GLOF Risk Management Experiences and Options: A Global Overview

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Summary

The prevalence and impacts of glacier lake outburst floods (GLOFs) in all glacierized mountain ranges globally underlines the importance of GLOF disaster risk management (DRM). A large variety of types of GLOF DRM measures exists, targeting the reduction of the hazard of a potential GLOF, of the exposure, or of the vulnerability of people and infrastructure. A wide range of such measures have been implemented in different mountain regions all over the world since the mid 20th century. While many of these measures have been reported, there are relevant gaps in the systematic documentation, analysis, and evaluation of GLOF DRM measures globally. A comprehensive compilation, classification and evaluation of GLOF DRM measures is required to establish a guidance for best practice approaches. DRM measures aiming at a reduction of the hazard component are typically structural measures, while vulnerability is addressed mainly by nonstructural measures. Hazard and exposure reduction measures cover all temporal ranges from short- to long-term interventions. The design and implementation of GLOF DRM measures is demanding due to harsh environmental conditions, remoteness, and rapidly changing hazard and risk situations on the one hand. Institutional and organizational aspects related to the funding, planning, and implementation of such measures, on the other hand, pose further challenges to successful GLOF DRM.

Keywords: glacier lake outburst flood, GLOF, disaster risk reduction, disaster risk management, risk reduction, hazard reduction, exposure reduction, vulnerability reduction

Subjects: Risk Management, Glacial Lake Outburst (GLOFs)

Introduction

GLOFs have been documented in glacierized mountain regions all over the world (Carrivick & Tweed, 2016; Emmer, 2017). They have caused extensive damage, including, for example, events in Peru (e.g., Huaraz in 1941; Mergili et al., 2020), Central Asia (e.g., Shakhimardan in 1998; Petrakov et al., 2020), the European Alps (e.g., Mauvoisin; Haeberli et al., 1989), and the Himalayas (F. Shrestha et al., 2023). Attempts to reduce the risk emanating from GLOFs began in the early 19th century, for instance, in Europe (Röthlisberger, 1978) and in the mid-20th century in Central Asia (e.g., Medeu et al., 2019, 2020, 2022) and in Peru (Portocarrero, 2014), and they have gained increasing attention in the natural hazard and disaster risk management (DRM) community since then. While research about the late 20th and early 21st centuries' trends in GLOF frequency is not yet fully conclusive (e.g., Harrison et al., 2018; Lützow et al., 2023; Veh et al., 2022), an increase in GLOF frequency can be expected for the future, as glacier shrinkage associated with climate change will give space to an increased number of glacial lakes in regions where slope instability might enhance the likelihood of mass movements (Harrison et al., 2018; Zheng et al., 2021). At the same time, increasing GLOF and other mass movement risk is closely associated with increasing economic development in mountain regions and is high especially in developing countries that lack resources for hazard mitigation and adaptation (Hock et al., 2022). As risks from GLOFs are expected to increase where new lakes develop, and where downstream exposure and vulnerability increases (e.g., Allen, Sattar, et al., 2022), GLOF DRM is increasingly in demand. As such measures may incur huge costs and efforts, and well-informed decision-making is essential for effective, efficient, and sustainable DRM. However, there are relevant gaps in the documentation, analysis, and evaluation of GLOF DRM globally. In this article, reported experiences with GLOF DRM measures from all glaciated mountain ranges in the world are compiled and reviewed to create a comprehensive information base and provide a set of best practice approaches for GLOF DRM. It is systematically analyzed what component of risk the DRM measures target (i.e., hazard, exposure, vulnerability), what type of measures they involve (i.e., structural and nonstructural measures), in what temporal frame they are applicable (i.e., short-, medium-, and long-term), and what their main benefits and challenges are. This work is based on scientific literature where available, as well as gray literature, according to the experience and knowledge of the experts and coauthors of this article.

Concepts and Approach

The United Nations Office for Disaster Risk Reduction differentiates between the terms disaster risk reduction (DRR)—referring to the policy objective of anticipating and reducing risk—and disaster risk management (DRM)—referring to the application of DRR policies and strategies, describing the actions that aim to achieve the objective of reducing risk (United Nations Office for Disaster Risk Reduction [UNDRR], 2016). In this review DRM is used, as it analyzes the specific measures that have been taken to reduce the risk posed by GLOFs.

In the context of climate impacts, risk is defined as the potential for adverse consequences of a climate-related hazard, on lives, livelihoods, health and well-being; ecosystems and species; economic, social, and cultural assets; services (including ecosystem services); and infrastructure (Intergovernmental Panel on Climate Change [IPCC], 2018). Risk results from the interaction of the (a) hazard as a combination of likelihood and magnitude of a potential event, (b) the exposure of any kind of assets including people, and (c) the vulnerability of the affected asset or system (IPCC, 2018). Measures to reduce risk, thus, target the reduction of one or more components of hazard, exposure, or vulnerability (Figure 1).

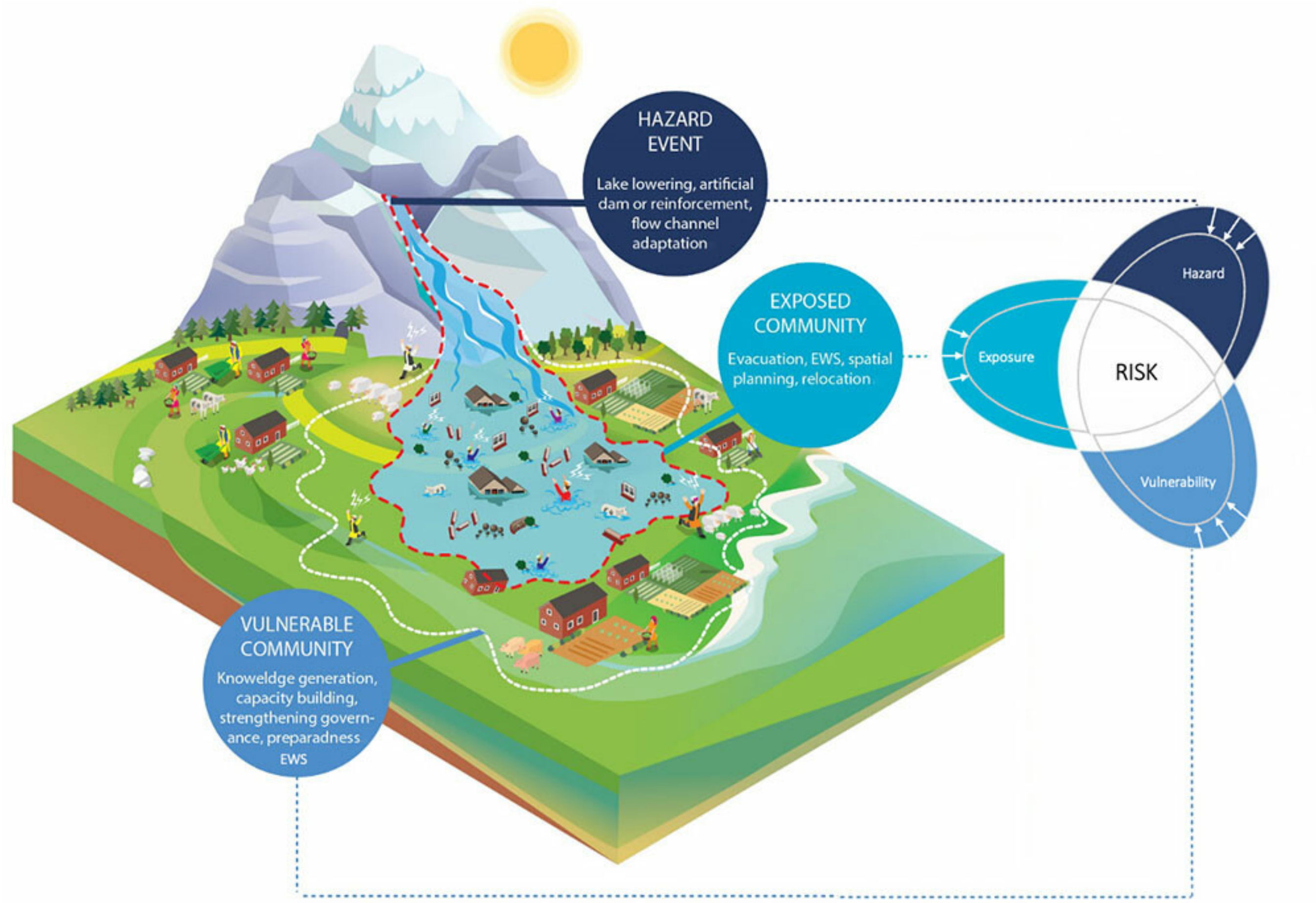

Figure 1. Schematic of the concept of risk with its components (namely, hazard, exposure, and vulnerability) and specific examples of action to reduce those components in relation to GLOFs.

Source: Adapted from Allen et al. (2018).

In this article, GLOF DRM measures were divided into three subchapters according to the risk component they primarily target. Nonetheless, it is important to be aware that many GLOF DRM measures address more than one risk component. For instance, measures targeted at the reduction of GLOF hazard magnitude by default also reduce GLOF exposure. Similarly, structural measures, such as anti-erosion structures and downstream sediment retention dams, that aim to reduce GLOF exposure also influence GLOF magnitude by allowing material entrainment or deposit. Structural measures refer to physical constructions that aim at reducing GLOF hazard or exposure or at achieving resistance and resilience. In contrast to structural hazard reduction measures, structural exposure reduction measures may not necessarily be targeted at a specific hazard but can be used for multihazard events. Nonstructural measures refer to measures not requiring physical construction. They may involve measures based on knowledge, practice, or agreement such as policies and laws, public awareness raising, and training and education, which again may transverse to reduce risk to multiple hazards. The GLOF DRM measures were divided into short-, medium-, and long-term measures in order to categorize them on a temporal scale representing hours or days to weeks, weeks to years, and years to decades, respectively. This refers to the time span over which a measure is operational. Further, it was analyzed for the different DRM measures, where they were practiced and what their advantages, challenges, and problems were (e.g., technical feasibility, energy, monetary cost, social acceptance, bottom-up or top-down processes, etc.). Based on these learnings, recommendations for optimizing the effectiveness of GLOF DRM are provided in the last section on "Major Challenges and Key Recommendations."

GLOF Risk Reduction

A reduction of the risk posed by GLOFs can be achieved through reduction of the GLOF hazard, reduction of the exposure to GLOFs, or reduction of the vulnerability to GLOFs. Figure 2 gives a global overview of the analyzed GLOF risk reduction measures. The following sections on "GLOF Hazard Reduction," "GLOF Exposure Reduction," and "GLOF Vulnerability Reduction" contain subsections on the most commonly implemented measures. These subsections are each organized into a general introduction to the measures, examples of their application, and an analysis of the functionality and challenges of their application.

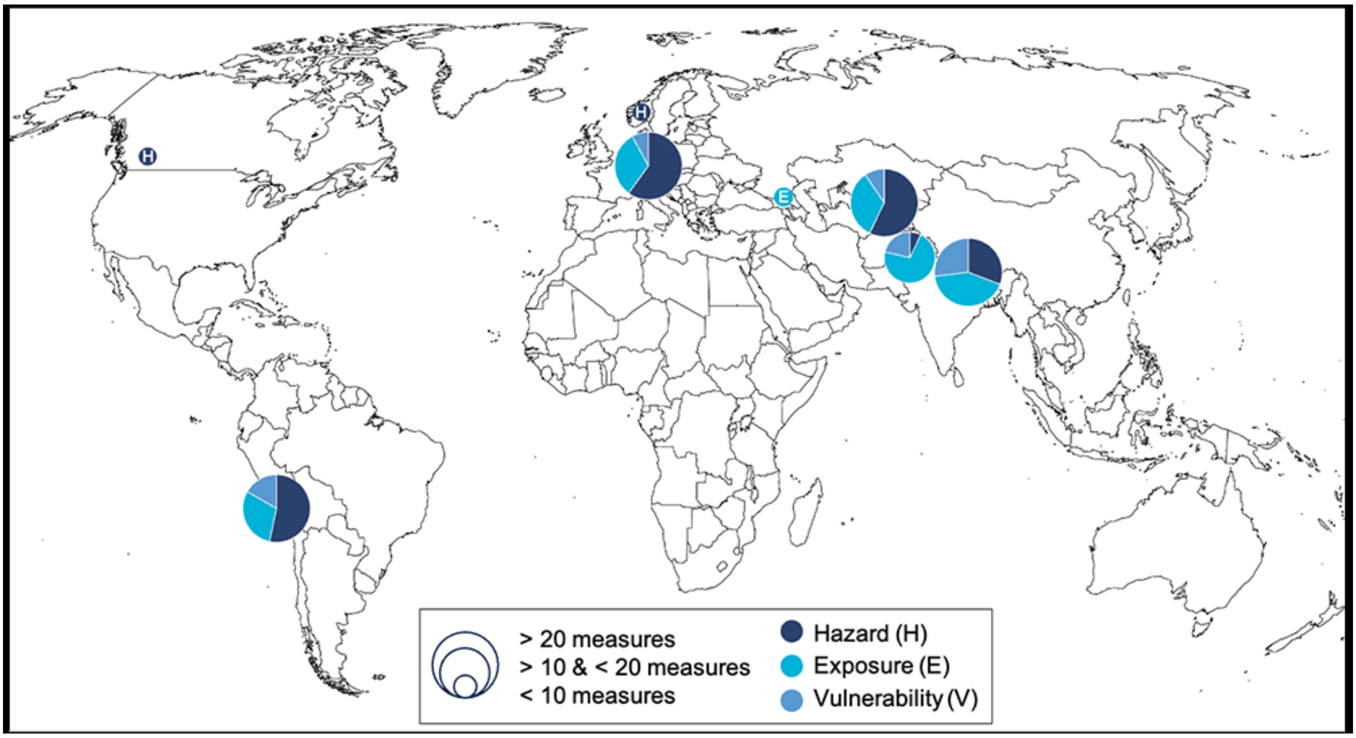

Figure 2. Overview of the analyzed GLOF risk reduction measures according to the risk component they target and their number for different mountain ranges (i.e., Rocky Mountains, South American Andes, Scandinavian range, European Alps, Caucasus, Central Asian ranges, Hindu Kush and Karakoram, and Himalayas).

GLOF Hazard Reduction

GLOF hazard reduction is mainly based on structural measures implemented, for example, at the source of the hazard, that is, at a glacial lake. Such measures can aim at the drainage, lowering, or regulation of lakes and the artificial fortification and stabilization of the lake dam or downstream channels. Structural measures can also be put in place farther downstream, for example, in the form of mass flow retention or deflection dams, where they aim at both a reduction of the hazard, when they reduce the magnitude of a GLOF, and a reduction of the exposure, when they, for instance, redirect or slow a GLOF. In this article, such measures are addressed under the exposure component in the section "GLOF Exposure Reduction."

