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Landslides and New Lakes in Deglaciating Areas: A Risk Management Framework

Yvonne Schaub, Wilfried Haeberli, Christian Huggel, Matthias Künzler, and Michael Bründl

Abstract

New lakes forming in high-mountain areas due to climate-driven glacier shrinkage are likely to be located in areas of potentially unstable slopes. Therefore they are prone to impacts from rock/ice-avalanches and other types of landslides, which might trigger outburst floods causing damage farther down valley. In view of an integral lake management, a risk management concept for the Swiss Alps is proposed in this study, which consists of risk analysis, risk evaluation and the integral planning of risk reduction measures. The pertinent question is how risk, resulting from natural hazard process chains involved with landslides and new lakes, can be assessed. The present knowledge basis together with currently available models, methods and tools is herein reviewed. Knowledge gaps are mainly identified in the determination of future landslide detachement zones and in the evaluation of changes in landuse and damage potential.

Keywords

Integral lake management • Natural hazards • Rock failure • Glacier lake outburst floods • Landuse change • Risk assessment

High-Mountain Lakes in a Changing Environment

Glaciers worldwide are shrinking at an accelerating rate as a consequence of climate change (Kaser et al. 2006; Solomon et al. 2007; Zemp et al. 2009, 2008). Correspondingly, the volume of the Alpine glaciers is annually decreasing by 2–3 % (Haeberli et al. 2007). Relying on realistic warming scenarios, 75 % of the glaciated area of the end of the twentieth century could vanish by the middle of this century (OcCc 2007; Zemp et al. 2006).

To illustrate this effect, first deglaciation scenarios for the entire Alps have been modeled by Haeberli and Hoelzle (1995). In the meantime more detailed models for large glacier ensembles have been developed (Paul et al. 2007; Zemp et al. 2006). New approaches allow the digital calculation of the terrain of the Swiss Alps without glaciers (Farinotti et al. 2009; Huss et al. 2008; Linsbauer et al. 2009). A method to model the glacier bed material is also available (Zemp et al. 2005). Taking these terrain models as a basis, GIS-based models show that at certain locations retreating glaciers uncover overdeepenings. These overdeepenings are considered as potential sites of future lakes (Fig. 1) (Frey et al. 2010b; Linsbauer 2008). So far, glacier lakes have mainly received scientific attention in terms of outburst floods (Clague and Evans 2000; Haeberli et al. 2010a; Hubbard et al. 2005). Such glacier lake outburst floods have the potential to wreak havoc; several severe events have been reported (Haeberli et al. 2010c; Hancox et al. 2005; Korup and Tweed 2007; Reynolds 1998; Richardson and Reynolds 2000; Vuichard and Zimmermann 1987).

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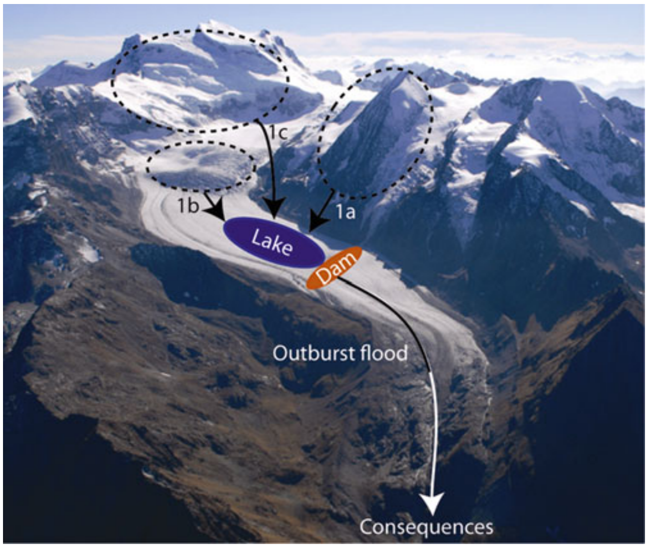

