Conceptual Development of an Early Warning System for Glacial Lake Outburst Floods in Central Asia: Pilot Site Modelling for Disaster Risk Reduction

GEO 510 Master's Thesis

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Abstract

Glacial lake outburst floods (GLOFs) are a common and dangerous glacial hazard which threatens millions of people in high mountainous regions worldwide. The availability of an early warning system (EWS) for GLOFs can alleviate the impact in case of an event. In Central Asia, devastating GLOF events caused fatalities and infrastructure damage in the past. This thesis aims to develop a conceptual EWS for GLOFs at the pilot site of the Aksay and Ala-Archa valleys in Kyrgyzstan, Central Asia. Utilizing an internationally recognized four-component framework for EWSs—risk knowledge, monitoring and warning, dissemination and communication, and response capability—the study offers a multi-faceted approach to Disaster Risk Reduction (DRR) in the region. Based on the possibility of a moraine-dam breach, different worst-case scenarios are developed with peak discharges between 300 m^3/s and 900 m^3/s that are used in a steady flow simulation within the hydrological modelling tool HEC-RAS to simulate the flooding extent of a GLOF. The study identifies GLOF hotspots and assesses the exposure and vulnerability of infrastructure and residential areas, estimating the GLOF danger of 251 to 407 residents along the Ala-Archa river channel. Based on the risk assessments, the study proposes an EWS including monitoring of the glacial lake and a detection and warning system. The system emphasizes redundancy, cost-effectiveness, includes suggestions for two types of detection sensors and the use of air and electrical horns for warnings. The study further proposes practical dissemination and communication strategies, and outlines response capability necessities including an emergency response plan. The thesis concludes by highlighting areas for future research, including community involvement, technical implementation, and dam vulnerability assessments, to further refine and possibly implement the conceptual EWS.

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List of Abbreviations

CA	Central Asia
CCA	Climate Change Adaption
EWS	Early Warning System
DEM	Digital Elevation Model
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
GLOF	Glacier Lake Outburst Flood
GLOFCA	Glacier Lake Outburst Floods in Central Asia
GIS	Geographic Information System
HAOC	High Arctic and Outlying Countries
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HMA	High Mountain Asia
IPCC	Intergovernmental Panel on Climate Change
LIA	Little Ice Age
'n'	Manning's 'n' Roughness Coefficient
OSM	Open Street Map
PNW	Pacific North West
QGIS	Quantum Geographic Information System
RAMMS	Rapid Mass Movement Simulation
SWE	Shallow Water Equations
UNESCO	United Nations Educational Scientific and Cultural Organization
USACE	United States Army Core of Engineers
UZH	University of Zurich
WMO	World Meteorologic Organization
1/2/3-D	One/Two/Three-Dimensional

1 Introduction

1.1 Glacier Lake Outburst Floods

1.1.1 Environment and Climate

Glacier Lake Outburst Floods (GLOFs) are hydrological phenomena occurring in glaciated high-mountain environments globally. These flood events are characterized by the sudden and often unforeseen release of substantial volumes of water retained in a glacial lake. The flood hydrographs of GLOF events typically have the characteristics of a dam break flood as they are often initiated by the failure of ice, moraine, landslide dams or a combination thereof, which impound glacial lakes (Carrivick and Tweed, 2016; Nie et al., 2018; Song et al., 2016). The high-altitude regions where GLOFs occur, can geomorphologically be characterized as paraglacial terrain in an unstable state and consequently are liable to modification through erosion and sediment release (Ballantyne, 2002). The instable terrain with steep slopes facilitates the rapid movement of water and the according sediment erosion during a GLOF event. Therefore, GLOFs often result in a transformation from a flood to a mud- or debris flow because the high volumes of water discharge during an event entrain sediment material from the flow path (Cui et al., 2010). This sediment bulking in combination with the possible entrainment of moraine material from a GLOF dam failure can result in a continuous cascade of transitions between different mass flow types (Cui et al., 2010; Shugar et al., 2020).

The warming climate, which is attributed to global climate change (IPCC, 2022), has been pushing deglaciation which led to an increasing number and the enlargement of glacial lakes around the world in recent decades (Bajracharya et al., 2007; Carrivick and Quincey, 2014; Shugar et al., 2020; Zhang et al., 2015). As glaciers retreat, lakes commonly form in the remaining depression of the glacial bed (Harrison et al., 2018) or behind the newly exposed terminal moraines (Bajracharya et al., 2007). A recent study for HMA (High Mountain Asia) provides some perspective on the increasing numbers and enlargement of glacial lakes in this region: Zheng et al. reported an overall increase of 5.9% in lake number and 6.8% in lake area from 1990 to 2015 for HMA (2021a). Different findings suggest that the increase in total lake area can be attributed to the expansion of proglacial lakes dammed by moraines (Nie et al., 2017; Zheng et al., 2021b). It is expected that the ongoing expansion of glacial lakes will create new hotspot-areas that have the potential for GLOFs (Furian et al., 2022; Zhang et al., 2022; Zheng et al., 2021a) and thus bring the according implications for GLOF hazard and risk (Haeberli et al., 2016).

Different studies have assessed the trends of GLOFs over time scales from several centuries (Carrivick and Tweed, 2016, Shrestha et al. 2023) to decades and years, (Emmer, 2018; Falátková, 2016; Harrison et al. 2017; Veh et al., 2018) on global and regional scales. Despite the growing number and size of glacial lakes, the frequency of documented GLOFs is rather constant (Veh et al., 2018). Harrison et al. found that the global GLOF frequency increased around 1930, which they attribute to a lagged response of post-LIA (Little Ice Age) warming, while for the recent decades, the study shows a decline in global GLOF events, despite a time of rapid glacier recession. However, the study mentions glacial lag times as a possible explanation and predicts increased GLOF frequencies during the next decades based on the assessment of climate forcing, lag times in glacier recession, lake formation and moraine-dam failure (2017). Therefore, it becomes apparent how the need for research on the brought topic of GLOFs is essential to gain a scientific understanding of this natural hazard with its current and prospective significance in high mountain environments.

1.1.2 GLOF Classification

GLOFs can be classified into three different categories based on the underlying mechanisms that initiate them. Each category represents a unique interplay of geomorphological and/or climatic factors. Different processes have previously been identified as direct or indirect triggers for a GLOF. The failure mechanisms are multifaceted, encompassing erosion, structural weaknesses in the moraine, and external triggers such as seismic or hydrologic activity:

1. Ice-dammed lake outbursts floods: These outburst floods involve the failure of a dam constituted of glacier ice. The melting process can be accelerated by climatic variations or geothermal heat, leading to a structural weakening of the ice dam and eventual failure. These events can be periodic, occurring with a certain regularity over long periods of time in some regions (Dømgaard et al., 2023; Gu et al., 2023)
2. Overtopping lake outburst floods: Dynamic slope movements incorporating ice or snow falls, rockfalls or landslides from degrading permafrost for example (Haeberli et al., 2016) can hit a glacial lake and oust the water (Awal et al., 2010; Jiang et al., 2004). This causes a displacement wave, as it also occurs in the case of glacial calving events or ice fall from nearby glaciers into a lake (Westoby et al., 2014; Worni et al., 2014). In both cases the displacement wave can overtop the dam of the glacial lake causing a flood.
3. Moraine-dammed lake outburst floods: These are predominantly occurring due to the failure of a moraine dam, influenced by factors such as seismic activity which can destabilize the moraine dam and therefore contribute to an eventual failure (Somos-Valenzuela et al., 2014; Westoby et al., 2014). Sudden increases in water levels of the glacial lake through intense ice or/and snow melt or rainfall can potentially strain dams and cause failure (Allen et al., 2015; Cook et al., 2018). Further, failure mechanisms including seepage, piping, ice-core melting, or mechanical instability can also lead to moraine dam failure (Mool et al., 2001; Yamada and Sharma, 1993).

This thesis addresses the case of a moraine-dammed lake outburst flood and therefore considers the different common triggers and the three key ‘phases’ which are listed by Westoby et al. (2014) as a possible cause of an outburst flood at moraine-dammed glacial lakes (Figure 1).

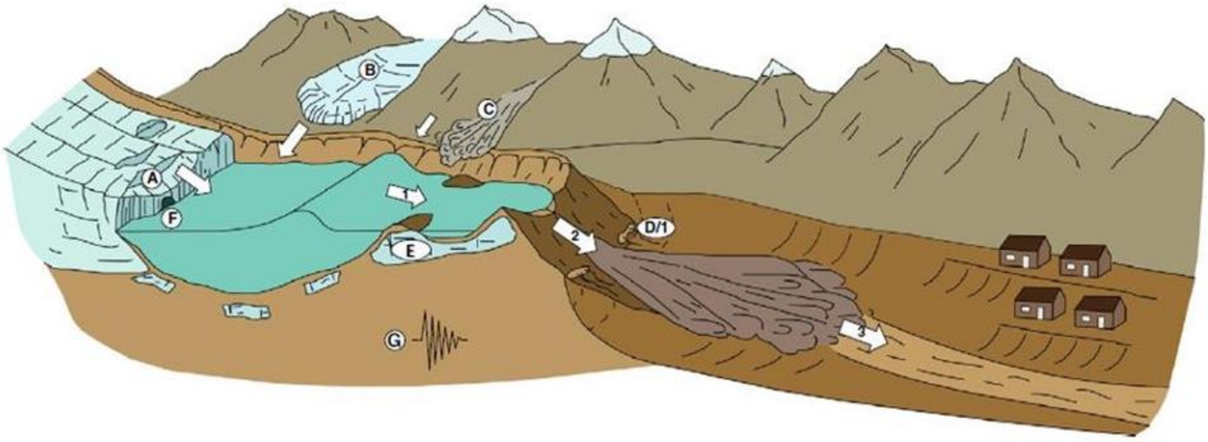

Figure 1: Different trigger mechanisms (A-G) and key phases (1-3) of a moraine-dammed outburst flood: A) glacial calving; B) glacial icefall; C) rock/ice/snow avalanches; D) dam subsidence and/or piping; E) ice-core melting within moraine dam; F) rapid increase in lake water level due to different hydrological factors; G) Seismic activity. 1) Flood wave propagation and/or piping; 2) overtopping or dam breach; 3) outburst flood wave. (Schematic adopted from Westoby et al., 2014)

1.1.3 GLOF Occurrence and Impacts

There are only few studies which have compiled detailed global datasets with inventories for GLOF events: The first was established by Carrivick and Tweed in 2016 who sourced a detailed GLOF database from the 1500s onwards, with records of 1348 GLOFs accompanied by the according physical attributes and societal impact data. While the total of the documented GLOF occurrences is not terminatory, the regional distribution shows how seven regions in the world are affected differently by the number of GLOF occurrences: The compilation showed that 2% of the occurrences happened in Greenland, 6% in South America, 9% in Scandinavia, 16% in Central Asia, 20% in Iceland, 22% in the European Alps and 25% in Northwest America (2016).

Veh et al. further expanded this global GLOF inventory by using more and updated regional inventories and a plethora of other different sources including satellite and aerial imagery, local authority reports and social media accounts among others. The study resulted in a total of 1997 dated GLOFs with physical attributes and societal impact data from 1901 to 2017. The study cannot directly be compared to that of Carrivick and Tweed (2016) as there is only occurrence data provided for the two areas with the most reported GLOF cases: The PNW (Pacific North West) accounted for 33% and HMA for 24% of GLOF events, while the occurrence numbers for the European Alps, the Andes, Scandinavia and Iceland are not provided (2022).

The global inventories differ in detail and the coherency of regional analysis but the main areas of GLOF occurrence remain the same, including the high-mountain ranges of HMA, the PNW, the Alps, the Andes and the HAOC as highlighted by Taylor et al. (2023).

Recent studies have established more regional GLOF data inventories for the strongly GLOF affected HMA region: Falátková found a total of 219 GLOFs between 1533 and 2015 and assessed their temporal and geographical distribution on the different mountain ranges of HMA, spanning the Caucasus, Pamir, Tien Shan, Karakoram and Himalayas (2016). Shrestha et al. documented 682 individual GLOFs which occurred in HMA between 1833 and 2022 with a detailed database including 60 differentiated variables on date, location, and physical attributes and societal impact data of the GLOFs. Differentiating by mountain range, 29% of the GLOFs were recorded in the Karakoram, 19% in the Eastern Himalaya and 28% in the Western Tien Shan (2023).

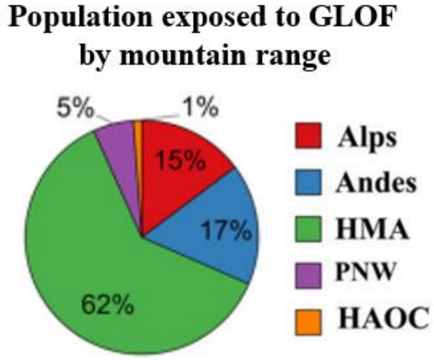

Figure 2: Global population exposure to GLOFs by mountain range. (Chart adopted from Taylor et al., 2023)

GLOFs pose a frequent hazard in high mountain areas and the impacts of GLOF events pose a threat to lives of humans and animals and can lead to the destruction of buildings, infrastructure commonly including bridges and roads and the erosion of cropland (Buchroithner et al., 2013). Taylor at al. argue that GLOFs represent a major hazard and can result in significant loss of life as their study tried to quantify contemporary exposure to GLOFs on a global scale: In the study, they considered the population living within 1km of a likely GLOF runout track along river channels up to a maximum distance of 50km from the lake at risk of an outburst. Their findings show that globally 15 million people are exposed to impacts from potential GLOFs. Breaking the exposure down by mountain range, the exposed population in the HMA region accounts for 62%, followed by the Andes (17%) and the Alps (15%) (Figure 2). For this study GLOF impact was differentiated simply between direct (death/injury) and indirect (loss of land/damaged infrastructure) forms of impact (2023).

Recording more detailed impacts of GLOF events proves to be difficult however: In their study, Carrivick and Tweed looked to record quantitative attributes of societal GLOF impacts including number of deaths, number of injured people, number of evacuees/displaced, total affected area, livestock lost, farmland lost, houses/farms destroyed, total people affected, road damage, bridges damaged, infrastructure damage and financial cost as well as positive impact wherever available (2016).

However, identifying these circumstantial societal impacts of GLOFs proved difficult due to the inconsistency or lack of available data on GLOF impacts: From the 1348 GLOFs identified in the study overall, only 24% also had a recorded societal impact. Furthermore, not for one single event all the societal attributes could be populated, therefore showing the lack of comprehensive data availability. Only the societal attribute of number of deaths had standardized quantitative reports and thus allowed for an according analysis: The study found a total of 12,445 recorded deaths due to GLOFs, a substantial portion of which can be attributed to just two catastrophic events: The 1941 event in Huaraz, Peru (Carey, 2005) and the 2013 disaster in Kedarnath, India (Allen et al., 2015), which together account for 88% of the total fatalities reported. Breaking down the death toll by region, there were at least 7 deaths in Iceland, 393 in the European Alps, 5,745 in South America, and 6,300 in Central Asia. It is important to note that no death records were found for Greenland, Scandinavia, and north-west America (Carrivick and Tweed, 2016).

The two major GLOF events in Peru and India significantly influence the global damage statistics by Carrivick and Tweed, contributing to 82% of the total caused damage and thereby demonstrating the severe impact a single event with a high death count can have. On the contrary, despite having a high number of events and GLOF sites, Iceland and Canada show low levels of damage in the report. In contrast, countries like Peru, Nepal, and India have experienced fewer events but have suffered very high levels of damage, underscoring the considerable variation in the societal impacts of glacier floods across different regions (2016).

In their study on HMA, Shresta et al. found 26 GLOFs (4%) to have accounted for 6907 deaths, although 6000 were attributed to the Kedarnath event in India (Allen et al., 2015). Most of the casualties from this study have been associated with moraine-dammed or supraglacial lakes, with no recorded fatalities stemming from breaches in ice-dammed lakes, although there might be unrecorded impacts. While exact figures are scarce, the number of individuals injured or displaced is presumed to be significantly higher than the overall death toll, a situation which is enhanced by the long-lasting negative impacts of infrastructure damage which often leads to relocation, sometimes not immediate but months after the actual GLOF event (2023).