One of the most important structural measures for reducing GLOF hazard is the reduction of the water volume in glacial lakes. This can be done through pumping or siphoning the water out of the lake; controlled breaching; installing an outlet control structure; or digging a tunnel through the moraine, rock, or ice dam (National Disaster Management Authority [NDMA], 2020; Reynolds et al., 1998), as well as sediment infilling into the lake (Haeberli et al., 2017).

Lake Lowering Through Siphoning and Pumping

Lakes can be artificially drained through siphoning or pumping. Water is led through pipes and discharged at a lower level, making use of the pull of gravity and hydrostatic pressure in the case of siphoning or with help of generators in the case of pumping (Figure 3).

Siphoning was applied as early as the 1960s on moraine lakes in the Kishi Almaty River basin in Kazakhstan (Kassenov, 2022) and was extensively used also in Peru and the European Alps (Table 1). Pumping was employed, for example, in the Canadian Rocky Mountains, when GLOF frequency increased throughout the 20th century, blocking the mainlines of the Canadian Pacific Railroad and the Trans-Canada Highway (Jackson et al., 1989), as well as several occasions in Europe and Central Asia since the 1980s (Table 1).

Figure 3. Drainage of lake No. 13 through a pumping system in the Ulken Almaty River catchment of the Kazakh Ile Alatau.

Source: Photo courtesy of M. Kassenov.

Table 1. Examples of Lake Lowering Through Siphoning and Pumping

Lake Lowering Through Siphoning			
Lake	**Lowering [m]**	**Year**	**Literature Sources**
Lake No. 2, Tuyuksu glacier, Kazakhstan	2	1960s	Medeu et al. (2022)
Lake 513, Peru	5	1988/1889	Reynolds et al. (1998)
Tsho Rolpa, Nepal	170 [l/s]	1995	ICIMOD (2011) Kattelmann (2003)
Lake Rochemelon, France	6	early 2000s	Vincent et al. (2010)
Lake Palcacocha, Peru	3	since 2009	Portocarrero (2014)
Lake Adygene, Kyrgyz Republic	16 [l/s]	2014	MoES of the Kyrgyz Republic (2019)
Lake Lowering Through Pumping			
Lake	**Lowering [m]**	**Year**	**Literature Sources**
Cathedral glacier, Canada	N/A	1985/1986	Jackson et al. (1989)
Lake No. 5, Gruben glacier, Switzerland	drained	1995	Haeberli et al. (2001)
Lake Effimero, Belvedere glacier, Italy	N/A	2002	Kääb et al. (2004)

Tête Rousse glacier, France	drained	2010	Vincent et al. (2012)
Lake No. 2, Zhetysu Alatau, Kazakhstan	N/A	2012	Kassenov (2022)
Lake No. 13, Ulken Almaty, Ile Alatau Kazakhstan	N/A	N/A	Kassenov (2022)

While the siphoning systems were technically operational in all the addressed cases, they also proved to be insufficient in some. The siphoning method is physically limited by the height of the freeboard between the water level and the upper limit of the lake dam, the challenge of keeping the pipes always airtight (Medeu et al., 2022; Vincent et al., 2010), the need of a large number of pipes, and a in some cases a lack of space to install them (Rana et al., 2000). This has occasionally led to water inflow still exceeding water outflow (MoES of the Kyrgyz Republic, 2019; Portocarrero, 2014; Vilca & Morales, 2017), and, for instance, the achieved water level lowering of two meters for Lake Tuyuksu in Kazakhstan did not prevent further lake development and its outburst in 1973 (Medeu et al., 2022). In order to lower lake levels by more than just a couple of meters, siphoning is, therefore, mostly used alternatingly with other measures, such as surface drainage channels.

The pumping systems succeeded in lowering the lake level and reducing the GLOF risk in all the mentioned cases. However, it only evacuates water at the time of the implementation. If no other factors influencing the input or output of water into or from the lake change, the danger of an outburst in the future can remain. Hence, just like siphoning, pumping is usually used as a temporary measure only, and it is then complemented by a more permanent measure such as a drainage channel (Haeberli & Epifani, 1986; Haeberli et al., 2001; Kassenov, 2022).

Lake Lowering Through Drainage Channels and Tunnels

Another possibility to lower the lake level is the excavation of an open V-shaped surface drainage channel or a tunnel through the lake dam (see Figure 4). These outflow systems can additionally be equipped with water level regulating structures (Emmer et al., 2018; Portocarrero, 2014; Rana et al., 2000). Surface channels and tunnels have been built through moraine material, solid rock, and ice.

Figure 4. Left: Clearing and deepening of a surface drainage channel from lake No. 6 in the Kishi Almaty River catchment of the Kazakh Ile Alatau. Right: Surface drainage channel at Lake Imja in Nepal.

Source: (Left) Photo courtesy of M. Kassenov. (Right) UNDP Nepal (2016).

Numerous drainage channels and tunnels have been implemented, for example, in the Cordillera Blanca of Peru since the 1940s, in Kazakhstan since the 1970s, and in the Himalayas and Europe since the 1990s, with some very early experiences in the 19th century (see Table 2). Beside surface channel excavation, use of explosives to create open cuts in moraine dams occurred in Kazakhstan and France, for example (Medeu et al., 2020, 2022; Vincent et al., 2010). In some cases at the same time, to lower the overflow level, lakes were deepened to enlarge their retention capacity (Haeberli et al., 2001; Meenawat & Sovacool, 2011), while in other cases excavated material from the drainage channel was deposited in the lake to reduce its volume even more (Haeberli et al., 2001; Kassenov, 2022).

Tunnels were designed, for instance, for several of the big proglacial lakes in the Cordillera Blanca and in Switzerland through bedrock or moraine dams. Channels and tunnels were also excavated directly through the ice for glacier lakes in Switzerland or France, for example. In some cases, lake-lowering efforts were tailored to fit additional purposes. At Tsho Rolpa, for example, sluice gates allow water regulation, and at Lake Paron in Peru, water regulation works were additionally used for energy generation (Portocarrero, 2014), and at Langtang glacier lake in Nepal, a multipurpose project was designed in 2020, generating electricity for 120 households in the downstream settlements (Dixit, 2021).

Table 2. Examples of Achieved Lake-Level Reductions by Surface Drainage and Through Tunnels

Lake Lowering Through Surface Drainage Channels			
Lake	**Lowering [m]**	**Year**	**Literature Sources**
Lake Jancarurish, Peru	15	1949–1951	Lliboutry et al. (1977)
Lake Cochca, Peru	3	1953	Emmer et al. (2018)
Lake Tullparaju, Peru	14/18	1953/1964	Lliboutry et al. (1977)
Lake No. 2, No. 6, Kishi Almaty, Kazakhstan Lake No. 6, Kishi Almaty, Kazakhstan	N/A 6.6	1970s and 2010	Medeu et al. (2022) Bolch et al. (2011)
Lake No. 1, No. 11, No. 12, No.13, Ulken Almaty, Kazakhstan	N/A	1970s	Medeu et al. (2022)
Lake No. 13, Kaskelen, Kazakhstan	N/A	1970s	Medeu et al. (2022)
Lake Bogatyr, Kazakhstan	10	1985	Medeu et al. (2022)
Lake 513, Peru	N/A	1990	Reynolds et al. (1998)
Lake Raphstreng, Bhutan	4	1995	Ives et al. (2010)
Gruben glacier lakes, Switzerland	2/10	1996/1997	Haeberli et al. (2001)
Lake Arhueycocha, Peru	8	2000	Emmer et al. (2018)

Lake Milluacocha, Peru	6	2000	Emmer et al. (2018)
Tsho Rolpa, Nepal	3	2000	ICIMOD (2011)
Lake Rajucolta, Peru	10	2004	Emmer et al. (2018)
Lake Rochemelon, France	6 + N/A	2005	Vincent et al. (2010)
Lake Faverges,* Switzerland	6	2019	Theiler Ingenieure AG (2021)
Lake Thorthormi, Bhutan	3.6	2009	UNDP Bhutan (2011b)
Lake Imja, Nepal	3.4	2016	Khadka (2016)
Lake Kargaly, Kazakhstan	3.7	2019	Medeu et al. (2020)
Lake Jialongco, Tibet	N/A	2020	Allen, Sattar, et al. (2022)
Lake Lowering Through Tunnels			
Lake	**Lowering [m]**	**Year**	**Literature Sources**
Giétro glacier,* Switzerland	N/A	1818	Röthlisberger (1978)
Lake Demmevatn, Norway	20	1899	Liestøl (1956)
Tête Rousse,* France	N/A	1899/1904	Vincent et al. (2012)
Gruben glacier,* Switzerland	N/A	1970	Röthlisberger (1978)

Lake Safuna Alta, Peru	38	1970	Portocarrero (2014)
Lake Paron, Peru	max. 52	1984	Emmer et al. (2018)
Lake 513, Peru	20	1994	Emmer et al. (2018)
Grindelwald glacier, Switzerland	overflow	2010	Bundesamt für Umwelt (BAFU, 2011)
Langtang glacier lake, Nepal	N/A	2020	Dixit (2021)

* The tunnel or channel here was dug directly through the ice.

Combined with the methods of siphoning or pumping, lake-level lowering through surface channels or tunnels ensured a significant reduction of the water volume of the respective lakes in most cases, by up to several dozens of meters. In many cases, lake lowering through surface channels significantly reduced (eliminated) the susceptibility to (spontaneous) dam failure (Emmer et al., 2018). Some general challenges and difficulties regarding lake lowering through drainage channels and tunnels were found in the analyzed literature.

For moraine lakes in permafrost areas, complete lake drainage is in some cases not recommended as the exposure of permafrost can cause irreversible and uncontrolled processes of degradation of the “glacier-moraine-lake” system that regulates glacial runoff (Kassenov, 2022). Lake lowering rather than complete drainage allows the control of a “safe” lake level, limiting the volume with discharge rates that do not lead to the formation of mudflows (Kassenov, 2022). The definition of such a “safe” lake level is, however, challenging. In Kazakhstan, for example, the 3.7 m lowering of Lake Kargaly proved insufficient—the lake burst shortly after. And for Tsho Rolpa, it was found that a lake lowering of around 20 m rather than only 3 m would be required to make it safe (Carey et al., 2015). At the same time, the lowering of Lake Thorthormi, which aimed at releasing pressure on its moraine dam (United Nations Development Programme [UNDP] Bhutan, 2011b), caused an increase of the hydraulic gradient between the upstream adjacent Lake Raphstreng and Lake Thorthormi, therefore increasing the risk of failure of the moraine dam separating the two lakes (Richardson & Reynolds, 2000).

Experiences have shown that remaining risks from glacier lakes must be considered, even after their water levels have been lowered significantly. Mass movements, earthquakes, and other natural processes have destroyed, damaged, and obstructed outlet structures on many occasions. At Lake Tullparaju in Peru, for example, an earth slide into the lake in 1953 caused a 12 m high wave that poured through the open trench and caused an 18 m lowering of the lake level until the drainage stopped due to moraine characteristics and sandbags thrown in by workers (Lliboutry et al., 1977). The tunnel at Lake Safuna Alta was damaged first during an earthquake in 1970 and then through an 80 m wave caused by a flank failure into the lake in 2002 (Portocarrero, 2014). In 1991, an ice avalanche into Peruvian Lake 513 caused a displacement wave that overtopped the moraine dam causing regressive erosion and damaging bridges several kilometers downstream (Reynolds et al., 1998). After the construction of a drainage tunnel through the bedrock dam, the lake had a freeboard of at least 20 m (Reynolds et al., 1998). Nevertheless, in 2010 a rock-ice avalanche triggered a displacement wave that overtopped the dam and again caused damage downstream (Carey, Huggel, et al., 2012). In addition to this, tunnels are susceptible to clogging as seen with Lake Paron where sediments filled the shaft (Portocarrero, 2014) or at Gruben glacier in Switzerland where calving ice obstructed the water inflow to the tunnel and a calving wave damaged a pipe used in the drainage tunnel (Röthlisberger, 1978).

The excavation of surface channels into moraine dams can be risky as it may initiate the formation of an uncontrolled breaching by starting a self-reinforcing process of increased discharge and increased erosion, eventually causing a GLOF (NDMA, 2020). This risk is especially high when channels are dug in melting ice-cored moraines (Medeu et al., 2022) or in areas with potential mass movements into the lake (Reynolds et al., 1998). In fact, lakes have burst out during preventive works in several countries including Norway, Peru, Switzerland, and Kazakhstan (Emmer et al., 2018; Liestøl, 1956; Lliboutry et al., 1977; Medeu et al., 2022; Röthlisberger, 1971). For instance, the construction of a surface channel at Bogatyr Lake in Kazakhstan led to an artificial GLOF (Vincent et al., 2010) draining the lake within only two days (Medeu et al., 2022). While the draining of Bogatyr Lake did not entail any negative impacts downstream, the lowering of the water level of Lake No. 13 in the Ulken Almaty River basin in 1976/1977 led to a lake outburst causing significant material damage and human casualties (Medeu et al., 2022). During lake-lowering efforts at the Peruvian glacier lake Jancarurish, the late removal of sandbags caused quick moraine erosion and dam failure leading to 200–500 fatalities (Lliboutry et al., 1977). The construction of outlet channels, hence, has to be accompanied by measures to prevent erosion in the created open cut (NDMA, 2020).

Additional difficulties were encountered associated with drainage through channels and tunnels of ice dams, which is generally hard to control (Medeu et al., 2022). Water-filled crevasses and dynamic englacial channels complicated works at Gruben glacier in 1970, and a blocked englacial channel, which had moved and made it impossible to be cleared in time, caused damage again in the areas downstream of the same glacier (Röthlisberger, 1978). While thermal erosion at Lake Faverges on the Plaine Morte glacier led to a welcomed channel deepening, in the case of Giétro glacier, an ice tunnel that collapsed due to the thermal erosion of a subglacial drainage path below the tunnel led to a catastrophic drainage and caused dozens of casualties and extensive downstream damage to settlements (Röthlisberger, 1978). The ice channel built at Lake Faverges filled up with fresh snow, blocking the drainage in 2019–2020 and calling for maintenance (Theiler Ingenieure AG, 2021). A tunnel that was drilled in Tête Rousse glacier in 1904 was found unsuitable for preventing GLOFs in the early 2000s. Instead of drilling another tunnel, the englacial lake was emptied via pumping, reducing the hazard of uncontrolled drainage but accepting the low hazard from glacier cavity collapse (Vincent et al., 2012).

