling, we used FLO-2D, a two-dimensional hydraulic flood-routing model for channel and unconfined overland flow (O’Brien et al. 1993). Flood wave progression over the flow domain is computed on the basis of topographic data, flood hydrographs, flow parameters and resistance to flow. FLO-2D is a finite difference model using the dynamic wave momentum equation to describe the fluid; it consists of the continuity equation and the equation of motion. When simulating sediment-laden flows with FLO-2D, flow rheology (yield stress and viscosity) and sediment concentration have to be specified (O’Brien 2003).

Before FLO-2D can be used to model specific scenarios, sensitive input parameters have to be defined. To test the sensitivity of a model parameter on simulation output, its value was adjusted within a reasonable range, while all other parameters were maintained at default values. We then looked at the change of modeled inundation depths before and after parameter adjustment. Parameter sensitivity was considered small when the influence on modeled inundation depths was insignificant.

### Table 2: Sensitive model parameters with corresponding values for FLO-2D

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Theoretical range</th>
<th>Field evidence</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_1$ and $\beta_1$ for viscosity Eq. 1</td>
<td>Thickness of a fluid or resistance to flow of fluid</td>
<td>(–) $\alpha_1$: $7.07 \times 10^{-4}$–2.72 $\beta_1$: 7.82–29.8</td>
<td>$\alpha_1$: 0.0648 $\beta_1$: 6.2</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>$\alpha_2$ and $\beta_2$ for yield stress Eq. 2</td>
<td>Shear stress vs. shear rate</td>
<td>(–) $\alpha_2$: $3.73 \times 10^{-5}$–0.13 $\beta_2$: 8.29–36.6</td>
<td>$\alpha_2$: 0.0765 $\beta_2$: 16.9</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>Sediment concentration (C)</td>
<td>Sediment concentration, by volume, in the lahar</td>
<td>%</td>
<td>0–0.89</td>
<td>0.4–0.5</td>
<td>High</td>
</tr>
<tr>
<td>Manning’s $n$ roughness</td>
<td>Measure of the texture of a surface</td>
<td>(–)</td>
<td>0.02–0.8</td>
<td>0.04–0.05</td>
<td>Moderate</td>
</tr>
<tr>
<td>Limiting Froude number (Fr)</td>
<td>Measure of the flowing state of a river</td>
<td>(–)</td>
<td>0–5</td>
<td>0.9</td>
<td>High</td>
</tr>
</tbody>
</table>

For each parameter, the sensitivity on simulation output was tested. For details, see text

- FLO-2D Software (2009)
- Values used in computation
tion depth was <10%, moderate if 10–20% and high if 20–40%. In Table 2, all sensitive parameters for the FLO-2D modeling are listed and described. The parameter values are based either on field data and observations, values proposed in the literature (Lavigne and Thouret 2002; Jakob and Hungr 2005; USGS 2011) and those suggested in FLO-2D user’s manual (FLO-2D Software I 2009). The previously defined flow hydrographs are used as the model’s upstream boundary condition.

In the retrospective modeling the computational area was divided into two different segments as (1) different flow volumes and different sediment concentrations can be simulated in each section and as (2) excessive computation times can be avoided. The latter is particularly important in the retrospective modeling, where multiple model runs are required for sensitivity analysis and model calibration. The upper modeling section covers the Páez and Simbola Rivers above Belalcázar. From Tóeza and Pueblo Nuevo the hydrographs were routed simultaneously downstream flowing together at the river confluence. In this segment, the lahar was modeled as a transitional flow with a sediment concentration on the boundary between debris flow and hyperconcentrated flow. The section from Belalcázar to Paicol represents the downstream modeling area, where the lahar was modeled as a hyperconcentrated flow.

In scenario modeling, the computational area was not split and a uniform sediment concentration of 40% by volume was applied. The hydrographs derived from geophone recordings at Tóeza and Pueblo Nuevo were used with adapted discharge values for upper boundary conditions. In the scenario modeling, 50% each of the total volume is assumed to flow through the Páez and Simbola valleys before the two flows merge at the confluence above Belalcázar.

The same roughness values and Froude numbers were applied for both the retrospective and scenario modeling. Based on the roughness coefficients provided by USGS (2011), n values of 0.05 were selected for the river sections above Belalcázar and 0.04 for the river section below Belalcázar. The analysis of flow deposits and flow signs indicate sections where the lahar was in a critical flow state (Fr=1.0). However, average flow conditions had Fr<1, and for modeling a value of 0.9 was applied.

LAHARZ model and calibration of governing equations

The LAHARZ flow model is a semi-empirical program developed by Iverson et al. (1998) that calculates flow extent and run-out distances of lahars in valleys. Flow depths can be derived from the flow delineation and the DEM. The following two equations form the basis of the program (Iverson et al. 1998):

\[ A = 0.05V^{2/3} \]  
\[ B = 200V^{2/3} \]

where A is the valley cross-sectional area from which flow depth can be derived, and B is the planimetric area inundated by lahars. Both A and B are functions of lahar volume V, the most important input factor when modeling with LAHARZ. The equations have a physical basis, which provide proportionality rules \( A \propto V^{2/3} \) and, \( B \propto V^{2/3} \) and a statistical basis in which the proportionality factors C and c in the equations \( A = CV^{2/3} \) and \( B = cV^{2/3} \) are calibrated.

Figure 8 shows the measured cross-sectional areas for 27 lahars and debris flows, plotted against their corresponding deposit volume (Iverson et al. 1998). A best least-square fit regression line is drawn with two surrounding sets of 95% confidence interval curves and was used to determine coefficients c and C. The calculated inundated cross-sectional areas and estimated volumes of the April 2007 and 1994 Nevado del Huila lahars were compared with those used by Iverson et al. (1998). The 1994 Nevado del Huila lahar had an average inundated cross-sectional area of about 3,000 m\(^2\) and a volume of 320 million m\(^3\) at the upper river sections (Calderón et al. 1997; Scott et al. 2001). The average inundated cross-sectional area of the April 2007 lahar was about 575 m\(^2\) near Belalcázar and the flow volume that passed this section was 30 million m\(^3\). Data points for Nevado del Huila lahars appear outside the predictive envelope at the level of analytical confidence, and show smaller cross-sectional areas for the corresponding volumes. Thus, calculating the April 2007 lahar volume using the original equation yielded highly exaggerated inundation depths.

We, therefore, adapted the constant C of equation \( A = CV^{2/3} \) to produce results consistent with data from the 2007 and 1994 lahars; the adapted constant yields values of 0.0067 and 0.0063 for the 2007 and 1994 lahars; the adapted constant yields values of 0.0067 and 0.0063 for the 2007 and 1994 lahars, respectively. As a reasonable average, a C value of 0.0065 was defined, resulting in the following equation:

\[ A = 0.0065V^{2/3} \]

This condition is fulfilled if \( V^{2/3} \) is held constant. A calibration based on field data was not directly possible for Eq. 4, and we had to adjust c in \( B = cV^{2/3} \) indirectly. Based on inflow discharge data from the Betania reservoir, there is evidence that the April 2007 lahar entered the reservoir with 10 million m\(^3\) of water and sediment. We, therefore, adjusted c in such a way that modeled flows with an input volume of 30 million m\(^3\) ended up in the reservoir. The recalibrated c value is 280, resulting in the new equation:

\[ B = 280V^{2/3} \]
Model results and model validation

The reconstructed hydrographs and flow parameters as well as the calibration of the flow models finally allowed retrospective modeling of the April 2007 lahar. FLO-2D and LAHARZ were run on a SRTM DEM, calculating lahar inundation depths and flow velocities (the latter only with FLO-2D).

Figure 9 illustrates the longitudinal section between the highest and lowest locations in the Páez and Simbola valleys where field data were collected and compared with flow heights modeled with FLO-2D and LAHARZ.

**Páez River (above Belalcázar)** A lahar volume of 50 million m³ was modeled. FLO-2D generally calculates slightly higher inundation depths than LAHARZ. The mean difference or root mean square error (RMSE) of calculated inundation depths between the two programs is 3.5 m. FLO-2D and LAHARZ calculate mean inundation depths of 18 and 15 m, respectively, for the 2007 lahar. Between 0 and 10 km, the mean deviation, consistently as overestimates, from measured flow depths is 6 m for FLO-2D and 4.4 m for LAHARZ. In the lower section, the programs overestimate flow depths even more, with RMSE of 10 m for FLO-2D and 5.5 m for LAHARZ.

**Simbola River** A lahar volume of 17.5 million m³ was modeled. Both programs calculate similar inundation depths (average=13.5 m) with a mean difference of 2.5 m between FLO-2D and LAHARZ. Observed inundation depths are only available for the lower section, and the RMSE between observed and modeled depths, consistently as model overestimates, is 4 and 4.5 m for FLO-2D and LAHARZ, respectively.

**Páez River (below Belalcázar)** A lahar volume of 30 million m³ was modeled. Over the whole flow distance inundation depths calculated by FLO-2D and LAHARZ differ from one another by 4.5 m on average, with a better agreement between 20 and 40 km (RMSE=3.5 m). For this section, FLO-2D better reproduces observed inundation depths. The mean difference between modeled and measured inundation depths is 2.25 m for FLO-2D and 4.75 m for LAHARZ. With increasing distance, LAHARZ increasingly overestimates real inundation depths, whereas FLO-2D is capable of reproducing the field-indicated general decrease in flow depths.

Table 3 presents flow velocities and travel times modeled with FLO-2D and relates them to velocities and travel times based on field evidence. In the upper river sections FLO-2D underestimates local flow velocities by 1–3 m s⁻¹. In the river sections below Belalcázar, the program produces local velocities that are almost equal to those obtained from arrival times. When comparing modeled and real travel times at different river sections, overall, FLO-2D calculates longer flow durations. Hence, average flow velocities were faster in reality than reproduced by FLO-2D.

Figure 10 presents the output hydrograph calculated with FLO-2D (solid line) and the one measured at Paicol (dotted line). Considering that the temporal resolution is 0.1 h for the calculated and 1 h for the measured hydrograph, both curves fit together well. The main difference is the flatter falling limb of the FLO-2D hydrograph. The integrated area below the curve (local flow volume) of the measurement-based graph is 17.4 million m³ and that of the modeled lahar 20 million m³.

**Scenario modeling**

With the calibrated and validated FLO-2D and LAHARZ programs we modeled scenarios for different lahars that may occur in the future. We assigned outburst volumes of 300 million, 600 million and 1 billion m³. The volume of 300 million m³ represents the volume of the 1994 and 2008 lahars, but also forms a hypothetical scenario because flow parameters and hydrograph forms were taken from the retrospective modeling. A flow volume of 600 million m³ is based on calculated water and material release associated with a collapse of Central peak. A lahar volume of 1 billion m³ can be regarded as a worst-case scenario with a collapse of Central and Crest peaks. Such peak collapses can be triggered by volcano instability related to glacier retreat, dome collapse, or a large eruption (Pulgarín et al. 2004; Huggel et al. 2007). Table 4 lists modeled inundation...
depths at different locations along the Páez and Simbola Rivers and lahar travel times from Tóez/Pueblo Nuevo to different downstream villages as calculated by FLO-2D.

In Fig. 11, inundation depths and flow extent are shown for the three different scenarios in the Belalcázar region. LAHARZ and FLO-2D model partly different inundation patterns and do not produce the same areas affected by the lahars.

A simulated volume of 300 million m$^3$ yielded maximum inundation depths between 30 and 40 m. A lahar of this volume would have major effects in the town of Belalcázar. Roads would be damaged severely and bridges washed away. Probably, more than 60 buildings would be (partly) inundated. FLO-2D suggests a bigger area being affected by the lahar than does LAHARZ, and although FLO-2D results show lower maximum inundation depths, the average inundation depth is higher. Modeled maximum flow depths exceeded 40 and 50 m for lahar scenarios of 600 million and 1 billion m$^3$, respectively. Large parts of the road would be destroyed, including the bridges crossing the river. About 160 and 350 buildings, respectively, would be flooded and some would be completely destroyed.

### Discussion

In this study, we modeled inundation depths and travel times for three hypothetical lahars larger than the April

![Fig. 9](image)

**Table 3** Field based and computed flow velocities and flow arrival times (travel times) at different locations, representing the April 2007 lahar

<table>
<thead>
<tr>
<th>Location</th>
<th>Field evidence (m/s)</th>
<th>FLO-2D (m/s)</th>
<th>Field evidence</th>
<th>FLO-2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tóez</td>
<td>15</td>
<td>14</td>
<td>3:26 a.m.</td>
<td>Start: 3:26 a.m.</td>
</tr>
<tr>
<td>Pueblo Nuevo</td>
<td>14</td>
<td>11</td>
<td>3:31 a.m.</td>
<td>Start: 3:31 a.m.</td>
</tr>
<tr>
<td>Avirama (Belalcázar)</td>
<td>13</td>
<td>11</td>
<td>3:50 a.m.</td>
<td>4:02 a.m.</td>
</tr>
<tr>
<td>Guadualejo</td>
<td>12.5</td>
<td>11</td>
<td>4:06 a.m.</td>
<td>4:20 a.m.</td>
</tr>
<tr>
<td>San Juanito</td>
<td>7</td>
<td>7</td>
<td>5:00 a.m.</td>
<td>5:20 a.m.</td>
</tr>
<tr>
<td>Paicol</td>
<td>5</td>
<td>5</td>
<td>6:30 a.m.</td>
<td>7:20 a.m.</td>
</tr>
</tbody>
</table>
2007 event. Simulation results are valuable for hazard prevention strategies, but it is vital that they are carefully evaluated. Programs can only be applied for scenario modeling after calibrating and validating model results against field data. This, however, was challenging with the limited data and information available on past lahar events. Therefore, an uncertainty analysis of the input parameters was particularly important in view of the general difficulties in modeling mass flows of tens to hundreds of millions m$^3$.

Uncertainty analysis

Flood modeling in remote areas is generally afflicted by errors because DEMs with rather limited resolution are normally available. Nevertheless, DEMs with a 30-m resolution have been shown to be suitable for a first overview of potential hazard zones and have the advantage of not becoming outdated as quickly as high resolution DEMs (Stolz and Huggel 2008). Different studies have shown that the choice of the DEM can have important effects on the determination of distal hazard zones (Stevens et al. 2002; Davila et al. 2007; Hubbard et al. 2007; Huggel et al. 2008). We did not specifically evaluate the effect of the DEM on model results, but the local irregularities of the SRTM DEM, such as sinks and ascending slopes in the river bed, are directly affecting model output.

One of the most important inputs for dynamic lahar modeling is the flow hydrograph. Lavigne and Thouret (2002) and Lavigne et al. (2000) report good linear regressive correlations between discharge and geophone signals for hyperconcentrated flows. We therefore adopted the $x$-axis and the form of the Tóez and Pueblo Nuevo geophone recordings for hydrograph reconstruction. The determination of (peak) discharge tends, in contrast, to be less accurate, particularly because flow velocities have a high uncertainty due to ambiguous information about flow arrival times at different locations in the Páez and Simbola valleys.

In non-Newtonian, sediment-laden flows, a change of volumetric sediment concentration from 10% to 40% increases both viscosity and yield stress by three orders of magnitude (O’Brien and Julien 1988). In this study, sediment concentrations in the April 2007 lahar were based on the prevalent flow type. Although this generalization is in some ways arbitrary (Jakob and Hungr 2005), it represents the best available approximation to reality.

### Table 4 Modeled lahar inundation depths for selected locations along the Páez and Simbola Rivers for lahar volumes of 300 million, 600 million and 1 billion m$^3$

<table>
<thead>
<tr>
<th>Location</th>
<th>300 million m$^3$</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flo-2D (m)</td>
<td>Travel time (min)</td>
<td>LaharZ (m)</td>
<td>Flo-2D (m)</td>
<td>Travel time (min)</td>
<td>LaharZ (m)</td>
<td>Flo-2D (m)</td>
</tr>
<tr>
<td>Tóez</td>
<td>22</td>
<td>Start</td>
<td>25</td>
<td>Start</td>
<td>35</td>
<td></td>
<td>34</td>
</tr>
<tr>
<td>Pueblo</td>
<td>27</td>
<td>Start</td>
<td>32</td>
<td>Start</td>
<td>45</td>
<td></td>
<td>42</td>
</tr>
<tr>
<td>Nuevo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talaga</td>
<td>23</td>
<td>12 min</td>
<td>26</td>
<td>12 min</td>
<td>37</td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>Avirama</td>
<td>25</td>
<td>12 min</td>
<td>33</td>
<td>12 min</td>
<td>38</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>Belacázar</td>
<td>24</td>
<td>12 min</td>
<td>33</td>
<td>12 min</td>
<td>30</td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>Coquiy o</td>
<td>27</td>
<td>12 min</td>
<td>37</td>
<td>12 min</td>
<td>32</td>
<td></td>
<td>51</td>
</tr>
<tr>
<td>Cohetando</td>
<td>30</td>
<td>12 min</td>
<td>40</td>
<td>12 min</td>
<td>42</td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>Guadualejo</td>
<td>23</td>
<td>12 min</td>
<td>32</td>
<td>12 min</td>
<td>36</td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>Ricaurte</td>
<td>27</td>
<td>12 min</td>
<td>35</td>
<td>24 min</td>
<td>40</td>
<td></td>
<td>47</td>
</tr>
<tr>
<td>Aranzazu</td>
<td>26</td>
<td>12 min</td>
<td>38</td>
<td>12 min</td>
<td>39</td>
<td></td>
<td>52</td>
</tr>
<tr>
<td>San Juanito</td>
<td>26</td>
<td>12 min</td>
<td>35</td>
<td>48 min</td>
<td>30</td>
<td></td>
<td>46</td>
</tr>
<tr>
<td>Paicol</td>
<td>22</td>
<td>1 h</td>
<td>32</td>
<td>1 h</td>
<td>31</td>
<td></td>
<td>41</td>
</tr>
</tbody>
</table>

Travel times are given with output intervals of 12 min
Modeling a constantly changing flow rheology and sediment concentration as occurred in the river sections above Belalcázar is impossible with currently existing models. Therefore, an intermediate sediment concentration must be applied, representing averaged flow conditions over a larger section. This, however, inhibits determination of maximum yield stress and consequently deposition rates during debris flow phases. Therefore, the model did not account sufficiently for volume decline in the uppermost river sections. Below Belalcázar, flow transformation were no longer an important control on flow, and the modeled decrease in flow volume corresponds very well with that established by observation and measurement (Fig. 10).

Model calibration and validation

LAHARZ has proved to be a useful tool for first-order modeling of lahars and has been applied at many sites around the world (e.g. Canuti et al. 2002). Recalibration of the governing equations is not required as long as the lahar has a flow behavior similar to those used in the scaling analysis to derive the original equations. Since Nevado del Huila lahars were found to be outside the range of events considered for the original equations, recalibration was of critical importance. The recalibrated LAHARZ model is able to retrospectively model the 1994 and 2007 lahars, and validity for further lahars in the Páez River can be reasonably inferred.

FLO-2D uses the Bingham model to describe rheology of sediment-laden flows. Coussot (1997) and Iverson and Vallance (2001) have shown that this might be a simplification, that reduces the accuracy of flow predictions, particularly for deposition processes (Schatzmann 2005). However, no better physically based codes designed specifically for lahar modeling are available, so the existing tools must be applied. This is a legitimate approach if models are accurately calibrated and validated for the systems modeled.
Program validation showed that FLO-2D and LAHARZ generally calculate similar inundation depths, which match measured inundation depths reasonably well. Over the entire model domain FLO-2D results depart by ~25% and LAHARZ output by ~35% from measured depths of the 2007 lahar event. This illustrates the robustness of the modeling approach and the potential of the tools applied. However, locally even larger deviations between modeled and observed inundation depths exist, and highlight the models’ limitations for detailed local analyses at high resolution. Important limitations exist in particular for LAHARZ regarding sediment deposition and flow attenuation. The program maintains the ratio of the inundated cross-sectional area over the entire flow path in order to distribute the volume. The program therefore overestimated inundation depths at lower locations, where in reality the flow discharge and volume had decreased due to deposition and flow attenuation. FLO-2D, in contrast, accurately simulated flow attenuation downstream of Belalcázar but was of limited accuracy in calculating average flow velocities. When comparing computed and observed travel durations of the lahar in different river sections, FLO-2D yielded significantly longer times and increasingly underestimated velocity where slope gradient is low. Nonetheless model results showed a satisfactory match with reality, which is necessary to apply the programs for hypothetical lahar scenarios from Nevado del Huila.

Scenario modeling

Definition of future lahar scenarios is inherently uncertain. The volumes applied in the scenario modeling are within one order of magnitude of past events, and represent worst-case scenarios related to volcano-glacier interactions or a partial collapse of the volcano. The collapse of entire flanks is not included as a scenario, as such processes can hardly be modeled in a realistic way (Carrasco-Núñez et al. 2006).

The modeled inundation depths (Table 4) form the basis for hazard mapping and the identification of safe places to be used in an emergency. In addition, calculated arrival times of the flow provide indications about times available for evacuation in the case of a lahar alert. As the applied programs tend to slightly overestimate inundation depths, results can be seen as worst-case inundation depths, which are useful for planning purposes.

The use of two totally different programs, calibrated and tested with the April 2007 lahar event, enhances the robustness of results. For the lahar scenario of 300 million m³, modeled inundation depths differ by 3 m or 10% between the programs. Scott et al. (2001) reported inundation depths of 40 and 20 m at Tóez and Belalcázar, respectively, for the 320 million m³ lahar in 1994. Model results of the 300 million m³ scenario are ~25 and 20 m, for the same locations. For a lahar volume of 600 million m³, model results vary by 4.5 m or 12% from each other, and for the largest scenario, FLO-2D and LAHARZ model outputs differ by 4.5 m or 9%. This shows that modeled inundation depths differ by ~10% between both programs for the scenarios.

Lahar travel times are less accurately modeled as already seen in the model validation process. They range between 1 (1 billion m³) and 1.5 h (300 million m³) between Tóez/ Pueblo Nuevo and Paicol.

The limiting factors for a hazard assessment mainly lie in the uncertainties of scenario definition and incomplete understanding of lahar flow and deposition. Nevertheless, data on past events and model results show that several communities in the Páez and Simbola valleys are located in a hazardous zone. They, therefore, can use this robust scenario modeling for planning and to implement adaptation and mitigation measures.

Conclusions

Very large water-sediment flows, on the order of several tens to hundreds of millions of cubic meters, are generally difficult to model with current capabilities. An appropriate way to increase the confidence of model results is to test flow models with data from past events. Direct measurements of past lahars, however, are rare and field evidence is often the only way to reconstruct flow dimension and dynamics. The Nevado del Huila volcano with its recent lahar events is an important case for the improvement of process understanding. A careful analysis of the April 2007 lahar allowed reconstruction of crucial flow parameters, which was necessary for the calibration and validation of the flow models FLO-2D and LAHARZ. The reconstruction of the flow hydrographs was an important contribution for the understanding of this lahar. Based on flow parameters obtained with the April 2007 lahar, possible scenarios for future lahars were simulated to provide data for hazard delineation and hazard mapping. Despite limitations, model results are reasonable and inundation depths calculated by the programs differed by only 10% from each other. Inundation depths calculated by FLO-2D and LAHARZ depart by ~25% and ~35%, respectively, from measured depths of the 2007 lahar event. Modeled inundation depths and flow velocities for future scenarios are an important contribution for hazard assessment and risk reduction. However, in order to reduce uncertainties and to further improve the quality of model output, more studies on very large events are needed. Material entrainment has shown to be a crucial factor in lahars, as it controls flow behavior and renders numerical modeling more difficult and uncertain. Further research should,
therefore, focus on lahar modeling in settings where sediment transport is a flow dominant component.

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4.3 Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina)

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Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina)

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\textbf{Abstract}

Although moraine dams are inherently prone to failure because of their often weak structure, loose internal composition and lack of an engineered spillway, the understanding of dam breaching processes remains largely incomplete and appropriate modeling approaches are scarce. This paper analyzes a recent glacier lake outburst, caused by the failure of the terminal moraine of Ventisquero Negro (Patagonian Andes, Argentina) in May 2009. The dam breach trigger, breaching and lake emptying processes, plus the dynamics of the outburst flood were reconstructed based on field evidence and the application of a dynamic dam break model. Results indicate that the moraine failure was caused most probably by a rising lake level due to heavy precipitation, resulting in high lake outflow which led to dam erosion and finally to dam failure. The lake volume of ca. $10 \times 10^6$ m$^3$ was released in ca. 3 h, producing high-discharge (ca. 4100 m$^3$ s$^{-1}$) debris flows and hyperconcentrated flows as the escaping water entrained large volumes of clastic material. The methodology presented in this paper provides valuable insights into complex dam breach and GLOF processes, and closes a critical gap in dynamic dam break modeling aimed at providing the lake outburst hydrograph. An accurate determination of outburst hydrographs constitutes one of the most crucial aspects for hazard assessment of unstable lakes and will gain further importance with ongoing glacier retreat and glacier lake formation.