Fig. 1 Scheme of the investigated process chain, illustrated with the example of the potential future lake Corbassière, Switzerland. *Dashed lines* = possible detachment zones of rock- (*1a*), ice- (*1b*) or combined rock/ice-avalanches (*1c*). Picture: U. Bläsi (www.airbox.ch/air/)

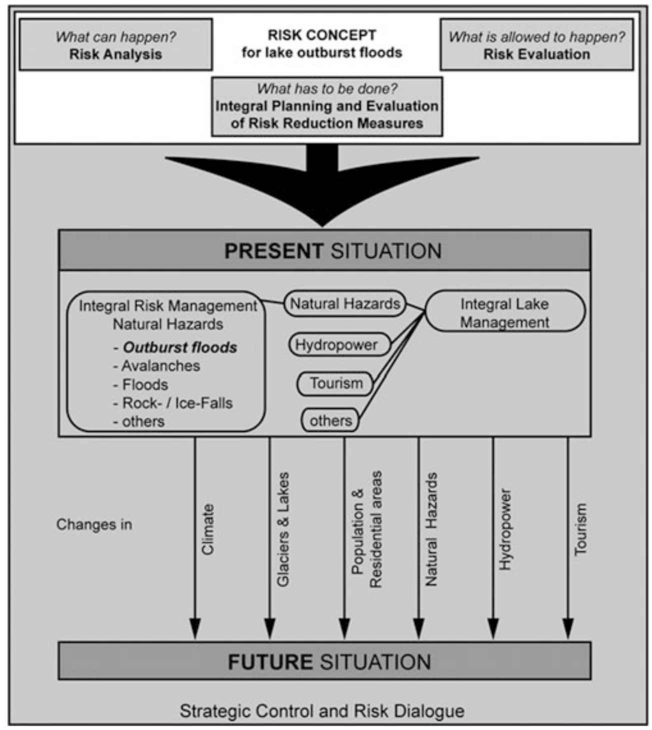

Fig. 2 The concept of integral lake management

Reducing newly forming high-mountain lakes to a hazard source would be inappropriate, as such lakes not only pose risks but may also offer opportunities, for example for hydropower generation or as a tourist attraction. This study proposes the development of a framework for an integral lake management (IM) in order to equally assess chances and risks posed by new high-mountain lakes. The main focus of this publication is thereby on integral risk management (IRM) regarding natural hazard process chains, such as landslides impacting lakes and triggering destructive outburst floods (Fig. 1). The research question is: What information exists to assess the risks resulting from future high-mountain lakes through impacts of rock/ice-avalanches? The results will be discussed in the context of IM and knowledge gaps will be identified. Although generally applicable, the approach presented here was developed for the situation in the Swiss Alps and illustrated using a case study of a potential new lake at Corbassière glacier (Valais, Switzerland).

Integral Lake Management

Application of the Concept of Integral Risk Management for Impact Waves from Rock/Ice-Avalanches

IRM is one of the aspects of IM, which correspondingly implies all possible kinds of hazards (Ammann 2004). The conceptual use of IRM is widespread, and Switzerland has taken a leading position worldwide regarding the implementation into practice (Bischof et al. 2008; DARA 2011).

The core of IRM is the risk-concept, which consists of the risk analysis, the risk evaluation and the integral planning of measures (Fig. 2). The following general definition of risk is the basis for the risk analysis (Bründl et al. 2009):

$$r_{ij} = p_j \times p_{ij} \times A_i \times V_{ij} \quad (1)$$

$$R = \sum r_{ij} \quad (2)$$

where r_{ij} = risk of object *i* in scenario *j*; R = societal risk; p_j = frequency of a hazardous process depending on scenario *j*; p_{ij} = probability of object *i* being affected by hazardous process depending on scenario *j*; A_i = value or type of object *i* and V_{ij} = vulnerability depending on object affected *i* and on scenario *j*.