Despite proper functioning at the time of implementation, in many cases tunnels were not effective anymore after some time. In the case of Lake Safuna Alta in Peru, for example, the lake level dropped so quickly that in only 3 years a new tunnel had to be built (Portocarrero, 2014). The tunnel that was built to drain Lake Grindelwald in Switzerland is not in use anymore as the corresponding glacier lowered and retreated way back out of sight (Stüdle, 2020). At Lake Demmevatn in Norway, the previously constructed tunnel was not functional around 40 years after construction when the lake unexpectedly burst, causing heavy damage (Liestøl, 1956). The tunnel had lost its effect as the lake had grown bigger due to glacier retreat (Liestøl, 1956).

Lake Regulation and Stabilization Through Artificial Dams or Dam Reinforcement

Artificial dams are built to increase dam freeboard and to prevent a lake outburst due to the direct impact of a displacement wave, an unexpected increase in the water level, and/or the erosion of the natural dam (see Figure 5). Artificial dams or dam reinforcement are often implemented in combination with open cuts (Emmer et al., 2018). The reconstitution of a moraine dam can be achieved by making a cut into the natural dam, building a channel, and covering it again to restore the freeboard (Reynolds et al., 1998). For example, concrete outlet structures are built and reinforced to avoid retrogressive erosion and piping below the dam (Haeberli et al., 2001).

Figure 5. Artificial dam of Lake Huallcacocha in the Peruvian Cordillera Blanca.

Source: Photo courtesy of C. Portocarrero.

In Peru and Switzerland, for example, the first dams for hazard reduction purposes at glacier lakes were built or reinforced in the mid-20th century (see Table 3), and construction plans are still being leveraged for new dams, like a proposed multipurpose project aiming at both energy generation and the reduction of glacier-related hazards from the glacier lake below Trift glacier in Switzerland (Haeberli et al., 2016).

Table 3. Examples of Artificial Dams and Dam Reinforcements for Hazard Reduction Purposes

Hazard Reduction Through Artificial Dams or Dam Reinforcement		
Lake	**Year**	**Literature Sources**
Lake Mauvoisin, Giétro glacier, Switzerland	1950s	Röthlisberger (1978)
Lake Ishinca, Peru	1951	Emmer et al. (2018)
Lake Palcacocha, Peru	1951/1974	Portocarrero (2014)
Lake Huallcacocha, Peru	1960/1978	Portocarrero (2014)
Gruben glacier lake, Switzerland	1990s	Haeberli et al. (2001)
Lake Weingarten, Switzerland	2001	Kolenko et al. (2004)
Lake Rajucolta, Peru	2004	Emmer et al. (2018)
Lake Jialongco, Tibet	2020	W. Wang et al. (2022)

In the Cordillera Blanca, Peru, partial drainage and damming of glacial lakes has been the most successful strategy for reducing GLOF disaster risk (Carey, Huggel, et al., 2012). The protection or construction of dams proved to be a well-functioning approach to stabilize the associated glacial lakes. The damming of lakes such as Ishinca, Palcacocha, Huallcacocha, and Rajucolta successfully controlled lake expansion. An earthquake in 1970 did not destroy any of the previously built dams but damaged some of the outlet structures. Some of the structures were renewed and strengthened or replaced by a higher structure (Portocarrero, 2014).

Reinforced retention structures can reduce the susceptibility of lakes to burst due to the erosion of their dams. To reduce the risk of overtopping, freeboard needs to be increased. In some cases where the lake level has only been reduced by a few meters, the dam could still be overtopped (Emmer et al., 2018). For example, in 2002, a landslide caused a displacement wave that overtopped the reinforced dam of Lake Palcacocha despite its 8 m freeboard, but erosion of the damming structure was prevented (Vilímek et al., 2005).

Hazard Reduction Measures: Summary and Lessons

Lake lowering has been a popular method of GLOF hazard reduction globally as it significantly reduces the likelihood and potential magnitude of a lake outburst (Medeu et al., 2022), does not require much maintenance once implemented, and allows downstream communities to retain their current location and practices (International Centre for Integrated Mountain Development [ICIMOD], 2011; Portocarrero, 2014).

Experiences show that while siphoning is an approach that is used a lot, it is often not effective/efficient enough to sustainably lower lake levels (ICIMOD, 2011; MoES of the Kyrgyz Republic, 2019; Portocarrero, 2014; Reynolds et al., 1998; Vincent et al., 2010). Due to its physical limitations, siphoning only allows for a water-level reduction of a couple of meters. Moreover, for siphoning and pumping the outflowing volume is limited by the capacity of the pipes. In many cases the water inflow into the lake has at times exceeded the outflow through the pipes. Furthermore, the movement of glaciers and surrounding slopes can damage pipes and communication lines, and for siphoning, the pipes need to be constantly submerged in the water for the system to keep functioning. Consequently, these methods require continuous maintenance to fix defects in the system and to adjust to the changing environment. While those challenges in combination with the quickly changing nature of the cryosphere environment make lake lowering through siphoning and pumping unsuitable as a long-term solution (Carey et al., 2015), they are very quick to implement and to have an effect. Therefore, both methods are often used as an initial short-term measure and in emergency situations (Haeberli et al., 2001; Jackson et al., 1989; NDMA, 2020; Semino et al., 2004) and can be effective solutions when they are combined with other, more sustainable engineering activities (Medeu et al., 2022).

Constraining and regulating lake levels through structural measures like artificial dams and surface drainage channels and tunnels have been used to more permanently address GLOF hazards. Respective engineering projects at several lakes in Peru have significantly reduced the GLOF risk, although they could not completely eliminate the hazard (Carey et al., 2015). As seen in various cases, even after significant lake lowering, a residual hazard remains if the lake is not completely emptied. Peruvian Lake 513 caused a GLOF in 2010, despite having been categorized as safe since 1994 after the construction of a drainage tunnel (Carey, Huggel, et al., 2012). As of 2021, the failure of the surrounding flank into Lake Safuna Alta remains a potential catastrophic scenario, despite an existing drainage tunnel (Klimeš et al., 2021). Likewise for Lake Jialongco in Tibet: a study from 2022 shows that the remedial measures undertaken to lower its water level, while effective in reducing small- and medium-sized events, would have little influence on downstream impacts resulting from a very large magnitude ice avalanche–triggered GLOF. This can potentially lead to a false sense of security and maladaptation if the significant residual risk is not clearly communicated to local stakeholders (Allen, Sattar, et al., 2022). The importance of taking all potential effects and changes in the environment into consideration is best highlighted in the case of Lake Raphstreng, Bhutan. After the lowering of Lake Raphstreng it was feared that this measure could induce failure of the moraine and cause a GLOF from Lake Thorthormi (Richardson & Reynolds, 2000). The hazard reduction measure at one lake had the unintended effect of (probably) increasing the GLOF hazard from this system of lakes.

The installation of structural works at the location of glacier lakes comes with logistical, financial, and personnel requirements. The implementation of large structural measures in difficult terrain requires a lot of time and human resources. The surface channel at Lake Raphstreng, for instance, was manually excavated by 200–500 laborers (Richardson & Reynolds, 2000), and the outlet construction for controlled lowering of Lake Imja took many army personnel and sherpas 6 months (Khadka, 2016). Helicopters may be needed for the transportation of construction material, experienced alpine and rescue guides and other specialized personnel may be required for implementing and overseeing the operations, and extreme weather conditions can make the implementation more difficult (Semino et al., 2004).

At sites like Lake Thorthormi in Bhutan, only 3 to 4 months a year are workable onsite (Meenawat & Sovacool, 2011). The use of heavy machinery may be completely impossible due to remoteness and unstable terrain, and helicopter landings may only be possible at a considerable distance from the working site, making the transportation of equipment and scientific instruments difficult (Meenawat & Sovacool, 2011). The cost of transporting equipment by helicopter is high, especially for lakes at high altitude like the one at the Tibetan Langtang glacier (Dixit, 2021). Construction in remote areas and at high altitudes compromise worker safety. During construction work at Lake Thorthormi, three people lost their lives due to altitude sickness and working conditions related to the remote, high-altitude environment combined with extreme weather conditions (UNDP Bhutan, 2011b).

In addition to these challenges, socioeconomic and cultural factors can further complicate the implementation and sustainability of hazard reduction measures. Beside the lack of funding and proper coordination among agencies that hampered quick and efficient structural measures, for example, at Tsho Rolpa (Dahal & Hagelman, 2011), other conflicts of interests have proven to have a negative influence on the sustainability of hazard reduction measures. In catchments with (seasonal) water deficits, reducing the volume of a glacial lake is sometimes not a viable option (Muñoz et al., 2016). For example, in Huancayo in Peru, many locals opposed the lowering of Lake Lazu Huntay, which caused a GLOF in 1969 because the catchment suffered from water shortages (Portocarrero, 2014). Similarly, in the case of Lake Paron, lake drainage for security stands opposed to lake damming and regulation for power generation (Carey, Huggel, et al., 2012). When tunnels and floodgates were eventually installed after initial disputes and a 10-year halt on the project (Portocarrero, 2014), prioritization of water use for energy generation to the disadvantage of local water needs, irrigation, and water treatment facilities caused discontent among the local residents and culminated in the seizure of the lake and floodgates by them (Carey, French, et al., 2012). When as a result, the lake filled up and posed a GLOF threat again, the national government declared a state of emergency and lowered the lake to its maximum security level, with the conflict remaining at a tense standstill in 2011 (Carey, French, et al., 2012) and the flood regulation system started to fail (Portocarrero, 2014), while in 2024 foreigners are still not allowed to visit the lake-level regulation system. Also the cultural role of lakes and other water bodies, in some cultures and traditions perceived as sacred elements of the landscape or mythical beings, must be taken into account when lake lowering or complete drainage is considered. A study of a rural sherpa community in Nepal found that traditional beliefs coexist with scientific interpretations of risks and concluded that the incorporation of social-cultural factors could improve DRM strategies (Sherry & Curtis, 2017).

In consideration of the fact that structural works at glacier lakes can be hugely cost intensive or even impossible for very remote areas inaccessible to machines and equipment, an alternative is to implement structural measures aiming at hazard and exposure reduction further downstream (NDMA, 2020). Rather than being lake or even GLOF specific, such downstream structural measures can also reduce risks associated with other flood and mass-movement processes. Such measures are described in the section "GOLF Exposure Reduction."

GLOF Exposure Reduction

The exposure in a downstream area at risk of GLOFs can be reduced by adapting the river or runout path to potential mass flows and by protecting the potentially affected areas through deflection and retention dams, anti-erosion gabions, and similar structures. Such structural measures aim at not only a reduction of the exposure but also a reduction of hazard. However, in contrast to structural measures at the glacier lakes, they do not aim at the prevention of GLOFs but rather at the reduction of the magnitude and impact of GLOFs farther downstream. This is why they are addressed under the exposure component.

Exposure can also be reduced by appropriate spatial planning, based on local hazard maps, and avoiding construction and operation in areas of potential mass movements. Alternatively, monitoring the hazard source, as well as the area through which a mass movement propagates, can provide early warning and reduce exposure of humans by evacuation in areas at risk during an event.

Flow Channel Adaptation, Deflection, and Retention Dams

Flow channel adaptation entails structural measures that aim at the protection of riverbanks to avoid undercutting and erosion or at the guidance of the river through the adjustment of the depth, width, or the direction of the riverbed. Deflection dams are built to redirect mass flows, while retention dams aim at separating larger from finer grained sediments and water to reduce the amount of mobilized material in a mass movement and to increase discharge capacity by increasing flow speed (see Figure 6).

Figure 6. Sediment retention structure in Täsch, downstream of lake Weingarten in Switzerland.

Source: Photo: C. Huggel.

Structures built in Central Asia, the European Alps, the Karakoram, the Himalayas, the Caucasus, and the Cordillera Blanca include large dams for mass flow retention and separation (e.g., Medeu Dam in Kazakhstan; Medeu et al., 2019) or for deflection (e.g., Macugnaga, Italy; Haeberli et al., 2002) as well as smaller scale measures such as riverbank protection works like check dams, sediment traps, flood protection walls, slope stabilization, and erosion control measures, for example, through embankments with gabion revetment or bioengineering measures (see Table 4). Furthermore, measures to clear, reconstruct, and adjust stream channels, for example increasing channel width and heights or smoothing turns to minimize run-up, were implemented.

Table 4. Examples of Mass Movement Exposure and Hazard Reduction Through Flow Channel Adaptation, Deflection and Retention Dams

Flow Channel Adaptation, Deflection and Retention Dams			
Catchment/Region	**Measure**	**Year**	**Literature Sources**
Macugnaga, Italy	Protection dam	early 1900s and 1979	Haeberli et al. (2002)
Quillcay River, Huaraz, Peru	Retention walls	1943/2015	Carey (2005)
Kishi Almaty, Kazakhstan	Medeu Dam	1960s/1973	Medeu et al. (2019)
Zailiysky Alatau, Kazakhstan	Mudflow protection dams	1973 onward	Medeu et al. (2020)
Täsch, Switzerland	Sediment retention structure	after 2004	Kolenko et al. (2004)
Elbrus camp, Russian Caucasus	Deflection dam, river channel reconstruction	N/A	D. Petrakov (personal communication, November 2022)
Terai districts, Nepal	Embankments with gabions and bioengineering measures	2013–2017	UNDP (n.d.-a)
Bagrot, Drmgrah and Bindo Gol valleys, Gilgit-Baltistan and Chitral districts, Pakistan	Flood protection walls, slope stabilization, check dams	2015	Rijal and Ali (2015)
Shuraki Kapali River, Tajikistan	Protection dam	after 2018	Zaripov et al. (2020)
Simme River, Switzerland	Sediment traps, riverbank stabilization	after 2018	Theiler Ingenieure AG (2021)

Flow Channel Adaptation, Deflection and Retention Dams			
Catchment/Region	**Measure**	**Year**	**Literature Sources**
Aksai, Ulken Almaty, and Korgas Rivers, Kazakhstan	Mass flow retention dams	2022: under construction	Kassenov (2022)
Korgas River, Kazakhstan	Riverbank protection	2022: under construction	Kassenov (2022)

As demonstrated by experiences in Kazakhstan, mass-movement retention and deflection structures were destroyed by mudflows, avalanches, and landslides. Nevertheless, in many cases, they significantly reduced the magnitude and impact of mass movements. For example, the construction of the Medeu Dam was finalized just in time to save the city of Almaty from heavy destruction in 1973 (Medeu et al., 2019). In general, in Kazakhstan, mudflow retention dams have been found to be the most reliable protection. One of their drawbacks, however, is that they do not prevent the formation of secondary flows that can occur once GLOFs pass below the dams. More recent voices from the early 21st century, thus, point out the need to equip dams with adjustable locks (Medeu et al., 2020). During the Bashkara GLOF in the Caucasus in 2017, a deflection dam successfully protected the Elbrus camp. During GLOFs in 2011, 2017, and 2022 in Tyrnyauz, no significant damage occurred anymore, except for the inundation of some houses due to partial damming of Baksan River. In Italy, however, a GLOF in 1922 destroyed roughly 100 m of the protection dam that had been constructed to defend the village of Macugnaga (Haeberli et al., 2002). Similarly, in Switzerland, a GLOF from Lake Weingarten in 2001 was too large for a sediment retention structure that had been built to protect Täsch from debris flows (Kolenko et al., 2004). This event then led to the reinforcement of the natural dam at Lake Weingarten. In Huaraz, Peru, the retaining walls along Quillcay River were built instead of further investigation and drainage of hazardous lakes, which caused locals’ frustration (Carey, 2005). Moreover, the walls were later accidently destroyed by the influx of water into Huaraz when Lake Cuchillacocha was drained. This greatly lowered the confidence in government programs (Carey, 2005).