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1. Introduction

Glaciated high-mountain regions are particularly susceptible to climate change (IPCC, 2007) and associated changes in hazard situations (Stoffel and Huggel, 2012). Recent glacier melt has given rise to the formation of moraine-dammed glacier lakes (Clague and Evans, 2000), which typically form between the glacier snout and end moraines during periods of glacier retreat (Costa and Schuster, 1988). Moraine dams are inherently prone to failure because of their often weak structure, loose internal composition and lack of an engineered spillway. Sporadic glacier lake outbursts may drain as powerful floods (Mergili et al., 2011) and are considered the most important glacier-related hazard in terms of direct damage potential (Osti and Egashira, 2009). Glacier lake outburst floods (GLOFs) have killed thousands of people in many parts of the world (Clarke, 1982; Hewitt, 1982; Clague and Evans, 1994, 2000; Watanabe and Rothacher, 1996; Richardson and Reynolds, 2000a; Huggel et al., 2004; Carey, 2005) and with ongoing glacier retreat new, often unstable glacier lakes are likely to develop in the future (Frey et al., 2010). As a result GLOF risks are receiving increased attention as a key climate change hazard (Malone, 2010).

The stability of a moraine dam has been shown to depend primarily on its geometry, internal structure, material properties and particle-size distribution (Costa and Schuster, 1988; Richardson and Reynolds, 2000b; Korup and Tweed, 2007). Melting of stagnant ice within ice-cored moraine dams has been reported to create conduits for lake water to percolate into moraines, contributing to a weakening of overall dam structure (Clague and Evans, 2000; Richardson and Reynolds, 2000b). However, most moraine-dammed
lakes do not burst catastrophically. At the same time, dams that are considered stable do not necessarily prevent disasters either, as was the case at Laguna 513, a glacier lake in the Cordillera Blanca of Peru, where a displacement wave (induced by an ice avalanche) caused water to overtop a bedrock dam and caused an outburst flood in 2010 (Carey et al., 2011). Moraine dams fail when the material strength of the dam is exceeded by driving forces that comprise, among others, the weight of the impounded water mass, seepage forces and shear stresses from overtopping flow or displacement waves (Korup and Tweed, 2007; Massey et al., 2010). Overtopping flows can be caused by heavy rainfall or a sudden influx of water from upstream sources; displacement waves are, in contrast, triggered by mass movements e.g. snow and ice avalanches, rockfalls, debris flows or landslides, entering the lake (Costa and Schuster, 1988; Clague and Evans, 2000; Huggel et al., 2004). Once the lake overflows water will typically induce dam erosion, forming an initial breach, that leads to greater outflow and increasing hydrodynamic forces that cause progressive breach enlargement (Singh, 1996). Critical shear forces on the dam material are exerted by the flow 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 glacier lake.

Before structural, land-use planning or emergency-oriented prevention measures can be undertaken to reduce the risks from GLOFs, the dimensions of an expected outburst flood must be evaluated. Hydraulic flood models are valuable tools for quantitative assessment of large-scale floods and a key instrument for the assessment of GLOF hazards and the planning of prevention measures (Valiani et al., 2002; Jorgenson et al., 2004; Worni et al., 2011).

One of the most crucial model input parameter for such assessments is the flood hydrograph, which reflects discharge per unit time. The hydrograph of a lake outburst flood can be approximated using empirical relationships (Evans, 1986; Huggel et al., 2004; Kershaw et al., 2005) or calculated using empirical and physical dam break models. Empirical dam break models use analytically-solved equations derived from past dam breach events with known breach dimensions and expansion rates (Singh, 1996). Physical models apply geotechnical considerations, erosion rates and hydraulic principles to take account of breach development. However, many physical dam break models (e.g. BREACH, Fred (1991) or BEED, Singh and Scarlatos (1985)) still require critical input parameters regarding the shape of the breach and its enlargement over time, which are often based on assumptions rather than on physical evidence, rendering these programs less site-specific (Hahn et al., 2000; Volz et al., 2010; Pickert et al., 2011). Recently, new erosion-based dynamic models (Faeh, 2007; Balmforth et al., 2008; Faeh et al., 2011) have been developed, which represent a promising approach to capture breaching processes with good accuracy. These models solve balancing equations for water and sediment flow in combination with empirical transport formulas to simulate embankment failures, thereby using clear physical input parameters.

No matter which approach is applied to calculate future outburst scenarios of unstable glacier lakes or other dam breaches, model calibration and validation based on past events remain crucial (Clarke, 1982; Mean and Schwarz, 1993; Walder and Costa, 1996; Tingisantchi and Chininarasi, 2001). This is challenging as little is known about outburst mechanics and the hydrodynamic characteristics of GLOFs, because many past moraine breaches and subsequent lake outburst floods often went unrecorded and in remote areas (Carrivick et al., 2009; Osti and Egashira, 2009). Therefore the moraine failure and lake drainage event at Ventisquero Negro (Mount Tronador, Patagonian Andes, Argentina) is an important contribution to the analysis of dam failures and GLOF processes, and an ideal case to calibrate and test dam break models.

The purpose of this study is to (i) reconstruct the moraine breaching, lake emptying and flood propagation processes of the Ventisquero Negro GLOF based on field evidence; and to (ii) apply and test the dynamic, erosion-based dam break model BASEMENT (Faeh et al., 2011). This reveals valuable quantitative insights into dam breaching and lake emptying processes that are rarely available from other GLOF events, and closes a critical gap in dynamic moraine breach modeling for which few detailed studies exist (e.g. Hancox et al., 2005; Balmforth et al., 2008; Xin et al., 2008).

2. Study area

Mount Tronador (41°10’S, 71°52’W; 3480 m asl) is the highest mountain in Nahuel Huapi National Park and straddles the border between Chile and Argentina in northern Patagonia. The upper part of the mountain is covered by a continuous ice cap, with eleven outlet glaciers. The total glacier area is about 64 km² and the largest glaciers reach down to 950 m asl, well below the local tree line of ~1700 m asl (Villalba et al., 1997).

The Rio Manso valley glacier in Argentina flows down the south-eastern flanks of Mount Tronador and is separated by a steep cliff several hundred meters high from the main ice cap. The glacier is fed by snow, ice and debris avalanches from the steep slopes above. Due to a thick debris layer covering large portions of its ice, the Rio Manso valley glacier is locally known as Ventisquero Negro, meaning black glacier. Ventisquero Negro is constrained by a massive terminal moraine with a fork-like shape, forming the Rio Manso outlet at its lowest point (Fig. 1). During the Little Ice Age, the glacier partly overtopped the older (>2000 year old) end moraine and subsequent glacier recession resulted in a debris-covered ice body abutting the inner slope of the end moraine (Masiokas et al., 2010).

Documentary evidence, satellite imagery and aerial photographs indicate that the glacier margin varied relatively little between 1937 and 1991. However, rapid thinning and recession of the glacier tongue was observed between the early 1990s and the present (Masiokas et al., 2010). The 1981 aerial photograph and a SPOT5 image from December 2008 (Fig. 1) illustrate the mass and length losses at Ventisquero Negro. The recession of Ventisquero Negro resulted in the formation of a proglacial lake between the end moraine and the glacier front. The lake grew rapidly after the 1990s and the SPOT5 image from 2008 shows the maximum lake extent with an area of ca. 47 ha before the moraine breach in May 2009. The damaged moraine and emptied lake can be seen on the GeoEye satellite image taken in November 2010 (Fig. 1). On its way to Mascardi Lake, located 22 km downstream of the glacier lake, the Rio Manso crosses the small settlement and tourist resort of Pampa Linda (ca. 7 km below the glacier lake).

3. Geomorphic, ground observation, and meteorological data

In February 2010, field work was carried out to analyze the residual Ventisquero Negro glacier lake, the breached moraine and the flooded Manso valley. The goal was to gather data on the dam, breach, and (former) lake geometry, the structure and material composition of the end moraine, and wetted cross-sections in the Manso valley.

The mapping of the lake, moraine and breach was carried out using a Tech-Geo GTR differential GPS and a Nikon LASER 550A S high-sensitivity laser distance measurement tool with an integrated angle measurement function. Ground measurements were
complemented by data from satellite imagery and aerial photographs. A pre-GLOF SPOT5 satellite image of 2.5 m resolution and a post-GLOF GeoEye satellite image with a 1.65-m resolution were extracted from GoogleEarth and georeferenced. Additionally, LANDSAT ETM+ imagery from April 2009 and an ALOS scene from March 2010 were used to document and map breach geometry and geomorphic changes before and after the GLOF. Aerial photographs from 1970 and 1981 were used to reconstruct recent glacier dynamics at Ventisquero Negro and lake formation, and to generate a digital elevation model (DEM) with a 7-m resolution of Ventisquero Negro and the Rio Manso area. Absolute and relative vertical accuracies of the DEM are ±24 m and ±4 m, respectively, based on a comparison of elevations using the DEM and GPS measurements.

Six hour-interval precipitation data from May 2009 and monthly precipitation data from 1985 to 1997, measured at the rain gauge at Lake Mascardi (22 km downstream of Ventisquero Negro), were analyzed to document the role of rainfall in the triggering of the dam breach. In addition, monthly precipitation data from 1905 to 2006 were available for Bariloche (45 km from Ventisquero Negro), as well as daily precipitation data from 1971 to 2005 from Lake Gutierrez (35 km from Ventisquero Negro). A strong W to E precipitation gradient exists between Ventisquero Negro and Bariloche/Lake Gutierrez (Villalba et al., 1997), but these longer records are useful to put the shorter, proximal records into a regional climatic context and extend the rainfall record into 21st century.

4. Modeling approach

4.1. Dam break model

The two-dimensional numerical model BASEMENT (Faeh et al., 2011) was used to investigate the breaching process of the Ventisquero Negro end moraine and the related lake drainage. The program is initially based on the existing 2dMB model, which has been applied successfully to breaching processes of earthen embankments (Faeh, 2007). BASEMENT has been designed as a tool for the analysis of breaching processes of non-cohesive earthen dam structures and water-sediment flows (Volz et al., 2010). The 2D shallow water equations (1) and (2) are general constitutive flow equations, and are solved with an explicit Finite-Volume method on unstructured meshes. The primary variables are water depth $h$ and specific discharges ($q = uh, r = vh$) in the coordinate directions.

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0$$

(1)

$$\frac{\partial}{\partial t} \left( hu \right) + \frac{\partial}{\partial x} \left( hu^2 + \frac{1}{2} gh^2 \right) + \frac{\partial}{\partial y} \left( huv \right) = -gh \frac{\partial z_B}{\partial x} - \frac{5}{2} \rho g$$

(2)

where $u$ is the velocity in $x$ direction, $v$ is velocity in $y$ direction, $g$ is the gravitational acceleration, $\rho$ is the fluid density, $z_B$ is the bottom elevation. The bed shear stresses ($\tau_{bx}, \tau_{by}$) act in the direction of
depth-averaged velocities and are determined using the quadratic resistance law with \( c_f \) being the dimensionless friction factor as
\[
\tau_{Bx} = \rho \sqrt{u'^2 + b^2 u'^2 / c_f^2}, \quad \tau_{By} = \rho \sqrt{u'^2 + b^2 v'^2 / c_f^2}
\]  
(3)

The hydraulic fluxes are calculated using an exact Riemann solver (Toro, 2001), which leads to an accurate and stable simulation scheme even for very unsteady flow conditions and changing flow regimes, which have to be expected during dam breaching. The model’s capacity to handle moving boundaries and drying–wetting fronts appropriately is of special importance for dam break simulations.

Erosion and transport of dam material due to overtopping flow is calculated with empirical sediment transport equations. The program evaluates surface erosion based on the bottom shear stress exerted by the flow on the dam material. Thus, sediment transport laws are used to determine vertical incision in earthen dam structures. Thereby a layer-approach is applied, i.e. grain sorting takes place in the uppermost (mixing) layer and additional sediment layers can be defined over depth with different compositions. In case of fractional transport the sorting equation (4) needs to be solved for each grain class \( g \).

\[
(1 - p) \frac{\partial (\beta_g \cdot h_m)}{\partial t} + \frac{\partial q_{Bx,g}}{\partial x} + \frac{\partial q_{By,g}}{\partial y} - s_{fg} = 0
\]  
(4)

and the total sediment mass balance (5) is obtained by summing all sediment fluxes,

\[
(1 - p) \frac{\partial z_f}{\partial t} + \sum_{g=1}^{n_g} \left( \frac{\partial q_{Bx,g}}{\partial x} + \frac{\partial q_{By,g}}{\partial y} \right) = 0
\]  
(5)

where \( \beta_g \) is the fraction of grain class \( g \), \( h_m \) is the thickness of the control volume, \( p \) is the porosity of sediment, and where \( q_{Bx,g} \) and \( q_{By,g} \) are components of transport rate. The bed level \( z_f \) and the grain fractions \( \beta_g \) are the primary variables of sediment transport. The source term \( s_{fg} \) describes the exchange of sediment particles between the control volume and the underlying soil layer (Faeh et al., 2011). For erosion, material from the underlying soil layer of composition \( \rho_{soil} \) enters the control volume. For deposition, material leaves the control volume and enters the soil layer. With \( z_s \) as the bottom elevation of the control volume and \( z_{sub} \) as the bottom elevation of the underlying layer, the source term \( s_{fg} \) becomes

\[
s_{fg} = -(1 - p) \frac{\partial}{\partial \beta_g} (\beta_g \cdot z_f - z_{sub}) / \beta_g \]  

with \( \beta = \beta_g \) for deposition and \( \beta = \beta_{sub} \) for erosion (6).

Within this study, the transport rate was determined using a modified Meyer-Peter and Müller (Meyer-Peter and Müller, 1948) formula (7) for fractional transport with the hiding function \( \xi \) after Ashida and Michiue (1971) and the critical bottom shear stress of incipient motion \( \tau_{Bcr} \) from the shields-diagram (Shields, 1936).

\[
q_{Bx,g} = \beta_g \left( \frac{z_f - z_s}{0.25 \rho} \right)^{3/2} \frac{1}{(\rho_s / \rho - 1)g}
\]  
(7)

The complex geotechnical processes of lateral breach widening due to slope collapses of the side walls are considered with a geometrical 3D bank failure operator, which is based on three different critical failure angles: (i) a failure angle for dry or partially saturated material at the breach side walls above the water surface which can exceed the angle of repose due to the stabilizing effects of negative pore pressures; (ii) a failure angle for bank material below the water surface, which is fully saturated. This failure angle is expected to be in the range of the angle of repose; (iii) a failure angle for deposited material resulting from slope collapses. It approximates the sliding of the collapsed material into the breach channel after failure and determines the soil’s redistribution in the breach channel. The deposition angle is not a pure material property, and therefore needs calibration.

If one of the failure angles is exceeded due to vertical erosion, gravitational bank failure is expected to occur and the slope is flattened until the critical angles are reached. The material moves in downward direction of the cell’s slope and is added to transport rates.

4.2. Computational domain

The model domain for the dam break simulation (i.e. lake, moraine, and flood plain) was discretized with a 2D unstructured mesh. To ensure mass conservation, BASEMENT uses a separate mesh for sediment calculations, which is constructed automatically from the given mesh. The Surface Water Modeling System (SMS) software (SMS, 2012) was used to create the computational mesh consisting of ca. 29,000 triangular cells. For a flexible adaptation to local geometry variable cell sizes and local mesh refinements were applied. Based on satellite imagery the mesh was drawn in planar view and then height information from the DEM was interpolated on the mesh nodes. Although the DEM represents the terrain in 1981, dam geometry has not changed significantly over the past 30 years, but glacier and glacier lake geometry had to be corrected significantly with field data and satellite imagery due to glacier retreat.

5. Field-based reconstruction of the moraine failure and lake outburst flood

The breach of the Ventisquero Negro end moraine on 21 May 2009 produced a lake outburst flood that devastated the Rio Manso Valley. According to eyewitness reports, the resulting sediment-laden turbulent flow hit Pampa Linda (7 km downstream of the lake) at around 10.30 pm and lasted 7 ± 2 h. Data from field reconnaissance show that the lake water level dropped by ca. 27 m during the moraine failure and that <5 m of water height remained in the basin. Together with the reconstructed lake bathymetry from satellite imagery before and after the GLOF and field survey, the volume of released water was calculated as ca. 10 × 10^6 m^3. The moraine breach revealed buried glacier ice lying against the inner flank of the terminal moraine on the orographic left side of the breach.

5.1. Properties of the moraine breach and outburst flood

The end moraine of Ventisquero Negro contains non-cohesive, unconsolidated and poorly sorted granular materials consisting largely of coarse, blocky and bouldery material with a matrix of sand and gravel. Grain size distribution of moraine material was performed for sediments of the sidewalls inside the breach and defined by classical dry-sieving (0.125–2 mm) for the finer and photogrammetric analysis (2–1000 mm) for the coarser fractions (Fig. 2). The slope angle of the moraine wetted by the lake before the GLOF was 40–45°, which corresponds to the natural repose angle of the moraine; this value also served as a guideline for the failure angle below the water surface. The walls inside the breach after the GLOF had slope angles of up to 80–90° and indicate a possible value for the failure angle above the water surface.

The 350-m long breach (Fig. 3A) has minimum and maximum cross-sectional areas of 1100 and 2500 m^2, respectively. The
narrowest section of the breach is located at its upper end where an ice core (Fig. 3C) limits the width of passage to 12 m at the river bottom and to ca. 60 m at the top of the ice core, ca. 25 m above the present river bed. Downstream of the ice core the breach widens to an average cross-sectional width of 70 m, with a maximum of 120 m at the lowermost end of the moraine body. In the upper, central and lower segments the breach is about 50, 30 and 10–20 m deep, respectively (Fig. 3 overview). Breach volume (i.e. the amount of material eroded from the moraine dam) is ca. 230,000 m$^3$.

The flood deposits of the Ventisquero Negro GLOF provided information about flow behavior and flow type. Debris flow levees with overlying rocks of up to 6 m in diameter (A axis) indicate that the outflowing lake water entrained moraine material to form a debris flow in the uppermost reaches of Rio Manso (Fig. 3D). Deposition en masse and terminal lobes some 350 m downstream of the breach mark the point where this first debris flow surge stopped. Below this point, the GLOF flowed for 150 m as a sediment-laden flow, which was indicated by the absence of significant deposition or erosion traces and the presence of pre-flood vegetation. According to field deposits, at 500 m downstream of the breach, the surge evolved again into a debris flow, transporting and depositing material downstream on relatively flat terrain (ca. 2° decline). Maximum grain sizes and levee heights decreased with increasing flow distance and terminal lobes at ca. 1000 m below the breach clearly indicate the runout zone of the second debris flow surge (Fig. 3 overview). The total approximate volume of the debris flows was assessed at ca. 250,000 m$^3$, which corresponds to the amount of eroded moraine material. Below the deposition area of the second debris flow, flow traces indicate that the GLOF propagated downstream as a hyperconcentrated flow to become a stream flow before entering Mascardi Lake.

In the first 10 km the outburst flood changed flood plain morphology significantly by removing entire forest stands (Fig. 3E and F) and rocks. After 4 km, the flood diverged from the main river channel and flooded an area of approximately 1 km$^2$. Part of the water flowed along the road to Pampa Linda where a bridge and parts of the road were destroyed, while a camp ground and houses were partly flooded. Downstream of Pampa Linda the channel of Rio Manso was able to accommodate most of the released lake water.

![Graph](image)

**Fig. 2.** Grain size distribution of moraine material as measured at the sidewalls inside the breach.

![Diagram](image)

**Fig. 3.** In the overview, flow type of the GLOF, inundated area, the moraine breach, the ice core and actual and former lake outline are illustrated, and the positions of pictures (A–F) are indicated. In addition, a longitudinal profile of the study reach and three cross-sections of the breach are provided. Pictures (A), (B) and (E) were taken shortly after the GLOF from a helicopter and show (A) the moraine breach, (B) the emptied lake and (E) the flooded area, respectively (Club Andino Bariloche, used with permission). The other pictures were taken during the field campaign and illustrate (C) the buried ice core, (D) debris flow deposits close to the moraine and (F) trees transported along the flow path.
5.2. Dam breach trigger and dam failure processes

Meteorological records from Lake Mascardi report unusually heavy rainfall (total 170 mm) with high temperatures (mean daily temperature = 7 °C) during the six days prior to the outburst. Both the length and the intensity (50 mm in 48 h preceding the GLOF) of the rainfall event were among the highest reported for the station and also for Bariloche (Fig. 4). As the glacier lake is located 16 km away from the meteorological station, precipitation totals and patterns might have been different at Ventisquero Negro. However, park rangers reported that heavy rainfalls occurred at Ventisquero Negro as well; and that these rainfalls would have increased the level and outflow of the glacier lake. As a further consequence, ice blocks originating from glacier calving were uplifted and subsequently floated towards the outlet.

The increasing lake level and lake outflow most likely induced the moraine failure, as other possible trigger mechanisms could be excluded due to the absence of traces of mass-wasting events impacting the lake. The influence of an ice core >25 m in diameter against the inner slope of the moraine is of particular interest regarding both initiation of dam failure and breach formation. In principle, three different failure scenarios (or a combination of several of these scenarios) are possible:

Scenario 1: Intense rainfall resulted in increased lake overflow discharge. In this case, an unusual high lake outflow was sufficient to break the armor layer of the outlet river bed and to initiate vertical dam erosion. After initial incision, more lake water was able to flow out with a subsequent increase in sediment transport rates and a progressive expansion of the breach.

Scenario 2: High lake level and outwards current caused stranded ice blocks in the lake to uplift and drift toward the outlet. The ice plugged the outlet, ponding the lake to an even higher level. Due to the resulting increase in water pressure the ice blocks were abruptly washed away and the critical shear stress to initiate erosive processes was exceeded by the released water. Once the erosion started, breach expansion continued until the force of outflowing lake water decreased such that bedload was no longer transported.

Scenario 3: The rising water level of the lake resulted in increased hydrostatic pressure on the dam, which ultimately led to instability of the ice core abutting the moraine (by uplift caused by the hydrostatic gradient, by partially breaking apart, or by gradual melting as a result of water infiltration). The ice body acted as a barrier between the lake and the moraine and consequently, a destabilization of the ice core led to a destabilization of the moraine. The water pressure caused partial collapses of the moraine body leading to more sudden lake emptying than in scenarios 1 and 2 (Fig. 5).

6. Modeling the moraine failure and lake emptying

6.1. Model setup

Moraine breach modeling started with a semi-quantitative sensitivity analysis of several hydraulic and morphologic model parameters. The sensitivity of model parameters on simulation output was tested by varying their value within a reasonable range (Table 1) while maintaining all other parameters at default values. Then the change of modeled discharge and breach erosion before and after parameter variation was analyzed. Parameter sensitivity was considered small when the influence on modeled discharge and erosion was <10%, moderate if 10–25% and high if >25%.

Most of these parameters given in Table 1 were directly measured in the field, others are typical material constants. The bedload factor, control volume thickness and deposition failure angle were difficult to derive but were required for the simulation and serve to some extent as calibration factors.

Lake bathymetry (represented by the mesh created in SMS) and water surface elevation prior to the lake outburst defined BASEMENT’s initial condition (Fig. 6). The sudden release of water from the lake and an associated high outflow right from the start of the model run were possible through the definition of a water surface elevation above the lake outlet. Such initial conditions might have existed at the study site due to an abrupt removal of ice blocks that temporarily dammed the lake (scenario 2). Once water is flowing, the hydrostatic force of the lake is the main driver for continuous outflow and dam erosion. In the present case, the initial water surface elevation had to be >2 m above the outlet to provoke sufficient initial bedload transport and to maintain breach expansion and lake emptying. An external water source of 25 m$^3$s$^{-1}$ was defined as an additional upper boundary condition, representing water inflow from ice melt and precipitation. However, this estimated lake inflow hydrograph had minimal influence on the dam breach process.

The moraine dam was defined to consist of erodible sediments with material properties, material failure angles and grain size distribution as defined in Table 1. The ice core lying against the inner flank of the moraine was replaced by erodible dam sediment,
whereas all other zones in the model domain were defined as non-erodible.