Beside the human casualties, Shresta et al.'s study also provides some qualifications on other societal GLOFs impacts and records the loss of 2000 livestock and over 2200 structures, including both residential and commercial buildings as well as hydropower plants, which were either destroyed or sustained substantial damage. The destruction in this HMA study further extends to numerous bridges and at least 71 square kilometers of agricultural land. In only 13 cases of GLOF events from the study, attempts to quantify the economic damages in monetary terms were attempted, amounting to an estimated total of 5.3 billion USD. It is important to note that these estimations are confined to the immediate damages which occurred because of the flooding events and do not take into account the prolonged economic consequences which include the loss of farmlands, disablement, or the long-term impacts on accessibility of health, education, or market facilities due to impacts on transport infrastructure (2023). This indicates that the true economic impact of GLOF events is far greater than the studies of direct damage can indicate, because of a wide range of long-term repercussions. The findings by Cheng et al. support this, showing how a GLOF in Bhote Koshi valley of the Himalayas affected local poverty and environmental vulnerability in a way which prolonged the post-disaster societal and environmental effects for nearly two decades (2023).

The number of GLOF occurrences across the globe and the devastating societal and economic consequences which affect the impacted areas on short and long-term time scales highlight the need for mitigation strategies against such events.

1.1.4 Mitigation Strategies

The capacity for disaster risk reduction (DRR) of natural hazards can be greatly improved with the implementation of new technologies, advances in disaster risk assessment, forecast, monitoring and early warning (Cui et al., 2021). There are several approaches which can be taken for DRR in association with GLOFs:

1. Structural and engineering interventions: The conceptualization and implementation of structural and engineering solutions can be an efficient measure to mitigate GLOF hazards: Lowering the level of the water in the glacial lake prone to outburst is considered an effective mitigation measure and usually involves methods like controlled breaching, the construction of an outlet control structure, pumping or siphoning out the water from the lake or boring a tunnel through the moraine barrier or under the ice dam. Such measures have been implemented with different amounts of success in both the Himalayas and the Andes (Bajracharya et al., 2007; Reynolds et al., 1998)
2. Community engagement and preparedness: Developing strategies and educational frameworks in collaboration with the affected mountain communities plays a pivotal role in enhancing community awareness and preparation for different GLOF hazards. DRR measures like community training and information programs, educational initiatives, and the development of trusted community-based strategies to enhance the response capability and resilience to GLOF events are essential (Muños et al., 2015; Thompson et al., 2020).
3. Strategic land use planning: Analyzing the potential GLOF hazard areas and establishing different hazard zones based on different GLOF scenarios with the according zoning regulations and building codes can be a valuable DRR measure to minimize infrastructural development in high-risk zones (Satar et al., 2021; Shjin et al., 2015).
4. Monitoring and early warning systems (EWSs): Implementation of systems for the continuous surveillance and monitoring of water levels in glacial lakes prone to outburst can be a critical tool for GLOF DRR measures. Because the nature of the hard-to-reach locations of glacial lakes limits the possibilities for detailed fieldwork, satellite imagery is a critical tool for monitoring. The remote sensing technologies help to identify potential risk factors and in combination with direct EWSs for the population in GLOFs hazard areas can facilitate the possibilities for warning and evacuation (Bajracharya et al., 2007; Gu et al, 2023).

While the implementation strategies of DRR measures for GLOF events depend highly on the circumstances of the area under consideration, ideally a combination of the aforementioned measures can be established depending on the different hazard extents and the financial and institutional factors at the considered location to provide a feasible set of DRR measures against GLOF events.

1.2 GLOFs in Central Asia and Kyrgyzstan

In HMA the population residing along the possible runout tracks of GLOFs is quite high which elevates the potential impact of GLOFs in the corresponding mountain ranges and therefore increases the hazard for these natural disasters in this area. In their study, Taylor et al. mapped the GLOF danger at basin scale for the entire HMA (Figure 3) and determined GLOF vulnerability for the countries in the area. The results show many medium to high GLOF danger areas for the Tien Shan Mountain range and accordingly high GLOF vulnerability for the Central Asian countries (2023).

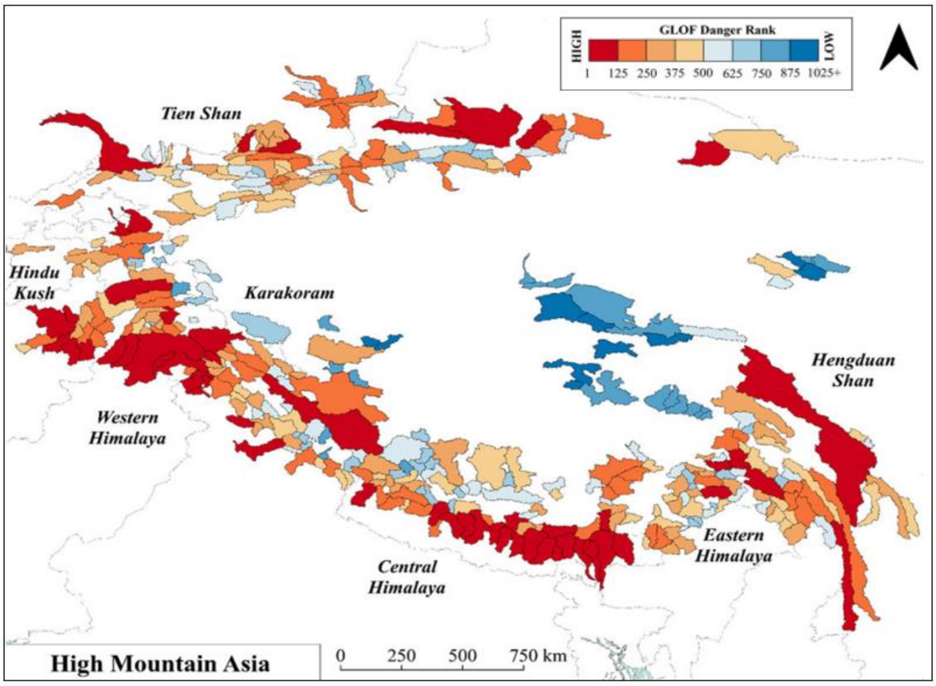

Figure 3: Spatial distribution of GLOF danger in HMA at basin scale from high (red) to low (blue) risk. (Map adopted from Taylor et al., 2023)

The Tien Shan is the main mountain range of Central Asia and spans approximately 2’500 kilometers from east to west across the countries of China, Kazakhstan, Kyrgyzstan, Uzbekistan and Tajikistan and covers about 39°–46°N and 69°–95°E. The highest peak of the range is the Jengish Chokusu, which stands at 7’439 meters above sea level. The dynamics of glacial retreat in the Tian Shan are strong with 97.5% of the glaciers shrinking over the past half-century (Chen et al., 2016). In line with the glacier recession, various studies have shown rapid growth of glacial lakes in the Tien Shan (Kapitsa et al., 2017; Wang et al., 2016; Zheng et al., 2019). Therefore, the many glaciers in the Tien Shan, its steep valleys and the glacier retreat with the according increase and growth in glacial lakes provide favorable conditions for GLOFs (Bolch, 2007; Narama, et al., 2010).

The GLOF records for the Tien Shan Mountains of Central Asia feature uncertainties due to different reasons: As Falátkova argues, only a certain number of GLOF cases in the region were described in scientific literature reasoning that the Tien Shan was long rather neglected by foreign researchers (2016). Furthermore, Thurman points out that there are significant gaps in datasets, in particular for the immediate aftermath of the collapse of the USSR (2011). Such declarations are supported by the peculiarity that according to Falátkova, not a single outburst flood was recorded for Tien Shan in the 1990s (2016). A decade of non-occurrence of GLOFs in an area that showed a rapid increase in GLOF occurrence from the 1950s to the 1990s indeed seems unlikely and is arguably a consequence of extensive efforts of the scientific community monitoring of GLOFs and debris flows until the end of the Soviet era which then died down as the Central Asian countries became independent in the post USSR era (Shresta et al., 2023).

Nevertheless, today extensive data collections exist on GLOF events in the Tien Shan Mountain range: In their recent study, Shresta et al. (2023) found 195 GLOFs causing 65 fatalities in the Tien Shan between 1833 and 2022. The study recorded the type of lake responsible for the outburst flood, showing moraine-dammed lakes to be the most common cause of GLOFs and being responsible for all fatalities in the Tien Shan (Table 1).

Tien Shan Glacial Lakes	**# GLOFs**	**# Fatalities**
Moraine-dammed	96	65
Ice-dammed	67	0
Supraglacial	17	0
Others/Unknown	16	0
Total	**195**	**65**

Table 1: Number of GLOFs and fatalities in the Tien Shan Mountains by type of lake outburst. (Table adopted from Shresta et al., 2023)

Further, the study highlights how certain lakes tend to have reoccurring outburst events with return periods varying between consecutive years and several decades. The return periods for ice-dammed lakes can in some cases be connected to the return period of the according glacier surge while there are no clear return periods for moraine-dammed lake outbursts. However, repeated GLOFs are common for all main types of glacial lakes.

According to Shresta et al. (2023) the lakes which accounted for the release of five or more GLOFs were responsible for more than 40% of their total event count. This shows how the circumstances of frequent GLOF release seem to enhance further event occurrence at the concerned areas. The Tien Shan is one of these areas as it is responsible for 41% of the GLOF recurrence locations with GLOF release frequency of five times or more. The outburst recurrence range for the seven locations in the Tien Shan ranges between 6 and 67 events and includes ice-dammed, supraglacial and moraine dammed lakes (Table 2).

Region	**Glacier name**	**Lake name**	**Outburst recurrence**	**Period of GLOFs**	**Lake Type**
Central Tien Shan	Southern Inylchek	Merzbacher	67	1902-2015	Ice-dammed
Northern/Western Tien Shan	Aksay	Unnamed	30	1877-2015	Moraine-dammed
Northern/Western Tien Shan	Kuturgansuu	Unnamed	17	1846-2010	Moraine-dammed
Northern/Western Tien Shan	Teztor	Unnamed	11	1910-2012	Moraine-dammed

Northern/Western Tien Shan	Bezymyannyi	Lake Nr. 6	8	1973-2014	Supraglacial
Northern/Western Tien Shan	Salyk	Unnamed	6	1938-1980	Supraglacial
Northern/Western Tien Shan	Topkaragay	Unnamed	6	1928-1993	Moraine-dammed

Table 2: Lakes with more than five recurring GLOFs in the Tien Shan Mountain. (Table adopted from Shresta et al., 2023)

From the locations of frequent GLOF recurrence in Table 2, six out of seven are located in Kyrgyzstan. This illustrates how the Kyrgyz Tien Shan Mountains with many glaciated ridges, steep valleys and an ongoing glacier retreat over the last decades provide good conditions for lake outburst floods (Jansky et al., 2010; Narama et al., 2010). Indeed, the Tien Shan shows a substantial amount of documented GLOFs: For the last century, the deadliest GLOF occurred in the Shakhimardan catchment in Kyrgyzstan and moved through the transboundary catchment into Uzbekistan, claiming over 100 victims across borders, leaving 500 to 600 people reported missing and leading to the evacuation of about 14’000 people (Petrakov et al., 2020). In Kyrgyzstan more than 70 disastrous cases of lake outbursts have happened since 1952 and according to the Kyrgyz lake inventory, the country has 382 lakes which are at risk of outburst (Jansky et al. 2010). Narama et al. who researched and documented the shift to rapid formation of glacial lakes which can cause GLOFs like the 2008 event in the Tong district of Ysyk-Köl Oblast, Kyrgyzstan, call for appropriate measures to protect against such lake outburst hazards in the region (2010). Thus, as the GLOF vulnerability in Kyrgyzstan is indeed high (Taylor et al., 2022) the threat of GLOF impacts is substantial, unless mitigation strategies are implemented (Thurman, 2011). Similarly, Petrakov et al. highlight the need for monitoring and the installation of EWSs at critical sites and the cooperation between the countries of the region to mitigate existing end evolving GLOF risks (2020).

1.3 GLOFCA

In the context of cooperation between the Central Asian countries for GLOF mitigation, the project Glacial Lake Outburst Floods in Central Asia (GLOFCA) can be introduced: This initiative has the objective to strengthen Climate Change Adaption (CCA) in Central Asia by reducing societal risks and vulnerabilities associated with GLOFs. The project involves the countries of Uzbekistan, Tajikistan, Kyrgyzstan and Kazakhstan and aims at a cross border strategic approach to hazard information and mitigation by establishing a knowledge management platform (GLOFCA, 2023). The project was implemented by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and is funded by the Adaptation Fund. The Adaptation Fund was created under the United Nations Framework Convention on Climate Change. It is designed to finance CCA projects and programs based on the priorities of eligible developing countries (World Bank, 2023). Past GLOF events in the region have shown that the response capabilities post-event have been generally greater than preventive measures. For this reason, the aim of the UNESCO is to enhance DRR measures by focusing on pre-disaster management. The collaborative effort encompasses governmental bodies, regional institutions, the UNESCO Cluster Office in Almaty, Kazakhstan as well as a team of scientific partners from University of Zurich (UZH). The research team from UZH is represented by C. Huggel, S. Allen, H. Frey, A. Cicoira, L. Niggli and M. Tom who act as a scientific partner of UNESCO in the GLOFCA project. The team aims to further develop the knowledge platform for decision-making in DRR in the context of CCA with a focus on monitoring strategies and the installation of EWSs (GLOFCA, 2023). The fact that GLOF events in Central Asia can cause transboundary impacts (Petrakov et al., 2020) presents concerns for impacts not only through the transboundary flood wave but also through ripple effects (for example road disruption with impacts on connectivity and trade) which can have repercussions across boarders (Shresta et al., 2023). For past GLOF events in the region which happened in transboundary catchments, warning communication and disaster assessment between countries showed difficulties (Petrakov et al., 2020). GLOFCA aims to provide a solution to such difficulties by providing an institutional platform to share knowledge and experience in the field of hazard management across borders by bringing together national and regional authorities, scientific experts, and local knowledge- and stakeholders. For every country represented in GLOFCA, scientific reports on GLOFs have been gathered to provide a brought knowledge base on the topic for the region. Pilot sites for GLOF hazard management have been defined in all four participating countries where initial studies and DRR measures will be evaluated (GLOFCA, 2023).

This thesis will be affiliated with the work of the research group from UZH and focuses on the GLOFCA pilot site in Northern Kyrgyzstan. The aim of the thesis is to contribute to GLOFCA through the assessment of different research questions regarding the GLOF impact, the development of DRR measures including the possibilities for an EWS at the pilot site of the Ala-Archa valley in Kyrgyzstan.

2. Scientific Background

2.1 Hazard, Vulnerability and Risk

In order to address natural hazards and to develop possible DRR measures, the key concepts need to be defined first: The risk for events of natural hazards, including GLOFs, is not only determined by the physical event itself but also by the exposure and vulnerability to these events. Thus, the implementation of effective adaptation and DRR measures not only depends on a detailed understanding of the natural *hazard* itself, but also on a rigorous understanding of the dimensions of *exposure* and *vulnerability*. The following aims to determine the concepts that are needed to define and understand *risk* and show that risk originates from a combination of social processes and their interaction with the environment as laid out by Cardona et al. (2012), to then apply these concepts on the evaluation for the pilot site in Kyrgyzstan.

2.1.1 Hazard

The term *hazard* refers to a possible future natural or human-induced physical event which may negatively impact vulnerable and exposed elements (Birkmann, 2006). Such an event may cause loss of life, injury, or other health impacts as well as damage and loss of property, infrastructure, livelihoods, and environmental resources. These physical events thus become hazards where social elements (or environmental resources that support human livelihoods and security) are exposed to impacts which have the potential for negative effects on them or exist under the predisposition to such effects (Hewitt, 2007; Wisner et al.; 2004). Therefore, a *hazard* is used in this thesis to describe a threat or potential for negative effects of an GLOF event, not the physical event itself.

2.1.2 Exposure and Vulnerability

The term *exposure* is used to refer to the inventory of elements in an area including the people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets that are located in places which could be negatively affected by physical events, and which thus are subject to potential future harm, loss, or damage. The levels and types of negative impacts as result of a natural hazard in interaction with the inventory of elements that are exposed then determine the *vulnerability* (Cardona et al., 2012; UNISDR, 2009).

The term *vulnerability* thus refers to the predisposition, susceptibilities, fragilities, weaknesses, deficiencies, or lack of capacities of the inventory of exposed elements that favor negative effects on them through the physical event (Cardona et al., 2012). Vulnerability is a key concept that is used in various fields including disaster risk but also in the context of ecosystem sensitivity or epidemiological and psychological fragilities (Cutter, 1994; Brklacich and Bohle, 2006; Villagrán de León, 2006). In the context of disaster risk, vulnerability shows strong manifestations of the social construction of risk (Wisner et al., 2004).

In common usage and literature *exposure* and *vulnerability* are often used as conglomerates. However, they are to be differentiated from one another: While exposure is a necessary determinant of risk, it is not sufficient because it is possible to be exposed but not vulnerable.