Monitoring and Early Warning Systems

Monitoring and Early Warning Systems (EWS) are measures with nonstructural and structural components, aimed at a reduction of the damage potential through warning and evacuation of the population in case of an outburst. As defined by the United Nations Office for Disaster Risk Reduction, an EWS is

> an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events.

While monitoring systems are limited to data collection, EWS are complex systems, involving not only technical but also social, political, and even juristic aspects (NDMA, 2020). They are based on four key elements, namely, risk knowledge, monitoring and warning service, dissemination and communication, and response capability (United Nations Development Programme [UNDP], 2018; Figure 7). While the element on “monitoring and warning service” mainly addresses exposure, aspects of preparedness and communication address the vulnerability component of GLOF risk. These aspects are discussed in more detail in the section “GLOF Vulnerability Reduction.”

A key aspect of GLOF early warning, as with many other mass movements, is that the system only becomes activated once an event occurs, and warning times for downstream communities are therefore typically in the range of minutes to a few hours. This contrasts with other hydrometeorological warning systems, for example for riverine flooding, that are based on event forecasts or predictions days in advance.

Figure 7. The four key elements of Early Warning Systems.

Source: UNDP (2018).

Simple manual warning systems based on smoke and fire were already implemented in the early 19th century, for example in Lake Mauvoisin in Switzerland (Röthlisberger, 1978), and in the late 19th and early 20th centuries were spread over the entire Pakistani Hindu Kush-Karakoram range (Iturrizaga, 2019). The first EWS for lake outburst floods in the Himalayas was set up in the Indian villages of Chamoli and Srinagar in 1894 for a landslide dammed lake (NDMA, 2020). For glacier lakes, however, monitoring and EWS in the area started about a century later. Monitoring and EWS were initially operated manually and equipped with satellite and radio communication sets, for example in Nepal, Bhutan, Pakistan, Bolivia, and Peru. More elaborate monitoring and warning systems, based on water-level change, ice velocities, moraine stability surveys, ice collapse, downstream runoff, and similar measurements with help of in-situ observation, video surveillance, pressure probes, contact sensors, and so forth were later implemented for example in Switzerland, Italy, Peru, Nepal, Tibet, Bhutan, India, China, Pakistan, Kyrgyz Republic, and Russia (see Table 5). In the most advanced cases, warnings were associated with expert alerting related to the surpassing of some predefined measurement threshold, automated alarms sent to nearby infrastructure, and sirens activated in potentially exposed population centers, and they were linked to some standard operating procedures and formal activation of evacuation plans.

Table 5. Examples of Monitoring and Early Warning Systems.

Monitoring and Early Warning Systems (EWS)			
Lake/Catchment	**System**	**Year**	**Literature Sources**
Lake Mauvoisin, Giétro glacier, Switzerland	Manual: based on in-situ lake observation, communication through smoking fire; Monitoring of glacier tongue	1818	Röthlisberger (1978)
Shimshal-Gilgit and Karambar-Gilgit, Hindu Kush-Karakoram, Pakistan	Manual: based on in-situ lake observation, communication through beacon fire	Late 19th, early 20th century	Iturrizaga (2019)
Shyok-Attock, Hindu Kush-Himalaya, India	Manual: based on in-situ lake observation, communication through beacon fire	Late 19th, early 20th century	Iturrizaga (2019)
Tsho Rolpa, Nepal	Manual: based on in-situ lake observation (in 1998 automatic warning system)	1997 and 1998	Richardson and Reynolds (2000) and Ives et al. (2010)
Lake Imja, Nepal	Manual: monitoring of lake level with time-lapse camera Automatic: based on water level at lake outlet and downstream through level radar; Communication through satellite	2000s and 2016	Ives et al. (2010), Gurung et al. (2021), and UNDP (n.d.-a)
Upper Bhote Koshi, near Friendship/ Zhangzangbo bridge, Nepal	Automatic: ultrasonic and float type water level sensors and threshold-based alarm to Hydroelectric power station	2001	ICIMOD (2011) Ives et al. (2010)

Monitoring and Early Warning Systems (EWS)			
Lake/Catchment	**System**	**Year**	**Literature Sources**
Belvedere glacier, Macugnaga, Italy	Automatic: based on lake level; Monitoring of lake and rivers through video cameras, regular moraine stability surveys	2002	Kääb et al. (2004) Semino et al. (2004)
Trift glacier lake, Switzerland	Automatic: threshold-based alarm to nearby cable car station; Monitoring of ice velocities, water level with pressure probes	2006	Geopraevent (n.d.) D. Bürki (personal communication, April 2024)
Bashkara glacier lakes, Adylsu valley, Caucasus, Russia	Semi-automatic: lake level, transmission through radio, threshold-based alarm to station; Monitoring of glaciers, lakes and dam elevation change	2008	Petrakov et al. (2012)
Apolobamba range, Bolivia	Monitoring of glacial lakes	2010	Hoffmann and Weggenmann (2013)
Lake 513, Peru	Automatic: based on geophones (avalanches) and pressure sensors (river), complemented by in-situ runoff observation by a warden of a fresh water intake below the lake	2011	Huggel, Cochachin, et al. (2020)
Ala-Archa, Kyrgyz Republic	Semi-automatic: based on impact detection in the stream bed	2011	Erokhin et al. (2018)
Lake Kyagar, Karakoram, China	Automatic: lake monitoring via camera, and river water level via radar; water level threshold-based automatic alarms via SMS to authorities	2011	Haemmig et al. (2014)

Monitoring and Early Warning Systems (EWS)			
Lake/Catchment	**System**	**Year**	**Literature Sources**
Lakes Luggye, Thorthormi, Rapstreng and Bay, Punaka-Wangdue, Bhutan	Manual: in-situ lake observation; Automatic: based on lake level;	N/A and 2011	Meenawat and Sovacool (2011), UNDP Bhutan, (2011c), and USD Enterprises and Sutron Corporation (2010)
Lake Faverges, Switzerland	Automatic: based on lake level change, and river discharge increase with automatic alarm via SMS to local authorities; Monitoring of discharge curve and manual warning for evacuations	2012	Geopraevent (2018) I. Kull (personal communication, January 2024)
Drongagh and Bagrot valleys, Gilgit-Baltistan and Chitral, Pakistan	EWS: based on glacier and glacial lake monitoring sensors and cameras	2015	Rijal and Ali (2015)
Lake Shishper, Hunza, Pakistan	Manual: camera-based lake observation, monitoring of lake water in and outflow, regular in-situ observations, satellite imagery	2020	Baigal (2022)
Lake Cirenmaco, Poiqu, Tibet	Automatic: based on lake level; Monitoring of lake, moraine displacement, ice collapse and downstream runoff	2021	W. Wang et al. (2022)

Overall, there was a very limited number of GLOF EWS operational globally as of 2020 (NDMA, 2020), and the situation had not changed significantly by 2024. While several modern EWS were claimed to be functional in publications in the 2000s and 2010s, most of them could not officially be verified as operational and some of them were found to have stopped working. Successful or currently operating systems were reported, for instance, for the Alps in Italy and Switzerland and the Himalayas in Tibet and Nepal (discussed later). The automatic monitoring system in Macugnaga, successfully detected the GLOF from Lake Effimero in 2003, leading to evacuations and the temporary closure of a chairlift and endangered trails (Truffer et al., 2021). The EWS at Lake Faverges in Switzerland successfully released a GLOF warning in 2018, leading to a precautionary evacuation of 110 people from a campsite and restaurant (Geopraevent, 2018). The system was still fully functional in 2024, but there had not been any major damage or evacuations since 2018. The Cirenmaco EWS, one of the most advanced systems in 2021, was reported to be functional for Tibet in 2022 (W. Wang et al., 2022) and was still regularly maintained and improved with alarms tested in 2023. In the Kyrgyz Ala-Archa valley, the semiautomatic EWS warned of a GLOF originating from Lake Teztor in 2012, guaranteeing some minutes to evacuate people. People in the Bhutanese Punaka-Wangdue valley were aware of the EWS and the monitoring at Lakes Luggye, Thorthormi, Rapstreng, and Bay, which was beneficial in 2015 when the system was used to warn of a GLOF that was triggered from Lake Lemthang, located in a valley to the west (M. S. Shrestha et al., 2016). The local Puberanj beacon fire systems in the Pakistani and Indian Hindu Kush-Karakoram had dozens of posts at high passes and extended over distances of around 150–200 km (Iturrizaga, 2019). The fact that there are no reports on fatalities during some of the large GLOF events in the Hindu Kush-Karakoram along the Shimshal-Gilgit line, and only one fatality along the Shyok-Attock line, despite destructive and far-reaching flows, can be interpreted as a success for the historical EWS (Iturrizaga, 2019). Similarly in the 2010s and 2020s, Shisper Lake in the Hunza basin drained and caused damage several times since 2018, but fatalities were averted thanks to the monitoring system (Baigal, 2022). The EWS in the Gilgit-Baltistan and Chitral districts in Pakistan reportedly reduced damage and allowed for villagers to move to safe places during a flash flood event in Chitral in 2014 (Rijal & Ali, 2015). However, it is not clear if a specific GLOF EWS was implemented, and the lack of recent information on such a system indicates that a functional GLOF EWS does not exist in 2024. It is also worth noting that the areas under consideration, Chitral and Gilgit-Baltistan, are in general most heavily affected by precipitation-induced mass movements of periglacial origin, rather than by GLOFs (J. Steiner, personal communication, January 2024).

Alongside these (partial) successes, challenges and failures were reported for most documented systems. One challenge relates to communication issues and the response of communities. For instance, while the warning for the Giétro GLOF, over two centuries ago, was issued as planned, the alert was not taken seriously as it was sent at the beginning of the event, but the lake burst catastrophically 3 days after drainage initiation, causing extensive damage and fatalities (Röthlisberger, 1978). A false alarm that was released because of a fire, which did not belong to the fire beacon line in the Eastern Karakoram in 1928, luckily had less catastrophic consequences (Iturrizaga, 2019).

Long-term maintenance of the systems is a main challenge. In some instances, this has been due to the loss or vandalism of key components. The EWS for Lake 513 in Peru was dismantled by locals after rumors spread that its rain gauges and antennas were the cause of a severe drought in 2016, and the EWS was never rebuilt (Huggel, Cochachin, et al., 2020). Similarly, for a monitoring system at Lake Shako Chho in India (Kumar et al., 2020), an inquiry with an official of the Swiss Federal Department of Foreign Affairs revealed that the system was not functional anymore in 2022 because the battery and solar panel had been stolen (M. A. Khan, personal communication, February 2022). The EWS at Tsho Rolpa inaccurately predicted an outburst initially in 1997, which led to an evacuation of the downstream areas (Dahal & Hagelman, 2011). After that, it only functioned for a short time and was no longer working 4 years after its implementation. It was no longer maintained by local residents, damage was incurred during political unrest and as a result of the construction of new roads, and key components of the system had been repurposed locally or vandalized or stolen by people from outside the Rolwaling valley (Carey et al., 2015; ICIMOD, 2011; Ives et al., 2010).

More often, long-term maintenance is compromised by a lack of funding and lack of institutional commitment. Despite their former success, the Hindu Kush-Karakoram fire beacon EWS were last operated in the 1960s, partly because of a reduction of the GLOF hazard due to glacier retreat, partly as a result of the high-operation workload, and progress in communication and infrastructure (Iturrizaga, 2019). The EWS in the Bhutanese Punakha-Wangdue valley was built to rely on water-level sensors only, and redundancy for the case of malfunction is not guaranteed (Royal Government of Bhutan [RGOB] et al., 2012). Furthermore, the EWS was found to be unsustainable as there was no funding mechanism to operate and maintain the EWS after project completion (RGOB et al., 2012). The monitoring system in the Apolobamba range in Bolivia was discarded following the prioritization of other indicators for monitoring by the National Service for Protected Areas (Servicio Nacional de Areas Protegidas [SERNAP]; R. Tarquino, personal communication, January 2024). Similarly in Peru, plans that had been made for an EWS in the Sacsara catchment in Santa Teresa were never executed after the new regional government dropped flood and GLOF risk management from its political agenda (Frey et al., 2016). Similarly, a planned EWS for Salkantaycocha was dropped due to lack of financial support from the local government the (I. Hagen, personal communication, June 2024). Subsequently, a GLOF from Salkantaycocha that occurred in February 2020 caused 5 fatalities and 10 people missing along with 300 destroyed houses and 290 affected families in the Salkantay catchment upstream of Santa Teresa (Centro de Operaciones de Emergencia Nacional [COEN], 2020; Vilca et al., 2021).

Other systems became inactive for various reasons that are not well documented. The EWS for Lake Imja had faced ongoing issues with communications, and its functioning as of 2024 was not assured (S. Gurung, personal communication, January 2024). The EWS for Kyagar Lake in the Chinese Karakoram successfully predicted GLOFs in 2015, 2016, 2017, and 2018 (Yin et al., 2019) despite the station at the lake being flooded 1 year after installation. However, it was reported to no longer be operational in 2020 (NDMA, 2020). The EWS at Bashkara glacier lakes in the Russian Caucasus did not set off any alarms between its installation in 2008 and 2012, and its functioning was never fully tested. The EWS was not functional during the GLOF that occurred from the lakes in 2017 and caused several deaths as well as the interruption of major transport ways and gas provision (Kornilova et al., 2021). It was still not operational in 2024.