### 6.2. Model results

The model domain, initial conditions and input parameters (see Table 1) were used to model the breach of the Ventisquero Negro end moraine and subsequent lake drainage with BASEMENT. The modeled breach evolution shows that the steepest section of the moraine, some 150 m below the outlet, experienced most initial erosion, which caused the downstream face of the dam to steepen at this point (Fig. 7B; 30 min). The resulting rapid flow in the steep section entrained more bedload and the breach evolved backward towards the outlet. This knickpoint retreat resulted in a lowering of the lake outlet and in increased discharge, thus leading to progressive vertical and horizontal breach enlargement (Fig. 7B; 60 and 120 min). Model results also indicate that higher flow velocities occurred as a result of increasing outflow and that the maximum value of 17 m s\(^{-1}\) was reached at 70 min after the simulation was started. With increasing flow velocities, bed shear stress increased simultaneously to a maximum of 5100 N m\(^{-2}\), which in turn enhanced erosion rates and vertical breach growth. Breach deepening resulted in steepening of the side walls, which collapsed as soon as critical failure angles were exceeded, leading to breach widening. The simulation of the growing breach cross-section allowed more outflow and progressive dam erosion. The model also suggests that deposition rates in the flood plain below the breach are directly correlated with breach expansion. The model run ended after 180 min when the lake level and outflow decreased below the threshold for bedload transport and breach expansion ceased.

The positive feedback loop as described above resulted in an exponential increase in discharge. During the first 45 min of the simulation discharge increased constantly up to 700 m\(^3\) s\(^{-1}\), before it steeply rose to a maximum of 4100 m\(^3\) s\(^{-1}\) after 80 min. The outflow hydrograph showed a steep falling limb which became flatter after 120 min and eventually returned to nearly normal outflow. The model runs also indicate that the complete water volume of 10 \(\times\) 10\(^6\) m\(^3\) was released within 180 min (Fig. 7A).

### 6.3. Model output validation

Model outputs were validated through comparison between modeled and measured breach and deposition geometry as well as lake level drop; it was assumed that a good match implies a reasonable reproduction of breach expansion rates.

Satellite imagery and field evidence clearly show a longitudinally curved breach whereas the modeled breach is straight but...
of similar extent. At the upper and lower end of the breach (points 1 and 7 in Fig. 8), the actual breach was ca. 5–7 m deeper than modeled (see inset in Fig. 8); otherwise, measured and modeled breach depths coincide well, with a mean deviation of 2.5 m. The model calculated a drop in lake level of 30 m with 1 m water depth remaining in the basin; field measurements indicate a lake level drop by ca. 27 m and ca. 5 m water depth remaining in the basin. Fieldwork revealed that the eroded dam material was transported by debris flows and deposited in two different zones (see dotted yellow lines in Fig. 8) with maximum thicknesses of 15 m some 120 m below the moraine. In BASEMENT all deposition of material occurs in the upper runout zone and the model suggests maximum deposition heights of 18 m ca. 280 m downstream of the moraine (Fig. 8). However, as the flow physics modeled in BASEMENT do not account for sediment motion as debris flow, differences in deposition between model and reality are not unexpected in this study.

Eyewitness reports indicate that the inundation at Pampa Linda lasted for 7 ± 2 h. The duration of the dam breach and lake outflow processes cannot, however, be easily compared with the time reported for the inundation because (i) flood attenuation effects might have increased the flood duration, and (ii) water presumably drained slowly on the large and flat valley plain at Pampa Linda. Hence, as there are no data on lake outflow duration and lake discharge the outflow hydrograph (as suggested by BASEMENT) can only be validated indirectly.

7. Discussion

The application of erosion-based, dynamic dam break models to real case events is still in the early stages of development.

Advances in this field of study are essential, as a proper modeling technique for moraine breaching is crucial to assess the hazard potential of existing glacier lakes, which to date is often limited to qualitative studies. Studies on past GLOFs and on outburst prone lakes exist for many mountain regions in the world, but few glacier lakes and GLOF events have been systematically analyzed in the Patagonian Andes (e.g., Dussaillant et al., 2010). More particularly, studies on lake outbursts, caused by moraine failure, are rare for this region (Harrison et al., 2006). The Ventisquero Negro case study provides original information from a poorly studied area and sheds light on a natural hazard that might become increasingly relevant in Patagonia, especially with respect to possible hydropower projects (Vince, 2010).

GLOF disasters are characterized by complex and interacting processes, typically resulting from cascades of processes rather than single phenomena (Haebeli et al., 2010). This was observed at Ventisquero Negro, where, in addition to heavy rainfall, two long-term processes may have contributed to trigger the failure of the moraine: (i) accelerated lake growth observed in the years preceding the outburst resulted in a steadily increasing hydrostatic pressure on the dam; and (ii) a gradual reduction of stability of the end moraine occurred as the ice core abutting the moraine progressively melted following loss of glacier contact. Hence, the stability of the moraine-lake system at Ventisquero Negro progressively decreased and the high lake outflow in May 2009 eventually triggered dam incision.

Based on field evidence and model results, the following dam breaching process seems plausible: Dam incision due to heavy lake outflow started at the lake outlet (or even below), which was downstream of the ice core (Fig. 9A). The outflowing water eroded the steepest part of the moraine initially and progressively incised back towards the ice core. The curved plan of the breach geometry around the ice block and the absence of ice on the orographic right side of the breach (Fig. 9B) indicate that water followed the path of...
minimal resistance to erosion (which is not the ice) and incised the sediment around the ice block, which then failed due to stress changes. Fragments of the ice core and floating ice blocks partly blocked the uppermost passage of the breach (Fig. 9B). Although this ice barrier was still water-permeable it reduced vertical and horizontal erosion rates. This resulted in forcing of the thalweg towards the ice-free part of the dam where incision and lateral bank collapse dominated. Similar developments of moraine breaches are described in the literature (Clague and Evans, 2000; Richardson and Reynolds, 2000b; Coleman et al., 2002; Hancox et al., 2005; Osti et al., 2011).

As there was evidence for a progressive breach formation driven by the water’s sediment transport capacity, we decided to test the dynamic, erosion-based dam break model BASEMENT for the first time under case-study conditions. Model calibration and validation were challenging as a result of the limited data availability and was therefore done primarily via the geometry of the final breach; nevertheless model results were consistent with field observations. As a result of limited data, an uncertainty analysis of four critical model inputs was particularly important in view of the difficulties prevailing for modeling real-case dam breaches in general:

(i) The quality of model results strongly depends on the accuracy of reconstructed dam and lake geometry, which are based on the DEM and field mapping. DEM data for Ventisquero Negro were of unusually high resolution (7 m) for such a remote location, however, some irregularities and inaccuracies along the flow path and at the moraine still persisted in the DEM and directly affected model results (e.g. breach position, breach evolution, or lake discharge).

(ii) The model’s initial conditions (lake water surface elevation and lake bathymetry; inflow hydrograph) have considerable uncertainties and are based partly on field observations (e.g. lake bathymetry), as well as on a trial-and error approach. The latter approach aimed at the identification of an initial water surface elevation of the lake high enough to result in a complete dam failure.

(iii) Since the ice body could not be considered in the dam break model, erosion rate and final cross-section geometry were slightly overestimated in the simulation for the upstream end of the breach. The smaller cross-sectional area observed in the field compared to model output also controlled max-
imum water discharge from the lake. It seems likely therefore that BASEMENT slightly overestimated the largest outflow values.

(iv) In BASEMENT, physically-based input parameters controlled breach formation, and the calibration parameters (i.e. bedload factor, failure angle of deposition, control volume thick-
ness) allowed minor adjustments to achieve a good match with reality. The definition of calibration parameters is challenging and must be adjusted through retrospective modeling of a past event. At Ventisquero Negro no multiplication factor was required for bedload capacity, even though the MPM equation used was defined for rather flat terrains with uniform flow conditions (Smart, 1984). The deposition angle has been shown to correspond to about half the repose angle of the dam material in a simulation by laboratory experiment (Volz et al., 2010). Yet, for the modeling of the moraine breach at Ventisquero Negro, a value representing one-third of the repose angle appeared more appropriate. Also, the default value of 0.1 m for the control volume thickness resulted in exaggerated erosion rates and in an unrealistic breach shape; a value of 0.05 m resulted in a much better agreement between model output and reality.

Parameters such as Manning's n roughness value, porosity, grain size distribution and slope failure angles are based on field data and values proposed in literature (e.g. Parriaux and Nicoud, 1990; USGS, 2012) and are therefore less poorly constrained.

The influence of an input parameter on model robustness can be assessed by comparing parameter uncertainty with its sensitivity in the model: The higher parameter sensitivity and uncertainty, the more critical it will be for the quality of the model output. Fig. 10 presents the most important model input parameters, qualitatively categorized according to their sensitivity and uncertainty. This information helps to identify the most relevant parameters when calibrating dam break simulations with BASEMENT.

When considering the parameter uncertainties and limitations of the model, BASEMENT is appropriate and valuable for hazard assessments of existing glacier lakes, provided it was previously carefully calibrated. The modeling approach presented in this paper can be applied to quantify lake outburst scenarios and to assess GLOF impacts at other locations. The availability of critical dam breach parameters will facilitate the planning and dimensioning of accurate mitigation measures and help the justification of decisions aimed at preserving infrastructure and populated areas from possible GLOF risks.

8. Conclusions

The detailed reconstruction of the Ventisquero Negro moraine breach is one of a very few case studies on a topic that is gaining increasing attention due to ongoing glacier retreat and lake formation. In principle, different outburst scenarios are possible in the present case, but field evidence and model results suggest that high lake outflow initiated significant bedload transport and dam erosion, leading to progressive breach enlargement and lake outflow. The field-based reconstruction of the Ventisquero Negro moraine failure provided valuable input data for the simulation of the breaching event and allowed calibration and validation of the dynamic BASEMENT model. The simulation, based on sediment transport laws, provided detailed insights into dam breach processes that are difficult to observe in nature and results were largely consistent with field evidence. As the model seemed to reproduce the lake outflow hydrograph accurately, we suggest that dynamic models such as BASEMENT could be implemented systematically in the future to define outburst scenarios for unstable moraine-dammed lakes. More investigations on moraine failure processes and dam break model applications are needed to further improve the quality of model output and other trigger mechanisms, such as overtopping impact waves, should be included in dam break modeling. This can provide information on the conditions under which dam failures occur, both in the model environment and reality. It is known that melting ice cores in moraines make dams more susceptible to failure and therefore, with ongoing climate change GLOF potential may increase. Several situations similar to Ventisquero Negro exist and in order to accurately assess GLOF risks, further research should focus on dam break modeling where the effect of ice is considered.

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References


4.4 Glacial lake outburst floods in the Pamir of Tajikistan: Challenges in prediction and modelling

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GLACIAL LAKE OUTBURST FLOODS IN THE PAMIR OF TAJIKISTAN:
CHALLENGES IN PREDICTION AND MODELLING

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ABSTRACT

Glacial lake outburst floods (GLOFs) are potentially highly dangerous events and have contributed to numerous disasters in history. Today, computer models are standard tools to estimate the magnitude of hazardous events in the future and to support risk mitigation. The present paper explores the potentials and limitations of modelling for predicting the motion of potential future GLOF events, based on examples from the Pamir (Tajikistan). Since the flow behaviour of GLOFs is in between debris flows and floods, different model approaches come into consideration, though none of them is perfectly suitable for GLOFs. RAMMS as a mass movement model and FLO-2D as a river hydraulics model were employed comparatively for the same areas. The friction parameters for RAMMS and rheologic parameters for FLO-2D were first calibrated by back-calculation with the well-documented Dasht event from summer 2002, and then applied to other areas. However, the applicability of such parameters to GLOFs of different volume and over a different topography remains questionable. The results may nevertheless be a valuable input for risk mitigation efforts, but due to the complex nature of GLOFs and the connected uncertainties, particular care is required when interpreting the model results. The critical points and potential approaches to deal with the limitations are discussed in the paper.

KEY WORDS: glacial lake outburst floods (GLOFs), modelling, Central Asia

INTRODUCTION

Natural dams of different size and origin do exist in mountain areas all over the world (COSTA & SCHUSTER, 1988). They often retain lakes which, in the case of a dam failure, may drain as powerful floods. If the outbursting lake is located within the glacial or periglacial area, such events are called Glacial Lake Outburst Floods (GLOFs). They can evolve in different ways (Fig. 1), for example:

- rock/ice avalanches or calving glaciers that produce flood waves in a pro-, supra- or periglacial lake which may overtop and breach glacial or morainic dams (TINTI et alii, 1999);
- rising pro-, supra-, sub- or periglacial lake levels, leading to overflow, progressive incision or mechanical rupture of a moraine or ice dam, as well as to retrogressive erosion of a moraine dam;
- enhanced ground water flow (piping) through moraines, or hydrostatic failure of ice dams which can cause sudden outflow of accumulated water (ITURRIZAGA, 2005a; 2005b);
- degradation of glacier dams or ice-cores in morainic dams leading to loss of stability and to subsidence resulting in internal failure or progressive erosion if a certain threshold is reached.

RICHARDSON & REYNOLDS (2000) provide an overview of failure mechanisms and case studies. GLOFs often have a highly destructive potential because a large amount of water is released within a short time, with a high capacity to erode loose debris, potentially

973
leading to a powerful flow with a long travel distance. Peak discharges are often some magnitudes higher than in the case of “normal” floods (Cenderella & Wohl, 2001). The source area is usually far away from the area of impact and events occur at very long time intervals or as singularities, so that the population at risk is often not prepared for such events (Schneider et alii, 2004). Deficiencies in risk communication are often responsible that events evolve into disasters (CAREY, 2005). A number of significant GLOFs resulting in fatalities and severe damage have occurred during the previous decades, particularly in the Himalayas, the mountains of Central Asia, the North American mountains, New Zealand, and the Alps. Case studies are provided e.g. by Clarke (1982); Hewitt (1982); Watanabe & Rothacher (1996); Richardson & Reynolds (2000); Schneider et alii (2004) and Vilimek et alii (2005). Climate change, with its impact on the glacial extent, the hydrological cycle and the condition of ice-bearing dams, may condition the occurrence of GLOFs in manifold ways and on different time scales (Evans & Clague, 1994; Dussaillant, 2009).

![Schematic representation of a glacial lake outburst flood (GLOF)](image)

**Fig. 1 - Schematic representation of a glacial lake outburst flood (GLOF)**

The present paper deals with computer modeling of the flow path of GLOFs. Using test areas in the Pamir (Tajikistan), the general potentials and limitations of such approaches as well as the suitability of different model concepts are explored and discussed. Particular emphasis is put on the capabilities of the models for the prediction of future events.

**BACKGROUND**

In summer 2002, the village of Dasht (Shakhdara Valley, Pamir, Tajikistan; Fig. 2a) was hit by a GLOF. 10 km upstream in the headwaters of the valley, a supra-glacial lake had suddenly released an estimated volume of 250,000 m$^3$ of water (Schneider et alii, 2004). The volume of debris deposited on the cone was estimated 1.0-1.5 million m$^3$, meaning that the ratio between entrained debris and water would be 4-6. This is a very high value compared to the ratio of 2-3 suggested by Huggel et alii (2004b). However, an even higher ratio than observed for Dasht was reported by Breien et alii (2008) for a GLOF in Norway. Possibly, subglacial water reservoirs connected to the superficial lake and highly saturated erodible material was involved in both events.

![Left: The debris cone resulting from the GLOF in Dasht in summer 2002, covering most of the village and damming a small lake upstream. Right: Lake dammed by a rock glacier in the upper Khavrazdara Valley](image)

**Fig. 2a - Left: The debris cone resulting from the GLOF in Dasht in summer 2002, covering most of the village and damming a small lake upstream. Fig. 2b - Right: Lake dammed by a rock glacier in the upper Khavrazdara Valley**

It was reported that the flood wave arrived in Dasht in three stages, a phenomenon that can be explained by temporary backwater in the canyon of the lower transitional zone due to blockage of large boulders transported by the GLOF or by lateral slope failures followed by vigorous breakthroughs (Schneider et alii, 2004). The event destroyed a large portion of the village of Dasht, killed a few dozens of people, and dammed a small lake at the Shakhdara river. The event hit the village completely unexpected, as there was no awareness of the hazard and preparedness for the event.

Even though potentially hazardous supraglacial, pro-glacial and periglacial lakes can be identified relatively easily with remote sensing tools and field work (e.g. Kaæææ et alii, 2005; Quincey et alii, 2007), modelling and prediction of the motion and reach of GLOFs still remain a challenge. Like many other GLOFs, the characteristics of the Dasht event underwent pronounced changes during the flow, converting from normal runoff to a hyperconcentrated flow and finally to a granular debris flow. Changes in flow behaviour imply some difficulties when using computer models to predict the flow path and velocities of such events. Simple empirical rules for debris flows travel distances show a large scatter among themselves and generally underestimate the travel distance of GLOFs (Fig. 3). Corominas et alii (2003) as-
sume an average runout angle of 21° for debris flows on unobstructed flow paths. Huggel et alii (2003), employing the Modified Single Flow direction model MSF, used an angle of 11° proposed by Haeberli (1983) as a minimum for observed granular debris flows. However, in the case of the Dasht event, both values underestimate the maximum travel distance of the debris flow which reached a runout angle as low as 9.3°. The debris flow actually did not stop before reaching the main valley. Rickenmann (1999) suggested the following empirical relationship for the travel distance of debris flows:

\[ L = 1.9V^{0.16}Z^{0.83} \]

Eq. 1,

where \( L \) is the travel distance of the flow, \( V \) is the involved volume, and \( Z \) is the loss of elevation. Using the release volume of 250,000 m³ in Eq. 1, the Dasht travel distance is again strongly underestimated, while the estimated deposition volume of 1.5 million m³ leads to a travel distance closer to the observation.

However, it is not the ‘fault’ of these empirical models not to fully capture the Dasht event, but rather a conceptual problem related to the characteristics of the event: The GLOF - as many others - was not a classical debris flow, it was characterized by several flow transformations (hyperconcentrated to debris flow and back).

Semi-deterministic approaches, using a friction model (e.g. Perla et alii, 1980 for snow avalanches) in combination with random walk routing techniques go one step further than strictly empirical models and are often applied in combination with GIS (e.g. Gamma, 2000; Wichmann, 2006; Mergili et alii, 2008). They can be used for back-calculating GLOFs and other types of mass flows, but are only partly suitable for prediction purposes. Reliable physically based dynamic models are therefore required when trying to predict the motion of potential future mass flows (Hungr et alii, 2005).

Several physically based model approaches and software packages are potentially suitable for GLOF runout modelling, some of which were developed within the mass movement research community, others within the river hydraulics community.

Many mass movement models go back to the Voellmy (1955) approach and were developed for snow avalanches, but are also applicable to other types of mass movements. A remaining problem is the entrainment of material that is an important characteristic of GLOFs (Breien et alii, 2008; Xu, 1988). Some models include entrainment modules, but rather on an empirical-statistical than on a physical base. Breien et alii (2008) emphasize the lack of appropriate data and knowledge on entrainment issues.

River hydraulics models commonly use flood routing algorithms based on volume conservation and a roughness parameter (usually Manning’s n) for estimating the extent and the depth of river flow and flooding events. Most of the widely used software packages (e.g. FLO-2D, HecRAS) include modules for sediment transport, hyperconcentrated flows, and debris and mud flows. In contrast to mass movement models, they require input hydrographs. Therefore, they allow accounting more detailed for the onset mechanism, which plays a crucial role for the flow propagation and the magnitude of the resulting flood wave (Walder & Costa, 1996). This type of model is particularly better suited for modelling the initial stage and flow path section of the event that depends more strongly on the input hydrograph. Bertolo & Wiczorek (2005) compare models following different concepts for the same set of debris flows. For an appropriate modelling of the motion of GLOFs, a combination of mass movement and river hydraulics models is suggested.

![Empirical approaches developed for the reach of debris flows and the observed travel path of the Dasht 2002 event](image-url)
OBJECTIVES

The general objective of the study presented was to elaborate a way to estimate the travel distance and travel times of potential future GLOFs by comparing the results of two different models for mass flows. Each of them partially represents certain characteristics of GLOFs but cannot fully reproduce the flow behaviour. The results and the model settings and parameters suitable for GLOFs, but also the needs for further research and model development are high-lighted, using examples from the Pamir (Tajikistan).

The paper concentrates on the movement of the flood wave itself, the breaching process of the dam is not considered. For the on-set of the GLOF process, scenarios for the outburst volume and hydrograph, as well as for the finally deposited volume (including entrained debris) were elaborated. The scenarios are based on the lake volume, the dam characteristics, and the susceptibility to rock and ice avalanches into the lake.

![Map of Tajikistan with the five selected areas for modelling](image)

Fig. 4 - Map of Tajikistan with the five selected areas for modelling

STUDY AREAS AND DATA

The modelling was performed for five study areas in Tajikistan (one for back-calculation, four for prediction; Fig. 4). All areas are located in the Pamir, a heavily glaciated high mountain area culminating in 7,495 m a.s.l. The lakes used in the case studies are distributed between 3,800 m and 4,800 m a.s.l.

The results for Khavrazdara, a Northern tributary of the Bartang Valley, will be discussed in detail below. 20 km upstream from the valley outlet, the tongue of a rock glacier dams a lake with a surface of 2 km², approximately, and an estimated volume of 40 million m³ (Fig. 2b). In the case of a climate-change-induced degradation of the rock glacier tongue, a breach of the dam followed by a flood wave down the valley is possible.

The following information was compiled for Kharvazdara as well as for all the other case studies:

- DEMs of different resolution were prepared for the investigation areas in order to allow the determination of the effect of resolution. SRTM-4 (90 m) was used as well as 10 m and 20 m DEMs derived from CORONA imagery and 5 m DEMs derived from WorldView1 imagery.

- Susceptible glacial lakes were identified using analysis of multitemporal satellite imagery, helicopter surveys, and field investigations. The surface of the relevant lakes was computed using ASTER imagery and the lake volumes were estimated.

- The peak discharges of potential outburst events were estimated from empirical rules (Evans 1986; Costa, 1988; Costa & Schuster, 1988; Manville, 2001; Hugel et alii, 2004a). Scenarios of outburst hydrographs were then created, based on the estimated peak discharge and the lake volume.

- The characteristics of the flow path and the area of deposition were mapped from satellite imagery, from the helicopter, and in the field (morphology of the valley, type of surface material, indicators for former outburst flood events).

METHODS

The first model used is the physically based mass movement model RAMMS (Rapid Mass Movements), developed at the WSL Institute for Snow and Avalanche Research SLF Davos, Switzerland (see Christen et alii, 2010a, 2010b for a more detailed description and for case studies). The frictional resistance $S$ is based on the Voellmy (1955) model that combines dry Coulomb friction $\mu$ with a velocity-squared dependent turbulent friction $\zeta$.

$$S = \mu H g \cos \phi + \frac{U^2}{\zeta} \quad \text{Eq. 2}$$

where $g$ is the gravitational acceleration, $H$ is the flow depth, $\phi$ the slope angle, and $U$ is the depth-averaged flow velocity. The maximum velocity $U_{\text{max}}$ is defined by Voellmy (1955) as:

$$U_{\text{max}} = \sqrt{\frac{2}{g} H (\sin \phi - \mu \cos \phi)} \quad \text{Eq. 3}$$

If $\mu$ equals zero, Eq. 3 can be further transformed
into the Chézy equation. Therefore, by applying low
μ-values, an approximation to turbulent clear water
open channel flow can be established.

RAMMS was originally designed to predict the
maximum travel distance and velocity of snow aval-
lanches. Calibrated parameters are available for this
type of process. They are only valid for the front of the
avalanche, so that the deposition geometry cannot
be predicted in a straightforward way (Christen et alii,
2010a). The model is able to compute entrain-
ment of material by the flow, governed by an empiri-
cally determined scaling factor and an entrainment
law. RAMMS has recently been used for modelling
other types of mass movements. Schneider et alii (ac-
cepted) successfully used it for the back-calculation
of large rock-ice avalanches and Preuth et alii (in
press) simulated various large rock avalanches in the
European Alps. It has further been used for the simula-
tion of debris flows in Switzerland (Naeff et alii, 2006;
Rickenmann et alii, 2006; Armento et alii, 2008) but not
yet for modelling GLOFs.

The second model - FLO-2D - was developed
by J. O’Brien (e.g. O’Brien et alii, 1993; O’Brien,
2001). It is a volume conserving model for flow rout-
ing of clear water floods, hyperconcentrated flows,
or debris flows over floodplains or through confined
channels. Topography, input hydrograph, and resis-
tance to flow determine the flow behaviour. Case
studies are provided e.g. by Huebl & Steinwendtner
(2001) or Bertolo & Wieczorek (2005). For clear
water flow, the governing equations are:

\[ \frac{\partial h}{\partial t} + \frac{\partial hU}{\partial x} = i \]  \hspace{1cm} \text{Eq. 4,}

\[ S_f = \alpha - \frac{\partial h}{\partial x} - \frac{U}{g} \frac{\partial U}{\partial x} - \frac{1}{g} \frac{\partial U}{\partial t} \]  \hspace{1cm} \text{Eq. 5,}

where \( h \) is the flow depth, \( U \) is the depth-averaged
flow velocity in one flow direction \( x \), \( i \) is rainfall in-
tensity, \( S_f \) is the friction slope component (based on
Manning’s Equation), and \( \alpha \) is the bed slope.