This can for example be in the case of infrastructure like a building in a flooding area which has sufficient flooding protection and therefore can mitigate potential damage. However, to be vulnerable to a physical event, it is a necessity to also be exposed (Cardona et al., 2012).

2.1.3 Risk

The term *risk* is often used in the literature describing either the probability of occurrence of a hazard event that acts to trigger a disaster or series of events with an undesirable outcome, or the probability of a disaster or outcome, combining the probability of the hazard event with a consideration of the likely consequences of the hazard (Brooks, 2003). Thus, risk is oftentimes described the function of the probability of a hazard event and the magnitude of its consequence through the different impacts in form of the exposure and vulnerability (IPCC, 2022).

However, when assessing the risk for GLOFs and especially moraine-dammed GLOFs, it becomes extremely hard to quantify the risk from a probability perspective. While the return periods for GLOFs from ice-dammed lakes can in some cases be connected to the return period of the according glacier surge, there are no clear return periods for moraine-dammed lake outbursts (Shresta et al., 2023) which can be attributed to the different outburst mechanisms and the complex processes behind them (Westoby et al., 2014). For this reason, following Taylor et al. (2023) this paper will prefer the term *GLOF danger* over *GLOF risk* due to the lack of outburst probability in the GLOF assessment of moraine-dammed lakes. Therefore, defining GLOF danger as the product of the GLOF event, exposure, and vulnerability (Figure 4):

$$\text{GLOF Danger} = [\text{GLOF Event} \times \text{Exposure} \times \text{Vulnerability}]$$

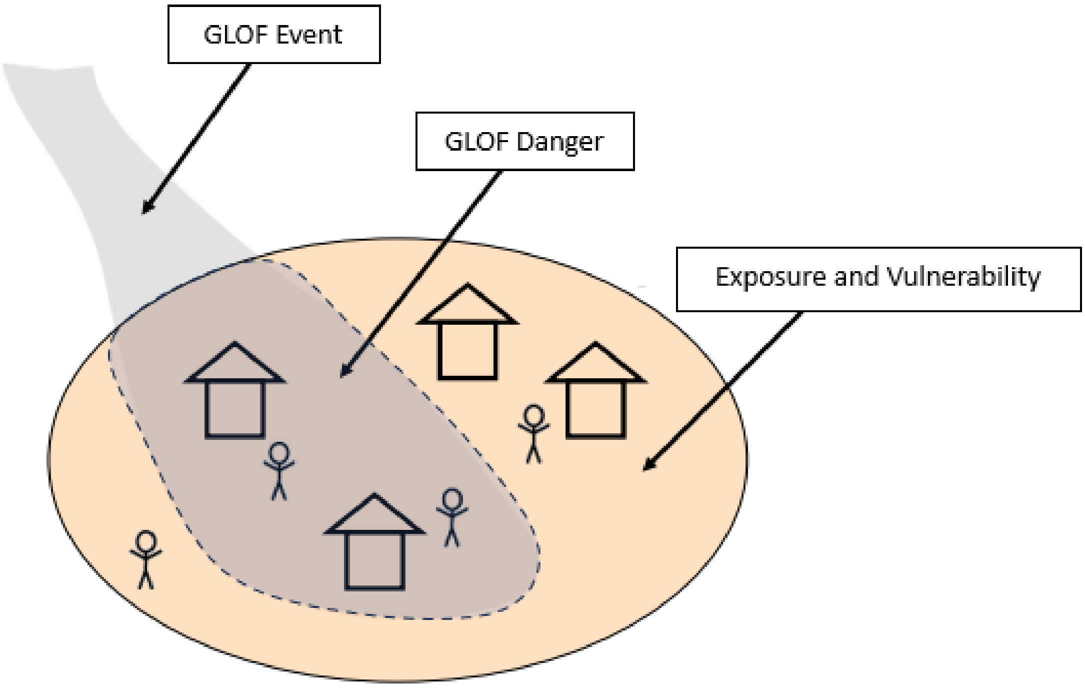

Figure 4: Visualization of the different components of GLOF danger including the GLOF event, the exposure, and the vulnerability. (Illustration adopted from Natural Hazards and Risk Analysis in Mountain Regions Block course GEO 805 UZH, 2022)

2.2 Disaster Risk, Reduction and Management

This thesis addresses hazardous physical events that occur in high mountain environments in the form of GLOFs. Because such hazardous physical events may cause severe alterations in the normal functioning of a community with different impacts which then may require immediate emergency response or external support for recovery, they are often referred to as *disasters* (Lavell et al., 2012). The literature distinguishes different terminology of related but discrete subareas when it comes to disasters, including *disaster risk*, *disaster risk reduction* and *disaster risk management*.

2.2.1 Disaster Risk

The definition of *disaster risk* originates from the two components of the physical hazard and the preexisting social vulnerabilities of exposed elements which, if brought together, have the potential for severe interruptions of societal functioning when disasters strike (UNISDR, 2009b, Wisner et al., 2004). Therefore, this general definition of *disaster risk* in the context of this thesis focusing on GLOFs can be set equal to what has been defined as *GLOF danger*.

2.2.2 Disaster Risk Reduction

Disaster Risk Reduction (DRR) describes both the policy objective and the strategic and instrumental measures which are employed to anticipate future disaster risk, to reduce existing hazard, exposure and vulnerability and to improve resilience of communities. DRR includes lowering the vulnerability of people, livelihoods, and assets as well as ensuring that the management of resources like land, water and other environmental components also contribute to the lowering of risk. The emphasis lies on strategies, considerations and activities that focus on the preventive measures before the potential impact of a hazardous event. This has led to the development of a strong relationship between DDR and development planning, which has been established and validated particularly, although not exclusively, in the context of developing countries (Lavell et al., 2012; Wisner et al., 2004; UNISDR, 2009b)

2.2.3 Disaster Risk Management

The term *disaster risk management* (DRM) describes the concern with different levels and intensities of disaster risk. It is required because of a residual disaster risk which ongoing DRR processes cannot mitigate or reduce sufficiently (IDB, 2007). DRM is defined as the social processes of designing, implementing, and evaluating strategies, policies and procedures which enhance disaster preparedness, response, and recovery at different organizational and societal levels. The processes of disaster risk management are put in place both before and after the occurrence of a hazardous event: Once there is evidence for the immediacy of a disaster, resources and capacities are established to respond prior to an event as well as post-impact. This includes the development and activation of EWS, planning for contingency, emergency response and recovery (Alexander, 2000; Wisner et al., 2011).

Therefore, DRR has the aim to reduce the risks of hazardous events such as GLOFs by anticipating their impact and addressing exposure and vulnerabilities before an event. This aim is further extended through DRM and includes the development and application of actions and strategies for immediate disaster response (Twigg, 2015). The development and implementation of an EWS can be an essential part of both DRR and DRM: It requires an understanding and knowledge of the physical dimensions before occurrence of the possible hazard as well as the social and economic dimensions of exposure and vulnerability to then develop a feasible solution for early warning of the people at risk in case of an event. This thesis aims to contribute to DRR and DRM through developing and evaluating GLOF EWS possibilities for the pilot site in Kyrgyzstan.

2.3 Early Warning Systems

EWSs generally refer to scientific research and engineering programs which are designed to detect and provide advance notice of impending hazards or crises, allowing for timely and effective preventive action against impacts. Kelman and Glatz explain that there is no universal definition of an EWS as the system depends on the context, scale and hazard in question (2014). In most fields of application EWSs feature some form of data collection, data transmission, data evaluation and analysis followed by the timely dissemination of early warning information and the beneficial and efficient response to such information if the defined parameters for issuing a warning are met (Quansah et al., 2010). EWSs are implemented across a variety of different fields:

1. Public health EWSs: These systems involve the collection of health data from hospitals and clinics and the use of machine learning algorithms to detect patterns indicative of an outbreak. Public health EWSs are used for the early detection of diseases such as viruses and help for the timely distribution of medical resources. Challenges in this field include balancing surveillance with individual privacy and the lack of infrastructure for data collection in many regions (Bibby et al., 2021; Elbe, 2010; Gao et al., 2020).
2. Cybersecurity EWSs: In the cyberspace, EWSs monitor network traffic for unusual patterns using intrusion detection systems and block unauthorized access using firewalls. These systems are used for data breach prevention and to ensure that critical systems are not compromised. Challenges include the continually evolving nature of cyber threats, requiring constant updates, and the risk of false positives, which may block legitimate traffic (Lodi et al., 2009; Petrenko and Makoveichuk, 2017; Yan et al., 2013).
3. Economic EWSs: These systems use a variety of mechanisms including probabilistic big data analytics and machine learning to identify potential risks and vulnerabilities in financial markets, economies, or specific sectors. For example, to warn from a financial crisis. The analysed data includes macroeconomic and financial market data such as growth and inflation rates as well as stock market performance and interest rates. Challenges for economic EWSs include data quality and availability for analytics and the identification of the alerting variables (Bussiere and Fratzscher, 2006; Koyuncugil and Ozgulbas, 2012; Samitas et al., 2020).

4. Natural hazard EWSs: As there is an abundance of different natural hazards, a variety of EWSs for different areas of application have been developed according to the specific hazard:
    - Meteorological EWSs are used for example to predict severe weather events including storms or heat waves using satellite and radar data but may face challenges due to limited resolutions leading to accuracy problems (Alfieri and Thielen, 2015; Åström et al., 2015; Harley et al., 2016; Lowe and Forsberg, 2011).
    - Hydrological EWSs are exemplified in flood protection and water management making use of rainfall data and river gauges but may face challenges with terrain modelling or data integration (Hasan and Deininger, 2004; Krzhizhanovskaya et al., 2011; Perera et al., 2019).
    - Seismological EWSs rely on accelerometers and seismometers and send out public alerts or shut down critical infrastructure in case of an earthquake. However, the challenge these systems generally face is that of very short warning times of only seconds or minutes (Allen et al., 2009; Cremen and Galasso, 2020).
    - Tsunami EWSs are based on seismic sensors on the sea floor as well as deep-ocean assessment buoys but face challenges from short time frames for warning and an effective warning dissemination in concerned areas (Amato, 2020; Lauterjung et al., 2010; Wächter et al., 2012).
    - Wildfire EWSs use both ground sensors, drones and satellite imagery to monitor areas that are prone to fire but are challenged through the rapid spread of fires and the integration of real-time data (de Groot et al., 2006; 2015; Li, 2018).

This listing of EWSs is not terminatory however, it provides an overview of different EWSs applications including those for common natural hazards around the globe. In most applications of EWS the collected data is transmitted to some kind of data or monitoring center which then issues a possible warning after analysis. However, this process and durations are highly dependant on both the preliminary lead times as well as the institutional frameworks in place at the location of the EWS (Quansah et al., 2010).

2.3.1 Central Components of EWSs

The United Nations Office for Disaster Risk Reduction and the World Meteorologic Organisation (WMO) have published an internationally recognized and widely used checklist for EWSs that are people centered and applicable for multiple natural hazards. The checklist outlines the four main components of any EWSs for natural hazards (UNISDR, 2006, WMO 2018). The four central components of EWSs include 1. risk knowledge, 2. monitoring and warning, 3. response capability, and 4. dissemination and warning (Figure 5).

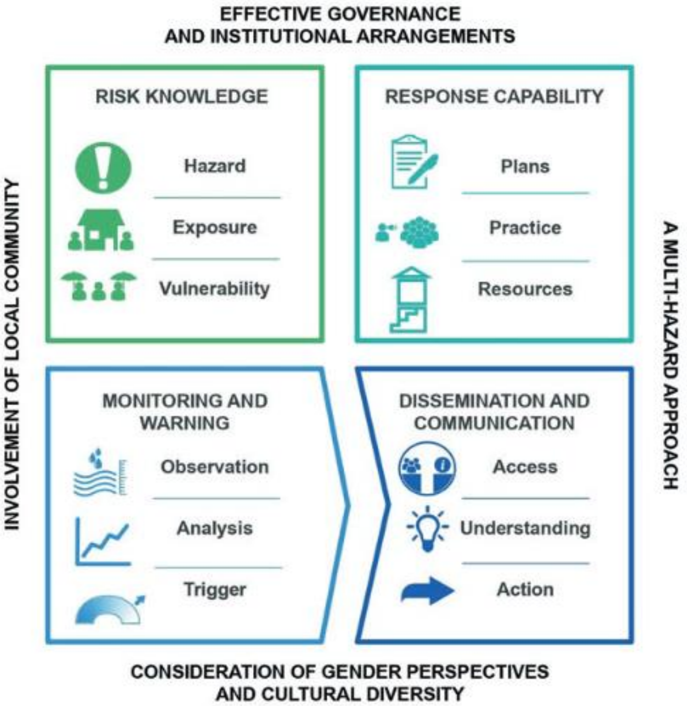

Figure 5: Components of an EWS. (Illustration adopted from Šakić et al., 2022)

2.3.1.1 Risk Knowledge

The essence of EWSs is to reduce the risk and prepare for a hazard in a certain area from the community scale over cities to whole valleys or regions. It is therefore essential to carry out a risk assessment to identify the areas prone to hazard occurrence, the locations of exposure and the nature of vulnerability concerning critical infrastructure and people. This information on risk is vital to design monitoring systems for the hazard, set up evacuation strategies and ensuring the warning message reaches the affected in the area (Šakić et al., 2022).

According to Alcántara-Ayala and Oliver-Smith, in EWS development exposure and vulnerability are often overlooked as there is more emphasis on the understanding of the hazard (2019). For this reason, this thesis will make an effort to carry out a holistic risk assessment based on the data available.

2.3.1.2 Monitoring and Warning

The process generating the natural hazard of concern needs to be scientifically understood and can then, based on past experience and the monitoring of current conditions, possibly be forecasted in advance, thereby increasing the lead time of the EWS (WMO, 2010). Such forecasting possibilities depend highly on the hazard of concern as well as the warning system related to it. In all cases though, a certain threshold of specific environmental conditions needs to be developed to set a point when a warning is issued (Šakić et al., 2022).

For moraine-dammed GLOFs the many different trigger mechanisms involved generally make for sudden outburst events and rather short lead times compared to other natural hazards as for example atmospheric storms. However, where the capacities are available, the monitoring of the water levels in the glacial lake prone to outburst can be an indicator for the possible hazard extent and can be followed by mitigation measures (Bajracharya et al., 2007; Reynolds et al., 1998).

2.3.1.3 Dissemination and Communication

The process of distribution of the warning by the groups responsible for taking action to those groups at risk is referred to as dissemination and communication. The dissemination includes the way in which the information reaches the end-users while the communication refers to the content of this information. The warning information and the way it is communicated should be tailored to the users so they can understand and prepare to act in advance of the hazard (WMO 2010).

Thus, for an GLOF EWS, the part of dissemination and communication should involve two temporal aspects: a) The preparedness and advance understanding through the response capability of the risk by the concerned and b) the immediate warning in case of an event. As many failures in EWSs still occur due to poor communication and dissemination practices (Basher 2006), especially in developing countries where many still lack the access to technology for receiving warning information (Šakić et al., 2022), the technicalities for a GLOF EWS in Kyrgyzstan needs to be considered well.

2.3.1.4 Response Capability

The response capability includes an exposed community’s knowledge of their risk, their ability to act on a warning as well as being familiar with the evacuation strategies when a warning is issued. In accordance with dissemination and communication, it is very important that this information is available to the concerned community well in advance of a possible disaster (Šakić et al., 2022). Further, the capacity of the community and first response agencies to act when a disaster occurs, needs to be built through long term planning and preparedness activities or drills: Familiarity with response capabilities are best developed through training and education (WMO, 2002). This involves having clear institutional frameworks of authorities in the decision-making process who develop these training and education strategies on the scales of national to community levels (WMO, 2015).

While the response capability of the community for a GLOF EWS in Kyrgyzstan depends highly on the local institutional frameworks, this thesis will still consider the aspect of first response agencies in the effort to conceptualize a possible EWS at the pilot site.

2.3.2 GLOF EWS as part of DRR and DRM

The EWS element of risk knowledge can be attributed to the DRR measures as it helps to anticipate the impact of the GLOF and thereby lays the groundwork for the following elements. In the literature DRR measures are classified as structural and non-structural (UNDRR, 2016): Generally, structural measures refer to engineered physical infrastructure as for example flood dikes, while non-structural measures refer to strategies, policies and approaches which involve education, training, and awareness-raising. While non-structural measures aim to decrease vulnerability and exposure and to increase the coping capacity of those at risk, structural measures aim at hazard reduction (Harries and Penning-Rowsell, 2011).