Spatial Planning and Relocation

Spatial planning in DRM aims at a spatial allocation of land and its use that limits the potential impact of natural hazards on the land's productive services, habitability, and built infrastructure. Land-use laws and regulations are ideally based on hazard maps and consider the needs of all stakeholders depending on the land and its resources. Examples of spatial planning as effective GLOF DRM measure are limited. Presumably, this is mostly related to the fact that land-use laws and regulations in most cases had been in place long before GLOF DRM became a topic of concern. Subsequent changes in land-use plans may have implications for areas that were distributed and built prior. In that sense, relocation is understood as the enforcement of retroactive spatial planning (Figure 8).

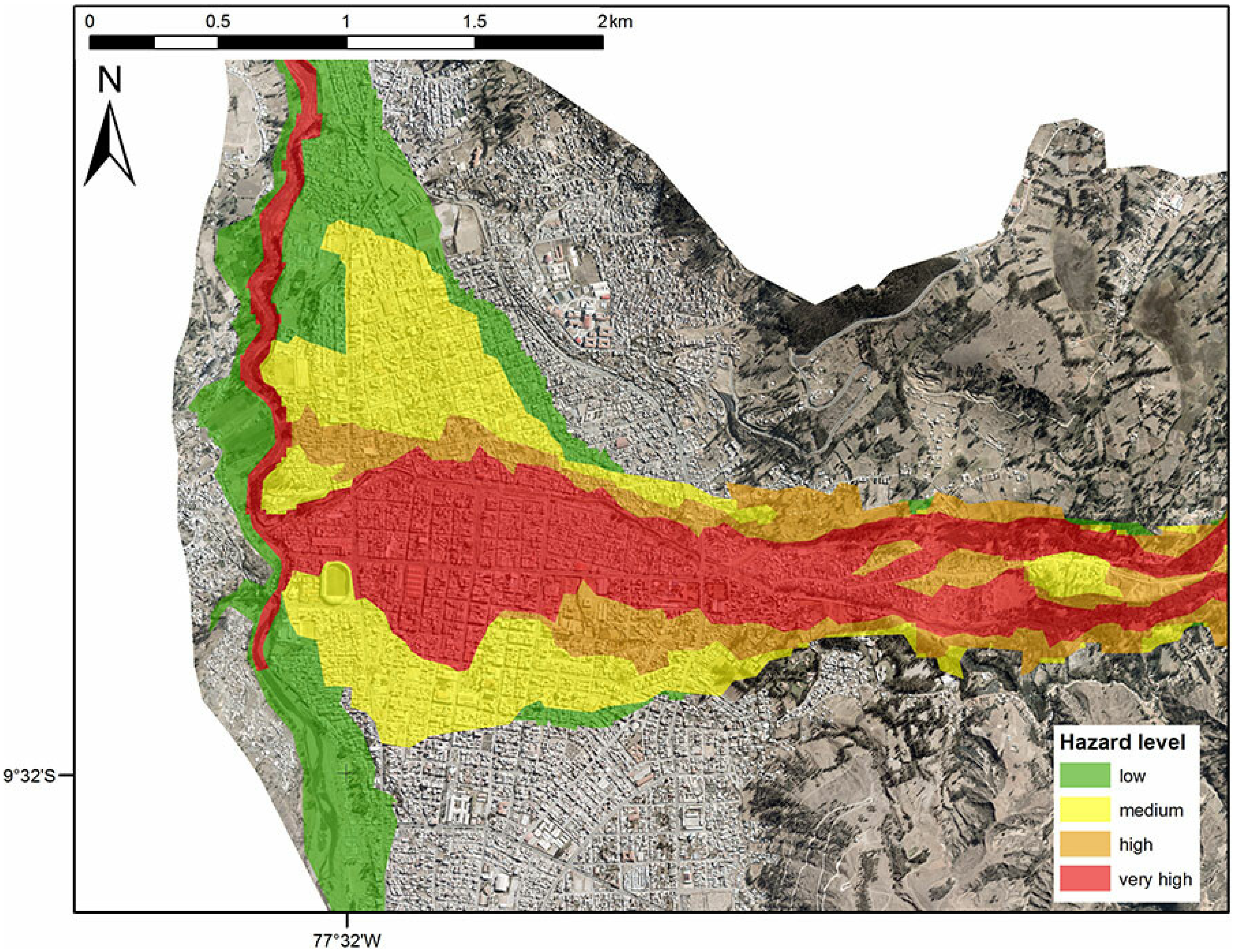

Figure 8. Section of hazard map for Huaraz by Frey et al. (2018).

In 1970, a study by a United Nations Educational, Scientific and Cultural Organization (UNESCO) delegation reported that glacial lakes in the Cordillera Blanca were unstable and specifically noted that Mount Hualcán above Lake 513 and Lake Cochca could produce ice-rock avalanches and GLOFs (Carey, Huggel, et al., 2012). Beside other measures, the delegation proposed new zoning laws and relocating local populations outside the Carhuaz floodplain and moving them to Huachac as a new site (Carey, Huggel, et al., 2012). A hazard map based on the reconstruction of the 2010 GLOF from Lake 513 (Schneider et al., 2014) was approved by the municipality of Carhuaz. Similarly, a hazard map was created for the city of Huaraz, based on GLOF scenarios for Lake Palcacocha, Lake Cuchillacocha, and Lake Tullparaju, which was approved by an interinstitutional commission of responsible authorities and technical expert institutions, and disseminated by the municipality to the local population (Frey et al., 2018). After partial destruction of Santa Teresa in southern Peru, the town was relocated to higher ground in 1998. GLOF hazard and risk maps were later elaborated and distributed for Santa Teresa and its adjacent towns and communities (Frey et al., 2016). Another GLOF in 2020 in Santa Teresa again led to self-organized relocation of parts of the local community (I. Hagen, personal communication, March 2024). Similarly, in the Ghulkin, Hussaini, and Passu villages of the Pakistani Hunza basin, short-term relocations to family members in other villages took place directly after GLOF events in 2007 and 2008 (Ashraf et al., 2012). In contrast, a formal relocation took place after a GLOF in 1977 in the Engaño valley in the Chilean Patagonia, where the Bahía Murta village was relocated to a higher area close to the original location (Anacona et al., 2015).

The postevent relocation of Bahía Murta did not lead to any reported resistance. However, in Carhuaz in 1970, the proposed zoning laws and resettlement of exposed areas were rejected by the people, as their perceived political, social, and economic risks overshadowed their perception of climatic or glacier hazards (Carey, Huggel, et al., 2012). For Huaraz, the authorities tried to prohibit construction in the GLOF path after the 1941 GLOF and again after the 1970 earthquake, but residents ignored the spatial planning policies both times and the government did not enforce its mandate (Huggel, Carey, et al., 2020). Due to population pressure, in 2014 an estimated 15,000–20,000 people were living in the area of the GLOF alluvial cone in Huaraz, along with governmental, educational, health, telecommunication, religious, commerce, and tourist infrastructure (Wegner, 2014). Similarly, there has been significant development of infrastructure in the flood zone of Nyalam, downstream of Lake Jialongco, despite known GLOF risk (Allen, Sattar, et al., 2022). In contrast, the short-term relocations in the Hunza basin were organized on a self-help basis mainly and despite the wish of most of the affected people; permanent relocation was not possible due to a lack of resources (Ashraf et al., 2012). Similarly, in Santa Teresa, relocation had not been formalized because safe, alternative parcels of land were unavailable (I. Hagen, personal communication, March 2024).

Exposure Reduction Measures: Summary and Lessons

Structural exposure reduction measures like flow deflection and retention dams or flow channel adaptation have reduced or averted GLOF damage in many locations. They are generally considered reliable measures to reduce primary impacts. However, they may not be able to completely stop the mass flow downstream of their point of implementation and changes in the potential hazard magnitude (e.g., due to climate change) may render them inept.

In many areas with relevant GLOF exposure and vulnerability, EWS have been recommended. They are a practical strategy from a technical point of view and are generally less expensive than large structural DRM measures. In addition, EWS can provide valuable monitoring data in the usually data-sparse high mountain areas (W. Wang et al., 2022). However, from a social and institutional perspective, they are much more complex. EWS require redundancy in monitoring and alerting, continuous maintenance, and persistent awareness in the population about response protocols and safe areas, which can be difficult to guarantee over longer time periods (Haeberli et al., 2017). Failure in any of the components (disaster risk knowledge; observations, monitoring, and forecasting systems; warning dissemination mechanisms; and preparedness and response capability) of an EWS will limit the success of the measure (United Nations Office for Disaster Risk Reduction [UNDRR] & World Meteorological Organization [WMO], 2022). A global survey recognized that the dissemination of warnings and the preparedness to respond are the weakest components of EWS (United Nations, 2006). There is a very limited number of operational GLOF EWS globally. The experiences with almost all reported EWS highlight failures and challenges, the causes of which were manyfold.

From a logistical point of view, exposure reduction measures with structural components often face the same challenges as hazard reduction measures, relating to accessibility, transportation, and work load and safety (Bell et al., 1998; USD Enterprises & Sutron Corporation, 2010). The installation of the physical equipment for GLOF EWS is often challenging in mountainous regions. At the same time, equipment life is reduced in such environments, as exemplified by the Kyagar Lake station that was flooded only 1 year after installation. Clouds or snow coverage limits solar power production, and energy problems and lightning impacts force regular checkups of batteries and solar panels (Fluixá-Sanmartín et al., 2018; Huggel, Cochachin, et al., 2020). Long system calibration periods are indispensable (Huggel, Cochachin, et al., 2020), and regular recalibration may be needed, for example, where the glacier morphology changes (Theiler Ingenieure AG, 2021). With internet connection not always available or stable in many mountain areas, data transmission possibilities are limited and expensive (USD Enterprises & Sutron Corporation, 2010; W. Wang et al., 2022). Mobile coverage is particularly low in mountain regions of Asia and South America (UNDRR & WMO, 2022) with unstable cellular networks, particularly during inclement weather, which also makes communication and warning difficult (Ikeda et al., 2016). The operational costs of EWS in remote areas and harsh physical environments can, thus, be high, as radio and satellite connections are expensive and energy intensive, and costly equipment is required (Bell et al., 1998) to ensure redundancy, sustainability, and durability (Huggel, Cochachin, et al., 2020).

As GLOF EWS are often implemented on a limited project basis, continuous maintenance contracts rarely exist. With tight financing, budgets for operational expenses have been insufficient, for example in countries like Nepal and Bhutan (Gurung et al., 2021; RGOB et al., 2012). At the same time, monitoring and early warning stations regularly suffer from vandalism and theft with equipment components like solar panels and batteries stolen and sold (for Nepal: S. Gurung, personal communication, January 2024; India: M. A. Khan, personal communication, February 2022). It is often social challenges that lie at the basis of this. For example, the theft at Shako Chho, suggests that there was not enough community information, sensitization, involvement and engagement (M. A. Khan, personal communication, February 2022). The dismantling of the EWS station at lake 513 was based on the belief of local farmers that the station was to blame for a strong drought in the area, reflecting distrust and lack of ownership toward the implementation of the EWS (Huggel, Cochachin, et al., 2020).

A lack of identification and ownership of the local population was also reported for the Nepali lake Imja and Tsho Rolpa. The alarmist media coverage and wide attention given to lake Imja and the Everest region, over other lakes that may in fact be more critical, was not well received by many local Sherpas (Khadka, 2016). In the case of Tsho Rolpa, incidental false alarms (Ives et al., 2010) caused a cry wolf effect in the local population, and the absence of positive long-term outcomes from the associated risk reduction project (Sherry & Curtis, 2017), a lack of participation (Ives et al., 2010), communication and follow-up (Dahal & Hagelman, 2011), not only created mistrust toward outside experts and authorities (Sherry & Curtis, 2017), but left the at-risk communities more vulnerable with a low risk perception and a false sense of security, as they assumed that the lake had been lowered to a safe level (Dahal & Hagelman, 2011). This is reflected in the tendency of building ever closer to the river (Dahal & Hagelman, 2011).

Partial lack of information was also reported for the Punaka-Wangdue valley, where it was found in focus group discussions, that in contrast to men, most women did not know the evacuation routes and safe sites and young women were not even aware of flood hazard maps (M. S. Shrestha et al., 2016). No official GLOF response plans were elaborated or communicated to the local population (M. S. Shrestha et al., 2016) and in similar other regions evacuations have mostly been organized non-formally on a self-help basis (Ashraf et al., 2012). Similarly, the failure to react to the warning during the Giétro GLOF event in Switzerland can be attributed to a lack of clear protocols, information and understanding of the complete local population.

In contrast to that, the declaration of state emergency and subsequent taking over of the responsibility and control over the involved parts of the armed forces, fire departments, police departments and regional and local authorities by the Italian National Department for Civil Defense in Macugnaga, established clear roles and responsibilities, making processes effective and fast (Truffer et al., 2021). While this legal framework clearly does not always apply, it is still to be said that meaningful integration of all relevant entities is important for the success of an EWS. Neglect to involve all key actors from the beginning of the project around lake 513, as well as changes in local governments resulted in lacking support and implementation delays, challenging the sustainability of the EWS in Peru.

Similarly, changes in the political government and agenda were the cause for the halt of the implementation of the EWS for Salkantaycocha (Vilca et al., 2021) and of the monitoring in the Apolobamba range (R. Tarquino, personal communication, January 2024). With the start of resource extraction in the region, a large part of the local workforce got employed in mining and drained from monitoring and maintenance of environmental services (R. Tarquino, personal communication, January 2024). Lack of technical expertise and workpower was an obstacle in Nepal as well (Gurung et al., 2021) together with low sense of commitment seen in workers of manual EWS baring the risk of being killed by GLOFs, not showing up for or falling asleep during work (Meenawat & Sovacool, 2011).

In addition to that, transmission (manual or automatic) of warnings is especially challenging in transboundary regions, where coordination between national authorities is needed (Allen, Sattar, et al., 2022). Considering that, the Karakoram fire beacon EWS was quite a remarkable system, especially considering its remote location with a strongly underdeveloped infrastructure and extremely difficult access, and the necessary cooperation across political and ethnic barriers (Iturrizaga, 2019).

Land use planning is considered a very effective, efficient and economical way of GLOF risk reduction and hence, favorable especially from a governmental point of view (NDMA, 2020; Thompson et al., 2020). Self-determination of the local population as well as small-scale and short-distance relocation can increase the success and effectiveness of such a measure (Anacona et al., 2015). For example, there are indications that the new village of Bahía Murta had already been planned and lobbied for by some of the local inhabitants before the 1977 GLOF, partially influenced by the frequent floods affecting the old village (Anacona et al., 2015). The GLOF in 1977 then only accelerated the relocation of the village (Anacona et al., 2015).