Both programs - RAMMS and FLO-2D - need a
DEM as input. RAMMS further requires the spatial
distribution and depth of the release volume, the co-
efficients and possible areas for entrainment, and the
friction parameters \( \mu \) and \( \zeta \). FLO-2D needs an input
hydrograph and values of Manning’s \( n \). When using
FLO-2D for debris flow modelling the rheologic flow
parameters viscosity and yield stress must be specified.

The following work flow was applied for the
modelling:
1. Back-calculation of a well-documented recent
GLOF: the Dasht event from summer 2002 was
used to test the models and to find suitable para-
meter values. Travel distance, the spatial distribution
of the deposit, and the travel time from the start to the
deposit were used as reference for the calibration;
2. Scenarios of possible future outburst events of se-
lected lakes (see Table 1 for an example) were elab-
orated. Outburst volumes, peak discharges, and
flow rheologies were varied among the different
scenarios. The friction parameters of RAMMS
with the best fit for Dasht were taken as a refer-
ce, but adapted according to the outburst volumes
and water content so that the worst case scenario
reached the former debris flow fan of the main
valley (compare Discussion and Conclusions);
3. The scenarios were run with RAMMS and FLO-
2D. The resolution of the DEM and the computa-
tion were varied in order to estimate the influence
of this setting on the model results.

RESULTS

BACK-CALCULATION FOR DASHT

First, the Dasht (2002) event was back-calcul-
ated using RAMMS (Fig. 5). The purpose was to
"
Friction parameters of $\mu = 0.14$ and $\zeta = 1,300$ proved to be the best guess for reconstructing the event, though it was necessary to assume lower values of $\mu$ (0.01) and higher values of $\zeta$ (2,000) in the flat starting area (representing the lake surface) in order to initiate the movement. The velocities and the extent of spreading in the area of deposit were larger when using the SRTM DEM (smoother terrain). The simulated travel time from the onset of the flow to the village was 55 minutes with the SRTM DEM and 76 minutes with the CORONA DEM. These values correspond reasonably with local reports concerning the time difference between the acoustic detection of the GLOF and its arrival at the village.

As the GLOF event in Dasht propagated as a debris flow, this case study was used to define the rheologic parameters for debris flow modelling in FLO-2D. It was found that values for viscosity $\eta = 279$ poises and yield stress $\tau = 798$ dynes/cm$^2$ represented best the debris flow in Dasht. Consequently these values were also used in the scenario modelling. FLO-2D was run on the CORONA DEM only. The simulated travel time, flow heights and extent matched well with the field observations.

**KHAVRAZDARA**

Different scenarios for lake outburst floods were then computed for Khavrazdara, Varshedzdar, Upper Rivakdara, and Rivakkul (see Fig. 4). The modelling results for Khavrazdara (see Fig. 2b) are discussed in detail.

The scenarios defined for an outburst flood in Khavrazdara are shown in Table 1. A cell size of 20 m was used for the RAMMS simulations and 40 m for the FLO-2D simulations, respectively. Whilst the GLOFs simulated with FLO-2D reached the outlet of the valley, the RAMMS simulations indicated a stop of the flow in the middle portion of the valley when using the friction parameters calibrated with the Dasht event. It was then tested how much the friction would have to be reduced to allow the flow to reach the valley outlet and to cover the debris cone there. Friction values of $\mu = 0.04$ and $\zeta = 1,000$ were found to be suitable. Decreased $\mu$-values of $\mu = 0.03$ were used to account for the lower sediment concentration expected in the upper section (before entrainment takes place), whilst increased values of $\mu = 0.05$ were applied to account for the higher sediment concentration expected in the lower section. $\zeta$-values were held constant for the entire flow path. The spatial distribution of the maximum flow height simulated with RAMMS and FLO-2D for selected scenarios is illustrated in Fig. 6.

With FLO-2D all scenarios were modelled as a hyperconcentrated flow with a volumetric sediment concentration of 20% on the one hand, and as a debris flow with volumetric sediment concentrations up to 50% on the other hand. Applying a range of different flow rheologies is a strategy to deal with the uncertainty regarding the flow type produced by the released water from a lake. The amount of water is the same in both flow types, but the debris flow is bulked with much more material. This is why its total flow volume and peak discharge are higher than for hyperconcentrated flows of the same outburst scenario. As the peak discharge has the highest influence on calculated maximum flow depths, and the higher viscosity results in lower flow velocities, inundation depths are higher when modelling the GLOF as a debris flow.

According to the simulation, the flow would reach the village of Pasar at the outlet of the valley between 48 minutes and 4.5 hours after the onset, depending on the scenario (see Table 1; average velocity between 1 and 6 m/s, respectively). This wide range shows the uncer-

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![Fig. 6 - Maximum flow depth computed with FLO-2D and RAMMS for different lake outburst scenarios of Khavrazdara](image-url)
GLACIAL LAKE OUTBURST FLOODS IN THE PAMIR OF TJAKISTAN: CHALLENGES IN PREDICTION AND MODELLING

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Starting volume</th>
<th>Deposition volume</th>
<th>Maximum discharge</th>
<th>Travel time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLO-2D (all simulations on CORONA DEM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1a Hfhw</td>
<td>15</td>
<td>19</td>
<td>2500</td>
<td>210</td>
</tr>
<tr>
<td>1b Dhhw</td>
<td>15</td>
<td>23</td>
<td>4000</td>
<td>210</td>
</tr>
<tr>
<td>2a Hfhw</td>
<td>15</td>
<td>20</td>
<td>10000</td>
<td>72</td>
</tr>
<tr>
<td>2b Dhhw</td>
<td>15</td>
<td>25</td>
<td>16000</td>
<td>90</td>
</tr>
<tr>
<td>3a Hfhw</td>
<td>30</td>
<td>38</td>
<td>2500</td>
<td>255</td>
</tr>
<tr>
<td>3b Dhhw</td>
<td>30</td>
<td>47</td>
<td>4000</td>
<td>270</td>
</tr>
<tr>
<td>4a Hfhw</td>
<td>30</td>
<td>38</td>
<td>10000</td>
<td>90</td>
</tr>
<tr>
<td>4b Dhhw</td>
<td>30</td>
<td>48</td>
<td>16000</td>
<td>90</td>
</tr>
<tr>
<td>RAMMS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 C</td>
<td>15</td>
<td>45</td>
<td>N/A</td>
<td>99</td>
</tr>
<tr>
<td>1 S</td>
<td>15</td>
<td>45</td>
<td>N/A</td>
<td>73</td>
</tr>
<tr>
<td>2 C</td>
<td>30</td>
<td>90</td>
<td>N/A</td>
<td>70</td>
</tr>
<tr>
<td>2 S</td>
<td>30</td>
<td>90</td>
<td>N/A</td>
<td>48</td>
</tr>
</tbody>
</table>

Tab. 1 - Modelling of a potential GLOF from the large lake in the upper Khuvrakula: Scenarios, involved volumes, maximum discharge, and travel times to the village of Passor (outlet of the valley). Hfhw = Hyper-concentrated flow, Dhhw = Debris flow, C = CORONA DEM, S = SRTM-4 DEM, N/A = not applicable.

tainties connected to the scenarios, topographic data and parameters used. The maximum velocity ranges around 10 m/s over most of the valley, with much higher values yielded in the upper portion, particularly by RAMMS. The influence of the DEM resolution on the model results is considerable: finer DEM resolutions generally lead to a rougher surface which significantly reduces the flow velocity and hence the reach of the debris flow (see also Christen et alii, 2010a). The smoother the original terrain is, the less this effect is observed.

DISCUSSION AND CONCLUSIONS

The present study illustrates that modelling of GLOFs remains a challenge. Each case study area has its individual characteristics and the results provided by different model approaches sometimes diverged considerably. These differences are not surprising as the two models follow disparate concepts, each requiring a specific definition of the initial conditions (sudden release of mass vs. discharge curve). In order to homogenize the results and to account for the generally larger amount of water, the friction parameters used in RAMMS had to be reduced considerably in comparison to those used for the Dasht event. This is of very high importance when the results are interpreted or shown to local authorities. However, adapting the friction parameters individually for each study area in a way that the simulated flow reaches the area of interest (often the valley outlet) provides useful information in two ways:

- A comparison of the assumed friction parameter values with those derived from the back-calculation of documented events allows an assessment of how realistic the assumed parameters are, and therefore the likelihood of the flow to reach the outlet of the respective tributary valley. Table 2 shows the friction parameters used in the RAMMS calculation, based on the assumption that the flow would reach the outlet of the respective valley.
- Approximate travel times to the outlet can be derived, given that the assumed parameters are considered as realistic.

A special characteristic of the RAMMS model is the sudden release of the start volume (mass), that well represents a sudden mechanical failure of a lake dam or the overtopping of a large impact wave. However, this is not always the way how GLOFs are triggered and may therefore lead to exaggerated flow heights and widths in the upper flow section. In contrast, the ability to erode material from the ground is an important feature of RAMMS because it accounts for the often observed fact that start and end volumes differ significantly (Berti et alii, 1999, Breien et alii, 2008).

In general, RAMMS predicts higher values of flow depth in the uppermost section of the flow path than FLO-2D. This is due to the sudden release of the mass (see above). FLO-2D makes use of an input hydrograph that distributes the release volume over a given time period, leading to lower flow depths for given total volumes. This can better reproduce a dam failure due to progressive incision.

RAMMS predicts the stop of the flow and the deposition of the mass on the debris cone whilst FLO-2D tends to predict a continuation of the flow along the stream path of the main valley. The potential impact areas derived with RAMMS are therefore smaller and the inundation depths are larger than those calculated with FLO-2D.

Partially good correspondence is found in the flow durations to the outlet of the valley. Table 1 shows that the range of the flow durations calculated with RAMMS are similar to those derived from the FLO-2D calculations, at least regarding the - more critical - lower boundary. This is remarkable because they are computed completely independently (the adaptation of $\mu$ and $\zeta$ is a purely frictional issue).
One has to conclude that, considering all relevant aspects, the simulation of the motion of potential future GLOFs remains a big challenge. Problems are in particular:

- The knowledge about the onset of the process is often limited (properties of dam, type of dam breach, understanding of process chains and interactions).
- The volume of water involved in the outburst flood is unclear. The lake bathymetry is often unknown and may change rapidly, whilst the ratio of water actually bursting out has to be estimated. Furthermore many lakes burst out within a short time after their development without being detected as potential source of hazard (NARAMA et. alii, 2010). Continuous monitoring is required to keep updated on the existing hazards.
- Uncertainties related to erosion and deposition are a big unresolved issue. Erosion of the dam and the bed as well as concomitant deposition can strongly change the rheology and the moving volume of the flow. These changes have a direct impact on the spreading and reach.
- The flow transformation processes of the natural phenomena are a challenge for the models (and in general for any assessment). Software developed by the hydrological community is specialized to simulate floods or hyperconcentrated flows with input hydrographs on moderately steep flow channels and with lower sediment loads. In contrast to this, programs for rapid mass movements are better suited for steeper slopes and sudden failure of the initial volume. The typical characteristics of GLOFs are in between and vary for different channel sections. Sediment transport models properly computing erosion and deposition are rather designed for less steep slopes, so that they are hardly applicable to GLOFs. Furthermore, the outburst scenario is very critical. Flood dynamics are quite well understood and model results can therefore be considered as confident. In contrast, debris flow modelling is a based on empirical components and the results are therefore more inaccurate compared to modelling pure water or hyperconcentrated flows.

Nevertheless it is important not to model only the outburst scenarios as hyperconcentrated flows, but also as debris flows. With such a modelling strategy a range of expectable flow rheologies can be covered. This increases the robustness of the results and does not pretend a wrong accuracy.

Existing programs also largely fail to simulate process interactions and transformations such as the development of a hyperconcentrated flow into a debris flow, the effects of multiple flood waves (including the modified topography after the first wave), or the effects of short-term storage of water and debris by self-induced blockage of the valley.

Considering all these points, it has to be concluded that up to now, no well suitable modelling approaches do exist for GLOFs, as these represent highly variable phenomena and often exhibit a behaviour in between debris flows and floods. However, applying a combination of different model approaches, as attempted in the study presented, helps to estimate realistic process magnitudes, areas of impact, maximum velocities, and travel times. As a general conclusion for any kind of modelling effort, a responsible interpretation of the results and a controlled knowledge transfer to local authorities is crucial.

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4.5 Glacial lakes in the Indian Himalayas – from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes

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Glacial lakes in the Indian Himalayas — From an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes

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HIGHLIGHTS
► We present the first comprehensive glacier lake inventory for the Indian Himalayas.
► In total, 251 glacier lakes > 1 ha were mapped and classified.
► For three critical glacier lakes a detailed risk assessment was carried out.
► Risk assessment is based on field work, remote sensing and dynamic modeling.

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BASEMENT

ABSTRACT
Glacial lake hazards and glacial lake distributions are investigated in many glaciated regions of the world, but comparatively little attention has been given to these topics in the Indian Himalayas. In this study we present a first area-wide glacial lake inventory, including a qualitative classification at 251 glacial lakes > 0.01 km². Lakes were detected in the free states spanning the Indian Himalayas, and lake distribution pattern and lake characteristics were found to differ significantly between regions. Three glacial lakes, from different geographic and climatic regions within the Indian Himalayas were then selected for a detailed risk assessment. Lake outburst probability, potential outburst magnitudes and associated damage were evaluated on the basis of high-resolution satellite imagery, field assessments and through the use of a dynamic model. The glacial lakes analyzed in the states of Jammu and Kashmir and Himachal Pradesh were found to present moderate risks to downstream villages, whereas the lake in Sikkim severely threatens downstream locations. At the study site in Sikkim, a dam breach could trigger drainage of ca. 16 × 10⁷ m³ water and generate maximum lake discharge of nearly 7000 m³ s⁻¹. The identification of critical glacial lakes in the Indian Himalayas and the detailed risk assessments at three specific sites allow prioritizing further investigations and help in the definition of risk reduction actions.

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1. Introduction

Glacier retreat is observed in most regions of the Hindu Kush Himalaya (HKH; Bolch et al., 2012), which has given rise to the formation of numerous new glacial lakes. Glacial lakes are an indirect indicator of glacier change (Gardelle et al., 2011) and unstable lakes can present hazards to downstream locations (Costa and Schuster, 1988). Sporadic glacial lake outbursts may drain as powerful floods (Mergili et al., 2011), and are therefore considered the most important glacier-related hazard in terms of direct damage potential (Osti and Egashira, 2009). Glacial lake outburst floods (GLOFs) have killed thousands of people in many parts of the world (Carey, 2005; Clague and Evans, 2000; Richardson and Reynolds, 2000a), and some of the largest events occurred in the Himalayas (Bhargava, 1995; Osti and Egashira, 2009; Tashi, 1994; Vuichard and Zimmermann, 1986). As a result, GLOF risks are receiving increased attention as a key climate change hazard (Malone, 2010), and awareness for glacial lake monitoring and hazard mitigation has increased recently.

Glacial lake inventories with a prioritization of detected lakes are important as they allow non-specialist local authorities to quickly identify lakes where more detailed and comprehensive studies should be directed (Allen et al., 2009). Glacial lakes have been mapped and analyzed in different regions of the HKH (Hewitt, 1982; Yamada and Sharma, 1993), yet the focus of past studies has been predominantly on Bhutan (Fujita et al., 2008; Komori, 2008; Pitman et al., 2012), Nepal (Bolch et al., 2008; Yamada and Sharma,
1993), and Tibet (Wang et al., 2008). A transboundary assessment of glacial lake distribution and evolution in the HKH was carried out by Gardelle et al. (2011) and also covered some regions in India; and ICIMOD (2010) compiled an extensive glacial lake inventory over large regions of the HKH, including three states in India. However, we are not aware of any glacial lake inventory covering the entire Indian Himalayas, and realize that generally few studies on glacial lakes have been carried out in the Indian Himalayas so far (Babu-Govindha-Raj, 2010; Randhawa et al., 2005).

An accurate and objective classification of glacial lakes is challenging but essential to maintain credibility towards stakeholders and local populations. Not all existing glacial lakes are unstable and most lakes will not burst out catastrophically (Huggel et al., 2004). Lake outburst probability is a function of the susceptibility of a dam to fail and the potential of external trigger processes (Richardson and Reynolds, 2000a). The stability of a dam depends primarily on its geometry, internal structure, and material properties (Costa and Schuster, 1988; Fujita et al., 2009; Korup and Tweed, 2007). Dam stability can change over time, as for instance melting of stagnant ice within moraine dams can contribute to weakening of overall dam structure (Clague and Evans, 2000; Richardson and Reynolds, 2000b; Worni et al., 2012a). Different authors (Huggel et al., 2004; Lu et al., 1999; Wang et al., 2008) proposed key parameters such as the dam width-to-height ratio, top width of dam, distal dam flank steepness or freeboard for a qualitative lake stability assessment. Parameters of most likely dam breaching help to assess the outburst probability of a particular lake. However, even unstable glacial lakes normally need a trigger to induce dam failure: Dams fail when the material strength is exceeded by driving forces that comprise, among others, the weight of the impounded water mass, seepage forces, earthquakes and shearing stresses from overtopping flow or displacement waves (Korup and Tweed, 2007; Masson et al., 2010). Overtopping flows can be caused by heavy rainfall or a sudden influx of water from upstream sources. Displacement waves are, in contrast, triggered by mass movements entering the lake, such as snow and ice avalanches, rockfalls, debris flows or landslides (Carey et al., 2012; Clague and Evans, 2000; Costa and Schuster, 1988; Huggel et al., 2004). To assess the probability for mass impacts into a lake, potential starting zones of mass movements must be identified, possible magnitudes estimated and corresponding run-out distances evaluated. Alean (1985), for instance, analyzed ice avalanches in the Swiss Alps with volumes between 0.2 and 5 × 10^6 m^3, and found angles of reach between 17° and 32°. Such dimensions are useful to delimit a reasonable range of potential ice avalanche volumes which might trigger a GLOF. Similar empirical relations are available for other mass-movement processes and are summarized by Rickenmann (2005).

For lake dams that are found to be susceptible to failure, magnitudes of potential GLOFs can be approximated with empirical relationships (Evans, 1986; Huggel et al., 2004; Kershaw et al., 2005) or calculated using empirical and physical models. Different types of dam breach and flood models have been applied to model glacial lake outburst scenarios and to assess potential downstream impacts (Bajracharya et al., 2007; Huggel et al., 2003; Mergili et al., 2011; Osti et al., 2012; Wang et al., 2008). For specific and local-scale scenario modeling the application of dynamic models is preferable to empirical models, as the latter represent an over-simplification of complex processes (Allen et al., 2009; Worni et al., 2012b). However, the large number of complex input parameters, the computational requirements and the topographic sensitivity of physically-based flood and dam breach models make dynamic GLOF modeling challenging.

Despite the existence of preliminary studies, little is known on the distribution and hazards of glacial lakes in the Indian Himalayas. Therefore the purpose of this study was (i) to provide a glacial lake inventory covering the entire Indian Himalayas and to prioritize lakes for further risk assessments; and (ii) to assess outburst probability and potential outburst magnitudes for three critical glacial lakes based on fieldwork and a sophisticated modeling approach. The two-dimensional dynamic BASEMENT model was used for this purpose as it allows simulation of cascades of complex processes which are typical for GLOFs.

2. Study regions

The Indian Himalayas have a glaciated area of about 23,300 km^2 (Philip and Sah, 2004), cover the northern boundary of India and span from west to east the states of Jammu and Kashmir (JK), Himachal Pradesh (HP), Uttarakhand (UK), Sikkim (SK) and Arunachal Pradesh (AP). Topography, morphology and climate vary significantly. Climate is influenced by the orographic barrier of the Himalayan mountain range in the north–south direction resulting in dry regions in the monsoon shadow. On the other hand, the Indian summer monsoon carries humidity from the Bay of Bengal into the eastern Himalayas but its influence weakens in the western portions of the range (Bookhagen and Burbank, 2006).

Based on a remote assessment of glacial lakes, as described in Section 3.2, three study sites were selected over the entire Indian Himalayas. The case study glacial lakes (Fig. 1) are located in different geographic regions and show contrasting climatic and topographic variability within the Indian Himalayas.

The first study site is located in the Zanskar mountain range which is aligned in parallel to the Indus valley on the plateau of Ladakh (JK). The crests of the mountain ranges are at 5400–5700 m a.s.l. on average, and reach maximum altitudes of 6000 m a.s.l. Rather small glaciers of 0.5–2 km^2 are common above 5100–5200 m a.s.l. (Burbank and Fort, 1985). The region of Ladakh lies north of the main Himalayan range and therefore escapes the full impact of the monsoon (Sant et al., 2011). The region is characterized by cool and arid climatic conditions. The Spong Togpo glacial lake (34°03’02”N; 76°43’04”E) is located in the Zanskar range at 5100 m a.s.l. some 26 km south of the village of Lamayuru. The Spong Togpo River reaches the first settlement (Honupatta village) 19 km downstream of the glacial lake and passes further small villages before discharging into the Yapola River (25 km) and finally into the Indus River some 50 km below the glacial lake.

The Lahaul–Spiti district (HP) comprises the NW–SE trending Pir Panjal and Great Himalaya mountain ranges, which are divided by the Chandra Valley. The valley bottom averages 3500 m a.s.l. and the surrounding steep and glaciated mountains reach altitudes above 6000 m a.s.l. The northern slopes of Pir Panjal and the Great Himalayan range lie in the monsoon–arid transition zone (Owen et al., 1997), and are alternately influenced by monsoon in summer and mid-latitude westerlies in winter (Wagnon et al., 2007). The Gopang Gath cirque glacier which is mainly fed from the steep north faces of Mount Gangep Goh (5870 m a.s.l.) is located in the Great Himalaya range 20 km east of the village Keylong. Its proglacial lake at 4100 m a.s.l. (32°31’38”N; 77°13’03”E) is the source of the steep Sissunala River which discharges into the Chandra River at Sissu village (3100 m a.s.l.), 10 km downstream of the glacial lake.

The state of SK is located between Nepal and Bhutan on the south-facing slopes of the Himalayan mountain range. The predominantly steep mountain topography ranges from 300 to 8598 m a.s.l. and encompasses the third highest mountain in the world (Mount Kanchenjunga). SK covers an area of about 7300 km^2 of which about 900 km^2 is covered by glaciers (Bhasin et al., 2002). Climate is strongly influenced by the monsoon with much precipitation from April to September and a dry period in winter. Extreme rain events are recorded periodically, causing major landslides and inundations (Bhasin et al., 2002; Krishna, 2005). The Shako Cho glacial lake (27°58’29”N; 88°36’58”E) is located at 5000 m a.s.l. and below the south face of Mount Kangchengyang (6889 m a.s.l.) in North SK. Shako Cho lake is 12 km northeast of Thangu village (3900 m a.s.l.), where the small tributary river from the lake discharges into Teesta River.

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3. Data and methods

3.1. Data

LANDSAT ETM+ imagery from 2000 to 2002 at 30-m resolution and high-resolution images from Google Earth (1.65 to 2.62-m resolution) were used for glacial lake mapping and lake classification. High-resolution images in Google Earth for areas of interest were mainly SPOT5 images of 2.5-m resolution, GeoEye images of 1.65-m resolution and Quickbird images of 2.62-m resolution. For Gopang Gath glacial lake a SPOT5 satellite image was available from 2010, and GeoEye satellite images (Google Earth) from 2011 and 2010 were used for Spong Toggo and Sheko Cho glacial lakes, respectively.

Topography for the GLOF scenario modeling was obtained from the Global Digital Elevation Model (GDEM) version 2 of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and from the digital elevation model (DEM) of the Shuttle Radar Topography Mission (SRTM). The spatial resolution of the ASTER GDEM v2 is between 71 and 82 m; the absolute vertical accuracy was found to be within ±0.2 m on average, with an accuracy of 17 m at the 95% confidence level (ASTER GDEM Validation Team, 2011). The resolution of the SRTM DEM is 90 m, with an elevation interval of 1 m. The indicated absolute and relative 90% horizontal accuracies are ±20 m and ±15 m, respectively, and the indicated absolute and relative 90% vertical accuracies are ±16 m and ±6 m, respectively (Strozzi et al., 2003).