An EWS for GLOFs will feature some kind of engineered elements for hazard detection as for example sensors or ripcords. These elements for hazard detection feature as part in the element of monitoring and warning, just before the warning goes into dissemination and communication. Therefore, a EWS for GLOFs can be assigned to non-structural DDR measures because it is a warning mechanism in the chain of monitoring and warning, contributing to the reduction of vulnerability and not directly to the hazard reduction as structural measure would.

Finally, the elements of dissemination and communication and of response capability form part of the DRM measures as they are concerned with the social processes of designing and implementing, of educational strategies, policies and procedures which enhance the community's disaster preparedness, response, and recovery. Both elements are further attributed to DRM as they both relate to the timeframe proceedings before and after the occurrence of a possible GLOF.

2.3.4 Existing GLOF EWSs

In different high mountain areas around the globe exposed to GLOF danger, approaches have been taken in the implementation of EWS with different grades of technicality:

One of the earliest GLOF EWS documented in the scientific literature was established in the Himalayas by the Department of Hydrology and Meteorology Nepal and installed in the Tama Koshi and Rolwaling valleys in 1998. The redundant system consists of two main components including a detection and a warning system. The detection system consists of six water level sensors which were installed at the river channel downstream of the lake prone to outburst. The sensor data is transmitted in case of an event to a transmitter station located 80 meters higher in elevation, through armored and shielded cables. From the transmitter station, the information is relayed to 19 warning stations in the 17 villages of the two valleys as well as to the main monitoring stations in Kathmandu. The transmission works through radio technology (Extended Line of Site radio) relying on transmitter and receiver antennas installed on steel poles of approximately 5 meters in height. The stations are either connected to local AC power with backup diesel generators for redundancy or in the case of the remote ones, powered by 12V batteries that are charged by solar panels. The warning signal is issued through an air horn which is operated through a charged air cylinder with an electric back-up horn (Bajracharya et al. 2007).

In the Andes, the first GLOF EWS with a fully functional service was established as a consequence of the 2010 GLOF from Laguna 513 in the Cordillera Blanca, Peru, and implemented in 2011-2012. The system includes geophones, cameras and pressure sensors for registering GLOF events with an emphasis on redundancy of the system in case of sensor or data transmission failure. For this reason, in addition to the technical installations at two measuring stations as well as a siren warning and a repeater station, a permanently manned hut with wardens next to the second measuring station was established. The full responsibility for the system was handed over to the local authorities in 2015 but then dismantled during a strong drought in 2016 by desperate local farmers (Huggel et al.; 2020).

In the Indian Himalayas a GLOF EWS with monitoring was developed and implemented by the private firm of ‘Center for Development of Advanced Computing (C-DAC)’ for the Sikkim state government in 2016-2017: Different glacier lakes in Sikkim were registered in a comprehensive Geographic Information System (GIS) database, studied for their growth through remote sensing data and prioritized for their probability of outburst. Two vulnerable lakes were then equipped with real-time, automatic water level monitoring sensors, transmitting their data through satellite communication to a base station, where a GLOF simulation model is predicting flood height and arrival time at villages in real time with warning lead times of 4.5 hours (Kumar et al., 2022).

Another recent GLOF EWS including monitoring was developed and implemented at the Cirenmaco lake in the central Himalayas boundary region of China and Nepal. The system is equipped with sensors for the water level of the lake and cameras which carry out real time monitoring data transmission through satellite and mobile networks. The nine different monitored areas include: The lake and its parent glacier, monitoring of the environment of the downstream river, water level monitoring of the glacial lake, water level monitoring of the downstream river and moraine dam dynamic monitoring. The Cirenmaco EWS was established in 2020 and validated in 2021 and presents the first use of such a fully automatic system in China. The system is quite sophisticated as it specifically copes with two typical moraine-dammed outburst mechanisms of dam overtopping and piping by making use of a water level sensor to detect a displacement wave and surface displacement monitoring through cameras with high accuracy and acquisition intervals (Wang et al., 2022).

Different other EWSs for GLOFs have been implemented across different locations in the HMA between 2009 and 2015, an overview is provided below (Table 3).

Location	**Lake name**	**Lake type**	**EWS Explanation**
Tien Shan, Kyrgyzstan	Teztor lake	Moraine-dammed	The EWS was installed in 2011 and successfully predicted the Teztor lake GLOF in 2012 (Erokhin et al., 2018).
Karakoram, China	Kyagar lake	Ice-dammed	The EWS combined three automatic terrestrial observation stations and successfully predicted different Kyagar GLOFs from 2015 to 2018 (Haemmig et al., 2014; Yin et al., 2019).
Central Himalaya, Nepal	Imja Lake	Moraine-dammed	The EWS that was set up in 2009 combined two camera monitoring stations with two relay stations (Gurung et al., 2010).
Eastern Himalaya, Bhutan	Raphstreng, Luggye, Thortthormi and Besta lakes	Moraine-dammed	The manual EWS includes weekly lake level monitoring and several river gauges which are checked regularly (Gurung et al., 2010).

Table 3: Different GLOF EWSs implemented across locations in HMA (Table adopted from Wang et al., 2022).

Therefore, a variety of EWS have been implemented across different high mountain regions where GLOF danger poses a threat to the valleys downstream of the lakes prone to outbursts. The range of different areas and circumstances under which GLOF EWSs have been implemented allows to draw from existing experience and expertise.

3. Research Objectives

3.1 Research Intention

When it comes to DRR and DRM measures against GLOFs a universal call for EWSs development can be found in the literature: From the scale of global GLOF assessments, Taylor et al. point out how advances are needed in EWSs for GLOFs (2022). Further, on a supra-regional level as well, researchers point out how EWS can be useful tools for the mitigation of GLOF impact (Bajracharya et al., 2007; Gurung et al., 2010) with different cases demonstrating the proof of concept in the respective high mountain environments of the Himalayas (Haemmig et al., 2014; Yin et al., 2019) and the Tien Shan (Erokhin et al., 2018). Focusing on the catchment scale for Kyrgyzstan, Zaginaev et al. point out how it is “necessary to develop an appropriate early-warning system” (2019) and how GLOF danger reduction measures should focus on designing an EWS (Erokhin et al., 2018) for the Ala-Archa valley.

Based on this background, this thesis aims to develop a conceptual EWS for the scenario of an outburst flood from the Uchitel glacial lake in the Aksay valley which is a tributary of the Ala-Archa valley and presents the GLOFCA pilot site in Kyrgyzstan. The EWS should encompass the internationally recognised main components of EWSs for natural hazards as laid out by (Fluixá-Sanmartin et al., 2018) including 1. risk knowledge, 2. monitoring and warning, 3. dissemination and communication, and 4. response capacity. According to Alcántara-Ayala and Oliver-Smith, usually, more emphasis in EWSs is given to the understanding of hazards, such as the physical behaviour of a flood or a landslide, while vulnerabilities and exposure are often overlooked (2019). Therefore, this effort of a conceptual EWS development and evaluation purposely aims to cover these components of risk as well for the GLOF danger analysis for the study site.

However, a distinct difficulty this EWS development effort faces, it that of uncertainty, data detail and data availability in general. While it is normal to consider uncertainty of risk in attempting to forecast damage or losses where insufficient data are available on the hazard and/or the system of risk that is analyzed (Grossi and Kunreuthner, 2005; Cardona, 2011), the data baseline for Kyrgyzstan is particularly thin when compared to countries like Switzerland or the United States. For this reason, data scarcity becomes a part of the analysis carried out in this thesis and it aims to highlight where sufficient data is available and where not and how this influences the conceptual development of an EWS for the study site. This might require approaches and criteria for simplification and for aggregation of different information types and sources that are used, due to a lack of data or the inherent low resolution of the information available. However, this can still lead to scientific or technical results of sufficient accuracy and completeness which are inherently desirable features (Cardona et al., 2003) when a GLOF danger evaluation and the resulting EWS are the goal of the process.

3.2 Research Questions

According to the formulated research intention this thesis is targeted to answer the following overarching research question:

What kind of an EWS for GLOFs including which components could be implemented at the pilot site in Kyrgyzstan?

Based on the internationally recognized four main elements of EWSs (UNISDR, 2006, WMO 2018), the overarching research question can be further broken down into the following sub questions:

1. Risk knowledge: *How could the hazard of a GLOF be manifested? What GLOF danger would result based on the exposure and vulnerability from such a hazard for the study site?*
2. Monitoring and warning: *What kind of specific monitoring and warning system could be put in place for the study site?*
3. Dissemination and communication*: How could the warning information for a GLOF event be effectively communicated and what information is needed?*
4. Response capability: *How can the affected communities as well as the first responders at the study site be prepared to act effectively in case of an event?*

These questions act as guidance for the conceptual development of the GLOF EWS for the Ala-Archa valley to achieve a preferably complete system as far as the data availability and research circumstances allow for.

Furthermore, the following question relating to the data availability for the study site is also addressed to provide insights and knowledge on how data availability influences the effort to develop and evaluate an EWS for the study site in Kyrgyzstan:

Data availability: *Where in the process of EWS development and evaluation is sufficient data available, where is a lack thereof and how does this influence the effort?*

The reasoning behind the research question addressing data availability is to provide a platform for the insights, required approaches and criteria for simplification and aggregation of different information types and sources that are used here which might could be applied for EWS development in contexts of similar data availability.

4. Data and Method

4.1 Study Site

4.1.1 Location

The glacial lake considered for outburst in this study is the Uchitel glacial lake which is located at the terminus of the Uchitel glacier (E 74◦3102000, N 42◦3101000) at an elevation of 3617 m.a.s.l. in the Aksay valley (Zaginaev et al., 2019). The Aksay valley is located in the upper part of the Ala-Archa river basin in the Ala-Too range of Northern Kyrgyzstan. The river is fed by the Ala-Archa glaciers which are spread through an altitudinal range of 3300-4800 m.a.s.l. The glaciers are mainly large valley glaciers and about 76% of the total glacier-covered areas are located between 3700 and 4100 m.a.s.l., receiving about 700mm of annual precipitation, mainly from April to June (Aizen, 1988; Aizen et al., 2000). The Ala-Archa river is located in the Alamudun district and flows through a south facing valley passing the Ala-Archa national park and the towns of Kashka Su (976 inhabitants) and Baytik (1647 inhabitants) towards the Kyrgyz capital of Bishkek (Figure 6). The Ala-Archa river feeds the closed drainage basin of the Chui river, which is a major irrigation and water source for northern Kyrgyzstan and southern Kazakhstan (Aizen et al., 2006).

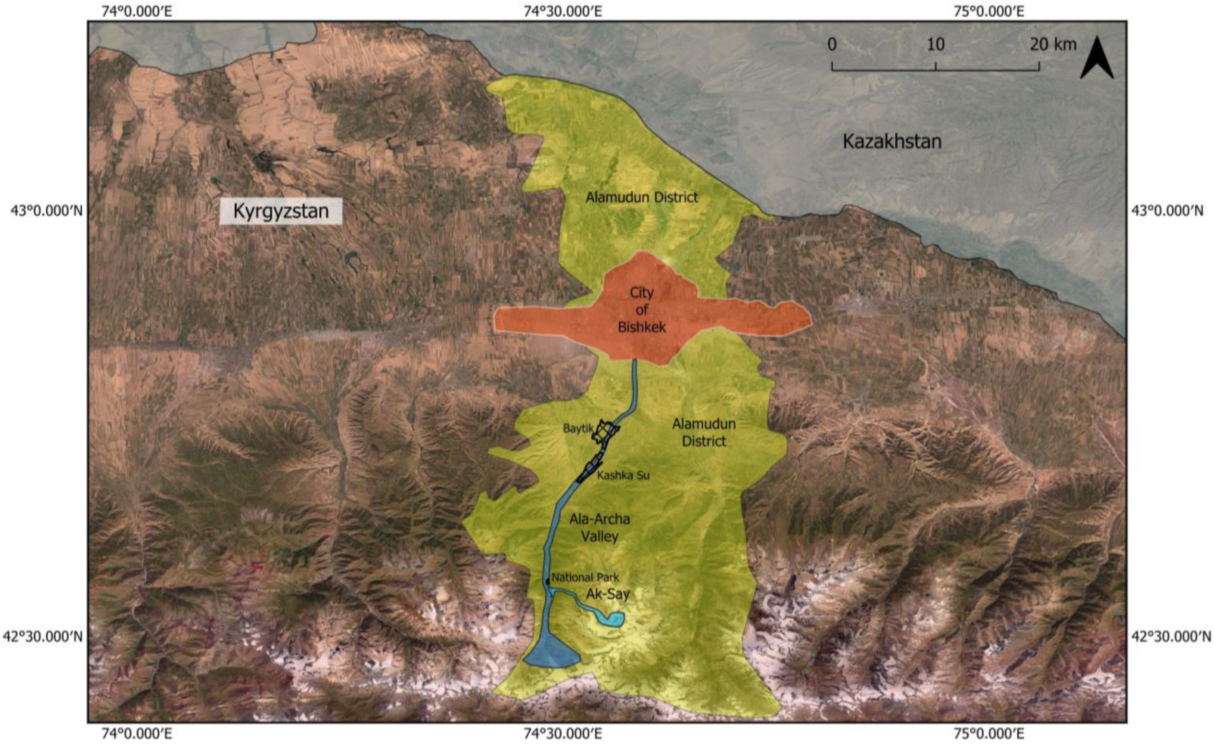

Figure 6: Location overview of the Ala-Archa study area in Northern Kyrgyzstan.

The Aksay valley ranges from 4895 m.a.sl. at the Semenov Tianshanskiy peak down to 2200 m.a.s.l. where the Aksay tributary enters the Ala-Archa river. In the upper part of the Aksay catchment the two valley glaciers of the Uchitel glacier and the Aksay glacier can be found. The pro-glacial lake of Uchitel can be found on its terminus and Aksay river emerges from underground about 500 meters downstream flowing down the Aksay valley first through the pro-glacial area, before entering a narrow canyon and finally ending on the alluvial fan of Ala-Archa national park where the Aksay tributary enters the main Ala-Archa river (Figure 7.) The two glaciers of Aksay and Uchitel likely used to be connected but have retreated since the LIA and thus form two different glaciers nowadays.

Figure 7: Overview of Aksay valley glacier complex.

The Aksay valley moraine-glacier complex presents one of the most dynamic developing glacier complexes in Kyrgyzstan and provides all natural conditions for GLOF formation (Zaginaev et al., 2019). Historic GLOFs including secondary debris flows events have repeatedly led to large-magnitude events which have led to the formation of an alluvial fan system at the mouth of the Aksay valley (Kroshkin et al., 1960). The GLOF events and secondary flow events have been subject to different studies including their genesis, frequency and detailed modelling efforts (Brüniger, 2023; Erokhin et al., 2003, Erokhin et al., 2011). Thus, the GLOF hazard of the Aksay valley presents a danger as the fan area of the Ala-Archa national park includes facilities for summer tourists and serves a base for different groups of outdoor enthusiasts with car parking and further amenities. The number of visitors to the valley is increasing constantly and can reach up to 500 people per day during the summer months (Zaginaev et al., 2019). While the Aksay valley has no resident population, the Ala-Archa valley is populated and includes access infrastructure such as bridges and roads. There are various buildings and infrastructure along the Ala-Archa river and the first population center is reached 11 kilometres from the national park in form of an outer quarter of Kashka Su, followed by Kashka Su at 15 kilometres and then the town of Baytik at 20 kilometres. Finally at the 30 kilometer mark south of the Aksay valley, the Ala-Archa river is channelized when entering the capital city of Bishkek.

4.1.2 Weather and Climate

The seasonal differences of the climate in the Ala-Archa valley can be described as follows: During winter, the climate is controlled by air masses coming from the north and northwest, and from the west, northwest and southwest during the summer. At high altitudes from 2000 to 3500 m.a.s.l., the climate is characterized by average air temperatures ranging from 11 to 18 °C in July and from −8 to −10 °C in January. The nival-glacial zone located above 3500 m.a.s.l. is characterized by average air temperatures in July reaching up to 4.9 °C, but −22 °C in January. As a result, widespread permafrost occurs at altitudes above 3500 m.a.s.l. (Erokhin et al., 2018). About 1 kilometer downstream from the end of the Aksay valley, the Alplager hydrometeorological station (42°33'56.06" N; 74°28'56.85" E; 2150 m.a.s.l.) is located, providing an overview of the meteorological conditions in the area: The mean annual precipitation for this region and altitude is about 560 mm and the mean annual air temperature is 2.9 °C. The mean maximum values in summer are 27 °C and the mean lowest values -22 °C in winter. The maximum recorded temperature was 31 °C in July of 1983, and the lowest recorded temperature was -25.8°C in December of 2001. The long-term trend shows increasing temperatures and decreasing annual precipitation in the Ala-Archa valley (Zaginaev et al., 2019).