However, rezoning can lead to devaluation of territory and reduction of the source of income for some households. For example, in Huaraz, it was feared that the relocation of the city would diminish its position as regional financial hub offering jobs, access to markets, transportation, commercial centers and so forth (Huggel, Carey, et al., 2020). In Carhuaz, relocation plans imposed new risks on the local communities, associated with decreased social status, loss of identity, diminished political autonomy, or infringements on values and cultural emblems (Carey, Huggel, et al., 2012). Discrepancies in perceived risks among locals and policy makers was a major reason for failed hazard zoning in Carhuaz the 1970s (Carey, Huggel, et al., 2012). In addition, usable land in areas like Huaraz or Ladakh are limited and the population is growing (Huggel, Carey, et al., 2020; Ikeda et al., 2016). Even after being affected by a flash flood in 2010, some people in the areas at risk of GLOFs in the region of Ladakh did not leave their land, as they could not afford to move (Ikeda et al., 2016).

In contrast to Switzerland, where all communities must have legally binding synoptic hazard maps that also include GLOFs (Lateltin et al., 2005), there are no widely accepted procedures or regulation on land-use planning specifically for GLOF prone areas, for example in India (NDMA, 2020). Nevertheless, hazard maps can also be used as a planning tool without a strict land use law, and regulations for flood prone or debris/mud flow prone land—which are applicable for GLOF events to a certain degree—do exist in many places. One challenge with this, however, is that, as GLOFs are normally non-returning events that originate in a rapidly changing cryosphere that now evolves beyond historical precedence and new hazards emerge in historically unaffected areas (e.g., through the formation of new glacier lakes). Therefore, existing hazard maps may lose their validity, without the wider population recognizing it.

Experiences show that the main difficulty with spatial planning lies with the institutionalization of hazard maps and the enforcement of the corresponding regulations (Huggel, Carey, et al., 2020). Due to missing clarity about the institutional procedures and responsibilities concerning the development of hazard maps, they often don’t reach beyond academic studies (Frey et al., 2018). Even with official construction prohibitions in place, people have chosen to stay in former GLOF paths for socio-economic reasons. The fear of direct economic losses incurred through inadequate compensations of land and houses by the government, as well as of opportunity costs due to missed economic gains of living along the river have kept people in hazardous areas in Huaraz (Huggel, Carey, et al., 2020). On the contrary, previously vacant land that had become affordable was being bought by historically marginalized people searching for higher living standards close to the city center and later in the 1990s by mineworkers moving to the region. Despite reformulated official prohibition of construction in the early 2000s, officials reportedly tolerate the construction of small buildings (Huggel, Carey, et al., 2020). Similarly, in Santa Teresa, despite prior knowledge of the risk of, and experienced loss related to living close to the river, some people continued living in the areas (Frey et al., 2016). Families opted to stay close to their farms and animals, prioritizing access to a wider space over reducing their GLOF risk (Frey et al., 2016). Relocation is often met with strong aversion by the affected local population. For example, in a survey in the Nepali Khumbu region 71.7% of respondents from nine villages said they would not to be willing to move their business to a different location due to GLOF risk (Thompson et al., 2020). Attempted relocation of affected populations in Huaraz to safer areas higher above the river were strongly contested as it was perceived as government-imposed assault on ruling-class privilege and equated with loss of socioeconomic status and downward movement in society (Huggel, Carey, et al., 2020).

GLOF Vulnerability Reduction

The reduction of vulnerability to GLOFs can be attained addressing physical, social, economic or environmental factors, where the reduction of socio-economic vulnerability is mostly associated with an improvement of the capacity to prepare, respond and recover from GLOFs. In comparison to GLOF hazard and exposure reduction, vulnerability reduction is generally less case or hazard specific and its positive effects can be seen in a broader sense. Vulnerability reduction measures have mostly been used as accompanying measures together with GLOF hazard or exposure reduction measures.

Information, Communication and Capacity Building

Hazard process and risk understanding is at the basis of DRM measures. Information and communication as well as capacity building around this knowledge is an important component of risk and especially of vulnerability reduction. Information on hazard and risk assessment and recommendations for disaster risk reduction (DRR) measures serve as basis for decision makers and have been communicated to local community leaders (e.g., Santa Teresa; Frey et al., 2016) as well as at district or national level (e.g., Bhutan: UNDP Bhutan, 2011a). Furthermore, dissemination and communication are one of the four essential components for EWS. In most of the GLOF risk management cases discussed so far, information was disseminated to the general public through channels like radio or TV, pamphlets, posters, signs, or through information events or workshops that were held for potentially affected local populations (Figure 9). In some cases, more spontaneous occasions like gatherings around the installation of EWS components were utilized as opportunities to raise awareness among interested villagers (e.g., Tsho Rolpa; Bell et al., 1998). Information and capacity building sessions for the general local population were conducted by or with the responsible authorities, as for example by the Civil Protection Department in the case of Macugnaga (Semino et al., 2004) or the communal government of Lenk in the case of lake Faverges (Einwohnergemeinde Lenk, 2019). Workshops, site visits and trainings aimed at both, awareness raising as well as capacity building (Pakistan: Rijal & Ali, 2015; Bhutan: Meenawat & Sovacool, 2011), and were for both, the general population as well as specific people like officials from line agencies and stakeholders of GLOF DRM (Nepal: UNDP, n.d.-a; Bhutan: Meenawat & Sovacool, 2011). While many of these events were of mainly unilateral type, in some cases, attention was also on participatory methods like focus group discussions or interviews aimed at exchange and incorporation of local experience, traditional knowledge or risk perception (e.g., Kaul & Thornton, 2014; NDMA, 2020). For example, as a consequence of the 2017 GLOF from Virjerab lake in the Pakistani Shimshal valley, flow modeling, evacuation planning and community awareness trainings were initiated (Iturrizaga, 2019).

Figure 9. Awareness raising campaign in 2016 around the GLOF hazard map in Huaraz, Peru.

Source: Photograph: CARE Peru.

Communication, information and training reportedly improved risk knowledge, management and response capacities (e.g., Ikeda et al., 2016; Muñoz et al., 2016). However, several problems exist. For example, as reported for Nepal, knowledge dissemination to local institutions was inconsistent, and knowledge sharing across organizations was largely lacking. Thompson et al. (2020) found that information mostly is extracted and stays on international and national levels being used by external stakeholders for reports and scientific publications rather than interactively flowing between external and local institutions. However, some progress has been made in the past years in India, for example, where only 20% of the literature published between 2017 and 2021 on Indian GLOF related topics were authored by foreign researchers without the involvement of local researchers (Emmer et al., 2022). The leading role of local researchers is important as they are closer to government actions on DRM (Emmer et al., 2022). In transboundary contexts information and communication may be even more difficult, because in border regions crucial information like satellite imagery, maps, aerial photographs and similar are, often classified and not publicly available (United Nations Development Programme & European Commission, 2009). In addition to this, local knowledge is often not incorporated despite being an important part of GLOF knowledge and information (RGOB et al., 2012). Furthermore, high turnover rates in important stakeholder institutions hinders sustainable capacity building (UNDP Bhutan, 2011a). Unclear and contradicting information has in some cases led to distrust of the local communities toward experts and authorities challenging the success of GLOF DRM strategies, for example in the Cordillera Blanca (Carey, 2005). One of the main challenges identified in GLOF research is the difficulty to interpret the growing number and often differing GLOF hazard and risk assessment schemes, results and approaches for decision making (Emmer et al., 2022). For instance, for lake Imja, extensive research activity resulted in discrepancies of outcomes, leading to confusion among the local inhabitants (Watanabe et al., 2016). Limited community involvement has led to misunderstandings and confusion about GLOF risk, causing the loss of credibility among donors and research groups (Watanabe et al., 2016). At the same time, selective media coverage diverted attention from Tsho Rolpa to the more easily accessible lake Imja, leading to even more confusion among the local communities and influencing both the funding of science and DRM in the area (Carey et al., 2015). While anxiety among downstream populations of lake Imja was especially high after the 2015 earthquake, understanding of GLOF processes, risk areas and DRM planning was very low (Byers et al., 2015). Additionally, it was found that people use information differently depending on their own experiences with GLOFs (Abdel-Fattah et al., 2021). While the integration of local knowledge and experience is an important factor for risk understanding and management, strongly relying on past experiences may lead to an underestimation of risks especially for events of unprecedented intensity, reach or frequency due to changes in the climate and environment.

Governance and Institutional Setting

Stable governance and a secure and reliable institutional setting with stable funding mechanisms are essential conditions for strong adaptive capacity. This includes, for example, a legal framework for implementing guidelines and standard operating procedures with a clear distribution of responsibilities and tasks, stable GLOF DRM financing mechanisms and solid enforcement of regulations. Official institutions in charge of GLOF DRM and formal guidelines have historically been implemented mostly after destructive GLOF events. For example, the Peruvian lakes security office was permanently established after a GLOF in the Los Cedros Canyon that destroyed a hydroelectric station in 1951, and was again strongly funded after the 1970 earthquake (Carey, 2005). In Nepal, recommendation of new regulations for engineering projects to include GLOF hazard assessments was issued after the Langmoche GLOF from Dig Tsho (Ives, 1986). After repeated GLOF events in the 1960s and 1970s, the Kazakh mudflow protection division (KSAMP) was established in 1973 as subdivision of the National Ministry of Emergency Situations (Kassenov, 2022). Institutionalization of risk management, including the implementation of standard operational procedures, policy frameworks, official GLOF management guidelines, risk management committees or hazard watch groups were part of DRM processes in Peru, Nepal, Bhutan, Pakistan and India (Fakhruddin & Basnet, 2018; Frey et al., 2016; Meenawat & Sovacool, 2011; Muñoz et al., 2016; NDMA, 2020; Rijal & Ali, 2015; UNDP Bhutan, 2011a).

When the local population does not trust appropriate government information, laws or projects, it becomes more vulnerable to disaster (Carey, 2005). Hence, public trust in stable institutions plays a significant role in enabling effective GLOF DRM (Thompson et al., 2020). While the lakes security office has been in place in Peru since the 1950s, the national plan for DRM that was consolidated in 2014 does not consider glacier related hazards as part of the most important hazards in Peru (Muñoz et al., 2016). In the 1980s and early 1990s, violent civil conflict related to the revolutionary group Shining Path also made engineering projects at glacial lakes in the Cordillera Blanca, Peru too dangerous (Carey et al., 2015). Historical instability, bureaucratic centralization, inadequate funding, and limited information exchange with the public reduced the trust of the population in the authorities in Peru since the 1950s (Carey, 2005). This absence of trust and communication among the local, scientific, and policy communities has increased people's vulnerability to GLOFs (Carey, 2005). Effective implementation of DRM is limited due to the authorities' lack of understanding of their roles and responsibilities, and of the current regulations, and it was observed that, in absence of stable institutions, DRM may de facto be dependent on single people, like the mayor of Huaraz in the case of lake 513 in Peru (Muñoz et al., 2016). Furthermore, most funding mechanisms go through international organizations to national governments and are largely driven by external agenda (Thompson et al., 2020). Slow and complicated bureaucratic processes, for example associated with bidding or authorization mechanisms, can hinder efficient GLOF DRM, as observed for lake Imja, Nepal, or in Pakistan (Rijal & Ali, 2015; Thompson et al., 2020). Similarly, conflicting priorities for resource allocation (for example between energy security and developmental needs), weak coordination between institutions and a lack of professionals for implementation were at the basis of Bhutan's missing institutional capacity to implement all their responsibilities (Meenawat & Sovacool, 2011).

Preparedness and Response

Response capability is one of the four essential components of EWS. In the Chucchún catchment downstream of lake 513 in Peru, preparedness was one of the prioritized GLOF DRM measures (Muñoz et al., 2016). In the corresponding efforts to implement a GLOF EWS, evacuation and emergency plans were developed, technical personnel of the DRM office, and the civil defense office was trained and evacuations were simulated in mock drills with schools and the population, in order to improve evacuation routes and to identify critical risk areas, and topics of climate change and GLOFs were included into the curricula of local elementary schools (Muñoz et al., 2016). In Santa Teresa, Peru, the DRM strategy included activities with the local population and authorities aimed at social and institutional preparedness (Frey et al., 2016). For lake Imja, evacuation centers were operationalized in order to provide safe shelter to vulnerable communities during floods and other disasters (Fakhruddin & Basnet, 2018; UNDP, n.d.-b). In high GLOF risk settlements, taskforces were formed and mock drills as well as first aid, search and rescue, and response trainings were organized (Fakhruddin & Basnet, 2018; UNDP, n.d.-b). In Bhutan, response planning, identification of safe havens and possible evacuation routes, trainings for school preparedness and mock drills were aimed at improving community preparedness (RGOB et al., 2012; UNDP Bhutan, 2011a). In Pakistan, preparedness measures included the development of access routes and mock drills, and trainings focus on search and rescue, first aid and camp management (Baigal, 2022; Rijal & Ali, 2015), as shelter relief is often organized non-formally in community's religious centers and schools (Ashraf et al., 2012). Similarly, in Tajikistan, volunteer rescuers were trained and an emergency reserve warehouse was installed in the Shuraki Kapali River basin (Zaripov et al., 2020). Other important measures to reduce vulnerability through preparedness and response, are the improvement of medical services, as well as mandatory and optional insurances and compensation schemes for uninsured disaster losses by different public administrative levels (NDMA, 2020).

Muñoz et al. (2016) state that authorities and population improved their capacities to respond to GLOFs as a consequence of the EWS implementation at lake 513 in Carhuaz, Peru. In the Punakha-Wangdue valleys in Bhutan, the level of preparedness was found to be high. This was, however, attributed to the 1994 GLOF originating from lake Luggye in Lunana (RGOB et al., 2012). At the same time, inadequate resources for setting up emergency operation centers or search and rescue equipment and trainings was seen as a major limiting factor in achieving GLOF preparedness (RGOB et al., 2012). However, in general, there is very limited documentation of any formal evaluation of the effectiveness of trainings and measures aimed at GLOF preparedness and response.

Fostering Economic Diversity and Improving Livelihoods

Diversifying and improving the livelihoods of local communities can reduce their vulnerability and strengthen their adaptive capacity. Being backed up by several sources of income, instead of depending on a single household income source, often based on local agriculture or livestock farming, can create resilience in case of damage to the land, crops or animals. Measures like the improvement of access to drinking water, sanitation, electricity, telecommunication and the internet can further improve people's livelihoods and reduce their general vulnerability.

In Nepal, for example, elevated tube wells were installed in flood-prone communities to ensure their access to drinking water during the flood season (UNDP, n.d.-a). While this is not a specific GLOF DRM measure only, it also reduces the communities' vulnerability to GLOFs. Similarly, in the downstream regions of lake 513 in Peru, water issues were found to be a major concern for the local population and it was recognized that water resources management should be a focus beside GLOF risk (Muñoz et al., 2016).