3.2. Glacial lake mapping and classification

Glacial lakes were automatically mapped over the entire Indian Himalayas using the normalized difference water index (NDWI; Eq. (1)), applied on the spectral bands TM1 and TM4 of Landsat ETM+ satellite images (Huggel et al., 2002).

\[
\text{NDWI} = \frac{\text{TM4} - \text{TM1}}{\text{TM4} + \text{TM1}}.
\]

Subsequently, misclassified lakes were corrected through the visual postprocessing of data. Only lakes in close glacier proximity and with a surface area > 0.01 km² were considered for the lake inventory. Based on remote sensing, lake-outburst probability was then assessed for all mapped lakes with available high resolution imagery in Google Earth. A qualitative approach was used by which four key indicators were assessed for each lake, namely: (i) dam type, (ii) dam geometry (iii) freeboard and (iv) potential for lake impacts. Thereby, each key indicator was assigned with one out of three possible attributes, indicating different lake outburst probabilities in the range of low, medium and high. The resulting matrix is used as a decision tool (Fig. 2) on which basis the expert can assign a general outburst probability for a lake (Huggel et al., 2004).

(i) Dam type: Moraine- and ice-dammed lakes may exhibit a high dam failure potential, whereas bedrock-dammed lakes are in general stable (Huggel et al., 2004). Lakes in flat topography in glacier forefields (often found in the Indian Himalayas west of Nepal) and without any clear dam structure are considered having low dam failure potential. Yet, lakes with rock dams or no dams can still present hazard situations in case of mass impacts into lakes that may cause overtopping waves. For these lakes the parameters (ii) freeboard and (iv) potential for lake impacts are critical for hazard assessments. Ice dammed lakes are practically inexistent in the Indian Himalayas and therefore not considered for this study. For moraine-dammed lakes (ii) dam geometry, (iii) freeboard and (iv) potential for lake impacts are crucial parameters. Parameters (ii) and (iii) influence hydraulic gradients within the moraine (Clague and Evans, 2000; Richardson and Reynolds, 2000a) (Fig. 2).

(ii) Moraine dam geometry: Moraine dams with high hydraulic gradients are more susceptible to collapses (Huggel et al., 2004). In addition, the dam width-to-height ratio, the width of the crest and the slope of the downstream face of moraine dams are an indication for the susceptibility of a moraine dam to fail (Huggel et al., 2004; Lu et al., 1999). In Fig. 2 critical values for these parameters are given in order to evaluate in a first-order assessment moraine dam stability.

(iii) Freeboard: The height of the freeboard is a crucial parameter for all dam types and must be considered in combination with the potential for lake impacts. The freeboard is a factor that influences whether a potential impulse wave will overtop the dam. Overtopping waves can lead to dam erosion and eventually to the failure of moraine dams. Even without partial or full failure of the glacial lake dam, overtopping waves may...
travel valley downstream and cause inundation (Carey et al., 2012). The exact height of the freeboard is difficult to measure by remote sensing. This is why relatively rough freeboard values were defined to assess lake outburst susceptibilities (Fig. 2).

(iv) Potential for lake impacts: Impact waves from rock or ice falls, snow avalanches or debris flows have been observed to be most effective triggers for dam failure and lake outburst (Clague and Evans, 2000; Huggel et al., 2002; Richardson and Reynolds, 2000a). If steep glaciated and non-glaciated slopes or glacier tongues – i.e. potential sources for mass movements – are in reach of lakes, it is possible that impact waves could occur. Values for runout distances of different mass movements can be found e.g. in Alean (1985) or Rickenmann (2005) (Fig. 2).

Moraine-dammed lakes surrounded by steep slopes or exposed to glacier calving, with a significant potential for dam breach triggers, low freeboards and/or unstable dam geometries (i.e. low dam width-to-height ratio or a low width of dam crest or high slope of downstream face of dam) are considered to have high outburst probabilities. In the case of lakes for which at least one and up to four of the key parameters indicated moderate lake outburst potentials, the outburst probability was considered to be moderate as well. Low outburst probability is assigned for lakes for which all key parameters indicate low outburst susceptibility.

In addition to the qualitative outburst probability, we also considered damage potential (i.e. the exposure of infrastructure and inhabited areas) downstream of a lake for the classification of the detected lakes. The final result was a glacial lake inventory with mapped lakes categorized as: (i) critical lakes (ii) potentially critical lakes, (iii) uncritical lakes and (iv) unclassifiable lakes (i.e. lakes where high-resolution imagery was not available in Google Earth) (Fig. 2). Critical in this context does not necessarily imply that a lake is about to burst out, but that it should be of high priority for detailed field investigations and process modeling. Potentially critical lakes are of some priority, still requiring monitoring and possibly field reconnoitering. Uncritical lakes have a lower priority and are designated for periodic observation (sensu ICIMOD, 2011).

Based on this assessment, three critical moraine-dammed glacial lakes in different states of India and climatic regions of the Himalayas were selected from the lake inventory. For these lakes further investigations on outburst probability and potential outburst magnitude were carried out, based on field surveys and/or process modeling. The aim was to assess the risk emanating from these lakes, by evaluating the hazard potential (i.e. a function of outburst probability and magnitude) and the damage potential (i.e. a function of exposure and vulnerability). Damage potential was qualitatively assessed by field surveys and satellite image based surveys. For each downstream area of Spong Togpo-, Gopang Gath- and Shako Cho lake, damage potential was assigned to one of four categories, low, moderate, high and very high (refer to Fig. 10).

In September and November 2010, fieldwork was carried out at Spong Togpo and Gopang Gath glacial lakes. Sakh Cho glacial lake, in contrast, is located in the restricted area of North SK and could not therefore be visited. During the field campaigns further evidence was collected to assess lake-outburst probabilities and to obtain different model input parameters. On-site mapping of the lakes, moraines and outlet rivers was carried out using a GPS (Garmin GPSMAP 62STC) and a high-sensitivity laser distance measurement device (Nikon LASER 550A S) with an integrated angle measurement function. These ground measurements, complemented by measurements from satellite imagery, helped to improve local topography of the model domains. Lake depth measurements in the proximity of the shore were performed with a sonar system (Humminbird Smartcast RF25) so as to gather data on lake bathymetry required for modeling.

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3.3. Dynamic modeling

BASEMENT is a fluid dynamics and sediment transport model for the analysis of water–sediment flow propagation and breaching processes of non-cohesive earthen dam structures (Faeh et al., 2012). The two-dimensional program simulates water and sediment flows in a two phase system with separate unstructured meshes for the water and sediment phase. The computational meshes were created by the Surface Water Modeling System (SMS) software (SMS, 2012), based on the DEM of the study sites and field mapping, which also included lake bathymetry reconstruction. For the hydrodynamic calculations the program solves shallow water Eqs. (2) and (3) with an explicit finite-volume method and the application of an exact Riemann solver. The primary variables used are water depth h and specific discharge \( q = uh, r = vh \) in the coordinate directions.

\[
\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0 \tag{2}
\]

\[
\frac{\partial}{\partial t} \left( hu \right) + \frac{\partial}{\partial x} \left( hu^2 + \frac{1}{2} gh^2 \right) + \frac{\partial}{\partial y} \left( hv u h v \right) = -gh \frac{\partial u}{\partial x} - \tau_{bx} \tag{3}
\]

where \( u \) is the velocity in x direction, \( v \) is the velocity in y direction, \( g \) is the gravitational acceleration, \( \rho \) is the fluid density, and \( z_b \) is the bottom elevation. Bed shear stresses \( \left( \tau_{bx}, \tau_{by} \right) \) act in the direction of depth-averaged velocities and are determined using the quadratic resistance law with \( \zeta \) being the dimensionless friction factor as

\[
\tau_{bx} = \rho \sqrt{u^2 + v^2} / \zeta^2 \cdot \tau_{by} = \rho \sqrt{u^2 + v^2} / \zeta^2. \tag{4}
\]

Erosion and sediment transport of single and multiple grain classes caused by water flows are calculated with empirical sediment transport equations. The program evaluates surface erosion based on the bottom shear stress exerted by the flow on the inundated material. Within this study, the transport rate was determined using a modified Meyer–Peter and Müller (1948) formula (5) for fractional transport with the hiding function \( \xi \) after Ashida and Michue (1971) and the critical bottom shear stress of incipient motion \( \tau_{cr} \) from the Shields (1936) diagram. The hiding function considers effects of hiding and exposure of the grain particles with different sizes at fractional transport.

\[
q_{bg} = \int_0^1 \left( \frac{\tau_{bg} - \xi \tau_{cr,g}}{0.25 \tau_{cr}} \right)^{1/2} \left( \frac{1}{(\zeta / \rho - 1)\zeta} \right) \left( \zeta / \rho - 1 \right) \tag{5}
\]

For dam breach modeling the lateral breach widening due to slope collapses of the side walls is considered with a geometrical 3D bank failure operator. It is based on three different critical failure angles: (i) one for dry or partially saturated material at the breach side walls above the water surface; (ii) one for bank material below the water surface; and (iii) one for deposited material resulting from slope collapses. If one of the failure angles is exceeded due to vertical erosion, gravitational bank failure occurs and the slope is flattened until the critical angles are reached. The material moves in downward direction of the cell’s slope and is added to transport rates.

We applied BASEMENT to simulate a typical process chain of GLOFs, i.e. an (i) impulse wave generation by mass flows into the lake and wave propagation over the lake; (ii) dam overtopping and dam breaching; and (iii) lake emptying and flood propagation (Fig. 3). Model input parameters were either derived from field measurements, constituted typical (material) constants (Table 2) or based on a model calibration process as presented in Worni et al. (2012a). For glacial lakes with a high freeboard, smaller values for the calibration parameter failure angle of deposition had to be applied, in order to simulate realistic dam breaching mechanisms.

(i) Impulse wave modeling: Impulse wave generation was reproduced by a sudden release of mass flow from a potential mass–movement starting zone into the lake. The mass flow is represented by equivalent water flow, as solid mass movements cannot be adequately modeled in BASEMENT (Faeh, 2005). Momentum of the rapid and high-discharge flow is transferred to the lake water, whereby impulse waves develop. The impulse wave generation, propagation and run-up at the shore are described by shallow water equations, which represent an approximation, especially for the impulse wave generation. Water surface elevations of the lake and of the volume to be released into the lake were the initial conditions of the model in this case.

(ii) Dam breach modeling: Dam overtopping flow leads to vertical breach erosion. Sediment transport laws determine incision rates, which are controlled by the properties of the dam material and the shear stress of the water flow. Vertical breach incision leads to a steepening of the breach side walls, which collapse when the critical failure angles are exceeded. Due to breach enlargement, lake outflow increases. Breach expansion ceases when the lake level and outflow decrease below the threshold for bedload transport.

(iii) Modeling flood propagation: The water–sediment discharge resulting from the dam breach propagated valley downstream based on hydrodynamic and sediment transport calculations. Inundation depths, flow velocities, bottom shear stresses and changes in bed elevations are reported for each cell of the computational mesh.

For each case study small and large lake impact scenarios were modeled, for which two different volumes of water were released from potential avalanche starting zones into the lakes. The small scenarios represent minimum required lake impacts to trigger dam failure; they were determined by a trial-and-error approach. Thereby release volumes (initial conditions) were constantly increased until dam failure occurred in the simulation. The large scenarios were defined such as to cause significant lake overtopping with the consequence of larger breach formations, but still representing realistic lake impacts. Lake impacts were not quantified primarily by the impact volumes but by the momentum fluxes \( p \) into the lakes (see Eq. (6) for details). These represent the actual trigger pulses for wave generation, eventually leading to dam overtopping and dam breaching.

\[
p = \int_0^1 Q \cdot v \cdot dt \tag{6}
\]

where \( \rho \) is the density of water, \( Q \) is water discharge into the lake, \( v \) is velocity at lake impact and \( dt \) is the time step of constant water flow.

4. Results

4.1. Glacial lake inventory and glacial lake assessment

A total of 251 glacial lakes > 0.01 km² were identified and mapped over the Indian Himalayas of which 45 lakes are not classifiable due to missing high-resolution imagery in Google Earth. All other lakes were qualitatively classified according to outburst probability and damage potential. Based on the remote-sensing analysis, 12 lakes were considered as critical and will require in-depth field analysis and process modeling in the future so as to evaluate their hazard situation in greater detail. Another 93 lakes were considered as potentially critical and 101 lakes were deemed to present no GLOF risk to downstream locations under present conditions. Critical lakes were detected in the states of JK (2 lakes), HP (2) and SK (8). For each of these states
the lake with the highest GLOF risk was selected for a detailed hazard assessment (Fig. 4; Table 1).

The proglacial Spong Togpo lake in JK (Fig. 5A) was considered as critical principally due to its low freeboard, the downstream damage potential and the possibility for mass movements to occur from the steep lake environments. On-site reconnaissance revealed that the low freeboard (1 m), the low dam top width-to-height ratio (0.15) and the unconsolidated moraine material would probably cause dam erosion in the case of overtopping flows. Average measured lake depth (at 30 m from the shore) was ca. 12 m, and empiric relationships indicate an average lake depth of 15 m, resulting in a lake volume of ca. $2.3 \times 10^8$ m$^3$ (Table 2). The hanging glacier above the lake has an angle of reach of ca. 22°, a major ice avalanche would therefore reach the lake (Table 2.). In addition, retreat of the flat glacier behind the lake would cause lake growing, resulting in smaller and more frequent avalanches reaching the lake, since the angle of reach would increase in the case of glacier retreat. However, based on satellite imagery, the glacier tongue remained almost stationary.

Fig. 3. Schematic sketch of cascading effects of a GLOF: The different phases 1–5 were simulated with the BASEMENT model at one stretch. The mass flow into the lake is represented by equivalent water flow (after Heller et al., 2008).

Fig. 4. Glacial lake inventory with mapped and classified glacial lakes over the entire Indian Himalayas. The coordinates of the mapped glacial lakes are given in Table 1. Three critical glacial lakes are indicated by arrows. For these lakes a detailed risk assessment has been carried out. The maps A, B and C illustrate three different regions within the Indian Himalayas (see inset in map A).
over the past 10 years. In addition, it is possible that calving processes into the lake could initiate dam erosion with subsequent breaching processes. The same phenomenon can be initiated by heavy cloudbursts, such as observed in August 2010, when lake overtopping resulted in the formation of a 2-m deep breach. However, the fact that this exceptionally intense cloudburst did not cause a complete dam failure also indicates that a more significant trigger might be needed to effectively drain the lake.

The proglacial Gopang Gath lake in HP (Fig. 5B) was considered as critical principally due to the steep slope of the downstream face of the moraine dam, the big lake area and the possibility for mass movements to occur from the surroundings of the lake. The dam is of variable geometry and incised at its northern end by an outlet river. The river flows at low descent around the moraine dam, which renders it somewhat less susceptible to breach drastically. However, a significant overtopping flow could erode the dam also at its southern end, where the dam width-to-height ratio is lower but the freeboard is still at 5 m (Table 2). Measurements taken at 30 m from the shore suggest average lake depths of ca. 30 m, and empiric relationships indicate an average lake depth of 27 m, resulting in a lake volume of ca. 15.5 × 10^6 m^3 (Table 2). Mass movements and debris flows from the south-facing mountains could reach the lake (angle of reach = 27°). At present, ice avalanches from the north-facing hanging glaciers are considered unlikely to enter the lake (angle of reach = 13–8°, depending on the source area). In the past 10 years the flat glacier behind the lake retreated by 300 m and further lake growth is probable to occur in the future. Hence, ice avalanches from the hanging glaciers could more easily reach the lake in the future. Calving activities of the massive glacier tongue entering the lake represent another possible trigger of dam breach processes.

The large proglacial Shako Cho lake in SK (Fig. 5C) was considered as highly critical due to the following key indicators: low width-to-height ratio of the end moraine, which consists of loose and granular material, the steep, glaciated, 1000-m high mountain face rising above the lake; and the position of Thangu village to the river flowing out of the lake. Although fieldwork could not be carried out in this case, photographs of the lake and dam as well as high-resolution satellite imagery were readily available to assess the hazard situation. Empiric relationships indicate an average lake depth of 27 m, resulting in a lake volume of ca. 15.5 × 10^6 m^3 (Table 2). Mass impacts into the lake from the mountain face above the lake appear likely and dam overtopping waves are possible, even at a freeboard of about 10 m (based on SRTM DEM measurements) (Table 2). An overtopping flow would likely lead to dam erosion due to the sharp dam geometry and weak dam structure. No armored lake outflow exists at present and lake drainage occurs through piping. Heavy earthquakes, as occurred in SK in September 2011 (magnitude 6.9), are yet another possible source for dam breach processes to be initiated at this lake.

4.2. Model results

The energies transferred to the lakes from the small and large impact scenarios are represented by the momentum fluxes and were calculated for the three case study lakes (Table 3). Table 3 also indicates lake impact volumes, which however, should not represent real impact volumes of typical mass movements, due to differences in immersion processes and densities between water (as modeled) and solids (e.g., ice, rock, debris).

4.2.1. Spong Togga lake

The smaller lake impact scenario eroded a breach of 24 m depth and 60 m width into the end moraine. The lake level was lowered by 24 m and 2.4 × 10^6 m^3 water drained in 120 min with a maximal discharge of 1400 m^3 s^-1. Only 70 min after impulse wave generation the flood wave reached Honupatta with maximum flood velocities of 7 m s^-1 and maximum flow depths of 7 m. Such a GLOF scenario would flood...
mainly farm land close to the river, threatening farmers working in the fields and trekkers frequenting the area (Fig. 6).

In contrast, the large lake impact scenario eroded a breach of 22 m depth and 120 m width, and $3.6 \times 10^6$ m$^3$ water drained in 120 min. Maximum discharge was calculated at 4000 m$^3$ s$^{-1}$ and the lake level was lowered by 17 m. The wide breach resulted in generally smaller lake outflow velocities than in scenario 1. As a consequence, bottom shear stresses were smaller, causing less vertical dam erosion and lake lowering. Some 50 min after mass-movement impact, the flood wave reached Honupatta village with maximum flow velocities of 9 m s$^{-1}$ and maximum flow heights of 8 m. Such a GLOF would inundate farm land located next to the river and flood a local road at various instances. Houses of local residents are, in contrast, unlikely to be affected by the flood (Fig. 6).

4.2.2. Gopang Gath lake

The smaller lake impact scenario eroded the dam at its northern end (i.e. in the lake outlet area), ending up in maximal breach depths of 16 m. This would lead to total lake lowering of ca. 7 m and a release of $5.3 \times 10^6$ m$^3$ water in 180 min, with maximal discharge of 1250 m$^3$ s$^{-1}$. Some 50 min after the generation of the impact wave, the flood wave reached Sissu village with maximum flow velocities of 7 m s$^{-1}$ and maximum flow depths of 6 m. Model results indicate that such a GLOF scenario would have minor effects in Sissu; only a ruin located next to the river would be inundated as well as some farmland upstream of the village. However, bridge foundation at the local road might be damaged (Fig. 7).

The larger lake impact scenario eroded the moraine dam at both its northern and southern ends. Final maximal breach depths were calculated to 20–27 m, and the lake was lowered by 13 m. The erosion of two breaches caused much stronger lake outflow and a total volume of $12.6 \times 10^6$ m$^3$ water was released in 180 min with maximal discharge of 3850 m$^3$ s$^{-1}$. Some 30 min after the lake impact, the flood wave reached Sissu with maximum flow velocities of 13 m s$^{-1}$ and maximum flow depths of 10 m. Such a GLOF would have minor to moderate impacts in Sissu; two ruins located next to the river would be likely destroyed and a larger surface of farmland (as compared to scenario 1) would be flooded. Model results also suggest minor flooding in the village’s periphery, but the DEM is inaccurate for the deep (25 m) and narrow (5–7 m) gorge below the bridge. It is likely that the flood would not leave the river channel here due to the strong incision; however, the bridge foundation could be...
Table 2
Key parameters to characterize the three case study glacier lakes, to evaluate their outburst probabilities and to model outburst scenarios. Field measured (M), empiric (E), visually assessed (V), remote sensing and DEM-based assessed (R), assumed values (A) and (typical) material constants (C). *Model input parameters. For some key parameters the sources are referenced.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spongo Toggo lake (1)</th>
<th>Gopang Gath lake (2)</th>
<th>Shako Cho lake (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinates; altitude (R, m)</td>
<td>34°03'02&quot;N; 76°43'04&quot;E; 5100 m a.s.l.</td>
<td>32°31'38&quot;N; 77°13'03&quot;E; 4100 m a.s.l.</td>
<td>27°58'29&quot;N; 88°36'58&quot;E; 5000 m a.s.l.</td>
</tr>
<tr>
<td>Base area; lake area (R, m²)</td>
<td>620 × 300 m; 0.15 km²</td>
<td>1700 × 500 m; 0.58 km²</td>
<td>1420 × 520 m; 0.575 km²</td>
</tr>
<tr>
<td>Mean lake depth (E, m); (Huggel et al., 2004)</td>
<td>15 m</td>
<td>27 m</td>
<td>27 m</td>
</tr>
<tr>
<td>Lake depth at 30 m (M, m); (Huggel et al., 2004)</td>
<td>12 m</td>
<td>30 m</td>
<td>–</td>
</tr>
<tr>
<td>Freeboard (M₁ ≤ R₃); (Huggel et al., 2004)</td>
<td>1 m</td>
<td>North: 0 m; South: 5 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Dam material (V₁ ≤ R₃); Non-cohesive, unconsolidated, poorly sorted, granular</td>
<td>Non-cohesive, unconsolidated, poorly sorted, granular</td>
<td>Non-cohesive, unconsolidated, poorly sorted, granular</td>
<td></td>
</tr>
<tr>
<td>Porosity* (C₁₋₃)</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td>Manning’s n of dam* (C₁₋₃) (USGS, 2012)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Dam width/height (M₂ ≤ R₃); (Huggel et al., 2004)</td>
<td>0.15</td>
<td>Northern end of dam: 0.6; Southern end of dam: 0.5</td>
<td>0.15</td>
</tr>
<tr>
<td>Dam top width (M₃ ≤ R₃); (Wang et al., 2008)</td>
<td>5 m</td>
<td>North: 10 m; South: 10 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Diatal dam flank steepness (M₄ ≤ R₃); (Xü et al., 2008)</td>
<td>30°</td>
<td>North: 5-13°; South: 30°</td>
<td>30°</td>
</tr>
<tr>
<td>Ice core dam (V₄); (Yamada and Sharma, 1993)</td>
<td>No evidence</td>
<td>No evidence</td>
<td>–</td>
</tr>
<tr>
<td>Material failure angles of dam material (M₅ ≤ A₁); (Huggel et al., 2004)</td>
<td>40° below-, 70° above water surface</td>
<td>33° below-, 70° above water surface</td>
<td>40° below-, 70° above water surface</td>
</tr>
<tr>
<td>Grain size distribution of dam material (M₆ ≤ A₂); (Huggel et al., 2004)</td>
<td>4 mm; 8, 22, 64, 128, 180 mm</td>
<td>4, 11, 32, 90, 256, 720, 10, 22, 12, 22, 15, 10, 8, 12, 64 128, 180</td>
<td>4, 11, 32, 90, 256, 720, 10, 22, 12, 22, 15, 10, 8, 12, 64, 128, 180</td>
</tr>
<tr>
<td>Angle of reach starting zone – lake (R, m); (Huggel et al., 2004)</td>
<td>48°</td>
<td>Ice fall: 13–18° debris flow: 27°</td>
<td>48°</td>
</tr>
<tr>
<td>Topography best represented with*</td>
<td>SRTM DEM</td>
<td>ASTER GDEM v.2</td>
<td>SRTM DEM</td>
</tr>
</tbody>
</table>

4.2.3. Shako Cho lake

At Shako Cho lake, impact magnitudes had a less significant effect on dam breaching and lake emptying. (A significantly differing effect can only be achieved with unrealistically large lake impact scenarios). For the small and large impact scenarios maximal breach depths of 43 m and 45 m were obtained, respectively. Maximal breach widths were 140 m and 180 m for the small and large scenarios, respectively. The lake level was lowered in both scenarios by 32 m and about 16 × 10⁶ m³ water drained in 180 min with a maximal discharge of 6100 m³ s⁻¹ and 6950 m³ s⁻¹ for scenarios 1 and 2, respectively. For both scenarios the flood wave reached Thangu village about 50 min after lake impact with maximal flow velocities of 15 m s⁻¹ and maximal flow depths of 12 m. About 12 min later the GLOF would have reached the village of Yathang 3.5 km below Thangu. Maximum flow velocities and flow depth were at Thangul calculated to 9 m s⁻¹ and 9 m, respectively. Both villages would be hit by the GLOF, and damage would be particularly severe in Thangu. Parts of the road, three bridges, about 100 buildings and farmland would be flooded and partly destroyed in Thangu; and parts of the road, one bridge and about 30 buildings would be flooded and partly destroyed in Yathang (Fig. 8).