4.1.3 Uchitel Glacial Lake

Zaginaev et al. conducted a study on the Aksay valley in which they investigated the Uchitel glacial lake in close detail including field studies and remote sensing analysis. They found that the pro-glacial Uchitel lake (Figure 8) is actively developing in an intra-moraine depression which formed during a phase of glacier retreat in the last 60 years and is still expanding today.

Figure 8: Uchitel glacier tongue and pro-glacial Uchitel lake in June 2023. (Image: Andrey Sivertsev, June 2023)

The lake formed between 1988 and 1994 and thus is a rather young feature of the Aksay glacier complex. The team carried out bathymetric studies between 2013 and 2016 to capture the change of the lake's depth and to assess the water volume stored in the lake. During the 2010 fieldwork campaign a meltwater supply to the lake through a scattered runoff system of several flow paths from the glacier surface was observed. At this point the lake had a surface drainage through the central part of the moraine dam with water flowing through loose rocks without a clearly defined channel. The water volume retained in Uchitel lake remained almost unchanged between 2010 (26.7×10^3 m^3) and 2016 (27.1×10^3 m^3). A lake basin subsidence led to a change in the runoff from the lake: A switch occurred from the predominantly surface overflow to flow via subsurface drainage channels. This change in drainage characteristics is important as it increases the lake's outburst potential (2018).

4.1.4 Possible Outburst Mechanisms

As laid out by Westoby et al. there are seven different trigger mechanisms for moraine-dammed outburst floods (2019). Several of these could be possible for the Uchitel glacial lake: According to Zaginaev et al. the dam of the Uchitel lake consists of a rock outcrop which is covered with moraine deposits containing ice and its erosion and an according outburst is possible when the lake drainage changes to superficial. The subsurface drainage of the lake makes the water level in the lake directly dependent on the capacity of the subsurface drainage channels. If the lake fills up and overflows, additional pressures on the drainage channels could lead to dam subsidence or piping (2019). The increase of waterflow through the drainage channels and the long-term trend of increasing temperatures in the area could further be reasons for ice-core melting within the moraine dam and thus cause piping and a consequent dam breach.

According to Neupane et al. the piping mechanism has the potential to increase the rate and magnitude of dam failure because internal erosion in the dam causes a seepage to appear in the moraine. This will erode a hole in the exit which causes an increment in hydraulic gradient leading to a hole extending along the path of the highest hydraulic gradient which forms a pipe into the lake. The water flowing from the pipe will displace moraine material, initiating a dam breach (Figure 9) (2019).

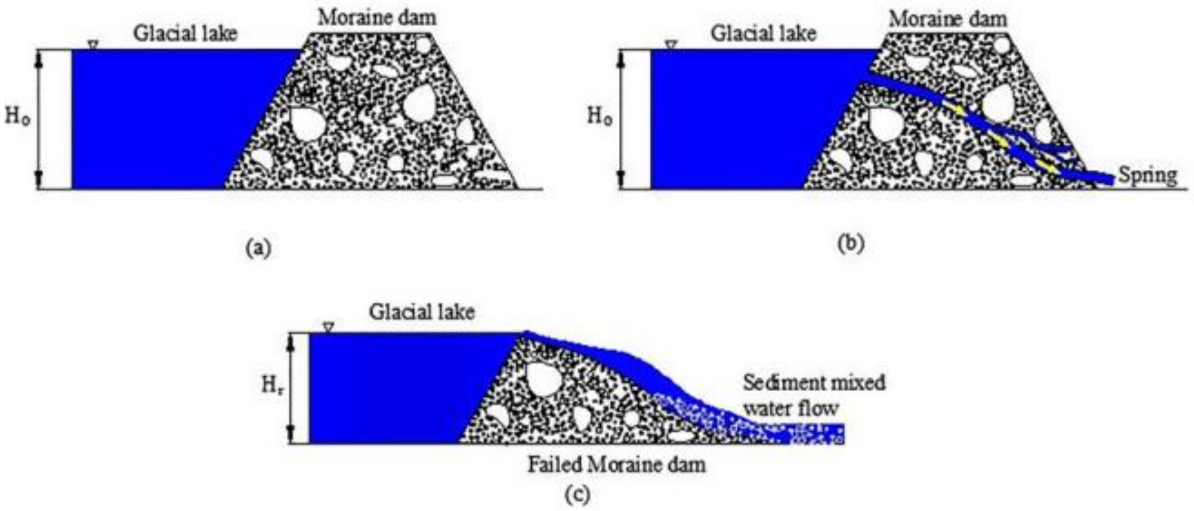

Figure 9: Illustration of piping outburst mechanism a) before failure, b) during piping process and c) after failure. H_0 *signifies initial water level and* H_r *reduced water level due to failure (Adopted from Neupane et al., 2019)*

Further, different reasons could lead to a flood wave propagation through the lake causing overtopping: The long-term trend of increasing temperatures is likely to have an effect on the permafrost on the steep slopes surrounding the lake which may lead to rock avalanches that causing a wave propagation. Further, the glacier is also falling into the lake from steep cliffs (up to 45–65°) which reach a height of 15–25 m (Zaginaev et al., 2018). This could lead to a glacial calving event which could be enhanced by the scouring of the glacier through the direct water contact with the lake, and thus presents another possible reason for wave propagation. Such wave propagation could cause overtopping and a consequent dam breach based on headwater erosion.

These scenarios are supported by the findings of Narama et al. who reported buried ice melting and moraine collapse due to headwater erosion of the dam and increased inflow leading to subsurface channel opening as main causes of lake outbursts in northern Tien Shan (2009).

Another possible reason for headwater erosion is that of a rapid increase in lake volume due to different hydrological factors. Indeed, according to Zaginaev et al., one cannot exclude the option of a GLOF as consequence of intensive precipitation. The torrential rains in the Aksay valley historically caused debris flows from a tributary of the Aksay river in 1999 and 2003, when rainfall intensity exceeded a significant trigger value from 10 to 30 mm per hour for a duration of at least 1 to 3 hours, respectively, based on data from the Alplager meteostation. The valley is especially hazardous during heavy rainstorms, often occurring during the months of May to June, when avalanche snow accumulates and thus provides a source for additional water supply through the melt-out of the wet avalanche snow (2018). Such conditions could therefore be considerable reasons for an increase in lake water levels and an according chain of events of overtopping and the subsequent headwater erosion which could result in a dam breach.

Finally, the possibility of an GLOF event through a moraine-dam breach caused by an earthquake presents another plausible outburst mechanism due to the following reasons: The northern Tien Shan is the most seismically active region in Kyrgyzstan, with earthquakes expected to reach a magnitude of five to six and an intensity of six to eight (Thurman, 2011). Sabirova et al., investigated the highly active North Tien Shan seismic zone at the Bishkek seismic research site and found that the study area and its immediate surroundings witnessed 6 catastrophic seismic events with a magnitude of 6.9 to 8.3 as well as a range of weaker earthquakes between 1885 and 2020. The study concludes that over 100 years have passed since two of the aforementioned catastrophic events and states that based on the assumption that strong earthquakes happen at the same location every 100 years, a strong earthquake can be expected in the near future (2022). Therefore, it becomes evident how seismic activity could be another trigger mechanism for a GLOF at the Uchitel lake.

Based on the wide range of plausible trigger mechanism a breaching of the moraine dam of Uchitel lake is considered as the worst-case scenario this study is focussing on. Under this scenario full drainage of the lake with a volume of 30’000 m^3 would occur. This possible outburst volume is based on the lake volume measurements from Zaginaev et al. (2018). It presents a similar value to the release volume utilized in the GLOF sensibility analysis for the Aksay valley by Brüniger (2023) and according to Dr. Cicoira, who is involved in the GLOFCA project, is a valid estimation for a possible worst-case scenario.

4.2 HEC-RAS Program

4.2.1 Program Overview

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) is a software developed by the U.S. Army Corps of Engineers (USACE) for modeling water flow in rivers, channels, and other hydraulic systems. The first version, 1.0, was released in 1995 and since then, there have been several major releases of the software package, including the latest 6.0 in 2020. The program is widely used for floodplain management, flood forecasting, and various water resources planning and engineering projects. The software can model steady, gradually varied flow as well as unsteady flow conditions, simulating how flow rates and water levels change over time. It can also model the effects of hydraulic structures like bridges, culverts, and weirs on water flow. Some versions of HEC-RAS can even model sediment transport, water quality and have debris flow capabilities, although these features are less commonly used than the hydraulic modeling capabilities. The software also has strong integration with GIS for spatial analysis and visualization (Brunner et al., 2023). Different studies have indeed coupled HEC-RAS with GIS tools to evaluate the extents of floodings (Khattak et al. 2016; Mestri et al. 2020; Pathan and Agnihotri 2020).

In terms of applications, HEC-RAS is commonly used to create floodplain maps, assess the flooding impact on various projects like dams and bridges, develop emergency response plans for flood events, and design and optimize hydraulic structures. Indeed, several studies applied the HEC-RAS model to simulate flood events and showed its robustness and stability (Kumar et al. 2017; Parhi 2018; Rangari et al. 2019). However, the software does have limitations, such as the need for high-quality topographic and hydrologic data for accurate modeling. Advanced simulations, especially those involving unsteady flow and sediment transport, can be very computationally intensive. Effective use of HEC-RAS also requires a good understanding of hydraulic engineering principles (Brunner et al, 2023).

4.2.1 HEC-RAS GLOF Modelling

For the evaluation of flood risk associated with dam failures such as moraine-dams at GLOF events, hydrodynamic models such as HEC-RAS can be powerful tools for assessing and preventing hydraulic hazards, namely that of flooding flow velocity and flooding depth (El Bilali et al., 2021). Both one-dimensional (1D) and two-dimensional (2D) models can be used in HEC-RAS. The 1D hydrodynamic models are based on the Saint-Venant's or shallow water equations (SWE) where conservation of mass and momentum is taken into consideration along a single direction (Brunner et al., 2023). On the other hand, 2D models solve SWE, to produce depth-averaged and spatially distributed hydraulic characteristics of a given flow (Chanson, 2004). The total volume of water which is released during a GLOF event presents a substantial input to determine the peak flow discharge rates in the hydrodynamic models simulating a moraine-breach event (Westoby et al., 2014).

The HEC-RAS program has been used for a variety of GLOF assessments and research scenarios around the globe including examples such as the Laguna 513 GLOF in the Cordillera Blanca in the Peruvian Andes (Klimes et al, 2012), different examples from the Central Himalayas concerning the Satopanth lake in the Alaknanda basin of the state Uttarakhand, India (Sattar et al., 2019) and concerning the Shako lake in the Tista basin of North Sikkim, India (Hazzra and Krisha, 2022) as well as a study for the Cirenmaco lake in the Zhangzangbo valley, China (Wang et al., 2015). For the Karakoram, Hussain et al. utilized HEC-RAS in combination with GIS applications to conduct a GLOF study for Khurdopin lake in the Shimshal valley in Northern Pakistan (Hussain et al., 2020). The different studies lay out how HEC-RAS can be used for GLOF danger assessments in various regions and contexts.

For this study, HEC-RAS version 6.3.1 has been used to model the worst-case dam breach scenario based on a steady 1D hydraulic simulation which calculates cross-sectional average water surface elevation and velocity at predefined cross-sections through solving Saint-Venant's equations with the boundary friction force based on the Manning equation (Brunner et al., 2023):

$$\frac{AR^{2/3}}{n} Sf^{1/2} = Q$$

The momentum equation incorporated the boundary friction force by incorporating the dimensionless friction slope (Sf):

$$\frac{\partial Q}{\partial t} + \frac{\partial (QV)}{\partial x} + gA\left(\frac{\partial z}{\partial x} + Sf\right) = 0$$

Where Sf comes from the Manning equation:

$$Sf = \frac{Q^2 n^2}{R^{4/3} A^2}$$

Explanation for variables: **A**: cross-sectional area, **Q**: discharge, **V**: volume, **R**: hydraulic radius **Sf**: frictional slope, **z**: water depth, **x**: distance along flow, **t**: time, **g**: gravity acceleration, **n**: Manning's Roughness Coefficient.

4.2.3 Study Area Geometry

Conducting a flood routing assessment using HEC-RAS requires detailed input information to the program on the potential flooding area and the stream channel through which the water would pass through, which in HEC-RAS is referred to as the study area's *Geometry* (Brunner et al., 2023). For the extraction of terrain information, a Digital Elevation Model (DEM) provided by Dr. Cicoira from the GLOFCA research group with a 12.5 meter resolution based on the WGS84 reference system was utilized. The main flow channels were determined based on satellite imagery in HEC-RAS from Google Satellite and ArcGIS World Imagery. The according bank lines for the river channel were determined in the same way, while for the floodplain flow path lines the results from preliminary RAMMS studies were used to define an approximate extent of the floodplain in case of a GLOF event. Along the flow channel of the Aksay and the Ala-Archa channel, cross sections were drawn perpendicular to the river flow direction at an approximate distance of 0.5 kilometers and 0.25 kilometers for the Ala-Archa and the Aksay valley, respectively. At points of hydraulic infrastructure, additional cross-sections were established for detailed assessment. This procedure resulted in a total of 157 river cross-sections for the Ala-Archa river and 75 river cross-sections for the Aksay river respectively. The junction of the Aksay tributary to the Ala-Archa was another input to the geometry (Figure 10).

For the main flow channel, the bank area and the floodplain area Manning's 'n' values had to be defined which ultimately leads to the sub, super or critical flow conditions which determine the flow height (Brunner et al., 2023). Based on the HEC-RAS user manual which refers to Chow (1959), the following 'n' energy loss coefficients were chosen (Table 4):

Area	Description	'n' value
Main flow channel	Mountain stream without vegetation in channel, gravels, cobbles, few boulders	0.040
Riverbank area	Same as above but some weeds and stones	0.045
Floodplain area	Light brush and trees	0.050

Table 4: Overview of Manning's 'n' values chosen from HEC-Ras user manual for different flow path sections of study area.

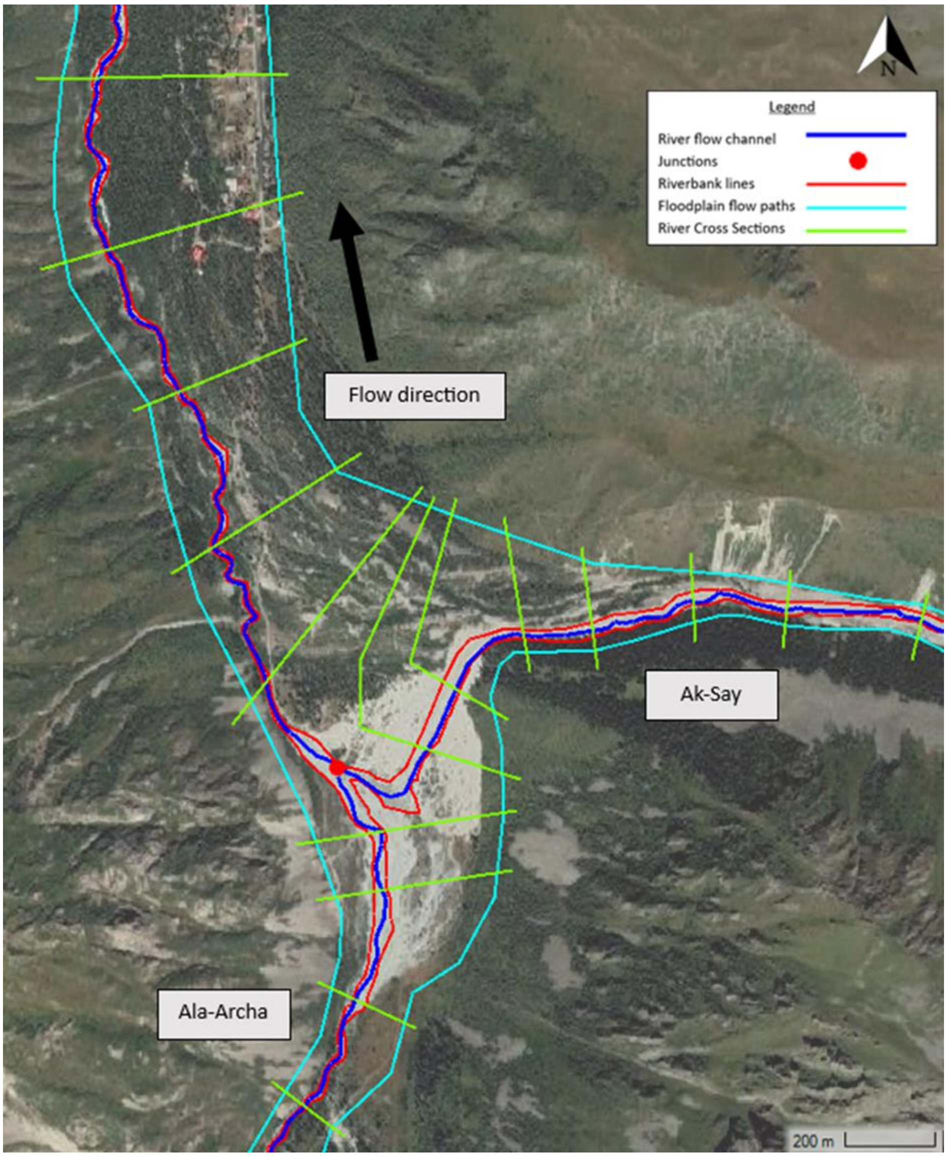

Figure 10: HEC-RAS Geometry overview of Aksay and Ala-Archa confluence.