However, the feasibility of the implementation of such measures aiming at diversifying and improving the livelihoods of local communities, is quite limited in remote mountain regions, especially in the context of weak institutional settings. Additionally, while it may be possible to track the effective implementation of measures that aim at economic diversity and improving livelihood, it is difficult to evaluate their actual effect on GLOF DRM, especially in a short-term.

Vulnerability Reduction Measures: Summary and Lessons

Vulnerability is a complex topic and its factors are difficult to keep disentangled. Not much attention has been paid to vulnerability reduction compared to hazard and exposure reduction. On the contrary, some of the GLOF DRM measures taken in the domains of hazard and exposure reduction have had negative effects on the vulnerability related to information, livelihoods, power dynamics, access to societal services, etc.

The main constraints for vulnerability reduction in the Peruvian Cordillera Blanca have been institutional, political and economic limitations (Hegglin & Huggel, 2008). While there were limited analyses on the results of GLOF-specific capacity building and trainings, a study about DRR capacity building on floods and landslides in Central Asia had a largely positive immediate evaluation, reporting that it served to share and discuss knowledge with and among local experts (Peresan et al., 2023). Nevertheless, Peresan et al. (2023) point out that periodic activities would be recommended in order to assess and monitor the long-term impact of capacity building. The main challenges they report are related to the need for clarification around concepts and definitions like "risk," to the identification of strategies that foster local participation, and to the strong concentration of knowledge and skills among a few experts (Peresan et al., 2023). Similarly, the main challenges in the field of governance, are related to communication with ministries, to the lack of political will to harmonize risk-related data and knowledge management as well as lack of legal frameworks, and to economic issues and lack of financial resources.

Vulnerabilities are especially high in mountain communities that are distant from centers of power and are politically marginalized and neglected in terms of infrastructure, health care, education, government assistance and economic investments. At the same time, in many cases such communities have historically been subjected to intrusions by outsiders (e.g., missionaries, mining companies, tourists, national park administrators, etc.) restricting local access to resources (Hock et al., 2022). In these cases, indigenous communities may not only have their own GLOF knowledge, but this knowledge may be additionally put into larger histories of colonialism, dispossession and racism (Emmer et al., 2022). While the importance of the involvement of local communities in GLOF studies and GLOF DRR policies and initiatives is gaining more attention in research, not enough attention is paid to the ways in which different researchers and stakeholders define the GLOF problem differently from the start (Emmer et al., 2022). Information gained through scientific studies often does not lead to tangible actions, especially when decision-making stakeholders are bypassed and the studies are not linked with the applied work of practitioners (Emmer et al., 2022). Even if projects include capacity building at the community level and integrate local perceptions, they are often not embedded into local long-term hazard management strategies. In the case of Vijerab lake in the Pakistani Shimshal valley, for example, some housing, a school and a tree nursery expanded into the hazardous flood zone, despite hazard modeling information and evacuation planning (Iturrizaga, 2019).

Temporal Scope and Risk Component of GLOF DRM Measures

Different disaster risk management (DRM) measures are aimed at different time scales, as some of them can be implemented quickly while others require longer planning phases. At the same time, some measures aim at long-term solutions, while others have more of an emergency character and act on a rather short-term basis. Figure 10 gives an overview of the different measures that were considered for this review in terms of the risk component they address, the temporal frame they act in and aim at, and the nature of the measure. In general, measures aiming at long-term solutions have longer implementation periods, while measures aiming at emergency short-term solutions have shorter implementation periods.

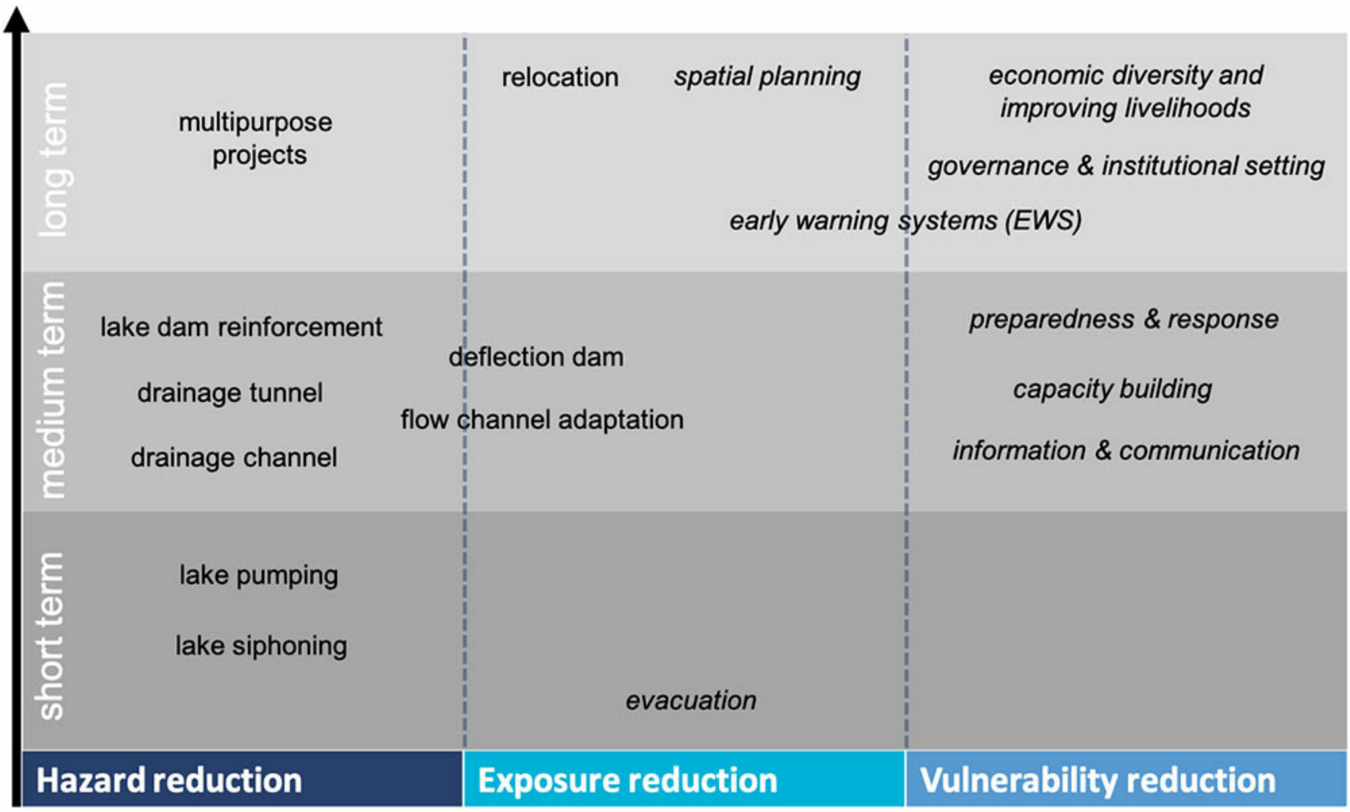

Figure 10. Categorization schematic of disaster risk management measures aiming at the reduction of hazard, exposure and vulnerability with respect to the temporal scale of their operation (y-axis: short-, medium- and long-term measures) and the type of implementation (i.e., structural [roman font] and non-structural measures [italic font]).

In most regions, efforts in GLOF DRM have been concentrated on hazard reduction approaches and were largely structural in nature. This is in line with the academic findings of Emmer et al. (2022) that state that most reviewed GLOF related publications cover topics of the physical sciences domain rather than of the social sciences domain, and that there is a focus on hazard over the other components of risk. While some research has stated that engineering measures like moraine dam reinforcement or lake drainage are among the most effective GLOF DRM measures (e.g., Portocarrero, 2014; S. Wang & Zhou, 2017), there are also clear drawbacks to this approach. As shown by many past examples, GLOF hazard reduction can be technically difficult, costly and its effectivity maybe temporally limited. Lake siphoning or pumping generally aim at short- or medium-term hazard reduction, as they can be quickly implemented measures, being functional over short time scales of several days to weeks and as such useful for emergency situations. More elaborate and expensive solutions including channels or tunnels take longer to be implemented and are intended to be functional over several years to decades, ideally. However, despite their aim at longer time scales, a strong focus on current and local single hazards has in the past led to results of limited temporal reach and functionality, due to the quickly changing environmental conditions and hazard landscape in cryospheric regions (e.g., Palcacocha: [Carey et al., 2015]). It is important to take into account, that lake lowering as well as general hazard reduction measures at glacial lakes only achieve medium- to long-term sustainability if they consider future changes in the lake's environment (Cuellar & McKinney, 2017), and are continuously maintained, reassessed, and updated (Carey et al., 2015).

There is a wide range of possible GLOF exposure and vulnerability reduction measures, most of which bring benefits across a range of geotechnical and hydrometeorological risks and are generally aimed at medium- to long-term time scales. Structural exposure reduction measures, that adjust flow paths through redirection, slowing, separation or retention of the flow, are implemented in and act in similar time frames as hazard reduction measures. Compared to structural measures directly at the lake, structural measures further downstream may be logistically easier to build thanks to better accessibility. While in some cases structural exposure reduction measures have been found to provide very reliable protection, reported destruction and damage to such structures in the past underlines the importance of the hazard event scenarios and assumptions about capacity requirements based on which they are built. The need of considering future scenarios accounting for changes in the hazard landscape and the possibility of cascading events also applies for structural exposure reduction measures.

Non-structural exposure reduction and vulnerability reduction measures cover a broad temporal range in terms of implementation time and sustainability. While the temporary closure of roads or whole areas, and evacuations, for example, can be carried out on very short time frames of minutes to days, measures like definite relocation or changes in land use or spatial planning, usually, require longer planning phases and aim at long-term solutions in the range of years to decades. Hazard and risk maps provide valuable information for any kind of GLOF DRM measure and are an indispensable basis for spatial planning. However, experiences have shown, that they often don't reach beyond scientific studies when institutional processes for their development and structures for their integration into official guidelines and governance are missing. New zoning laws are difficult to enforce and are often resisted, especially when intransparent development and institutionalization processes challenge the legitimacy and intention of such laws. In consequence, inclusive and transparent elaboration of hazard maps and their institutionalization is time-intensive.

Early Warning Systems (EWS) have been increasingly recommended as relatively quick to implement and long-term DRM measures for natural hazards. The Sendai Framework for Disaster Risk Reduction (DRR) pushes to "substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030" (United Nations Office for Disaster Risk Reduction, 2015, p. 12). However, experiences show, that despite being foreseen as an immediate measure to protect people's lives from GLOFs, operationalization of EWS can be a slow process. Complicated institutional and administrative processes with multi-stage procedures for technical approval and financing, collaborative design and implementation including all relevant institutions, stakeholders and the local communities, system calibration, mainstreaming and testing of standard operating procedures related to an alarm can take months in the very best case to years in most cases. Required time increases with low institutional capacities and political and governmental instabilities (Frey et al., 2018). Hence, there needs to be more focus on reaching the "last mile" of EWS as an effective DRR measure (UNDRR & WMO, 2022), with the last mile referring to the communication of warning messages to and empowerment of the end-users, especially the most vulnerable in the community (Huggel et al., 2012; M. S. Shrestha et al., 2021).

All the addressed vulnerability reduction measures aim at a long-term DRR effect. While information, communication and capacity building, as well as preparedness and response can be implemented and achieved in the medium-term, typically taking weeks to years, the improvement of governance and the institutional setting and the fostering of economic diversity and improving of livelihoods requires long-term efforts rather ranging from months to decades.

Cost-Benefit of GLOF DRM Measures

When assessing costs and benefits of GLOF disaster risk management (DRM), cost refers to the monetary and non-monetary cost of a GLOF DRM measure, while benefit refers to the avoided potential damage that could be caused by a GLOF event (e.g., Schaub et al., 2013). Monetary costs for different GLOF DRM measures are known from past projects and reported implementations. Assessments with specific numbers for GLOF damage potential, on the other hand, are rarely available. Especially for forward calculations of potential damage, it is worth noting that GLOF damage estimates are based on one scenario or several scenarios that represent qualitative probabilities of occurrence at most (i.e., low, medium and high probability). The related probabilities are mostly not statistically assessable, through for example, return periods, as it is common practice for floods or similar recurring events. Therefore, directly comparing the cost of GLOF DRM measures with the cost of the potential damage based on a scenario that may or may not happen has its inherent conceptual limits. Nevertheless, it is worth to roughly compare costs among different GLOF DRM measures and compare against GLOF damage costs from real events, in order to get an understanding of the orders of magnitude that potentially come into play.

Damages due to GLOF impacts can reach very high monetary costs especially in increasingly used areas with growing infrastructure. The total economic value of exposed assets to a potential outburst of Tsho Rolpa or lake Imja in Nepal, for example, are estimated 2.4 billion and 8.98 billion $ US, respectively (ICIMOD, 2011). Implementation costs of related DRM measures are roughly an order of magnitude lower: the artificial spillway for lake level control, constructed at Tsho Rolpa in 2000, cost about 2.7–3 million $ US (of which 1.1 million was for transportation costs; Kattelmann, 2003; Mool et al., 2001), and the lowering of lake Imja via an open channel and a gate cost around 3 million $ US (Khadka, 2016).

The cost of structural measures is in general considered to be relatively high (NDMA, 2020). The range of costs for hazard reduction measures is wide, reaching from several thousand $ US to several hundred million $ US depending on the type, complexity and lifetime of the structure and system. Annual costs for repeated drainage in Kazakhstan amount to 10,000–60,000$ US per lake (Kassenov, 2022), whereas the extensive works at Jialongco including the removal of much of the frontal moraine, the artificial strengthening of the dam and the construction of an outlet amounted to >10 million $ US (Allen, Sattar, et al., 2022). The construction of a massive retention dam for mass movements, including GLOFs and debris-flows, from a larger catchment in Kazakhstan cost around 40 million $ US (Kassenov, 2022). Costs of course vary substantially between the scope, dimension and complexity of projects, as well as between countries and their price levels. For example, the simple Nepali Langtang multipurpose project (weir and spillway at the moraine and penstock pipe and powerhouse with power generation capacity of 100 kW) cost > 0.5 million $ US (Dixit, 2021), whereas for the large multipurpose project planned at Trift lake in Switzerland (177 m high dam and reservoir with 85 million m^3 retention capacity and power generation capacity of 80,000 kW), a cost of around 440 million $ US (387 million CHF) is expected (Kraftwerke Oberhasli AG, 2017).