5. Discussion

5.1. Glacial lake inventory

Within this study, only lakes with a surface > 0.01 km² were considered in the inventory, since smaller lakes were assumed not to present a relevant hazard potential to downstream locations (ICIMOD, 2011). This threshold is reasonable to cope with the large number of small lakes and helps to ensure efficient use of limited resources for on-site investigations and glacial lake monitoring. As the inventory is based on satellite imagery taken between 2000 and 2002, it represents the state of glacial lakes from that period. However, we assume that only a limited number of lakes > 0.01 km² would have developed since then (Gardelle et al., 2011). On the other hand, all lakes detected on the ~10-year-old images were still present on the high-resolution Google Earth images from 2010 to 2011, but glacial lake areas have indeed changed in some instances since the early 2000s.

The evaluation and classification of outburst probabilities of glacial lakes by remote sensing are challenging and different approaches have been presented in the literature (Huggel et al., 2004; McKillop and Clague, 2007a,b; Wang et al., 2011). The approach presented here considers previous studies and is efficient for analyzing a large number of lakes. Four key parameters and critical guiding values (Fig. 2) form the basis for the evaluation of the mapped glacier.

Table 3
Momentum fluxes and impact volumes into the three case study glacier lakes. For each lake large and small dam breach trigger scenarios were modeled. Small scenarios represent minimal required lake impacts to trigger dam failure and were evaluated in a trial-and-error approach. Large scenarios provoke in each case significant dam breaching.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Spongo Toggo</th>
<th>Gopang Gath</th>
<th>Shako Cho</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Momentum [lx N·s]</td>
<td>Impact volume [m³]</td>
<td>Impact volume [m³]</td>
</tr>
<tr>
<td>Large (2)</td>
<td>9.84 × 10⁷</td>
<td>1,600,000</td>
<td>6.82 × 10¹³</td>
</tr>
<tr>
<td>Small (1)</td>
<td>1.6 × 10⁶</td>
<td>600,000</td>
<td>1.35 × 10¹³</td>
</tr>
</tbody>
</table>

Fig. 6. Model results of small and large lake outburst scenarios for Spong Topo glacial lake. The overview shows flow velocities of scenario 2. Included are the lake outburst hydrographs, breach geometries and flow velocities during a potential GLOF impact at Honupatta. Water was released into the lake from the mass-movement starting zone.

Fig. 7. Model results of small and large lake outburst scenarios for Gopang Gath glacial lake. The overview shows flow velocities of scenario 2. Included are the lake outburst hydrographs, breach geometries and flow velocities at Sissu. Water was released into the lake from the mass-movement starting zone.

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lakes within the Indian Himalayas. Yet, expert knowledge on the stability of glacial lakes is required for the assessment, since analysis cannot only be based on the semi-quantitative decision tool, but also needs a holistic perspective and consideration of the dam, lake and lake surroundings.

The glacial lake inventory for the Indian Himalayas shows an overall trend for rather small and generally less critical glacial lakes when compared to other countries in the HKH such as e.g. Nepal or Bhutan (ICIMOD, 2010). Yet, a clear exception to this trend is the state of SK, where many large and (potentially) critical glacial lakes exist. Within the Indian Himalayas glacial lake distribution is more uniform in the glaciated areas of JK, HP, and UK (west of Nepal) than in SK, where glacial lake density is high, or in the case of AP, where lake distribution is very sparse. However, regional differences within the states can be substantial. The lake distribution pattern corresponds with lake characteristics in the different regions, which is also manifested in the number of critical, potentially critical, and uncrical lakes per state (Table 4).

Areas of all detected lakes are plotted in Fig. 9, illustrating again the remarkable situation in SK. Especially in North SK a high proportion of (very) large lakes exists, whereas in all other states medium to small lakes are dominant. Yet, the largest glacial lake in the Indian Himalayas is Samudra Tapu lake (77°32′52″E; 32°29′53″N) located in the Chandra Valley (HP) (Kulkarni et al., 2007). Two large lakes are located in the Karakoram mountain range of JK and AP have, in contrast, very few and small lakes.

Beside a rather small number of lakes west of Nepal which should be monitored in the future, SK clearly represents a hotspot region in terms of possible GLOF occurrences, and more research and monitoring are urgently needed there. High-quality imagery in Google Earth indicates that moraine dams in SK very often have a low width-to-height ratio and that they consist of unconsolidated, granular

| Table 4 |

<table>
<thead>
<tr>
<th></th>
<th>JK</th>
<th>HP</th>
<th>UK</th>
<th>SK</th>
<th>AP</th>
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<tr>
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<td>45</td>
<td>27</td>
<td>50</td>
<td>26</td>
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<tr>
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<td>4%</td>
<td>0%</td>
<td>16%</td>
<td>0%</td>
</tr>
<tr>
<td>Pot. critical</td>
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<td>36%</td>
<td>52%</td>
<td>60%</td>
<td>0%</td>
</tr>
<tr>
<td>Uncritical</td>
<td>41%</td>
<td>24%</td>
<td>40%</td>
<td>22%</td>
<td>96%</td>
</tr>
</tbody>
</table>

Fig. 8. Model results of small and big lake outburst scenarios for Shako Cho glacial lake. The overview shows low velocities of scenario 2. Included are the lake outburst hydrographs, breach geometry and low velocities at Thangu and Yathang. Water was released into the lake from the mass-movement starting zone.

Fig. 9. Glacial lake areas of all mapped lakes in the Indian Himalayas, divided by states. The y-axis shows the number of lakes, and the x-axis illustrates lake areas. Sikkim has a high proportion of (very) large lakes, whereas rather small lakes prevail in the other states.

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materials. As a result, they appear to be easily erodible by overtopping flows. Fujita (personal communication, February 2012) mapped and classified glacial lakes over large parts of the HKH and identified lakes which might potentially burst out with a volume > 10 × 10^9 m^3. Shaklo Cho lake is among the lakes mapped by Fujita and process modeling performed in this study clearly confirms that it should be considered as one of the most critical glacial lakes in the Indian Himalayas.

5.2. Modeling

This study represents a pilot to model the chain of GLOF hazards, from mass-movement induced impact wave generation to dam breaching and flood propagation. The release volume and release location of the impacting mass define the GLOF scenario and are initial conditions of the model. Scenario definition is inherently affected by uncertainties, and we therefore defined small and large lake impact scenarios for each case study site, covering a reasonable range of potential dam breaches. We did not represent real lake impacts, since mass movements composed of ice and/or debris cannot be simulated with BASEMENT. In contrast, through the release of water volumes into the lake, we reproduced realistic impulse waves which have the potential to trigger dam breaches. This approach represents a sophisticated scenario definition, which is more accurate than any speculation about potential dam breach scenarios, where the shape of the breach and its enlargement over time must be assumed. However, the approach presented in this paper does not encompass all possible dam breach trigger mechanisms and does, for instance, ignore overtopping flows induced by extraordinary rainfall.

Uncertainties, which may potentially affect model results, also exist in the definition of critical model input parameters and the DEM. The sediment transport components in the model have more limitations than the hydraulic components, as the former are based partly on empirical equations and geotechnical simplifications, and thus require several critical input parameters. The calibration of such critical input parameters based on similar past events is crucial, and was done in detail in a previous study on the basis of a moraine dam failure in the Patagonian Andes (Worni et al., 2012a). The resolution and accuracy of the DEM are correlated to the accuracy of model results (Wang et al., 2012), which is especially pronounced for advanced numerical models such as BASEMENT. Therefore a lack of recent and highly resolved elevation data from the Indian Himalayas remains a limiting factor in representing complex flow and dam breach dynamics (Allen et al., 2009). However, Wang et al. (2012) tested the influence of the SRTM DEM and ASTER GDEM version 1 data on hydraulic GLOF modeling in Tibet, and concluded that although flood inundation extent and water depths depend on the applied DEM, the level of deviation was of little significance when predicting high-discharge floods.

5.3. Risk assessment

Overtopping waves typically erode an initial breach into moraine dams. As soon as the initial breach depth is deeper than the lake freeboard, the hydrostatic lake pressure becomes the driving force for continuous breach enlargement and lake outflow. Hence, the smaller the freeboard, the less initial erosion is required to trigger dam failure, and the smaller a lake impact needs to be effectively trigger a breach process. This correlation was confirmed with the GLOF modeling at Spong Togpo and Shaklo Cho lakes, but only partially for Gopang Gath lake. Although the freeboard at Gopang Gath lake was only 0–5 m, only massive lake impacts were resulting in significant dam failure (scenario 2). In this particular case, the limiting factor for moraine breaching was more related to dam geometry and only to a lesser extent to freeboard. Another reason for differences in dam breach processes is the mass impact location, which was at an angle of 90° with respect to the dam (whereas the angle was 180° at Spong Togpo and Shaklo Cho lakes). The impulse waves with the highest energy therefore hit the shore opposite of the impact location and the waves will have attenuated significantly by the time they reach the dam (Heller et al., 2008). Hence, in addition to freeboard, dam and lake geometry, mass impact location and direction have to be seen as other critical parameters regarding the impact magnitude required to trigger moraine dam failure. The key question to assess lake outburst probabilities is to decide whether the minimal lake impacts required to induce dam failure are realistic or not. The geotechnical aspect of the lake outburst probability assessment (i.e. the susceptibility of a dam to breach) was covered with the BASEMENT simulation.

The minimum momentum flux required to induce dam failure at Spong Togpo lake in JK was calculated to be about 1.6 × 10^5 Ns. An ice volume \(q_{IC} = 917 \text{ kg m}^{-3}\) of ca. 60,000–90,000 m^3 impacting instantly Spong Togpo lake with 30–20 m s^-1, respectively, would transfer the same momentum \(p = m v\) to the lake, where \(m\) is the impact mass and \(v\) the impact velocity. Although such ice avalanches are plausible and not particularly extreme, little evidence for ice fall activity was found at the base of the hanging glacier at Spong Togpo lake during field surveys. However, warming may increase susceptibility of steep glaciers to fail (Huggel et al., 2010) and avalanches may occur at locations without precedence. Hence, moderate outburst magnitude and outburst probability have been assigned for Spong Togpo lake (Fig. 10).

![Fig. 10. Hazards and risks emanating from the three case-study glacial lakes were semi-quantitatively assessed, based on process modeling, field reconnaissance and remote sensing, and illustrated in a magnitude-probability and hazard-damage matrix.](image-url)
If a debris flow ($q_{debris} = 2200 \text{ kg m}^{-3}$) is assumed to trigger dam failure at Gopang Gath lake in HP, a sudden lake impact of 200,000–300,000 m$^3$ with velocities of 30–20 m s$^{-1}$ would be required. Alternatively, an ice volume of 480,000–720,000 m$^3$ (assuming similar velocities) would result in $1.35 \times 10^{10}$Ns as well, which was found to be the minimum lake impact needed to trigger dam failure. Such volumes seem more realistic for ice avalanches than for debris flows, based on a visual judgment of potential source areas and evidence of past events. The occurrence of such ice avalanches reaching the lake with high velocities will become more likely to occur in the future with further glacier retreat. An ice impact volume of roughly 2–3 $\times 10^{10}$ m$^3$ would be required to trigger a large (scenario 2) dam break. Such trigger magnitudes are generally considered to be unlikely. As a consequence, a low outburst probability and a moderate outburst magnitude were finally chosen for Gopang Gath lake (Fig. 10).

Due to the steep terrain, potential ice impact velocities of 30–40 m s$^{-1}$ were assumed for Shako Cho lake in SK. Ice impact volumes of 700,000–900,000 m$^3$ would transfer about 2.55 $\times 10^{10}$Ns to the lake, which was found to be the minimal lake impact to induce dam failure. The highly glaciated, steep mountain faces above the lake clearly favor the occurrence of such an impact scenario. This results in a high outburst probability for Shako Cho lake and model results indicate high outburst magnitudes (Fig. 10).

Lake outburst probabilities were assigned for the three case study sites, based on the calculated mass impacts and the qualitative assessment of probability of occurrence of such mass movements: Spong Togpo lake was accordingly attributed a moderate outburst probability, Gopang Gath was considered to present a low outburst probability and Shako Cho was assigned to have a high outburst probability. Based on the modeled lake outburst hydrographs, the expected magnitudes of potential outburst floods are moderate for Spong Togpo and Gopang Gath lakes and high for Shako Cho lake (refer to chapter 4.2). Based on the modeled flow extents (Figs. 6–8), field surveys and the analysis of satellite imagery, the damage potential in Honupatta (JK) and Sissu (HP) was considered to be moderate, and high in Thangu (SK) and Yathang (SK). The semi-quantitative parameterization of lake-outburst probabilities, potential outburst magnitudes and damage potentials, was then used to qualitatively assess the risk for each lake as illustrated in Fig. 10.

6. Conclusion

In this study we followed a multi-level approach from basic detection of glacial lakes over large areas using LANDSAT imagery, an assessment of hazard potential of detected lakes based on high-resolution imagery, to local-scale risk assessments of individual lakes based on field evidence, remote sensing data and model output. So far, no glacial lake inventory existed for the entire Indian Himalayas, and therefore the contribution of a comprehensive inventory with mapped and classified glacial lakes is important for the identification of potential hazard sources and for the planning of adequate coping strategies. The existence of Spong Togpo and Gopang Gath lakes is hardly known to local people and therefore awareness building in villages downstream of critical glacial lakes should become a priority. The glacial lake inventory is also the basis for further analysis of priority lakes. The schemes used for the three lakes of this study can serve as a reference for the risk assessment at other lakes in the Indian Himalayas. Whereas ground observations remain crucial, novel modeling capabilities have been shown to be highly relevant for integral glacial lake assessments. Despite prevailing uncertainties in the modeling process the dynamic BASEMENT model has been demonstrated to be a valuable tool to assess lake-outburst probabilities and potential lake outburst magnitudes. Such data facilitates the planning and dimensioning of accurate mitigation measures in the form of, e.g., early warning systems, and helps the justification of decisions aimed at preventing infrastructure and populated areas from being possibly at risk. Yet, apart from potential hazard sources, glacial lakes can also have a touristic potential (e.g., Samundra Tapu lake in the Chandra Valley, HP), and when considering glacial lake patterns and characteristics over large regions, glacial lakes can be used as an indirect indicator of glacier change.

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4.6 Extreme flow events in mountainous regions – advanced approaches to model processes and process chains

R. Worni, J. J. Clague, C. Huggel, M. Künzler, Y. Schaub, M. Stoffel

In review in *Earth-Science Reviews*
Extreme flow events in mountainous regions – advanced approaches to model processes and process chains

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Submitted to Earth-Science Reviews

Abstract

Extreme flow events in mountainous regions are highly mobile mixtures of water and sediment with sudden occurrence that are capable of traveling tens to hundreds of kilometers and exceeding normal discharge and volumes by several orders of magnitude. They usually tend to flow along existing river channels, extending from mountain areas with snow, glaciers and permafrost occurrence into populated downstream regions and thus pose people and infrastructure at risk. Many extreme flow events observed over the past decades involved process chains such as mass-movements impacting glacial lakes and triggering glacial lake outburst floods (GLOF). There is concern that effects of climate change with an increasing destabilization of high mountain slopes can exacerbate such process chains and associated extreme flows. Modeling of extreme flow events and process chains is a valuable tool for improving knowledge of complex processes and assessing the hazard and risk of potential future events. A number of numerical models have been developed and applied to simulate different types of extreme flow events but are confronted with challenges due to a lack of process understanding and difficulties to measure extreme flows for calibration purposes. Here we review the state of knowledge on key aspects and modeling of extreme flow events, with a focus on complex process chains. The analysis and simulation of the onset, propagation and potential impact of extreme flows is based on instructive case studies. Numerical models are presently available for simulating impact waves in lakes, dam failures and flow propagation, but only to a limited extent for integrated simulations of process cascades. We therefore present an extensive spectrum of modeling case
studies from the Andes, the European Alps, Central Asia and Himalaya, simulating single processes and process chains of past and potential future events. We conclude that both process understanding and model development for interphases of downslope propagating process chains need to be strengthened and research efforts should focus on a more integrative treatment of processes in numerical models.

Keywords: Extreme flow events, glacial lake outburst flood (GLOF), lahar, process chain, dynamic modeling, natural hazard.

1. Introduction

Extreme flow events are highly mobile mixtures of water and sediment capable of traveling $10^1$ to $>10^2$ km at velocities exceeding tens of kilometres per hour (Iverson, 1997; Manville et al., 2012) They are a serious threat in mountainous regions due to their sudden onset, rare and short-lived nature, high-magnitude discharge, long run-out distance, and their tendency to flow along existing river channels where humans and their assets are concentrated (Carrivick, 2010; Cui et al., in press; Manville et al., 2012). Hillslope and mountain environments where abundant sediment can be entrained by floodwaters, producing hyperconcentrated and debris flows, are particularly prone to extreme flow events (Iverson, 1997). These events are highly dynamic processes; their volume and peak discharge can increase by a factor of three or more relative to initial values through erosion and entrainment of sediment, as long as they contain or acquire sufficient water values (Manville, 2004; Mergili et al., 2011). This water commonly originates from intense cloudbursts (Joshi and Kumar, 2006; Hobley et al., 2012), dam failures (Huggel et al., 2004), or from melt of snow and ice due to mass-movement impacts on glaciers (Huggel et al., 2005; Evans et al., 2009) or volcanic activity (Worni et al., 2012a). Sediment is typically entrained from periglacial environments exposed after glacier retreat (Haebeli et al., 1989; Chiarle et al., 2007), deep incision of channels in areas of thick unconsolidated deposits (Stoffel and Huggel, 2012), or through erosion of landslide debris in channels of rivers and torrents (Cui et al., in press; Savi et al., in press). Extreme flow events are highly unsteady and are commonly characterized by pronounced changes during flow, from normal runoff to hyperconcentrated flow and granular debris flows and vice versa (Mergili et al., 2011; Worni et al., 2012b; Manville et al., 2012). These transformations are mainly related to sediment deposition and bulking or dilution of a debris flow/hyperconcentrated flow by stream water (Smith and Lowe, 1991).

Extreme flow events typically occur as combinations or cascades of the processes listed in the previous paragraph. Process cascades are, for instance, characteristic of glacial lake outburst floods (GLOFs), where 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 (Haebeli et al., 2010). Similar process cascades can occur following the blockage of rivers by landslides (Plafker and Ericksen, 1978;
Scott et al., 1995; Korup et al., 2004; Cui et al., in press). Most landslide dams fail within hours, days, months or years after their emplacement (Costa and Schuster, 1984).

Modeling of extreme flow processes or process chains is a valuable tool for 1) improving knowledge of complex surface processes and 2) assessing the hazard and risk of potential future events. Several researchers have attempted to model extreme flow processes and chain reactions (Worni et al., 2012a, 2012b). Hydraulic models have yielded accurate results for water floods; they represent flow physics with reasonable precision. Dynamic models in particular have proven to be valuable tools for reconstructing past events and assessing potential hazards of different types of flow events. Modeling of sediment transport and sediment-laden flows has been more problematic, because empirical equations and geotechnical simplifications must be used and critical input parameters are often missing.

In this paper, we illustrate recent progress and limitations in modeling extreme flow events, with a focus on high mountain regions where changing climate is thought to exacerbate the frequency and magnitude of extremes (Huggel et al., 2012b; Stoffel and Huggel, 2012). Our goal is to improve understanding of extreme flow events and advance the use of modeling tools and techniques for simulating different natural hazard processes and process chains. We provide examples of how extreme flows from glacial and other high mountain lakes, as well as volcanic lahars, can be modeled more realistically and of how process chains can be designed that include both triggering processes and data on potential impacts in downvalley areas. We cite illustrative extreme flow events from around the world to 1) identify key processes and process cascades and 2) propose solutions for modeling problems.

2. Processes and typical process chains of extreme flow events

2.1 Current developments

Glacier thinning and retreat over the past century has resulted in the formation and growth of lakes at the margin of glaciers in all high mountain regions of the world (IPCC, 2012). Sudden drainings of these lakes has caused severe disasters in high mountain regions, including 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, 2000; Wang et al., 2008), Island (Björnsson, 2002; Russel et al., 2006), North America (Post and Mayo, 1971; Clague and Mathews, 1993; Clague and Evans, 2000; Geertsema and Clague, 2005; Kershaw et al., 2005) and the European Alps (Haeberli, 1983; Haeberli et al., 2001). Glacial lakes can be classified into several types according to their position relative to the glacier and the damming mechanism (Costa and Schuster, 1984; Clague and Evans, 2000; Richardson and Reynolds, 2000; Roberts, 2005).
The formation of new glacier and high mountain lakes in a warming climate is paralleled by slope destabilization in many regions. Debuttressing of rock slopes adjacent to downwasting glaciers is an important process in 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). There is also increasing evidence that thawing and related processes in permafrost in bedrock 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 verified on local and regional scales in the Alps (Huggel et al., 2012a). The contemporaneous development of new and expanding glacial lakes and the decreasing stability of steep bedrock slopes increases the risk that landslides and ice avalanches will impact lakes, producing huge, historically unprecedented downstream floods. Many lake outburst floods in the recent past have resulted from process chains triggered by such impacts. In the following sections, we consider three pertinent case studies that are instructive in terms of such process chains.

2.2 Case study analysis

Nostetuko Lake, British Columbia

Nostetuko Lake was located at the head of Nostetuko River in the southern Coast Mountains of British Columbia. It was impounded by a large Little Ice Age moraine built by Cumberland Glacier. During the 20th century, Cumberland Glacier retreated from the moraine, and Nostetuko Lake developed between the moraine and the retreating glacier. On 19 July 1983, the moraine impounding Nostetuko Lake failed, and $6.5 \times 10^6 \text{ m}^3$ of water flowed from the lake into the valley below (Fig. 1; Blown and Church, 1985). The level of the lake dropped about 40 m during the outburst.

The lake outburst was caused by an ice avalanche from Cumberland Glacier, which had retreated out of the lake and up a steep bedrock slope prior to the disaster. Although relatively small, the waves were still able to breach the natural armour of the outlet channel and initiate catastrophic incision. Once down-cutting commenced, outflow increased from the lake, increasing the erosion. The lake emptied in about four hours. Approximately $1.5 \times 10^6 \text{ m}^3$ of sediment were eroded from the moraine and deposited as a large fan directly downstream from the dam. Farther downstream, floodwaters extensively eroded alluvium and colluvium in Nostetuko valley, damaged large tracts of forest, and left piles of trees and coarse sediment on bars and channel margins.

The flood attenuated as it moved downvalley. A gauging station 67 km downstream from the dam recorded an increase in discharge from a background level of $330 \text{ m}^3 \text{ s}^{-1}$ to over $900 \text{ m}^3 \text{ s}^{-1}$ in one hour. The increase in discharge at a site a further 45 km downvalley, at the head of Bute Inlet, was less and slower.
**Fig. 1**: Nostetuko Lake before (A) and after (B) the moraine dam breach and lake outburst flood on July 19, 1983.

**Queen Bess Lake, British Columbia**

Queen Bess Lake, located near the head of a major tributary of Nostetuko River, partially drained in August 1997, when a large ice avalanche from Diadem Glacier entered the lake and generated a train of waves that overtopped the moraine dam (Kershaw et al., 2005). The Little Ice Age limit of Diadem Glacier is marked by lateral moraines that reach up to 150 m above Queen Bess Lake. Diadem Glacier retreated more than 500 m between 1949 and 1970, and left the lake in 1995, receding up the adjacent steep rock slope. On 13 August 1997, a ca. $2 \times 10^6$ m$^3$ of ice broke away, slid on a smooth rock slope and impacted the lake. The outburst flood began when the first large wave generated by the avalanche overtopped the moraines at the east end of Queen Bess Lake. At the east end of Queen Bess Lake, the wave climbed sharply and overtopped both the inner and outer end moraines. The highest point reached by the wave in this area is 33 m above the pre-outburst level of the lake. About $7.5 \times 10^6$ m$^3$ of water escaped from Queen Bess Lake during the outburst. The level of the lake dropped 8 m, and a steep-walled ravine up to 15 m deep, 60-75 m wide, and 360 m long was carved into the moraine dam along the axis of the former overflow channel. The flood wave travelled about 20 km down Nostetuko valley, slowly attenuated but still generated a marked spike at a gauge at Bute Inlet, 100 km from the source. The hydrograph shows a sharp peak indicative of the passage of a single flood wave. Exposures of flood deposits and paleodischarge estimates in the west fork of Nostetuko valley show that the flood along the upper part of the path was a two-phase event (Kershaw et al., 2005). The initial,
overtopping phase produced a large flood spike that rapidly attenuated away from the dam. The second, breach phase lasted longer and attenuated more slowly.

**Lake 513, Peru**

Lake 513 in the Cordillera Blanca, Peru, is a bedrock-dammed glacial lake that formed after the 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). As in the case of the Queen Bess event, the avalanche travelled over smooth bedrock and impacted Lake 513, generating a wave that overtopped the dam by 23 m (Carey et al., 2012).