The eventuality of a rock/ice-avalanche triggering an impact wave is often underestimated, even though historical ice or rock/ice-avalanches are documented (Huggel et al. 2002a; Raymond et al. 2003). Recent cases of impacts into lakes have also been reported (Fischer 2009; Haeberli et al. 2010b; Kershaw et al. 2005). In Fig. 3 an assessment scheme regarding the scenario of a lake outburst flood due to an impact wave triggered by a rock/ice-avalanche is presented. For the assessment, use can be made of existing knowledge or similar case studies, for example the assessment of a tsunamigenic rockslide in Åknes, Norway (Eidsvig et al. 2011; Lacasse et al. 2008) or the hazard analysis of glacier lake outburst floods in Bhutan (Richardson and Reynolds 2000).

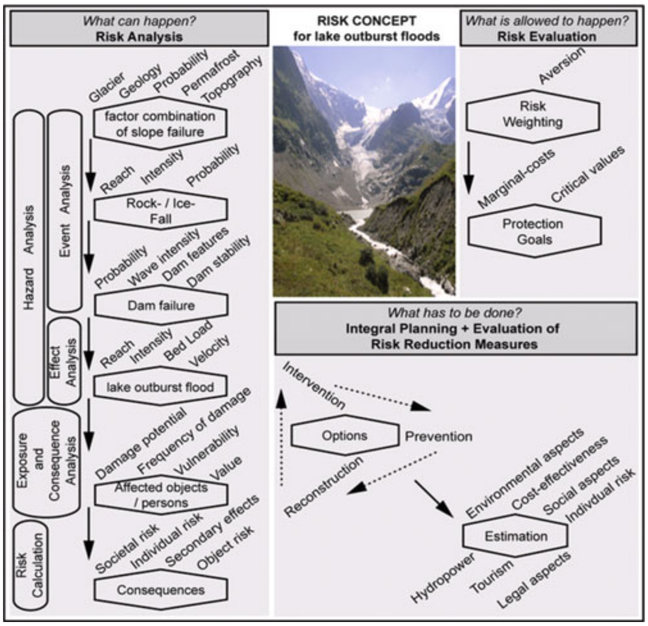

Fig. 3 The risk concept adapted to the question of glacier lake outburst floods

Risk Analysis

Standards for assessing glacier-related hazard potentials in high-mountain regions are well developed (Haeberli et al. 1989, 2006; Huggel et al. 2004, 2005; Kääb et al. 2005). For instance, a multilevel strategy for anticipating lake formation and hazard potential has been elaborated elsewhere (Frey et al. 2010a). Methods for hazard assessment of potential ice-avalanches using remote sensing and Geographic information systems are also available (Huggel et al. 2002b; Salzmann et al. 2004).

In an event analysis (Fig. 3), critical factors have to be identified, in order to estimate the susceptibility of a slope to failure. In Table 1, an overview of recent studies summarising the most important factors influencing slope stability is provided. Permafrost distribution, as one factor affecting slope strength, can be estimated based on simulations of surface and subsurface thermal conditions (Nötzli and Gruber 2009; Nötzli et al. 2007). In Switzerland a permafrost map is officially available (Gruber et al. 2006). Based on the evaluation of different factors, potential detachment zones can be identified, followed by the assessment of the runout distance of a potential rock/ice-avalanche. Widely used approaches consider the angle of reach for both, rock-avalanches (Evans and Clague 1994; Heim 1932; Nötzli et al. 2006; Romstad et al. 2009; Rothenbühler 2006) and ice-avalanches (Huggel et al. 2004; Rothenbühler 2006). Avalanche volume, ice content, sliding over a low-friction glacier surface or flow transformation into more mobile debris flows influencing the runout distance and the extent of impact can be assessed (Schneider et al. 2011). Romstad et al. (2009) have developed a GIS-based rock-avalanche runout-approach, which can be applied in alpine conditions. In addition to magnitude, the frequency is an important determinant of landslide hazards (Raetzo et al. 2002). Landslide frequency is influenced by factors such as topography, rock strength and structure, proximity of glaciers or presence of permafrost (Fischer 2009; Gruber and Haeberli 2007; Harris et al. 2009). In the case of ice-avalanches, the glacier type (cliff or ramp) is an important factor determining avalanche volume and frequency (Alean 1985; Huggel et al. 2004). Probability distributions of all type of landslide volumes (Brunetti et al. 2009) and relationships between magnitude and frequency (Korup and Clague 2009) have been established and can be used as references. Hazard assessment schemes that integrate several of the aforementioned steps into a comprehensive approach are particularly useful for the purpose of this study. Frattini et al. (2008) presented such an assessment scheme for rockfall, applying the HY-STONE code (Agliardi and Crosta 2003) for rockfall modeling. Santi et al. (2009) explain a rockfall hazard rating system. For ice-avalanches, aprroaches were presented by Margreth and Funk (1999) and by Wegmann et al. (2004). These approaches provide valuable input for estimations of rock/ice-avalanches, but the most generic assessment procedure for several types of glacier hazards was developed by Huggel et al. (2004).