4.2.4 Hydraulic Infrastructure

Additionally to the basic geometry inputs needed in the model, hydraulic infrastructure in form of bridges and inline structures were added into the model for assessment in the flooding scenario. The infrastructure includes the bridge of the main road to the national park, a smaller bridge at the first population center in an outer quarter of Kashka Su and a dam with a dual gate system just as the river enters the town of Kashka Su. The dimensions of these structures could be determined in different ways, for the national park bridge as well as the Kashka Su dam with the dual gate system, different images were provided by PhD candidate Niggli who is involved in the GLOFCA project and retrieved this valuable data from the field. Based on these images the discharge capacities and dimensions of the infrastructure could be estimated and were further backed with evaluation from measurements based on satellite images from Google Satellite and ArcGIS World Imagery. For the bridge in the outer quarter of Kashka Su it was possible to rely on visuals of the bridge from Google Street view, as well as the mentioned sources of satellite imagery for dimensional measurements. The following presents an overview of the details of the hydraulic infrastructure entered into the model.

4.2.4.1 National Park Bridge

The bridge closest to the Ala-Archa national park is located 6 kilometers from the junction of Ala-Archa and Aksay valley and appears to be a reinforced concrete bridge on a solid foundation which spans about two meters out further from the extent of the bridge itself (Figure 11). The bridge's dimensions which were entered into the model set the bridge at 10 meters wide, 22 meters long with a deck thickness of 2 meters including the supporting beam and the roadside barrier protecting the sidewalk. The freeboard was approximated to be 3 meters on average. In the HEC-RAS geometry visualization, structures are displayed at the length of the according cross section, however, the calculations refer to the entered dimensions (Figure 12).

Figure 12: HEC-RAS geometry visualization of national park bridge.

Figure 11: Access bridge to National Park. (Image by Laura Niggli, August 2022)

4.2.4.2 Bridge in outer quarter of Kashka Su

Figure 13: Bridge upstream of Kashka Su. (Google Streetview Image, Mai 2023)

The bridge at the outer quarter of Kashka Su is located 11 kilometres from the national park and appears to be a steel bridge on a foundation of concrete elements (Figure 13). The dimensions entered into the model for this bridge were set at 5 meters wide and 15 meters long, with a deck thickness of 0.5 meters. The freeboard for this bridge was approximated to be 3.5 meters on average. The bridges profile was visualized in HEC-RAS (Figure 14).

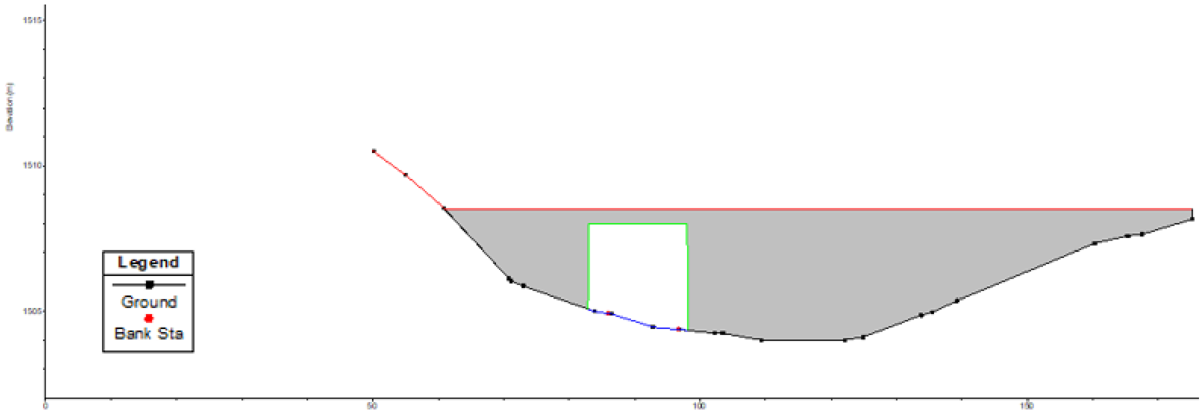

Figure 14: HEC-RAS profile visualization of bridge in outer quarter of Kashka Su.

4.2.4.3 Dual gate dam at Kashka Su

15 kilometres from the national park just at the beginning of the town of Kashka Su a dam is located: The broad crested dam seems to serve several purposes: First, its wide and shallow basin acts as a sediment collector for the bedload carried by the Ala-Archa river. Second, the dam features a dual gate system of which the one located to the left in direction of flow (east) is an overflow gate directing the water to a channel which leads north-west, away from the Ala-Archa river and likely serves irrigation purposes. The second gate to the right in direction of flow (west) is a radial gate construction regulating the amount of water which flows over an ogee spillway crest and continues further in the Ala-Archa river channel. The residual flow from the overflow gate flows over the same ogee spillway if channel capacity is exceeded (Figure 15). The dimensions for the gate openings entered into the model were approximated at a width of 4 meters and the same height as the dam freeboard of 3 meters. The automatically calculated spillway weir coefficient resulted at the value of 2.14 based on the provided input dimensions.

Figure 15: Dual gate opening of Kashka Su dam with overflow gate on the left and a radial gate to the right in direction of flow with ogee spillway crest in the back. (Image by Laura Niggli, August 2022).

The dimensions of the radial gate design at the Kashka Su dam opening (Figure 16) were added into the model as follows: Water head between upstream water level (Z_U) and water level at spillway height (Z_{sp}) at 1 meter, the trunnion height over Z_{sp} at 2 meters and the gate opening height (B) between the gate and Z_{sp} at 0.5 meter (Figure 17. Values for the radial discharge coefficient and the orifice coefficient which describe forms of energy loss of water passing under the gate were set at typical values of 0.7 and 0.8 respectively, as recommended by Brunner et al. (2023).

Figure 16: Radial gate design at Kashka Su dam. (Image by Laura Niggli, 2022)

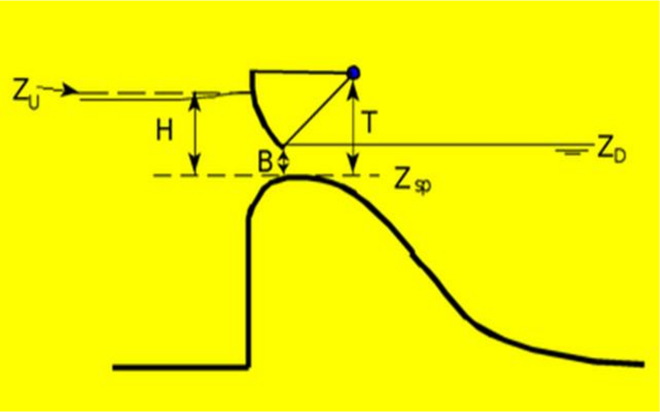

Figure 17: Typical radial gate design as presented in HEC-RAS manual for defining input values for ZU, Zsp, ZD (water level upstream/spillway/downstream), T (trunnion height), H (water head) and B (gate opening). (Brunner et al. 2023).

4.2.5 River Baseflow and Discharge Scenarios

The baseflow for the Aksay river was defined for the model at 0.5 m^3/s as described for the average annual discharge of the river by Zaginaev et al. (2019). For the discharge of the Ala-Archa river, long term monthly averages flow values were retrieved from the Global Runoff Data Center (2023), Station ID 2415900: 'Mouth of KashkaSu', and the according yearly average was calculated resulting in a value of 4.5 m^3/s and used for the modelled baseflow of the Ala-Archa river.

According to Westoby et al., the use of empirical formula represents the simplest approach to dam-break modelling with a number of different approaches taken in research (2014). For this study, Froehlich's peak discharge equation (Froehlich, 1995) was chosen as there is low uncertainty compared to other approaches (Wahl, 2004). Therefore, the peak discharge Q [m^3/s] was estimated as follows:

$$Q = 0.607V^{0.295}h^{1.24}$$

In the equation V presents the outburst volume and h the depth of the water above the breach invert at the time of the failure. According to Zaginaev et al., the drainage channels of Uchitel lake are located at the bottom of the lake and the nature of these subsurface drainage channels increase the lake's outburst potential (2019). Therefore, h was adopted with a breach scenario at the base of the lake near the drainage channels and therefore possible peak discharges calculated with the volume of 30'000 m^3 and h values based on the lake depth as measured by Zaginaev et al. (2019). For the average lake depth of 7.1 meters the resulting peak discharge is 144 m^3/s while for the maximum lake depth of 12.1 meters the peak discharge would be 280 m^3/s. However, these peak discharge values neglect the bulking and entrainment of moraine and sediment deposits during the outburst process which can contribute significantly to GLOF volume in the Aksay and Ala-Archa valleys as different studies have pointed out (Brüniger, 2023; Erokhin, 2017; Zaginaev, 2013). Therefore, this study adheres to three peak discharge scenarios which have been proposed for the Aksay valley by Zaginaev et al., (2019):

1. Profile (PF1): 300 m^3/s for flows caused by partial outbursts.
2. Profile (PF2): 600 m^3/s for major outbursts involving an englacial water pocket.
3. Profile (PF3): 900 m^3/s for the most powerful flows as estimated for past events.

It needs to be pointed out however, that currently only PF1 represents a realistic scenario, because the volume of Uchitel lake today is too small for 600 m3/s and 900 m3/s peak discharge scenarios. However, as Zaginaev et al. further point out, in the future the volume of the lake can increase and a formation of powerful events with high peak discharges is possible (2019). Hence, the HEC-RAS simulation incorporates all three peak discharge profiles to bring in a long-term perspective incorporating a range of worst-case scenarios which could be relevant for GLOF danger and an EWS today and in the future.

4.3 Exposure Data Acquisition

For the generation of risk knowledge of the Ala-Archa valley study area, this study relied on mapping buildings based on Google Satellite Imagery in QGIS for exposure assessment utilizing preliminary RAMMS inundation overlays to map the buildings in the vicinity of the riverbank which could be affected by a GLOF scenario. In the process, 217 buildings were registered. For a better understanding of flooding vulnerabilities of these buildings, Google Streetview was utilized to evaluate the construction type and building height thereby differentiating between concrete/stone and wooden buildings and buildings with one or more stories. However, only 84 buildings could be attributed with the according data, due to limited Google Streetview availability in the Ala-Archa valley.

Gaining insights into the exposure of parts of the population within the hazard zone is a crucial aspect of risk knowledge generation (Cardona et al., 2012). To assess population numbers within the potential flooding zone, a method suggested by Buchanan from the USACE was chosen which involves the average household size and was applied before in a case study for Iraq (2016). By accessing population data from the Global Data Lab (globaldatalab.org) the average household size for 2021 of 4.11 for the Chuy region, whereof the Alamudun district with the Ala-Archa valley is a part of, could be retrieved. Further, addressing the social vulnerability class of age, the percentual age distribution data for the Chuy region from 2010 was also retrieved from the Global Data Lab platform.

5. Results

The structuring of the results for the conceptual development and evaluation of an EWS for a worst-case scenario of a GLOF event from Uchitel lake follows the setting of the checklist for EWSs main components as proposed by UNISDR (2006) and WMO (2018).

5.1 Risk Knowledge

The strong possibility of a hazardous GLOF due to different failure mechanisms which could lead to a moraine-dam breach provided the reasoning for a modeled analysis of the possible impacts. The results from the HEC-RAS modelling provide an overview of the flooding extent resulting from such a GLOF based on a worst-case scenario. At closer examination, the flooding extent in the valley reveals certain hotspots which show an eminent GLOF danger in the vicinity of the main river channel of the Ala-Archa. These strongly affected areas include the infrastructure of the Ala-Archa national park, the outer quarter of Kashka Su and the Kashka Su dam (Figure 18). For better risk knowledge assessment, these areas were evaluated in more detail including exposure and vulnerability data.

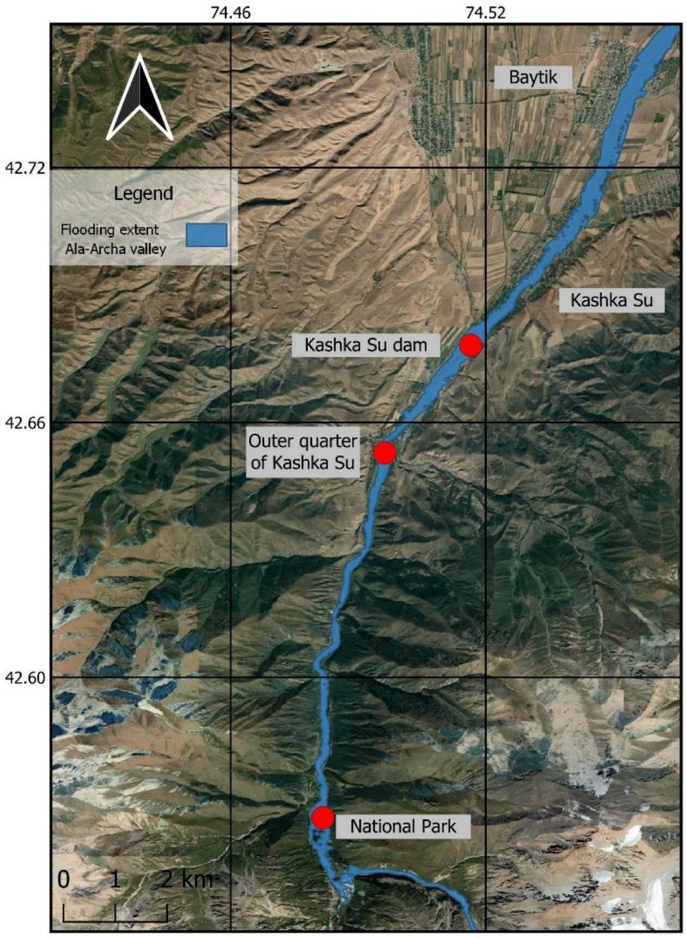

Figure 18: Overview of GLOF scenario flooding extent in Ala-Archa valley including areas of eminent GLOF danger.

5.1.1 General Exposure and Vulnerability

Based on the inundation boundary maps for the 3 GLOF scenarios PF1, PF2 and PF3 from the HEC-RAS simulation, the overlap with the mapped buildings along the river could be assessed for exposure of buildings, depending on the scenario. From the flooding extent of the chosen scenario 61 (PF1) to 99 (PF3) buildings were attributed to the flooded perimeter in the valley. Based on the according building counts, the exposure of people could be calculated based on the average household size in the Chuy region, taking the assumption that the mapped buildings are inhabited. This procedure indicates that depending on the scenario, 251 (PF1) to 407 people (PF3) live in exposure to flooding and thus are subject to the GLOF danger. Based on the percentual age distribution data for the Chuy region, the social vulnerability category concerning the group of elderly people could be assessed, as the elderly are more vulnerable in the event of a disaster (Cutter and Finch, 2008). The elderly vulnerability group was defined at an age of 70 years and above, making up 3.75% of the population in the Chuy region based on information from the Global Data Lab (2023). An overview of the gathered residential risk knowledge data for the different scenarios is given below (Table 5).

Scenario	Peak Discharge [m^3/s]	Exposure Buildings	Exposure People	Exposure of Vulnerability Group Elderly People
PF1	300	61	251	9
PF2	600	92	378	14
PF3	900	99	407	15

Table 5: Overview of residential exposure to flooding through GLOF danger in the Ala-Archa valley for different scenarios.

The data on residential exposures and vulnerability groups provides a first estimate for the risk knowledge of the GLOF danger, however it cannot be terminatory as it does not account for perambulate people such as tourists who visit the valley. According to Zaginaev et al., the Ala-Archa valley sees constantly increasing numbers of visitors which can reach up to 500 people per day during June and August (2019). Therefore, a much higher number of people's exposure and possible vulnerability must be taken into account, contributing to an enhanced GLOF danger overall.