While in the physical, sociopolitical and economic context of countries in the European Alps, the construction of tunnels like the one in Grindelwald is considered a good and technically feasible option to ensure safe working conditions at a moderate cost (Gemeinde Grindelwald, n.d.), in regions with more lakes in remote areas and less available financial resources, extensive structural measures may be a less viable solution. In Kazakhstan, the cost of short-term GLOF hazard reduction is reported to be much lower than the cost of larger structural exposure reduction measures (Kassenov, 2022). Simple calculations based on the cost of annual lake drainage and a large retention dam suggest a wide range of 40–270 years for amortization of such a large structure. This comparison is, however, limited to rather small lakes, as the costs of lowering larger lakes to a safe level increase steeply in relation to technical limitations. Furthermore, while hazard reduction measures like lake drainage only reduce the risk from GLOFs originating at specific lakes, structures located at lower elevations, can serve multiple purposes and may provide risk reduction from various hazard sources including meteorological floods, mudflows, several critical lakes in the upstream catchment of the measure, and even from potential future lakes that do not yet exist. This is especially relevant in view of the rapid climate driven changes occurring in mountain regions. Multipurpose projects like the Langtang (Nepal) or Trift (Switzerland) projects have the additional benefit of providing services like hydropower generation, water regulation, and a touristic attraction possibly beyond the duration of the local hazard situation, and therefore operate on longer time scales than the hazard reduction purpose is required. In the long term, it is worthwhile to incorporate such benefits that go beyond damage prevention into cost-benefit assessments of the measures (e.g., Schaub et al., 2013).

While the costs of structural and non-structural GLOF DRM measures can be compared, direct comparison of their benefits is inconsequential, as the measures have different objectives that are not directly financially comparable. Structural hazard mitigation measures are built to prevent damage to exposed assets, whereas measures like Early Warning Systems (EWS) primarily aim at saving lives, but not at protecting infrastructure. Contrasting the cost of an EWS with the benefit of an EWS is complex, as the value of life is usually not measured in monetary terms.

Non-structural and organizational measures are often more cost-efficient compared to big structural GLOF DRM measures (NDMA, 2020). For example, the EWS set up in 1998 for Tsho Rolpa, including 19 warning and relay stations in 17 villages, cost little more than 1 million $ US at the time (Ives et al., 2010), and more recently, the cost of the EWS for lake Cirenmaco, that was installed in 2020, was below 0.5 million $ US (W. Wang et al., 2022). At the same time, as noted for many EWS, maintenance and sustainability require a significant additional effort that has often not been considered in large donor-based projects and which can create additional financial requirements that have not usually been reported on in projects' cost overview. While most vulnerability reduction measures involve no cost-intensive structural components, they often require large amounts of human resources, significant engagement and commitment of stakeholders as well as the legal scope, and room for systemic change. Nevertheless, non-structural DRM measures aiming at the vulnerability component of risk, have been reported to be particularly cost efficient. For example, capacity building and institutional strengthening has an excellent benefit to cost ratio of around 10:1 according to UNDRR (2023). Unfortunately, specific and detailed cost reporting for measures that aim at vulnerability reduction, for example through diversifying livelihoods, strengthening governance and institutional settings, and improving communication and information flows or providing capacity building, are largely unavailable. Such costs can, however, be expected to generally be significantly lower than the costs of structural measures.

In general, however, one approach need not be favored over another, and best-practice and experiences suggest that a comprehensive approach to DRM is needed and likely to be most cost-effective in mountain regions, combining structural and non-structural measures, and responding to a multi-hazard perspective. Forward-looking, scenario-based approaches, for example in Tibet, suggest that the focus on hard engineering strategies could prove costly and inefficient if not complemented more by comprehensive strategies with a focus on multi-hazard and cascading risk approaches (Allen, Sattar, et al., 2022). Not only are there challenges to the efficiency and effectivity of hazard reduction measures for GLOF DRM, but they can even generate additional hazards (e.g., through structural instabilities as seen for lakes Thorthormi/Raphstreng or Tête Rousse) or increase risk through other risk components than the one they are aimed at. For example, in Peru, hard GLOF DRM solutions have achieved mixed results, including altered power dynamics and social relations (Carey, 2005; Carey, French, et al., 2012). Such possible unintended maladaptive outcomes must be anticipated and avoided in the DRM design process, and potential effects must be included in the evaluation of the cost-benefit and efficiency of GLOF DRM measures.

Major Challenges and Key Recommendations

Challenges that hamper the success of GLOF disaster risk management (DRM) occur for measures aimed at any of the risk components. The discussed GLOF DRM experiences highlight some reoccurring major challenges. These are namely (a) the oftentimes unprecedented nature of hazards, risks and impacts related to high mountain processes, such as GLOFs, (b) the top-down approach of most GLOF DRM projects, (c) institutional instability and lack of coordination among the involved agencies and stakeholders, and (d) a lack of ownership, identification and sense of responsibility of the local communities toward the GLOF DRM measures. These four **challenges** are elaborated as follows:

1. The cryosphere is a **rapidly changing environment** that requires constantly reassessed, reevaluated, and updated hazard reduction techniques (Allen, Frey, et al., 2022). With new hazards emerging in areas that have been historically safe or only affected in other ways, current risk awareness and knowledge is naturally inadequate. Existing hazard maps may become invalid, and at the same time, acceptance of DRM measures may be low if historical precedence is missing. Compared to hazards that have occurred historically and are now experiencing changes in frequency or magnitude (e.g., river floods), it is an open question how to assess the threat from a future lake (Allen, Sattar, et al., 2022). It is still often common practice to base scenarios on historical events, neglecting worst-case scenarios that may far exceed historical precedence. Moreover, experiences suggest, also small lakes can cause extensive damage, and can emerge over monthly time scale, and hence pose particular challenges for DRM. It is especially important to take into account the possible cascading effects of events, considering that small initial GLOF volumes have resulted in extensive damage, for example due to entrainment of secondary lakes (Vilímek et al., 2005) or mobilization of large amounts of sediment that was previously deposited (Chen et al., 2023).
2. Most large GLOF DRM projects have been **donor-driven** (e.g., in the Himalayas, the Andes, Central Asia, etc.) and as such, have followed a **top-down approach**. This means that the impulse to make GLOF risk a priority often comes from an outside institution (based on money availability and expertise), instead of being based on local actors seeking support. Especially paired with low involvement of the local communities and institutions, this has reportedly created a lack of ownership and commitment toward the approaches, tasks, outcomes and results of such projects. This significantly hinders the long-term sustainability of the project outputs, as seen with the non-commitment of local governments to finance and support implemented measures in Pakistan, for example. A study from the Nepali Khumbu region, shows that only about 5% of the population think that international agencies should play a role in GLOF DRM, and that two third of the respondents expect their government officials to lead and fund such projects (Thompson et al., 2020). In top-down approaches, the local setting of perceived risks, religious and

cultural beliefs and practices, and needs and priorities is often not taken into account sufficiently. For example, perceived social, political, and economic risks associated with GLOF DRM measures can outweigh the perception of GLOF risk and the implementation of GLOF DRM measures through imposed government policies accompanied by knowledge disparity can even increase local communities' general vulnerability.

3. **Institutional instability and a lack of coordination** among the involved agencies has been a major hindrance in effective GLOF DRM (Carey, Huggel, et al., 2012; Dahal & Hagelman, 2011). Government and institutional capacities to manage GLOFs are often poor (Meenawat & Sovacool, 2011), while the cooperative abilities of local communities are judged to be good (Kaul & Thornton, 2014). In many contexts, and especially in donor-driven top-down projects, there is a significant disconnect between external institutions, the national government, national and international organizations, local informal institutions, and the incorporation of local knowledge (Thompson et al., 2020). Moreover, the relationship between scientific findings and the corresponding institutional responses has been found to be slow, exacerbating existing mistrust between communities and external institutions, when there are long time gaps between knowledge dissemination and the implementation of concrete actions (Carey, Huggel, et al., 2012; Thompson et al., 2020). Where hazards emerge in transboundary contexts, the institutional setting becomes even more complex and institutional cooperation is fundamental. Nepal, for example has experienced numerous GLOF events, originating in Tibet but having severe impact on Nepali territory (A. B. Shrestha et al., 2010). Similar issues have arisen in Central Asia with poor coordination in transboundary catchments and politically disputed areas, causing significant loss and damage.
4. Both, top-down approaches as well as poor stakeholder coordination and cooperation weakens the stakeholders' **sense of ownership and responsibility** required for effective and long-term sustainable GLOF DRM measures. Past project outcomes show that the operation and maintenance of such measures are neglected if they are not backed up by the responsible local authorities, which is often not achieved when policies and measures are pushed by external institutions and local stakeholders and communities are not heavily involved throughout the whole process of DRM, including needs assessments, design and development, as well as implementation and operation. In many legal settings, liability is an impeding factor for responsibility and ownership building. For instance, when institutions or individuals do not adopt/accept formal ownership, wanting to avoid liabilities in case of failure of an Early Warning Systems (EWS; e.g., due to technical issues or a not accurately set threshold; Haeberli et al., 2017). In other cases, exploitative regional development strategies for resource management, including the promotion of tourism industry was hindering the building of ownership (Thompson et al., 2020).

In order to address the most important challenges found and to provide best practice suggestions for a way forward, five **key recommendations** for GLOF DRM were identified:

1. In a rapidly changing cryospheric environment, GLOF DRM strategies need to consider **future scenarios** and **cascading processes**, that may include events beyond historical precedence. Rather than being based on historical largest events, worst-case scenarios

should encompass unprecedented future magnitudes and frequencies as well as potential cascading processes. Assessing and communicating the risk of such events is a unique challenge for GLOF DRM. Flexibility and adaptability are needed in any DRM approach, as it is impossible to fully anticipate the future natural environmental and societal changes, and our understanding of the physical processes is likely to change.

2. While GLOF hazard reduction does require specifically GLOF-tailored solutions especially in the case of structural measures, it is important to embed GLOF DRM in the wider context of **integrated multi-hazard management**. Rather than looking at GLOF hazard in isolation, taking into account other physical hazards that may be present in a specific area, allows for understanding of complex processes that may, for example, exacerbate single hazards through cascading hazards and impacts. Considering this, DRM focus in mountain regions should not be on GLOF hazard reduction alone, but should pay attention to measures in downstream areas to reduce exposure and vulnerability, bringing wide-ranging co-benefits for the larger multi-hazard space, and reducing overarching risks. This is in line with the current push from the UNDRR toward multi-hazard and people-centered approaches (UNDRR, 2023). For instance, multi-hazard EWS are designed to "address several hazards and/or impacts of similar or different type in contexts where hazardous events may occur alone, simultaneously, cascadingly or cumulatively over time, and taking into account potential interrelated effects." A system, that is designed to warn of several hazards, and is based on coordinated and compatible mechanisms, efforts and capacities, is more efficient and likely more sustainable. Also regarding structural risk mitigation measures, multi-purpose projects have the potential to tackle challenges beyond GLOF risk management and to attract external funding and investments from other sectors such as hydropower production or water resource management for irrigation or domestic use purposes.

3. Most effective GLOF DRM strategies are **comprehensive and cross-cutting across all components of risk**. No single measure typically is successful on its own. Combinations ideally include short- and long-term solutions and approach different components of risk. For GLOF DRM to be effective, the measures should address the current main drivers of the risk. Through the expansion of human activity and infrastructure in many mountainous regions, these drivers are increasingly related to vulnerability and exposure components, rather than to the hazard component only. It is important to understand that the implementation of any type of measure cannot reduce the risk of GLOFs to zero (Emmer et al., 2018) and that, therefore, comprehensive combinations of risk reduction measures like EWS and land-use planning are essential to build local response capacities and an understanding of residual risks (Allen, Sattar, et al., 2022; Huggel, Cochachin, et al., 2020). Integrated frameworks addressing, for example, disaster and water risk, can cover complex and interconnected needs through multi-purpose projects (Drenkhan et al., 2019).

4. Strengthening of local **institutions** and good, stable **governance** is key for the long-term sustainability of GLOF DRM. This includes the institutionalization of DRM, as well as the strengthening of political leadership and commitment. The fact that GLOF DRM outcomes like hazard maps often don't reach beyond academic studies, calls for clear guidelines and

regulations already in the process of GLOF DRM, that increase the legitimacy and credibility of the involved institutions and the respective outcomes (Frey et al., 2018). There is a need to establish closer ties and stronger collaboration among different sectors and institutional departments, including scientific institutions, development practitioners and local stakeholders and communities (UNDP & European Commission, 2009; UNDRR & WMO, 2022), and communication and knowledge dissemination needs to address different organizations at every scale (Thompson et al., 2020). For example, integrating risk management activities with community development strategies is important for community preparedness (Paton et al., 2010). A strong institutional framework enables efficient and smooth collaboration between involved institutions, with clear roles and responsibilities, allowing for effective GLOF DRM such as EWS (UNDRR & WMO, 2022). It is important to establish stable relationships between formal agencies and the local communities. In order to achieve that, local and informal institutions need to be recognized and included significantly into the DRM development process (Thompson et al., 2020).

5. Incorporation of the **cultural and socioeconomic context, and local knowledge, beliefs and perception** is fundamental for successful GLOF DRM implementation, operation and sustainability. In order to understand and integrate these, it is important to meaningfully engage local communities, for example, in risk knowledge generation, through the assessment of their own vulnerabilities and the design of GLOF DRM measures that address their needs (Sherry et al., 2018). Particular emphasis needs to be given to the engagement of the most marginalized and vulnerable members of communities, including ethnic minorities and lower social classes, and ensuring diverse representation across ages and genders. For many mountain communities, the identity-forming relationship and deep attachment to the physical, social and cultural dimensions of their land is an important component of their wellbeing and vulnerability (Sherry et al., 2018). Western scientific knowledge co-exists with local knowledge and the local religious belief systems, influencing how GLOF risk is interpreted and responded to (Sherry & Curtis, 2017), and has been historically perceived and responded to on a self-help basis (Ashraf et al., 2012). As cultural, spiritual and religious aspects can enhance social cohesion and contribute to the coping with fear and uncertainty, they can yield valuable resources to GLOF DRM strategies (Sherry & Curtis, 2017). Therefore, focus should be on strategies that support, preserve and incorporate local cultural capacities (Sherry et al., 2018). The empowerment of the people, and the accommodation of cultural issues and social justice is especially important, as trust of local communities in formal and external authorities is often low due to remoteness and social distance of mountainous regions, that are often seen as periphery to the overall interest of the national government (Thompson et al., 2020). Bottom-up, or at least inclusive, transparent and needs-oriented approaches based on open communication are therefore essential for effective and sustainable GLOF DRM.

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