Once it is assessed that a rock/ice-avalanche potentially can reach a lake, the effect of the landslide impact into the lake has to be estimated. Research on impulse waves dates back to Russel (1837). More recent developments are presented by Heller et al. (2008) and Zweifel and Minor (2004). Approaches to assess the effect of impact waves from landslides include: (a) empirical formulas, that have been established based on laboratory tests and field observation, (b) 1D models, which have been developed based on Saint-Venant or Bussines equations simulating the evolution of waves in space and time, (c) 2D models, which are required for more appropriate results. Normally they are also based on Saint-Venant equations (Leveque 2006), (d) 3D experiments, which further allow the modeling of the runup waves generated by landslides (Di Risio et al. 2009).

As an impact wave will hit the shoreline, the dam conditions of the lake have to be investigated for every case. Costa (1994) and Costa and Schuster (1988) presented a general survey on features of artificial and natural dams and on possible causes for their failures. The most common types of natural dams in high-mountain regions are ice dams, moraine dams, landslide dams and bedrock dams. Lakes in deglaciating areas are usually enclosed by moraine and bedrock dams. In order to estimate the susceptibility of moraine dams to failure, Huggel et al. (2004) and Xin et al.

Table 1 Factors mentioned in literature, which define the location of possible detachment zones of rock/ice-avalanches

Rock-avalanches		
Factor		Source
Topography	Gradient	(Fischer 2009; Frattini et al. 2008; Gruber and Haeberli 2007)
	Elevation	(Fischer 2009; Gruber and Haeberli 2007; Nötzli et al. 2003)
Geology	Transition zones	(Fischer 2009; Frattini et al. 2008; Gruber and Haeberli 2007)
	Lithology	(Fischer 2009; Frattini et al. 2008)
Hydrology	Fluid pressure	(Fischer 2009)
Glacier	Proximity	(Fischer 2009; Haeberli et al. 1997; Wegmann et al. 2004)
Permafrost	Distribution	(Fischer 2009; Gruber and Haeberli 2007)
	Surface temperature	(Gruber et al. 2004; Nötzli et al. 2003)
	Rock temperature	(Davies et al. 2001; Gruber et al. 2004; Nötzli and Gruber 2009)
Vegetation cover	Absence of vegetation	(Frattini et al. 2008)
Ice-avalanches		Source
Factor		
Topography	Gradient	(Alean 1985; Huggel et al. 2004; Rothenbühler 2006)
Glacier-permafrost	Interaction	(Huggel 2009)

(2008) give an overview on influencing parameters. A few recent approaches have furthermore developed probability-based schemes of dam failure of glacier lakes (Hegglin and Huggel 2008; McKillop and Clague 2007a, b). Moreover a number of numerical models simulating dam breaching do exist. BREACH (Fread 1991) was applied for several case studies, such as in New Zealand (Hancox et al. 2005) or in the Himalayas (Xin et al. 2008). Other programs to model moraine stability are SLOPE/W implemented by Hubbard et al. (2005) for a case study of a moraine dam in Peru and BASEMENT (Faeh 2007; Volz et al. 2010). Khan and Jamal (2000) used a probability approach for dam failure risk assessment, defining estimation factors for dam safety, whereas Lavallee et al. (2000) applied a multicriteria method on the same question.