5.1.2 National Park Infrastructure

The entrance to the Ala-Archa national park with its infrastructure such as a parking area and various buildings is located only about 1 kilometre from the entrance to the Aksay valley where the potential GLOF would originate from. There is only one access way to this point which is the main road coming up the valley from Kashka Su which crosses the Ala-Archa river at a bridge 6 kilometres further down the valley. All these elements are considered as infrastructure of the national park and are subject to exposure to the GLOF hazard which was modelled in HEC-RAS. Large parts of the national park area including most of the buildings and the parking lot are flooded even with the smallest scenario PF1 (Figure 19). From the 16 mapped buildings in the area, 13 are affected already with scenario PF1, two more with PF2 and one single building is only affected with PF3 according to the model output. In case the 16 buildings were populated according to the Kyrgyz household average, about 66 people were exposed to GLOF

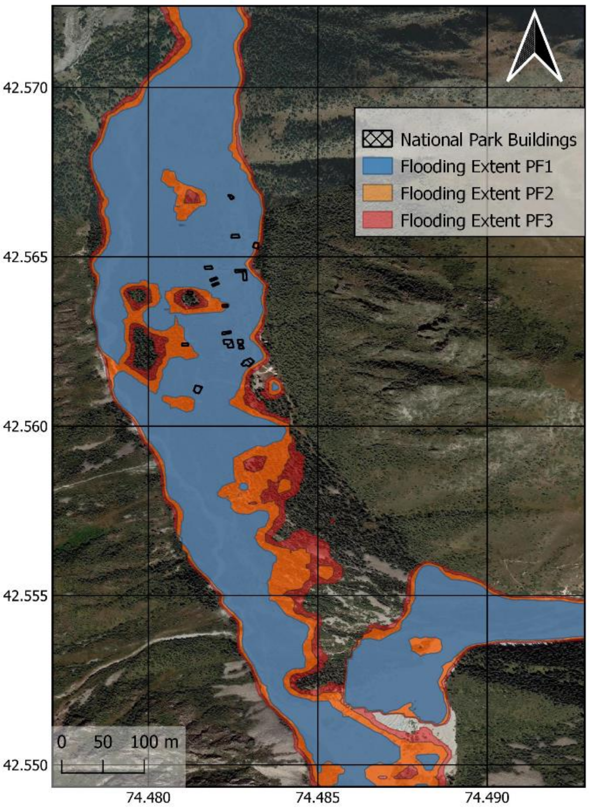

Figure 19: Flooding extent at national park infrastructure for scenarios PF1, PF2 and PF3.

danger in this area. However, as the national park infrastructure is unlikely to represent residential housing and as the frequentation of the national park depends highly on the season (Zaginaev et al., 2019) the area is likely to be much more populated during the summer season and less during the winter months, therefore having seasonally changing levels of people exposure which has to be considered.

The bridge to the national park was assessed in detail as it presents the traffic bottleneck for access to the national park. Based on the PF1 scenario the model output calculated the water surface to stay barely within the run-through possibilities of the bridge, leaving close to 0.5 meters of freeboard open (Figure 20). However, based on the nature of an GLOF event and the environmental circumstances given in the Aksay and Ala-Archa valley leading up to the bridge, the flood wave could be carrying substantial amounts of eroded material in the bedload and additional debris such as brush and trees which could cause a blockage and lead to overflow onto the bridge deck. For scenarios PF2 and PF3 such overflow is the case as there is no freeboard left under the bridge and the water surface level reaches about 0.5 meters and 1 meter, respectively, over the bridge deck. Therefore, based on the reinforced concrete construction of the bridge, it could be expected that the structure withstands the flooding pressure but a certain level of blockage of the road passing the bridge deck can be expected due to overflow, or/and residual debris and possible railing damage. Such a blockage of the access bridge to and from the national park would have according impacts for the exposed people in the park area

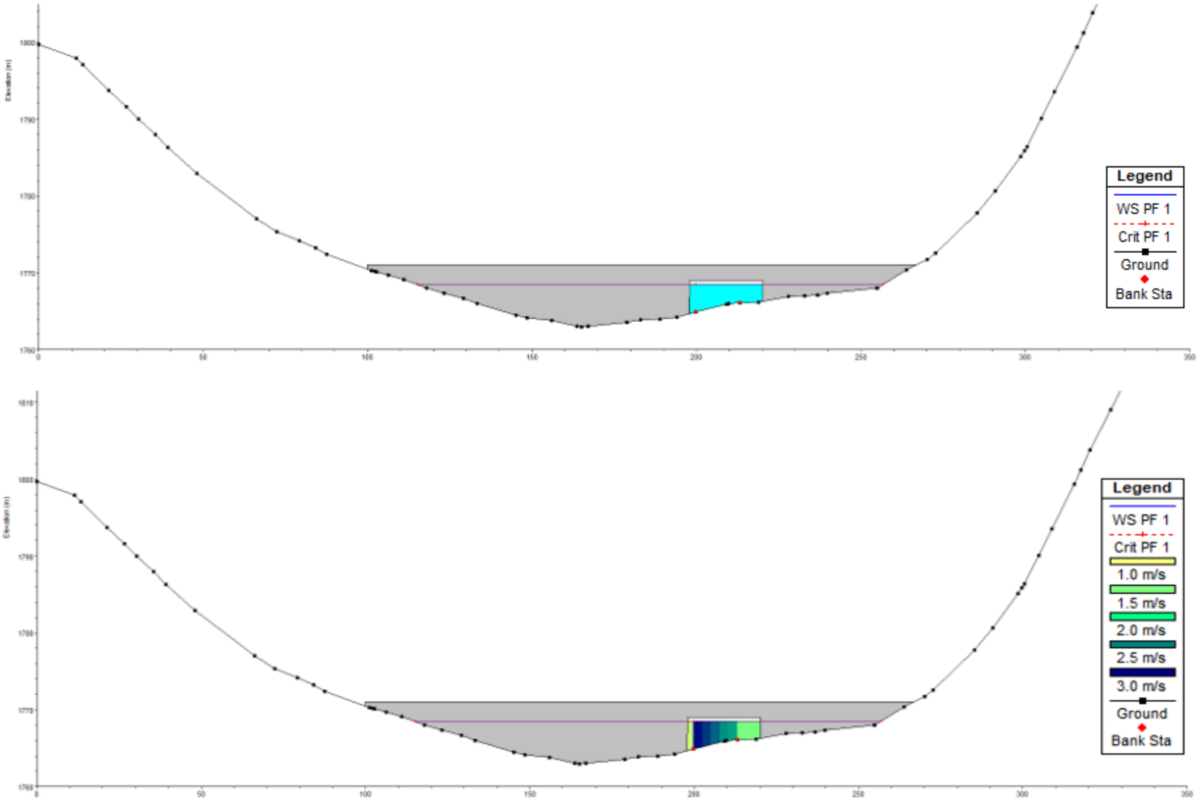

Figure 20: HEC-RAS simulation for watersurface level (top) and water velocity (bottom) at national park bridge for scenario PF1.

increasing their vulnerability to entrapment and having further implications for the general response capabilities.

5.1.3 Outer Quarter of Kashka Su

The outer quarter of Kashka Su, 11 kilometres from the national park, is not severely affected in terms of residential exposure, the flooding levels of scenario PF1 impact 8 buildings and another 13 buildings would be affected by the water surface levels of scenarios PF2 and PF3. Thus, setting the counts of exposed people in form of residents at 33 (PF1) and 86 (PF2 and PF3), respectively. However, what makes this location an important area to focus on for risk assessment is the exposure and possible vulnerability of the bridge connecting the left-hand side of the valley (in flow direction of Ala-Archa river) and its main access road towards Kashka Su and Bishkek with the right-hand side of the valley where the population center of this outer quarter is located. Based on the HEC-RAS simulations, the bridge is already overtopped at the PF1 scenario, with water surface levels reaching about 1 meter over the bridge deck (Figure 21).

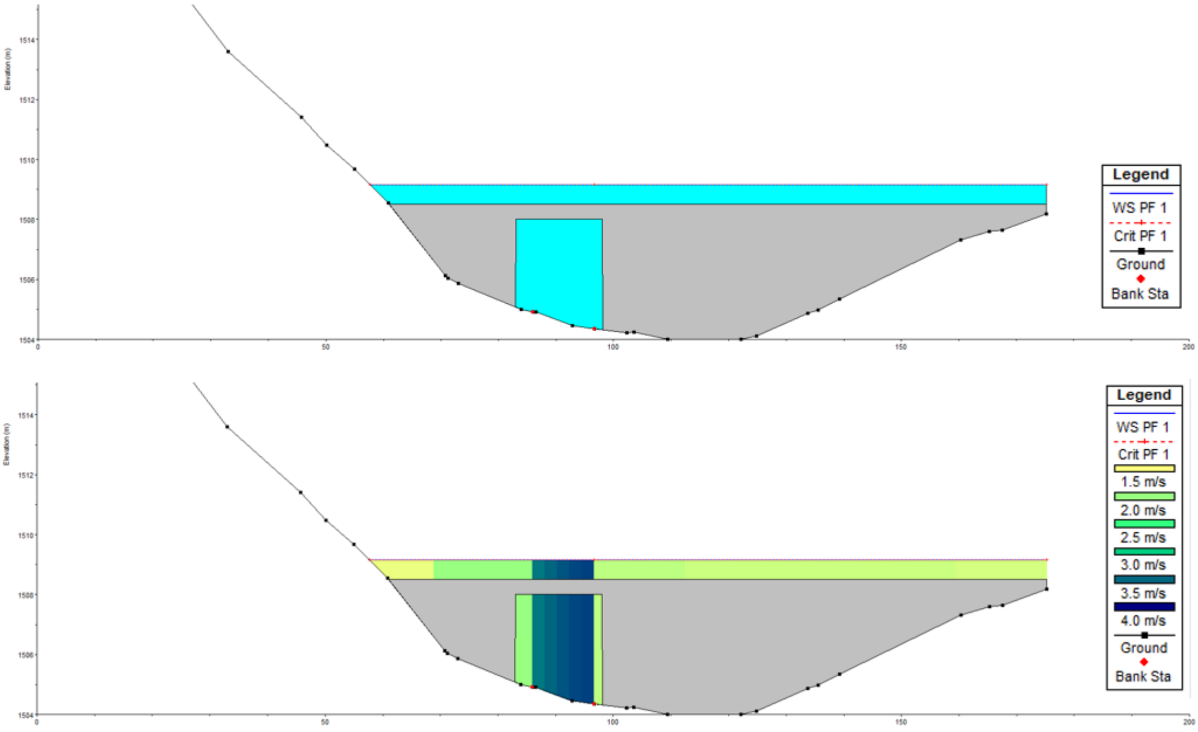

Figure 21: HEC-RAS simulation for water surface level (top) and water velocity (bottom) at bridge at outer quarter of Kashka SU for scenario PF1, showing overtopping.

For scenarios PF2 and PF3 the water surface level rises even further to approximately 1.5 and 2 meters over the bridge deck. As this bridge is of a less rigid construction type than the national park bridge and its deck is a steel only construction of relatively small thickness, damages to the bridge leaving it impassable are presumable. This circumstance is of higher consequence because the next river crossing downstream just below the Kashka Su dam also shows to be affected by flooding and is likely to be impassable as well. Accordingly, the implications are an increasing vulnerability to entrapment of the exposed people in this outer quarter of Kashka Su. As accessibility becomes an issue, this again has consequences for the response capabilities.

5.1.4 Kashka Su Dam

The dam located just at the beginning of the town of Kashka Su, presents the main and only feature of a structural flood mitigation measure in place in the Ala-Archa valley. Originally likely designed for irrigation purposes and doubling as a sediment collector, its wide and long basin can act as a flood retention reservoir in a flooding scenario. As the HEC-RAS simulations show, this is indeed the case, and the dam causes a backlog reaching about 1 kilometer upstream filling the entire basin. Nevertheless, the basin capacity is too small, and the dam is overtopped by water surface levels of about 0.5 meters for scenario PF1 and 0.9 and 1.1 meters for PF2 and PF3 (Figure 22). Overtopping water velocity stays below 1m/s however, for all three scenarios. The settings for the dual gate were kept as approximated from the image of the facility, with the radial gate opened about 0.5 meters.

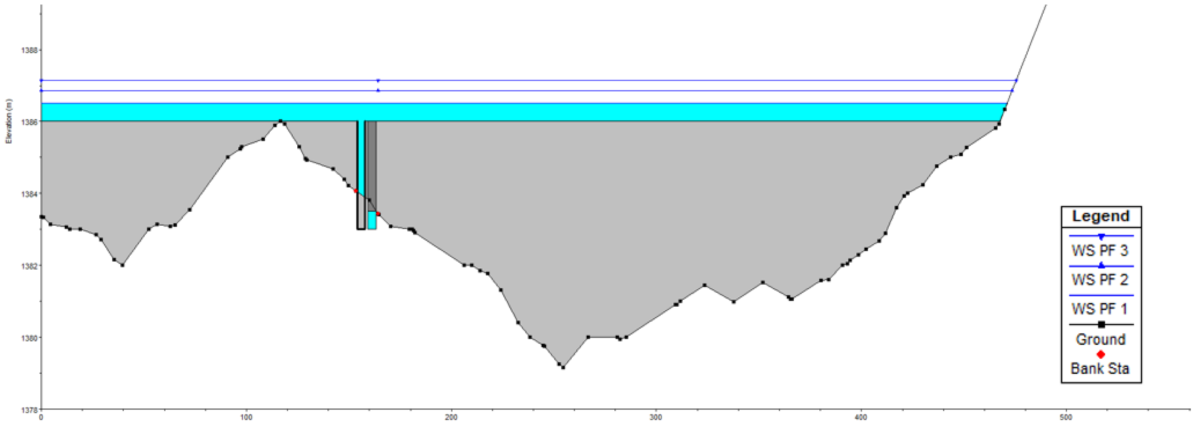

Figure 22: HEC-RAS simulation showing overtopping watersurface level at Kashka SU dam for scenarios PF1, PF2 and PF3.

The Kashka Su dam overtopping leads to the consequent flooding of the immediate downstream area of Kashka Su encompassing the river crossing just downstream of the dam and a considerable number of buildings (18, PF1; 34, PF2/3), within 800 meters behind the dam (Figure 23). These exposed buildings are indeed residencies thus setting possible people exposure counts at 74 (PF1) and 140 (PF2/3). However, despite this impact, the dam shows an effect in that it dampens the flood peak and thereby confines the flooding extent about 1 kilometer down from the dam more or less into the floodplain leaving only a hand full of exposed buildings in Baytik for the different scenarios.

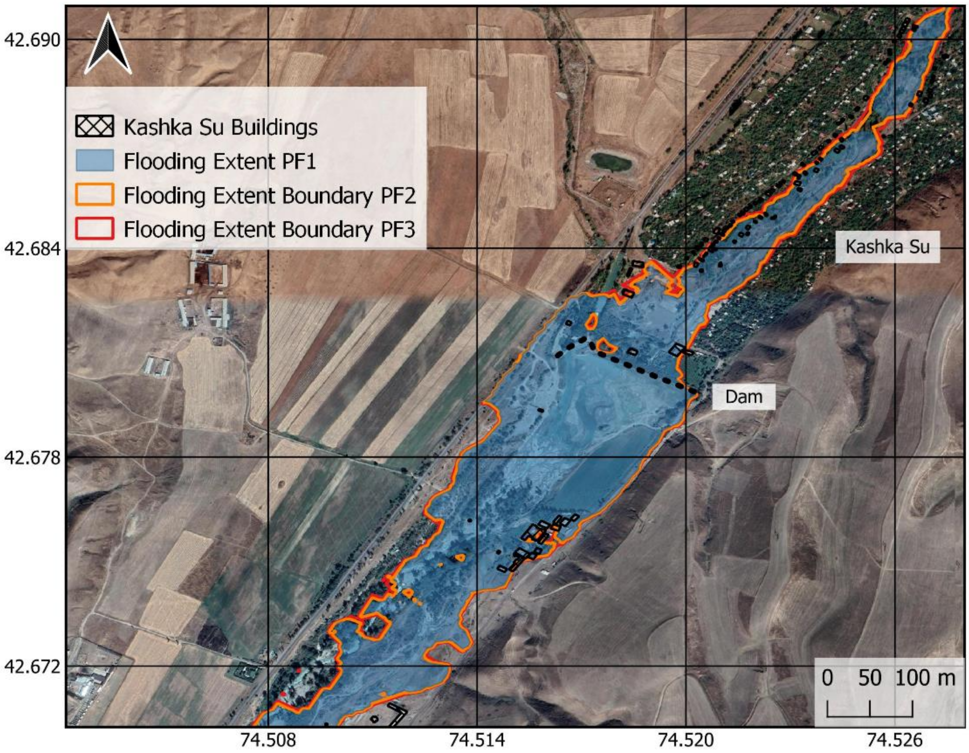

Figure 23: Overview of flooding extent at Kashka Su dam for scenarios PF1, PF2 and PF3.