The overtopping wave was $< 1 \times 10^6$ m$^3$, but it ran down the steep of Hualcán Canyon. Although the dam was rock, significant volumes of sediment were entrained during the outburst and a debris flow formed. The debris flow came to rest and deposited its sediment load at about 3650 m asl in the upper part of the flat Pampa de Chonquil. However, a water flood continued down the Chucchun River below the Pampa de Chonquil, severely eroding the valley floor. The flood reached the fringes of the city of Carhuaz (ca. 25,000 inhabitants), but there were no casualties. The Chucchun River and the Santa River in the main valley farther downstream had high flows for about 16 hours following the outburst.

The level of Lake 513 was lowered in the 1990s by drilling a number of tunnels in the bedrock dam to reduce the risk of overtopping waves. This mitigation measure probably saved lives in Carhuaz because a much larger volume of water would have been displaced from the lake had it been full to the rim of the dam.

2.3 Process synthesis

The above events and others involving sudden large discharges from lakes can be systematically analyzed by considering the cascade of processes that constitute them (refer to Fig. 16). At the boundary between the lake and the impacting landslide or ice avalanche, we identify several types of wave generation and related floods. In the case of Nostetuko Lake a single-pulse flood resulted from overtopping and incision of a moraine and by a relatively small wave generated by an ice avalanche. This example shows that even a small wave was sufficiently energetic to initiate incision of the outflow channel. Initial incision initiated a positive feedback, in which increasing outflow from the lake increased erosion of the outlet. Single-pulse floods can also be caused by overtopping waves without dam breaching, as in the case of Lake 513 with its bedrock dam. In contrast, the 1997 Queen Bess Lake event was a two-pulse flood – the initial flood pulse was caused by wave overtopping, whereas the second resulted from breaching of the moraine dam. The two flood pulses fully coalesced about 6 km below the dam.
The events described above also illustrate the continuum of flow behavior during outburst floods. Floodwaters that flow along channels steeper than about 10° and that are not sediment-limited generate debris flows that may bulk up to many times the volume of the discharged water, as in the case of the Lake 513 event. In contrast, where the channel gradient below the moraine dam is low, as in the case of Nostetuko valley below Nostetuko and Queen Bess lakes, the outburst event remains a flood because high sediment concentrations are not maintained beyond the breach.

A conclusion of the analysis of many lake outburst floods, including the case studies presented above, is that flow dynamics and rheology can change several times during a single event. The Lake 513 event started as a flood, transformed into a debris flow, then became a hyperconcentrated flow, and reverted to a debris flow in steeper terrain with abundant sediment. In contrast, the Queen Bess event fluctuated between a hyperconcentrated flow and a flood over the first 8 km of its path, controlled largely by the channel gradient. In several historical moraine dam breaches, a debris flow formed during the dam breach process but most of the boulder fraction was deposited shortly afterwards and a mobile hyperconcentrated flow continued downstream (e.g. Ventisquero Negro case, section 4.2).

3. Modeling process components and chains

Different trigger mechanisms and process cascades can lead to extreme flow events. The initiation phase of process chains can be completely different from one another (e.g. extreme precipitation events, volcanic eruptions, dam breaches), but the events generally converge towards their ends. The same is true for modeling: A large number of model classes are available to calculate all sort of processes, but it is beyond the scope of this study to consider them all. 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. We then present an approach to integrally model an entire GLOF process chain.

3.1 Impact wave modeling

Many analytical and numerical models exist to describe tsunami waves triggered by submarine or subaerial landslides (Falappi and Gallati, 2007; Heller et al., 2008; L’Heureux et al., 2011; Ataie-Ashtiani and Yavari-Ramshe, 2011). Analytical methods are based on empirical studies and general computational guidelines about landslide-generated impulse waves (e.g. Heller et al., 2008). Numerical models (e.g. 2D-BING; L’Heureux et al., 2011) generally apply Boussinesq formulations (e.g. Madsen et al., 1997), linear and non-linear two-dimensional shallow-water equations (SWE) and potential flow equations (Ataie-Ashtiani and Yavari-Ramshe, 2011). SWE,
however, are only valid when the height of the waves is much less than the water depth, and wavelength is much longer than the water depth. In order to include non-linear effects of waves, Boussinesq models must be included in impact wave simulations (L’Heureux et al., 2011). The 2D-BING model uses a flexible box with prescribed velocity progression and propagation on a straight line to represent the landslide that generates the impulse waves. Mass movement models can be applied to evaluate required landslide parameters. The LS3D tsunami model is a two-dimensional, fourth-order Boussinesq-type numerical model used to simulate landslide-generated waves in reservoirs (Ataie-Ashanti and Yavari-Ramshe, 2011). All relevant processes, specifically wave generation, wave propagation, dam overtopping and wave run-up, are considered in the model, and model results have shown good agreement with experimental data.

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, 1989b; Tingsanchali and Chinnarasri, 2001). Singh (1996) described a number of dam breach models such as BRDAM, Lou model, BREACH, DAMBRK and BEED, and 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 (US Army Corps of Hydraulic Engineers, 2012) and NWS DAMBRK (Fread, 1982) provide outflow hydrographs based on parameters related to 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 mechanic principles.

Many physical dam break models require critical input parameters, such as the shape of the breach and its enlargement over time, which are often based on assumption rather than physical evidence (Pickert et al., 2011; Worni et al., 2012b). New erosion-based dynamic models are an improvement in this respect (Balmforth et al., 2008; Faeh et al., 2012); they show promise in their ability to capture the breaching process with good accuracy. These models solve balancing equations for water flow in combination with empirical transport formulas to simulate embankment failures, thereby using clear physical input parameters. BASEMENT is a two-dimensional dynamic model (Faeh et al., 2012) for simulating breaching processes of non-cohesive earthen dam structures. The program solves the SWE for water flow calculations, and sediment transport laws are used to determine vertical incision in dam structures due to
overtopping flow. The complex geotechnical process of lateral breach widening due to collapses of the side walls is considered with a geometrical 3D 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.

3.3 Flow modeling

Diverse models, ranging from simple empirical models to physically based dynamic models, simulate the propagation of water and sediment flows. Unlike empirical models, sophisticated models can handle complex flow behaviors governed by fluid and particle interactions, turbulent flow or changing flow regimes. No existing modeling approach, however, can fully characterize the complex nature of extreme flow events, for example constantly changing flow rheology, and thus a careful selection of the best model for a particular problem is crucial. Below we review different empirical and physical models used in Chapter 4.

Empirical models are based on statistical analyses of field measurements derived from past extreme flow events. The average behavior of future flows is predicted from past events (Manville et al., 2012). A simple modeling approach can link cross-sectional areas, flow run-out distance or velocities with total flow volume using semi-empirical relationships (Iverson et al., 1998; Pierson, 1998). LAHARZ is a widely used semi-empirical model for lahars that is based on such principles. Based on 27 lahars and non-volcanic debris flows, Iverson et al. (1998) calibrated the proportionality factors $C$ and $c$ of the physically based equations $A=CV^{2/3}$ and $B=cV^{2/3}$, where $V$ is lahar volume, $A$ is the valley cross-sectional area and $B$ is the planimetric area inundated by lahars. Statistical analysis of past events yielded values of $C=0.05$ and $c=200$. Worni et al. (2012a) recalibrated these proportionality factors for lahars from Nevado del Huila volcano in Colombia and found a better match with values of $C=0.0065$ and $c=280$.

Physical flow models generally involve: 1) a set of terms that describe conservation of mass and momentum; 2) a method to quantify flow resistance; 3) a numerical approach to solve partial differential equations; and 4) 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. One-dimensional models such as HEC-RAS solve the full 1D St. Venant equations for unsteady open-channel flow. For two-dimensional models such as BASEMENT or FLO-2D (O’Brien et al., 1993), the SWE are general constitutive flow equations that are solved, for example, with an explicit finite-volume or finite element method on structured or unstructured meshes. In hydraulic models, flow resistance is generally described by a term that encompasses viscous and turbulent dissipation and frictional losses, where the empirical Manning coefficient $n$ is a common resistance term (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, debris-flow 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, 2012). The sediment concentration of a flow and flow rheological parameters are specified by the user, 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 both sediment and water are solved numerically (Manville et al., 2012).

RAMMS (Christen et al., 2010) is a model used to simulate a variety of rapid mass movements, such as snow avalanches, ice-rock avalanches and debris flows. In contrast to FLO-2D, it is capable of computing material entrainment by mass flows. Frictional resistance is described using a Voellmy approach, which incorporates a parameter for the dry Coulomb friction $\mu$ and a turbulent friction $\xi$, which is dependent to the square of the velocity. 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).
Integrated modeling means that models from different fields and process types are merged, yielding an integrated system description and a more complete representation of reality (Geidl, 2007). Hydrologic modeling and hydraulic modeling are combined, for example, in the FLO-2D program. 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, for many types of extreme flow events such as lahars or GLOFs, which are characterized by cascades of processes, no systematic integrated modeling approach exists to date. Erosion-based dam breach models apply hydraulic principles and are therefore able to simulate flow propagation subsequent to dam breaching, but dam-breach trigger processes have not yet been included. We therefore
adapted the simulation setup with BASEMENT in order to model GLOF scenarios from dam breach triggering due to lake impact through dam breaching and flood propagation. Here we describe three different modeling phases within a single model run with BASEMENT (refer to Fig. 16) (Worni et al., in press):

(1) **Impulse wave modeling.** BASEMENT does not simulate the propagation of dense mass-movements, therefore a sudden release of water into a lake from a steep mountain slope was chosen to represent such a mass movement (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. Impulse wave generation, propagation and run-up at the shore are described by the SWE.

(2) **Dam breach modeling.** Impulse waves overtopped the dam, initiating vertical breach erosion. Sediment transport laws determine incision rates, which are controlled by the properties of the dam material and the shear stress of the water flow. Vertical breach incision led to a steepening of the breach side walls, which collapsed when critical failure angles were exceeded. Breach expansion ceased when the outflow decreased below the threshold for bedload transport.

(3) **Modeling flood propagation.** Water and sediment flow through the breach was propagated downstream based on hydrodynamic and sediment transport calculations. Inundation depths, flow velocities, bottom shear stresses and changes in bed elevation were determined for each cell of the computational mesh.

4. **Illustrative case studies of modeling extreme flow events**

4.1 Modeling dam breach scenarios at Gopang Gath glacial lake, India

Gopang Gath lake (32°31’38’’N; 77°13’03’’E; 4100 m asl) is a moraine-dammed proglacial lake with an area of ca. 0.58 km$^2$ (Fig. 3), located in Himachal Pradesh, India. The lake is thought to have a moderate outburst probability based on field, modeling and remote sensing analyses. In the event of dam failure, the downstream village of Sissu might be impacted by the flood wave (Worni et al. in press).

Potential dam failure scenarios were triggered in BASEMENT by a mass impact into the lake from the south-facing mountain slope. The minimal impact required to trigger dam failure transferred a momentum flux of $1.35 \times 10^{10}$ N·s to the lake. Such an impact scenario led to the formation of one breach at the north end of the dam and caused a lowering of the lake by ca. 7 m (Fig. 4A). In a simulation involving a 4-5 times larger impact, the moraine dam was eroded at its north and the south ends, and the lake lowered by 13 m (Fig. 4B) (Worni et al., in press). Lake impact scenarios thus can significantly affect subsequent dam breaching and the amount of water discharged from the lake, and are a key element in GLOF process chain modeling. In the case of
Gopang Gath, only modeling indicated the potential for dam breaching at two places; this possibility was not recognized in the field.

Fig. 3: Gopang Gath glacial lake in Himachal Pradesh, India.

Fig. 4: Output of dam breach modeling with BASEMENT. A: Minimal impact required to trigger dam failure, with breaching at one place in the dam. The momentum flux transferred to the lake by the mass impact was $1.35 \times 10^{10}$ N·s. B: A realistic worst-case lake impact created two breaches with more lake outflow than in scenario A. The transferred momentum flux was $6.82 \times 10^{10}$ N·s.

4.2 Retrospective dam breach modeling at Ventisquero Negro glacial lake, Argentina

The end moraine impounding the 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 downstream (Fig. 5). The dam breach was triggered by an increase in lake level caused by heavy precipitation and temporary blockage of the lake outlet by ice blocks. Based on field evidence, the ice at the outlet was probably abruptly washed away and the increased outflow exceeded the critical bottom shear stress required to initiate dam erosion. Once dam erosion had started, the hydrostatic lake pressure was the driving force for continued lake outflow and dam erosion (Worni et al., 2012b).
Retrospective moraine breach modeling with BASEMENT simulated a sudden release of water from the lake. An accurate simulation was achieved by setting the lake level above the outlet, thus creating a high initial lake discharge and dam erosion at the start of the program. The model showed that the steepest section of the downstream face of the moraine experienced the greatest initial erosion (Fig. 6; 30 min). The resulting rapid outflow entrained more sediment and the breach evolved backward towards the outlet. This knickpoint retreat lowered the lake outlet and increased discharge and erosion, leading to progressive breach enlargement (Fig. 6; 50 min). Flow velocities increased due to the increasing outflow, resulting in a simultaneous increase in bottom shear stress to a maximum of 5100 N m$^{-2}$ (Fig. 6; 70 min). The outflow and erosion rates decreased as the level of the lake fell (Fig. 6; 120 min), and 120 minutes after the start of the model run further breach enlargement ceased (Worni et al., 2012b).

This case study proved to be useful for calibrating model input parameters (Worni et al., 2012b) and for testing dynamic, erosion-based dam breach modeling. Model results quantified key processes and provided insights into complex dam breach mechanisms that are difficult to observe in nature. In addition, it showed that high lake discharge could be a dam breach trigger process.
4.3 Retrospective GLOF modeling at the lower Grindelwald glacial lake, Switzerland

On 30 May 2008 supraglacial lake on the terminus of lower Grindelwald Glacier (46°35'41"N, 8°3'26"E; 1380 m asl) in Switzerland drained catastrophically (Fig. 7). Of a total lake volume of 800,000 m³, 570,000 m³ of water were released subglacially within three hours, with a maximal peak discharge of 100-110 m³ s⁻¹. The lake drained through a channel at the bottom of the glacier and then discharged into a deep and narrow gorge (Gletscherschlucht), where significant amounts of material were entrained into the flow. Below the outlet of the gorge, the GLOF inundated the Weisse Lütschine River floodplain at Aspi (Fig. 8). 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, reducing its cross-sectional area. The sediment concentration in the flow did not significantly alter its rheology, therefore the hydraulic model BASEMENT was applied to retrospectively model the event. The aim was to gain insights into flooding and sediment transport processes and to test BASEMENT for river flooding conditions. 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. Flood modeling was attempted downstream of Gletscherschlucht because discharge measurements available for the end of the gorge provided initial model input. The simulation reasonably accurately captured
flooding on the east side of the river side, but also predicted significant flooding on the west side, which did not occur (Fig. 8). Differences in modeled and actual sediment deposition account for this discrepancy. Although a variety of sediment transport conditions were tested, the model predicted too much accretion in the river channel in each case, with the consequence that the water overflowed westward. This example illustrates that the simulation of sediment transport is challenging, and model output remains questionable even when input data are precise.

Fig. 8: Results of flood and sediment transport modeling of a GLOF in Grindelwald in May 2008 using BASEMENT. Modeled flooded areas are shown in blue; actual inundation extent is delineated by the red line, (data from BVE (OIK I) and BAFU).
4.4 Retrospective and scenario-based lahar modeling at Nevado del Huila volcano, Colombia

Three major lahars with volumes between $70 \times 10^6$ m$^3$ and run-out distances up to 160 km occurred in 1994, 2007 and 2008 on Nevado del Huila volcano (2°56′4″N, 76° 1′38.84″W; 5364 m asl) in the Cordillera Central, Colombia (Worni et al., 2012a). The 1994 lahar was triggered by an earthquake, and those in 2007 and 2008 were caused by volcano-ice interactions during volcanic eruptions. The 1994 lahar claimed nearly 1000 lives, and all three devastated downstream areas (Fig. 9). Fieldwork conducted after the April 2007 event revealed that the lahar behaved as a debris flow along its upper course and as a hyperconcentrated flow lower along the river. However, flow rheologies changed constantly, with repeated flow transformations from debris to hyperconcentrated flows and vice versa.

Two models (LAHARZ and FLO-2D) were applied in a retrospective analysis of the 2007 Nevado del Huila lahar. Hydrographs reconstructed from geophone recordings formed the basis for the scenario modeling (Worni et al. 2012a). The governing equations of LAHARZ and key input parameters of FLO-2D were calibrated based on the 1994 and 2007 lahars. The models were then used for scenario modeling, with applied volumes of the order of past events ($300 \times 10^6$ m$^3$) and worst-case scenarios ($600-1000 \times 10^6$ m$^3$) (Worni et al. 2012a). Modeled inundation depths and approximate lahar travel times provide a basis for risk reduction actions (e.g. an early warning system) at downstream locations.

Fig. 10 shows lahar travel times from Central Peak to downstream villages based on FLO-2D modeling, and inundation depths and the extent of the flow in the Belalcázar region based on LAHARZ and FLO-2D modeling. The two models yield somewhat different inundation patterns, and travel times, which were not modeled with LAHARZ, differ significantly depending on the lahar scenario. Nevertheless, the use of different models and the simulation of a range of realistic lahar scenarios enhance the credibility of the results.

Fig. 9: A: Crater (dotted orange line) of Nevado del Huila and dome (yellow line) that formed during and after the eruption in November 2008. B: Traces of lahars that flowed down the flanks of the volcano. C: Lahar path in the Páez River valley above Belalcázar. (Photographs by INGEOMINA)
4.5 Modeling lake outburst flood scenarios in Khavrazdara, Tajikistan

Periglacial Lake Khavraz (38°34’10”N, 72°36’31”E; 4000 m asl) in Khavrazdara, Tajikistan, has an area of about 2 km² 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). Lake outburst scenarios were modeled using FLO-2D and RAMMS to assess in more detail the hazard situation related to the lake. Input parameters of the FLO-2D model were calibrated based on a GLOF event in Dasht, Tajikistan, in 2003, and friction parameters in RAMMS were adjusted such that the flow reached the floodplain. Four realistic lake outburst scenarios were then defined (Table 1).
Table 1: Four lake outburst scenarios, represented by triangular hydrographs with different volumes (V) and peak discharges (Q\(_{\text{max}}\)).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>V</th>
<th>Q(_{\text{max}})</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>15 × 10^6 m(^3)</td>
<td>2000 m(^3) s(^{-1})</td>
</tr>
<tr>
<td>2</td>
<td>15 × 10^6 m(^3)</td>
<td>8000 m(^3) s(^{-1})</td>
</tr>
<tr>
<td>3</td>
<td>30 × 10^6 m(^3)</td>
<td>2000 m(^3) s(^{-1})</td>
</tr>
<tr>
<td>4</td>
<td>30 × 10^6 m(^3)</td>
<td>8000 m(^3) s(^{-1})</td>
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</table>

All scenarios were modeled with RAMMS to simulate debris flows, and with FLO-2D to simulate floods and hyperconcentrated flows. The result was a set of 12 model outputs, which provided a range of flooding probabilities in Pasor. Scenarios 1 and 4 for the three different flow simulations are shown in Fig. 11. All 12 model outputs clearly indicate that zone A in Fig. 11 would be affected in the event of a catastrophic lake outburst, hence high flooding probability can be assigned to that zone. 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 flooding probability in that area can be considered small. Six model outputs indicate partial inundation of the populated area west of the river (zone C). Hence, the flooding probability for that zone is uncertain. The probability of flooding depends importantly on the susceptibility of the dam to breaching, which requires geotechnical investigation, but nevertheless, modeled inundation depths and flow arrival times are important data for mitigation measures and the development of evacuation plans.
4.6 Modeling the process chain of a potential outburst of Shako Cho glacial lake, India

Proglacial Shako Cho lake (27°58′29″N, 88°36′58″E; 5000 m asl) in Sikkim, India, covers an area of 0.575 km² and is dammed by a sharp-crested end moraine consisting of loose granular sediment. The steep, 1000-m high mountain face behind the lake is a potential source of ice-rock avalanches that could impact the lake and trigger failure of the moraine dam (Fig. 12). Worni et al. (in press) considered this lake to have a high outburst potential and to present a considerable flood risk to downstream villages.
To assess the potential consequences of a dam breach, we modeled the following process chain using BASEMENT: 1) mass movement impacts the lake; 2) wave overtopping and dam erosion; and 3) lake outburst and flood propagation. The mass movement scenario illustrated in Fig. 13 is the minimum required to cause dam failure. This impact transferred the energy of about $2.55 \times 10^{10}$ N·s to the lake, equal to ca. 700,000 – 900,000 m$^3$ of ice entering the lake at 30-40 m s$^{-1}$ (Worni et al., in press). The overtopping waves formed a 10-m-deep breach, initiating lake outflow and dam erosion driven by hydrostatic lake pressure. The impact in the lake occurred 30 seconds after the start of the program; the first wave overtopped the dam at 100 seconds; a second overtopping occurred at 250 seconds; and steady lake outflow was achieved after 800 seconds (Fig. 13). The most rapid breach enlargement coincided with maximum lake outflow.

Fig. 12: Shako Cho glacial lake in Sikkim, India. (Picture obtained from a mountaineer).

Fig. 13: Example of results of impulse wave modeling at Shako Cho glacial lake with BASEMENT. A landslide impact produced waves that overtopped the dam and eroded an initial breach 10 m deep. Water continued to flow out of the lake after the breach formed.
between 1200 and 2400 seconds (20-40 minutes). Breach expansion ceased about 7200 seconds (120 minutes) after the start of the program. The simulation indicated that about $16 \times 10^6$ m$^3$ water would drain in 180 minutes, with a maximum discharge of ca. 6100 m$^3$ s$^{-1}$. The flood wave would reach Thangu village with maximum flow velocities of 15 m s$^{-1}$ and maximum flow depths of 12 m about 50 minutes after lake impact (Fig. 14). Thangu and Yathang would be impacted by the GLOF, with damage especially severe in Thangu (Worni et al., in press).

![Fig. 14: Results of modeling a typical GLOF process chain at Shako Cho glacial lake, showing dam breach evolution and maximum flow velocities. The mass starting zone is the release location of the landslide mass that impacts the lake. The villages of Thangu and Yathang would be severely impacted by such a GLOF. (After Worni et al., in press).](image)

4.7 From flow modeling to risk analysis in Ibagué, Cordillera Central, Colombia

The regional capital Ibagué (ca. 500,000 inhabitants) in the Cordillera Central of Colombia is prone to lahars and rainfall-triggered floods and landslides from glacier-covered Nevado del Tolima volcano (4°36'N, 75°20'W; 5220 m asl). We modeled the inundation zones of four scenario lahars and two scenario floods using LAHARZ (Iverson et al., 1998) and HEC-RAS (Brunner, 2002). The lahar scenarios (0.5, 1, 5, and $15 \times 10^6$ m$^3$ volumes) were based on melting of 1, 2, 10, and 25% ice, firn and snow, respectively, due to volcanic activity and subsequent lahar formation (Künzler et al., 2012). Design floods with return periods of 10 and 100 years were based on discharge measurements made over about the past 20 years. We then created a combined lahar-flood hazard map based on the modeling results, return periods, and flow
intensities. We also produced vulnerability maps that integrated market values of dwellings, population density, and social aspects expressed by a poverty index provided by the local government. The hazard and the vulnerability maps were subsequently standardized, with a range from 0 (no hazard/vulnerability) to 1 (maximum hazard/vulnerability), weighted and finally multiplied to create a risk map (Fig. 15). This series of maps provides a first overview of the spatial distribution of hazard, vulnerabilities and risk. They are useful for effective disaster planning and facilitate an integrative view of hazards and risk.

The probability of occurrence of lahars in the study area is low (return periods between 100 and 1000 years), but impacts would be large, with about 20,000 people or more at risk. Floods are much more frequent, but the affected areas are generally smaller. High-risk zones in Ibagué are socially vulnerable urban populations close to the main river (Künzler et al., 2012). An early warning system was installed by local and regional authorities to prevent injuries and death (Huggel et al., 2010), and an educational campaign continues.

Fig. 15: Risk map of Ibagué, based on lahar and flood modeling, return periods, and physical and social vulnerability (Künzler et al., 2012).

5. Discussion

Extreme flow events are commonly characterized by chain reactions that have high hazard potential far from their sources. Yet, few observations or quantitative data of events exist and the hydraulics of high-magnitude flows and mechanisms of erosion, sediment transport and
deposition are poorly understood and remain largely unquantified (Carrivick, 2006). It is therefore essential to improve our understanding of extreme flow events and their triggering and causative processes by studying and characterizing them and by applying state-of-the-art numerical modeling techniques (Carrivick et al., 2009). Only by quantifying relevant flow and sediment transport processes is it possible to fully understand extreme flow events, which is a necessary first step in reducing the risk they pose. Advanced approaches to simulate entire process chains are, in this respect, essential for future hazard assessments.