The next investigation in the risk analysis procedure concerns outburst flood processes. Depending on the sediment entrainment, outburst floods vary within a range of flow rheologies. Different numerical models exist to estimate the reach and the spatial probability of flood occurrence, like MSF (Huggel et al. 2003) or FLO2D (O'Brien 2003). For the estimation of the hydrograph of a lake outburst flood, several empirical equations (Costa and Schuster 1988; Xin et al. 2008) can be considered, along with further quantitative hydrodynamic analysis (Hancox et al. 2005; Jakob and Friele 2010; Osti and Egashira 2009; Xin et al. 2008). The main challenge of our study will be to link these approaches into one framework.

If the hazard analysis indicates that an outburst flood is possible, the consequences farther downvalley have to be estimated. This includes the specification of the damage potential (possibly exposed people, objects or infrastructure) regarding its value, its probability of exposure and its vulnerability to the corresponding hazard scenario. Regarding today's vulnerability values, research has recently seen important progress (Carey 2005; Fuchs et al. 2007; Hegglin and Huggel 2008; Uzielli et al. 2008). In Switzerland these results were partly incorporated into software tools, such as EconoMe (BAFU 2010). However, little is known on how to estimate the vulnerability development of objects in the near future. Some efforts have now been undertaken (IRV 2007), but they did not provide the expected results yet.

Essential for the consequence analysis is the number and the value of possibly exposed objects. Whereas this information can easily be gained for present cases through field survey and census data, assumptions have to be taken for future landuse and settlement areas. These landuse changes can either be modeled by normative approaches, as done in a study in Switzerland (Perlik et al. 2008) or in the project "MOUNTLAND" for the Alpine region (Huber and Rigling 2010). These projections would need to be downscaled to the required local scale and interpreted for the present question. Landuse changes can furthermore be modeled by explorative studies, which refer to a defined region, such as conducted in ALPSCAPE (Walz 2006) or by Rothenbühler (2006).

Based on the accomplished hazard and consequence analysis, the societal risk can be calculated, summing up the risks for each individual person and object (2). Regarding the frequency of a hazardous process (1), it should be considered that high-mountain areas have undergone important climatically related changes and therefore risk assessment for future conditions cannot fully rely on former conditions. Thus, open questions in the risk analysis procedure with respect to future lakes remain regarding the location and characteristics of detachement zones and the probabilities of occurrence of different hazard processes. But also knowledge on changes in landuse and damage potential needs to be further deepened.

Risk Evaluation

Within an IRM approach, the assessed risk needs to be confronted with what is considered an acceptable level of risk. In Switzerland this is on the one hand done by rating the individual risk. A person should not face an individual risk higher than $4 \times 10^{-6} < r_i < 3 \times 10^{-5}$ for involuntarily taken risks, otherwise safety measures are considered the society's responsibility (Bründl et al. 2009). On the other hand the societal risk is analyzed using the concept of "proportional cost". This approach includes the willingness of the society to financially support risk reduction measures, which reduce the risk at proportional costs (PLANAT 2009).

A further weighting of risks by incorporating risk aversion might be adequate. This evaluation considers the phenomena, that rare and extreme events are often perceived as worse than small and frequent events causing the same cumulative amount of loss (PLANAT 2008). Hazardous process chains resulting from high-mountain lakes belong to the processes with high magnitude and low but increasing probability. Their management will further be analyzed regarding the integration of risk aversion.

Risk Reduction Measures

For an integral planning of risk reduction measures, all available measures have to be considered (PLANAT 2004). An overview over possible measures for glacier hazards, such as monitoring and prediction, drainage, tunnel, shelter or road blockage, was elaborated in the framework of the GLACIORISK project (Wegmann et al. 2004). Early warning systems are likely to be among the primary risk reduction measures for future glacier lakes, as they are recognized as a promising combination of technical instruments and human behavior (Huggel et al. 2010). In this regard, it can be drawn on recent experiences such as described in Huggel et al. (2010) or in Medina-Cetina and Nadim (2008). It should be emphasized that for each individual case the most appropriate risk reduction measures have to be evaluated and the public acceptance of measures has to be regarded at an early stage of the planning phase. In view of IM, the potential of risk reduction measures for other purposes (such as hydropower or touristic use) has not been sufficiently addressed yet.

Integral Lake Management: Illustrated with the Case of Lake Corbassière

Here we briefly highlight some aspects of the aforedescribed IM with the example of Corbassière glacier area. As indicated in Fig. 1, a lake is expected to form around the middle of this century with a volume of several tens of million m^3. The lake will be surrounded by several steep slopes with a potential for rock and ice-avalanches that can reach the lake. Glacial bed modeling indicates a rockbed, possibliy covered with some moraine material. Impact waves from landslides are projected to overtop the dam irrespectively of the dam stability and imply an outburst flood. The expected damage caused by the outburst flood depends on the volume and velocity of the landslide impact, and consequently on the amount of overtopping water. In case of a major impact, roads, buildings and other infrastructure in the Val de Bagnes will most likely be affected and consequences even in Martigny (at a distance of about 25 km with a current population of approx. 15,000) cannot be excluded. The effective amount of damage is difficult to assess at this stage, as the future degree of settlement and landuse of the region is not known.

Furthermore, a recent study has shown, that this lake might be interesting for hydropower generation by extending the existing Mauvoisin hydropower scheme (Terrier et al. 2011). In addition, the region is popular for hikers and mountaineers, and therefore the lake might also turn into a tourist attraction. This was for instance recently observed at the lake that formed in front of Trift glacier (central Swiss Alps). Against this background, IM could consist of implementing multi-functional installations, which meet the requirements of all the aspects of lake use (hazard mitigation, hydropower generation and touristic activities) to the degree possible.

Conclusions

Due to retreating glaciers, new lakes have been forming in the last years and further lakes will likely arise in the future in many high-mountain regions worldwide. These lakes will often be located near unstable slopes and will therefore be prone to impacts of rock/ice-avalanches and other landslides. A concept that considers existing knowledge and methodologies as a base for developing a framework for the analysis and evaluation of risks related to glacier lake outburst floods is presented here and outlined on the example of Switzerland. It is proposed to estimate potential risks and opportunities induced by the formation of new lakes in the framework of integral lake management. It is shown, that a good knowledge basis for the determination of present detachment zones as well as tools, methods and models for the investigation of rock/ice-avalanches, dam stability and outburst floods are available. Similarly, several landuse scenarios for Switzerland are known.

Current gaps in knowledge and methods, as well as open question are also pointed out: In order to fully analyze the future hazard potential, efforts have to be made on specifying future areas of potential detachment zones. Their location and characteristics are influenced by morphological changes in high-mountain landscape, by the existence of glaciers and by the climate. The changes and their influence on the probability of processes correspondingly have to be incorporated in the hazard process chain. Risk perception and acceptance, as well as management of low-probability/high-magnitude events have to be considered and will be subject to further studies.

For a regional comparison of the risk and the identification of priority areas, we will focus on the hazards caused by rock/ice-avalanches falling into lakes and the consequences further down-valley. Therefore the evaluation of landuse change and damage potential on a regional scale will also be a field of interest. This includes the downscaling of existing projections to the required local scale.

Another focus will be put on potential sinergies of risk reduction measures with other aspects of lake use, as for example tourism or hydropower.

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