The aim of this paper is to provide insights into complex processes and process chains of extreme flow events by field- and model-based analysis of past and potential future GLOFs and lahars. Each of the case studies that we have presented illustrates important aspects of extreme flow events. By way of visualization, we summarize different processes, process cascades and modeling approaches for the case studies in Fig. 16.

Process modeling of extreme events can be retrospective or scenario-based. In the case of retrospective modeling, past events are reproduced by model simulations, which on one hand contribute to an improved understanding of process and on the other hand is useful for model calibration and validation, which are indispensable for scenario modeling. Scenario modeling is used to predict potential future events for hazard assessments and risk mitigation. Numerical modeling requires the definition of input parameters and initial and boundary conditions, which in retrospective modeling are mainly based on field observations and measurements and in scenario modeling are partly based on assumptions and scenario definitions.

Fig. 16: Schematic sketch of a typical GLOF process chain. 1) A landslide impacts a lake, producing 2) an impact wave that 3) overtops the dam. 4) After overtopping, erosion and failure of the dam results in 5) a flood that travels downstream and 6) eventually impacts population centers or infrastructure. The case studies presented in this paper are positioned according to their processes and process cascades. In addition, modeling approaches summarized in section 3 are assigned to processes and process chains.
5.1 Retrospective modeling

The characterization of extreme flow events and definition of model input parameters are challenging, yet valuable tasks. Retrospective modeling provides valuable insights into complex processes that are difficult to analyze in reality. Moraine breach modeling at Ventisquero Negro and GLOF modeling at Grindelwald, for example, enabled an analysis of erosion and sedimentation processes, and model output visualizations facilitated interpretation of field observations and event reconstruction.

Empirical models depend on parameter calibration, whereas physical models represent processes on the basis of physical principles such as mass and momentum conservation. However, even sophisticated physical models are rarely capable of accurately simulating extreme flow events, thus model calibration is essential (Walder and Costa, 1996; Tingsanchali and Chinnarasri, 2001). Although model calibration is common under laboratory conditions (e.g. Balmforth, 2008), such an approach has limited application in the real world. Ideally, models have to be fully calibrated and validated with high-quality field data (Carrivick et al., 2009). However, the number of well documented past 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 determined using a past GLOF event in Tajikistan. Sediment transport and dam breach parameters used in BASEMENT were determined from the Ventisquero Negro moraine failure and were then applied for modeling dam breach scenarios in the Indian Himalayas.

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

5.2 Scenario modeling

Although the definition of scenarios is inherently arbitrary, this key element in deterministic modeling of natural hazards must be carefully evaluated. For example, a scenario of heavy rainfall should be based on past meteorological records, whereas the scenario definition of a potential mass flow into a lake requires morphologic, geotechnical and/or glaciological investigations. To define reasonable lahar scenarios, one must investigate volcanic history and consider potential volcano-ice interactions. Yet, determination of triggers and event magnitudes, and forecasting when events will occur remain problematic (Haeberli et al., 2010). To minimize uncertainties, it is crucial that the remaining model input parameters be based on physical principles and field measurements. Thus credible scenario modeling requires a previous field survey to provide appropriate input data.
An alternative approach to defining single (e.g. worst-case) scenarios is modeling a range of realistic initial conditions between best and worst cases. This approach was used to model the lahars scenarios at Nevado del Huila and Tolima and GLOF scenarios in the Indian Himalayas. In addition to different initial conditions, a range of input parameters (e.g. dam composition), topographic inputs (e.g. DEMs) and flow types (water-sediment flows/debris flows) can be applied in modeling, as it was done in Khavrazdara, Tajikistan. Modeling different flow types may require different modeling tools for the simulation of different rheologies. The result is a set of model outputs representing a realistic range of potential extreme flow events, and follows the idea of a probabilistic modeling approach. Defining a realistic range of model outputs is an appropriate approach for estimating process magnitudes, probabilities of impact, maximum velocities and travel times of extreme flows (Mergili et al., 2011).

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). In a multi-hazard analysis all relevant hazards in a region are considered and possible interactions and cascading effects between hazardous processes are taken into account (Delmonaco et al., 2006). Different software tools (e.g. HAZUS (FEMA, 2008), RiskScape (Reese et al., 2007) and CAPRA (CEPREDENAC et al., 2011)) exist to compute sequences of natural hazard processes and facilitate the performance of multi-hazard analyses. Kappes et al. (2011a), for example, applied the MultiRISK tool (Kappes et al. 2011b) to investigate the risk of river damming by landslides and subsequent catastrophic dam breaching in the Barcelonnette watershed, France. For this purpose zones susceptible to shallow landslides were modeled and overlaid in a GIS with the water courses, yielding zones potentially prone to damming.

Multi-hazard simulations primarily focus on risk reduction rather than on physically based, dynamic process modeling. In the latter field, important advances have been made in model development and application to simulate complex processes of extreme flow events (e.g. Bajracharya et al., 2007; Procter et al., 2010; Worni et al., 2012a, 2012b). Comparably little work, however, has been done on modeling cascades of processes, and program codes for dynamic, integral modeling are scarce.

There are three feasible approaches for dynamic, integrated modeling of process chains in natural hazards: 1) Specific processes within a process chain are modeled, and model outputs of one process are used at each subsequent step as model input. As an 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. The dam breach model calculates a lake outflow hydrograph, which serves as a basis for initial conditions of a flow model. The advantage of such an approach is that the most appropriate model can be applied at each step in the modeling exercise. Disadvantages are that model outputs may not exactly fit the required model input: A hydrograph of a dam-over-topping flow derived from a tsunami model, for example, does not represent the real motion of waves at the dam, and its use in an erosion-based dam breach model is therefore inaccurate.

(2) Existing models are adapted to simulate process chains within a single model run. Using such an approach, not all processes may be represented as state-of-the-art, but transitions between different processes are smoother and closer to reality. A practical advantage is that only one program is used, thus the approach is more cost- and time-effective. The use of BASEMENT to model a typical GLOF process chain (Chapter 3.4) has provided promising results in the context of other studies (Wang et al., 2008; Osti and Egashira, 2009). It is one of the most complete and integral GLOF modeling approaches.

(3) The two approaches outlined above are only approximations of real integral modeling. It is preferable to unite the most appropriate models into a single integrated model to simulate process chains of extreme flow events. For this purpose program codes of existing models would be required and interfaces would be needed in a new model. Few models offer such solutions, although a variant of the BREACH model was implemented in FLO-2D.

The performance of multi-hazard simulations and dynamic process chain modeling must be evaluated in a series of single steps, therefore the modeling procedure is inherently time-consuming, data requirements are large and computing power is intensive. Modeling of process chains is challenging, as also uncertainties in the process cascade, which grow along the process chain (Haeberli et al., 2010), rendering model results more sensitive to errors. Thus, when attempting to model a process chain, interpretation of the results is as important as the modeling itself.

6. Conclusions and perspectives

Extreme flow events in high mountain regions are a growing threat; in extreme cases, they can kill hundreds, or even thousands of people. Changes in temperature, precipitation, glacier cover or permafrost due to recent and continuing atmospheric warming are shifting hazard zones beyond their historical limits, and empirical knowledge must be supplemented by improved process understanding and modeling. Extreme flow events are characterized by dynamic and interconnected behavior; processes cannot be treated discretely, but rather as components of

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1 Dam breach triggers such as piping, melt of internal ice or 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).
integral systems and process chains. This issue has been recognized, but interconnection and interactions among processes are still rarely taken into account when modeling natural hazards. To fill this gap, useful simulation tools have been developed recently to assess in a holistic manner different types of natural hazards (multi-hazard analyses). Another approach focuses on dynamic modeling of entire process chains. Besides illustrating existing and feasible modeling methods, our aim in this paper was to give impulse to further develop physically based, dynamic process chain modeling in the natural hazard community. Completely new program codes are not necessarily required to achieve this goal, but interfaces must be created to connect models to simulate coupled events. This approach allows the complex nature of extreme flow events to be considered in an integrated manner and would result in advanced process analyses and hazard assessments. Nevertheless, thorough documentation of real events remains crucial for process comprehension and modeling, and lessons learned from past case studies are the basis for reducing the impact of future disasters.

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References


5. Synthesis, discussion and outlook

5.1 Summary and main findings

Chapter 4.1: Numerical Modeling of Flows and Falls

A wide range of programs currently exists for modeling mass movements. Thereof we provided a selective overview by presenting different approaches for modeling flows (e.g., debris flow and hyperconcentrated flow) and falls (e.g., rockfall). This paper assembles a selection of modeling techniques and programs and aims at identifying possibilities and limitations in reproducing highly dynamic processes of flows and falls. As a first approach, the energy-line principle is widely applied, but not all flow and fall processes can be simulated with this rather simple method. Therefore, dynamic, process-based models have been developed, each one adapted to specific mass-movement problems. The energy-line principle and models based thereon are explained, as well as modeling problems presented. Then, dynamic models are introduced, which are used to describe flows with equations of motion and continuity. Representative case studies are provided also for such dynamic modeling approaches. Rockfall is often modeled by trajectory models, which are explained theoretically and illustrated with an applied example.

Chapter 4.2: Challenges of modeling current very large lahars at Nevado del Huila Volcano, Colombia

Between 1994 and 2008, four very large lahars were recorded from the glacier-covered Nevado del Huila Volcano in the south of Colombia’s Cordillera Central. Three of them had volumes between ca. 70 and 300 million m$^3$ and devastated heavily the downstream valleys. The complex flow behavior and changing flow rheologies made lahar modeling challenging. The semi-empirical model LAHARZ and the physically based hydraulic model FLO-2D were calibrated on past lahar events from Nevado del Huila, and model outputs helped to reconstruct the April 2007 lahar. Especially the reconstruction of the flow hydrographs was an important contribution for the understanding of this lahar. Inundation depths calculated with FLO-2D and LAHARZ differ by 25% and 35%, respectively, from measured depths of the 2007 lahar event. The calibrated
models could then be applied to model potential future (worst-case) scenarios, which provide essential data for risk reduction measures.

Chapter 4.3: Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina).

The moraine dam of the proglacial Ventisquero Negro lake, Patagonian Andes, Argentina breached catastrophically in May 2009 and devastated the downstream valley. The dam breach trigger, breaching and lake emptying processes, plus the dynamics of the outburst flood were reconstructed based on field evidence and the application of the dynamic, erosion-based dam break model BASEMENT. Field measurements provided on the one hand valuable input data for the dam breach and lake outburst simulation, on the other hand allowed calibration and testing the dynamic BASEMENT model. Model outputs provided detailed insights into dam breach mechanisms that are difficult to observe in nature and model results are largely consistent with the real case conditions. Based on field evidence we concluded that the moraine failure was caused most probably by a rising lake level due to heavy precipitation. This resulted in high lake outflow which led to dam erosion and finally to dam failure. Model results indicate that the lake volume of ca. $10 \times 10^6$ m$^3$ was released in ca. 3 h, producing high-discharge flows of ca. 4100 m$^3$ s$^{-1}$.

Chapter 4.4: Glacial lake outburst floods in the Pamir of Tajikistan: Challenges in prediction and modeling

This paper explores the potentials and limitations of modeling potential future GLOF events from glacial lakes in the Pamir, Tajikistan. The general objective of the study was to elaborate a way to estimate GLOF travel distances and travel times. Since the flow behavior of potential GLOFs has to be expected in between debris flows and water floods, different model approaches and flow models were applied. RAMMS as a mass-movement model and FLO-2D as a river hydraulics model were employed comparatively for the same areas. The rheologic parameters for FLO-2D were first calibrated on a past GLOF event in Dasht (Tajikistan), and friction parameters in RAMMS were adjusted such that the flow reached the floodplain. The models were then applied for scenario-modeling. In general, RAMMS predicts higher values of flow depth in the uppermost section of the flow path, which is due to the sudden release of the mass in RAMMS. In contrast, FLO-2D makes use of an input hydrograph that distributes the release volume over a given time period, leading to lower flow depths for given total volumes, and can therefore better reproduce a dam failure due to progressive incision.
Chapter 4.5: Glacial lakes in the Indian Himalayas – from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes

In contrast to other regions of the Hindu Kush Himalayas, comparably little attention has been given to glacial lake hazards and glacial lake distributions in the Indian Himalayas. This paper presents a first area-wide glacial lake inventory, including a qualitative classification at 251 glacial lakes >1 ha. In addition, three glacial lakes, from different geographic and climatic regions within the Indian Himalayas, were selected for a detailed risk assessment. For this purpose we followed a multi-level approach from basic detection of glacial lakes over large areas, an assessment of hazard potential of detected lakes, to local-scale risk assessment of individual lakes. Risk assessments of individual lakes are based on field survey and lake outburst scenario-modeling with the BASEMENT model. The glacial lakes analyzed in the states of Jammu and Kashmir and Himachal Pradesh were found to present moderate risks to downstream villages, whereas the lake in Sikkim severely threatens downstream locations. Model results indicate that for this lake a dam breach could cause an outburst flood with a volume of ca. $16 \times 10^6$ m$^3$ and a maximum discharge of nearly 7000 m$^3$ s$^{-1}$. The identification of critical glacial lakes in the Indian Himalayas and the detailed risk assessments at three specific sites allows prioritizing further investigations and helps in the definition of risk reduction actions.

Chapter 4.6: Extreme flow events in mountainous regions – advanced approaches to model processes and process chains

Extreme flow events are often characterized by dynamic and interconnected processes and therefore integral systems and process chains must be considered. Different case studies of past and potential future extreme flow events that are characterized by cascading processes were identified and specific modeling approaches are presented. Different programs were introduced to simulate single processes of a typical process chain of GLOFs, i.e. (i) impulse wave generation by mass flows into a lake; (ii) dam overtopping and dam breaching; and (iii) lake emptying and flood propagation. Further we present an integral modeling approach for dynamic modeling of entire process chains. For this we adapted the simulation setup with BASEMENT to model GLOF scenarios in a single modeling chain from lake impact, to dam breaching and flood propagation. Besides the illustration of existing and feasible novel modeling methods, the aim was to give impulse to further develop physically-based, dynamic process chain modeling within natural hazards.

5.2 Overall discussion

The physics of high-magnitude flows and mechanisms of erosion, sediment transport and deposition are poorly understood, and remain largely unquantified (Carrivick, 2006). It is
therefore elementary to improve our knowledge of extreme flow events and their triggering processes through the study of well-characterized events and the application of numerical modeling techniques (Carrivick et al., 2009). The quantification of relevant flow and sediment transport processes are essential for hazard assessments and risk reduction (Worni et al., in review). This thesis provides crucial insights into complex processes of extreme flow events by using field- and modeling-based reconstructions of important past events. Sophisticated applications of existing modeling tools and novel approaches to simulate entire process chains are the basis for the improvement of future hazard assessments. Nonetheless, important gaps persist in the process understanding and the simulation of very large water-sediment flows, in the order of several tens to hundreds of millions of cubic meters, and complex dam breach events remains a big challenge.

The hydraulics of water floods are quite well understood and model results can therefore be considered as confident. However, when critical amounts of sediments are entrained into a flow, process descriptions are partly based on empirical laws. Therefore, the simulations of hyperconcentrated flows and debris flows are normally more inaccurate compared to the modeling of pure water flows. Yet, under real case conditions, sediment transport should not be neglected and furthermore, a constant changing flow rheology and flow transformation between different flow types are common for extreme flow events. Bulking and debulking processes imply that also the moving volume of the flow varies which has a direct impact on flow spreading and reach (Mergili et al., 2011). These effects render modeling a real challenge and currently no program exists that would cope with such situations. A reasonable approach to face this problem is to simulate a range of possible flow types and present different (likely) model outputs. In addition, the confidence of model results increases when testing models with data from similar past events and calibrate on them critical input parameters.

Yet, for scenario modeling the biggest uncertainty often lies in the scenario definition itself, which is inherently based on assumptions. While the motion of a flow in a given terrain is predictable to a certain extent, the knowledge about the onset or trigger of a process is often limited. For GLOFs, for instance, the lake bathymetry is often unknown and the expected volume of water involved in an outburst flood is normally unclear. Again, a range of likely scenarios (e.g. different volumes and discharges) can be modeled, and finally various results between best and worst case are presented. An alternative strategy is to include preceding processes of a process chain in the simulation. By including a lake impact (leading to an outburst flood) into the model setup, assumptions regarding the lake outburst volume can be avoided, as this is calculated by the model. However, in such approach the scenario definition is shifted to the previous step, i.e. the definition of the lake impact scenario. Nevertheless, such a proceeding is meaningful, because extreme flow events are often characterized by cascades of processes, and integrated system approaches represent in most cases better the reality than a treatment of isolated processes. The modeler must be, however, aware, that in process chain modeling also uncertainties cascade, i.e. get larger along the process chain (Haeberli et al., 2010) and render model results more sensitive to errors. Hence, on one hand it is preferable to account for as many
processes as possible in the model setup, in order to minimize arbitrary assumptions; on the other hand, each process added will entail its own error, which cascades in the models and thus uncertainties of model outputs may increase. This discrepancy should, however, not inhibit efforts to assess natural hazard processes with integral (modeling) approaches, but the awareness and an appropriate communication of uncertainties is crucial.

In chapter 4.4, lake outburst hydrographs (which are the model’s initial conditions) were estimated and they define different realistic outburst scenarios. Here the main uncertainties lied in the appropriate definition of scenarios and to a lesser extent in the actual flow modeling. For GLOF scenario modeling in the Indian Himalayas (chapter 4.5) the BASEMENT model was used to simulate a typical process chain within a single model run (i.e. (i) impulse wave generation by mass flows into the lake and wave propagation over the lake; (ii) dam overtopping and dam breaching; and (iii) lake emptying and flood propagation). Scenario definitions of potential mass movements (e.g. ice and snow avalanches, rock fall, debris flows) into the lakes were partly based on morphological and glaciological considerations, which is more accurate than a direct prediction of outburst hydrographs. Nevertheless, even the reproduction of lake impact, impulse wave generation, dam erosion and flood propagation with sophisticated, dynamic models represents approximations to real case conditions. This is why model calibration and testing on past real case events is important as this provides information on model behavior and deviations from reality.

Process modeling is data and time intensive and cannot therefore normally be applied over large regions to simulate all potential extreme flow events. Prioritization is necessary to define cases on which process modeling should focus on, in order to assess potential risks. For this purpose potential hazard sources must be identified, which may be relevant if also damage potential exists in the reach of possible flow events. In terms of glacial lake hazards, glacial lake inventories provide first information of potential hazard sources. Further assessment is then required to categorize the detected lakes and to define high priority lakes for which outburst scenarios should be modeled. For volcano hazards normally more profound studies are required to assess the hazard potential. Volcano histories and extensive volcanological investigations are required to provide information about outburst probabilities and potential lahar hazards.

5.3 Conclusions and perspectives

All research papers that are part of this thesis deal with a variety of natural hazard processes and the challenges of modeling processes and process chains of extreme flow events. The overall goal was (i) to improve the understanding of such complex processes through the reconstruction of past events and the interpretation of model results, and (ii) the advanced application of existing modeling tools to simulate various aspects of extreme flow events.
Flow hydrographs and important flow parameters such as flow rheologies, flow velocities and inundation depths could be reconstructed for lahars from Nevado del Huila Volcano (Colombia). This formed the basis for FLO-2D and LAHARZ model calibration and to simulate finally potential future lahar scenarios. The latter provide important data for risk reduction actions in the downstream valleys. Through the retrospective modeling of the dam failure at Ventisquero Negro glacial lake (Argentina), key parameters such as outflow hydrograph, flow velocities and bottom shear stresses could be quantified. Field based reconstruction of the dam breach event allowed calibrating and testing the BASEMENT model, which was then applied for simulating potential GLOF scenarios in the Indian Himalayas. Besides a first detailed risk assessment of three critical glacial lakes in different regions of the Indian Himalayas, this paper also provides the first area wide glacial lake inventory with a rough classification of the detected lakes in the Indian Himalayas. This is the basis for further monitoring the hazard potential of existing glacial lakes and allows prioritizing lakes, which require further investigations and risk assessments. Outburst scenario modeling of different glacial lakes in Tajikistan provided important data within the TajHaz project, necessary to plan concrete adaptation and mitigation measures. For these lakes so far no detailed risk assessments existed, which is an important contribution to avoid resettlements of local people to the lowlands. Chapter 4.1 and 4.6 finally present and discuss state-of-the-art modeling approaches for the simulation of different types and processes of extreme flow events. In chapter 4.6 advanced integral modeling techniques are presented for the simulation of cascading processes, which are typical for many natural hazards.

Based on the current state of research and the findings of this thesis, research topics that should be addressed in the future are outlined in the following.

- In order to reduce uncertainties of model results and to further improve the quality of model output, more studies on very large flow events are needed. Material entrainment has shown to be a crucial factor in lahars, as it controls flow behavior and renders numerical modeling more difficult and uncertain. Further research should, therefore, focus on lahar modeling in settings where sediment transport is a flow dominant component (Worni et al., 2012a).
- Future challenges for modeling flows and falls are to develop more complete descriptions of the physical processes active during mass movements and to link them to true, physical properties measurable in the field (Worni et al., in press a).
- The application of erosion-based, dynamic dam break models on real case events is still in the early stages of development. Advances in this field of study is essential, as a proper modeling technique of moraine breaching is crucial to assess the hazard situation of existing glacial lakes, which to date is often limited to qualitative studies (Worni et al., 2012b).
- The BASEMENT model seemed to reproduce the lake outflow hydrograph accurately and we therefore suggest that it could be implemented systematically in the future to define outburst scenarios for unstable moraine-dammed lakes (Worni et al., 2012b).
- More investigations on moraine failure processes and dam break model applications are needed to further improve the quality of model output and other trigger mechanisms, such as
overtopping impact waves, should be included in dam break modeling. This can provide information on the conditions under which dam failures occur, both in the model environment and reality (Worni et al., 2012b).

- It is known that melting ice cores in moraines make dams more susceptible to failure and therefore, with ongoing climate change GLOF potential may increase. Several situations similar to Ventisquero Negro exist and in order to accurately assess GLOF risks, further research should focus on dam break modeling where the effect of ice is considered (Worni et al., 2012b).

- Many natural dammed lakes burst out within a short time after their development without being detected as potential source of hazard (Narama et al., 2010). Therefore, continuous monitoring is required to keep updated on the existing hazards (Mergili et al., 2011).

- The existence of Spong Togpo and Gopang Gath glacial lakes in the Indian Himalayas is hardly known to local people and therefore awareness building in villages downstream of critical glacial lakes should become a priority action (Worni et al., in press b).

- Apart from potential hazard sources, glacial lakes can also have touristic potential (e.g. Samudra Tapu lake in the Chandra Valley, HP), and when considering glacial lake patterns and characteristics over large regions, glacial lakes can be used as indirect climate and glacier change indicators (Worni et al., in press b).

- Uncertainties which potentially affect model results exist in the digital elevation model (DEM) which is in most cases the basis to reconstruct the model domain. The resolution and accuracy of the DEM is correlated to the accuracy of model results (Wang et al., 2012), which is especially pronounced for advanced numerical models such as BASEMENT. Therefore a lack of recent high resolution elevation data from many remote high mountain regions in the world remains a limiting factor in representing complex flow and dam breach dynamics (Allen et al., 2009). Further improvement of DEMs would enhance significantly the model results as the topography in computation would be more accurately reproduced. Yet, this necessitates at the same time smaller mesh sizes, which requires higher computing power. (Worni et al., in press a; Worni et al., in press b).

- When modeling future scenarios, scenario definition often bears the biggest uncertainties. The definition of scenarios, which are the model’s initial conditions, imply e.g. estimation of released water amount, water content in a sliding mass, block sizes and shapes of falling rocks, or the volume of erodible material in a channel or a natural dam. These uncertainties cannot simply be reduced by increasing the computing power, input parameter quality or physical knowledge. An approach in modern natural hazard assessments is therefore to use an integral modeling technique, meaning to reproduce as many as possible involved or precedent process elements of an event. Such an integral modeling approach would highly reduce arbitrary assumptions and account for important cascading processes that typically produce the largest catastrophes (Worni et al., in press a).

- Besides the illustration of existing and feasible novel methods in the field of integral modeling approaches, the aim was to give impulse to further develop physically-based,
dynamic process chain modeling within natural hazards. For this, not necessarily completely new program codes need to be developed, but real interfaces between existing models must be created in order to interconnect specific models to one system for the simulation of distinct coupled events. This allows accounting for the complex nature of extreme flow events in an integrated approach and would result in advanced process analyses and hazard assessments (Worni et al., in review).
References


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- Remote sensing-, field work- and modeling based hazard assessments of existing glacial lakes in the Indian Himalayas and Tajikistan and of a volcano in Colombia.
- Calibration and validation of dam breach and hydrodynamic modeling tools.
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Project assistant
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