5.2 Monitoring and Warning

Monitoring the level of the Uchitel glacial lake could help to determine the pressure on the drainage channels and its consequent risk for outburst including estimates for the status quo of the volume and consequent peak discharge scenarios. In addition to the lake's water level, the state of the moraine-dam could be monitored for detection of visible deterioration in the moraine-dam as for example through ice-core melting or overflow events. For monitoring of the lake water level, water level sensors could be installed, similar to the approaches taken for the monitoring system in the EWSs according to Bajracharya et al. (2007) or Wang et al. (2022). If such water level sensor installment would not present a feasible option for technical, financial, or institutional reasons, a simple water level marker could present a low-cost and simple installation for accurate water level assessment based on manual monitoring. Independent of the systems technicalities, any system of in-situ monitoring requires some form of institutionalized responsibility for regular sensor checks and upkeep or manual monitoring and control efforts. This would need to be established as part of the EWS for the Uchitel lake as well. Erokhin et al. (2018) point out how glacial lakes such as Uchitel are hard-to-reach locations and therefore often limit the possibilities of manual assessment and monitoring, resorting to remote sensing technologies as a critical tool for monitoring. Indeed, the use of satellite data for assessing the extent of Uchitel lake has been shown to be a feasible option for remote monitoring by Zaginaev et al. (2019). This form of monitoring needs to be integrated into the EWS for the Aksay valley and could further be supplemented by drone surveillance: Cui et al. (2021) point out how new technologies can bring advances in monitoring and early warning. Today, high-capacity drones with long ranges are commercially available and easy to use. Therefore, the utilization of remote imagery from a drone could supplement monitoring efforts that could be based from the location of the national park infrastructure. The accessibility to the Uchitel lake which is located at an aerial distance of about 6.5 kilometers from the national park should present no issues for a drone, as high-end commercial drones have a reach of up to 15 kilometers. Ideally, such monitoring would also be done regularly within an institutionalized framework with extended efforts during the summer months when high precipitation events could increase the lake water level enhancing outburst likelihood and when people exposure in the national park is high due to seasonal tourism. Therefore, the use of commercial drones presents a low-cost technology that could effectively supplement other monitoring efforts of Uchitel lake and the moraine.

Concerning the GLOF detection and warning system, the following is proposed for the study site: The location of the narrow canyon in the Aksay valley, beginning about 3 kilometers down valley from Uchitel lake, is suited best for the installation of detection technologies. Because of the narrow gorge of the canyon, the GLOF flow is confined within the canyon area leading to rising flooding height (Brüniger, 2023; Zaginaev 2019) and therefore giving a clear indication of an ongoing event. As redundancy plays an important role in GLOF EWSs because of possible sensor or data transmission failure (Huggel et al., 2020), two locations for the installation of detection devices are proposed. The first location could be located at 3.2 kilometers from the Uchitel glacial lake just at the beginning of the narrow canyon. The second location could be located at the distance of 4.5 kilometers from the lake just below a confluence point where the canyon is met by a smaller tributary from the north-west (Figure 24).

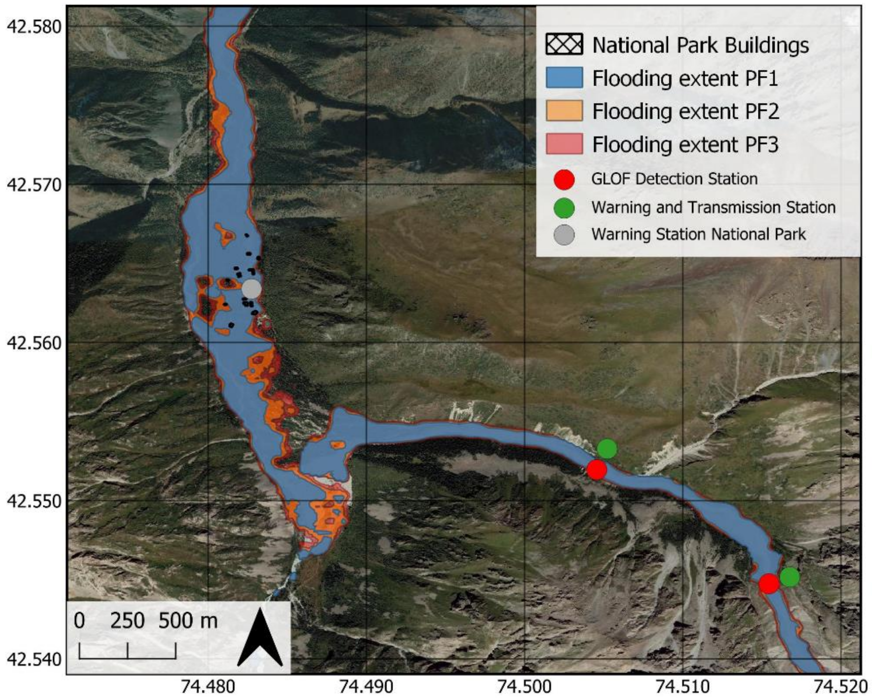

Figure 24: Overview of GLOF EWS at Aksay valley with GLOF detection stations (red), air horn warning and transmission stations (green) and electrical horn warning system (grey).

Different technologies for GLOF detection are available and in use at different locations (Geoprevent, 2023). At the proposed locations steel cables could be spanned across the canyon and then be equipped with either of two options for detection technologies. The first and technologically more advanced option is that of radars. The radar measures the distance from the device to the valley surface therefore detecting preset thresholds of reduction in distance caused by the flow of a GLOF event. This technologically advanced option enables touchless measurement and provides the benefit of being ready for use before and after a possible event. The second option of rip lines is simpler and more cost effective. From the cross-spanning cables, a rip line with a weight attached to it is lowered towards the valley surface and placed at a predefined threshold height for GLOF flow. In case of an event the weight is struck by the GLOF flow and a magnetic or electrical trigger is released. While being cost effective the downside of the rip line system is that they have to be replaced after an event (Geoprevent, 2023). For the warning threshold of GLOF flow height it can be resorted to the studies of Brüniger (2023) and Zaginaev (2019) whose results point to possible threshold heights of 1 to 3 meters, depending on the modeled scenario.

Concerning the warning after the detection of a GLOF event, it is proposed to make use of an air horn system placed in the immediate vicinity with a direct wired connection to the event detection sites above the national park. According to Bajracharya et al., such air horn systems are powered by a charged air cylinder which can operate for the duration of 2 to 4 minutes providing a sound of 80 decibel (2007). These warning systems could be used to alarm the immediate exposed people in the Aksay valley and on the cone. The two air horn systems in the Aksay valley should be supplemented with electric horns which can run for longer durations at the national park and further down in the Ala-Archa valley at the locations in the outer quarter of Kashka Su and the town of Kashka Su itself and possibly another in the town of Baytik. For redundancy, these warning locations could be equipped with air horns or generators in case of an electrical blackout. For the transmission of the warning signal from the detection stations to the warning stations different communication systems could be used such as radio, mobile network or satellite. Both the detection and warning stations would need to be equipped with a form of stored energy supply such as storage batteries to power the detection and communication system. Ideally, both systems are designed to be low in energy consumption and the storage batteries would be rechargeable through solar panels. The warning signal should further be transmitted to some local or national emergency response facility or institution, likely to be located in Bishkek, in order to activate an emergency response to the GLOF event.

Therefore, the monitoring and warning possibilities for the study site EWS include a number of different proposals which would have to be implemented according to the regulations and proceedings of the local agencies and institutions.

5.3 Dissemination and Communication

According to the WMO, the warning information and the way it is communicated should be tailored to the exposed people so they can understand and prepare to act in advance of the hazard (2010). In the case of the Ala-Archa valley, this includes two main groups based on the exposure analysis: Resident population of the valley and tourists who visit the valley and the national park. In their 2022 study, Aslam et al. found a lack of proper risk communication by the national and provincial authorities to the concerned communities in Pakistan. Indeed, the process of distribution of the warning and preparedness information depends on the groups responsible for taking action, including local and national authorities and institutions to reach out to the people and communities at risk. The following proposes some dissemination and communication strategies for the study are which could be used by the groups responsible for communication.

As there are no specific guides in the literature for GLOF specific warning messages, this proposal is orientated on the USACE's guide to public alerts and warnings for dam and levee emergencies by Mileti and Sorensen (2015). According to the guidelines for warning communication, the message should address four key elements in the following order:

1. Source: The message should clearly address the intended addressee in a way that is appealing and grabs the addressee's attention. In the case of the study site this would either be the resident population or visitors to the valley.
2. Danger: The hazard of flooding has to be described and explained to the addressee in a way which provides an understanding for the hazard and the danger of its potential impact.

   For the GLOF hazard in the study area a short, worded description of the danger could be supplemented with a simple illustration of the GLOF hazard for visual support of the message.
3. Location: The impact area has to be defined to the addressee and he must be informed of his location within the impacted area.

   This information can be derived from the gathered risk knowledge on the GLOF scenarios for the study area and consequently applied to the message.
4. Warning and guidance: The addressee must be informed that in case of an event a warning is issued, it must be made clear how this warning looks like and how the addressee should consequently react when receiving the warning. Guidance should be provided as to where the addressee should evacuate to.

   For the study site information should be provided that the warning is issued through the sound of an acoustic horn and that people should evacuate to higher ground away from the river channels of the Aksay and Ala-Archa.

As the guidelines further highlight, the message should use clear language, short sentences, be concise in wording and make use of colors and illustrations for visual support of the message. Further, the warning message should be compiled in all languages of concern in the area where the message is issued and should also be issued in formats that are suitable for people with disabilities (Mileti and Sorensen, 2015).

For the area of the national park of the study site, the warning message with its four key elements could be issued in form of signposts which could be installed at key locations including: The parking areas at the national park bridge and at the entrance of the national park. At the official entrance to the park as well as on key areas within the park such as popular picnic and rest spots, general attractions, and crossings of important hiking routes. The message should be formulated both in the Kyrgyz language and Russian, as it is still used as a lingua franca in Central Asia. Whether the message should be supplemented with the English language for international tourists highly depends on their frequenting numbers to the area and should be determined by the local authorities and institutions. The warning message on the signposts, should not be limited to the area of the national park however, to enhance dissemination the warning signposts could be distributed in the Ala-Archa valley to key locations such as popular places along the river as well as being located beside bridges.

Further, the resident population of the valley could be addressed by the responsible local or national authorities and institutions through their official information channels. In this way it could be assured that the local population receives the warning message including the four key elements and thereby can relate to the different signposts along the river, at the bridges and in the national park warning of the GLOF danger in the Ala-Archa valley. Besides the general information of the warning message stated above, the message for the local resident population should further entail the information of not evacuating over the bridges in the outer quarter of Kashka Su as well as the river crossing behind the Kashka-Su dam as they could be subject to flooding. While signpost warning information is held to be rather concise, the warning information for the resident population could for example be provided in the form of a leaflet and entail more detailed information on the hazard, possibly include further information on educational events and/or scheduled evacuation trainings and reference past events in the valley to show the actualism of the GLOF danger.

As risk communication is a complex cross-disciplinary field that involves reaching different addressees to make risk comprehensible, it is key to understand and respect the addresses values, their possible response to the communication, and to improve awareness for the needs of the addressed community (Cardona et al., 2012).

Therefore, it is proposed to local and national authorities and institutions to configurate their warning communication according to the needs of the people and communities in the Ala-Archa valley. The warning communication could utilize both signposts and official communication channels for dissemination, to provide both residents as well as visitors to the Ala-Archa valley with warning information. The proposed communication of the warning message is based on the four key elements from the guidelines for warning messages from the guide to public alerts and warnings for dam and levee emergencies by (Mileti and Sorensen, 2015).

5.4 Response Capability

According to Cardona et al., the response capability encompasses the exposed community's knowledge of their risk, their ability to act on a warning as well as being familiar with the evacuation strategies when a warning is issued (2012). All these factors depend highly on the proceedings of local and national authorities and institutions regarding dissemination and communication, but also educational and training or drill efforts for evacuation from the GLOF danger in the Ala-Archa valley. Therefore, it is proposed to the responsible groups to include such measures in their decision-making process.

Further, addressing the capability of first responders to act in the case of a GLOF event the following proposals can be made: A GLOF represents the scenario of an extreme natural hazard only proper training and preparation can help first responders overcome such events. Thus, having emergency plans ready for the case of a GLOF event in the Ala-Archa valley is essential. It is proposed to include an access strategy in such an Ala-Archa GLOF emergency plan as the outer quarter of Kashka Su would need to be accessed through a side-road by the right-hand side (in flow direction) of the Ala-Archa river, demanding that first responders cross the river at the bridge in Baytik as further upstream bridges and river crossings are likely to be impassable. Further, including allocations for heavy machinery to possibly clear the national park bridge from debris and erosive material and clearing the way towards the national park infrastructure for general access could present valuable preparatory measures to be considered by first responder agencies. Finally, concerning the overtopping of the Kashka Su dam, the basin capacity could be relieved not only by fully opening the radial gate, but also by opening the irrigation channel which leads north-west bound into the fields and away from the Ala-Archa valley. If this irrigation channel was quickly opened to its full potential by a responsible agent, a significant amount of water could potentially be diverted onto the fields and reduce the risk of overtopping of the Kashka Su dam.

Therefore, it is proposed to the local and national authorities and institutions in charge of developing the response capacities of the local communities and first responder agencies, to put educational and training programs in place for evacuation of the population as well as preparing first responders for possible GLOF danger in the Ala-Archa valley with adequate training and a strategic emergency plan including access strategies, machinery allocation and a strategic use of the irrigation channel for basin relief of the Kashka Su dam.

6. Discussion

6.1 Data Availability

A major challenge in this conceptualization of an EWS for the Ala-Archa valley has been that of data detail and data availability in general. For this reason, one of the addressed research questions relates data availability at the study site and aims to provide insights and knowledge on how data availability influenced the EWS development effort:

Where in the process of EWS development and evaluation is sufficient data available, where is a lack thereof and how does this influence the effort?

For the scientific background on GLOFs in the Tian Shan and Kyrgyzstan, many different papers and studies are available. Even the Ala-Archa valley is well studied and different papers with detailed elaborations and data could be considered for the EWS. While few of the papers are only available in Russian, translation technology helped to gain insight into the studies although the precise wording of the original language got lost in translation.

Concerning specific maps and cartographic data however, data scarcity is eminent: There are no official cartographic agencies of Kyrgyzstan, therefore it was resorted to open street map (OSM) for possible maps of buildings and streets. Unfortunately, the OSM databank for Kyrgyzstan only covers parts of the capital of Bishkek. Another possible source for building maps is the Google Open Buildings platform. While this database covers nearly the whole globe, there is a blank patch spanning most of the Central Asian countries, only northern Kazakhstan is available. For this reason, it was resorted to hand mapping buildings in the vicinity of the Ala-Archa river based on Google Satellite and ArcGIS World Imagery in QGIS. Manual mapping provided a feasible solution but also comes with some limitations, further addressed below.

In order to make use of the evacuation modelling program LifeSim from the USACE for the research area, an effort was made to gather the building attributes such as foundation height, number of floors and construction type to build a structural inventory. This data was manually retrieved from Google Streetview. Unfortunately, Google Streetview data in the Ala-Archa valley mainly covers the access road to the national park only, which provided a good starting point but does not allow for a detailed building structure inventory which would have been needed. In accordance with an USACE expert, it had thus to be refrained from working with the LifeSim program for the area. Interestingly, Google Streetview data received a small but significant update during the research period and while it mainly concerned a few streets in Baytik, the update enabled the dimensional data acquisition for the bridge in the outer quarter of Kashka Su, which had not yet been possible to view in 2022.

For detailed data on the population, official census data in the form of a report and an excel sheet in the Kyrgyz language could be accessed. With the help of translation technology, the overall inhabitants of the towns of Baytik and Kashka Su could be investigated. More detailed population data for the Ala-Archa valley could not be retrieved from the census data, and for this reason, following the recommendation of Buchanan K. from the USACE, population exposure was assessed through household averages extracted from the Global Data Lab platform. Further, population age percentages could also be retrieved from the Global Data Lab. The use of this population data brings some limitations with it which are addressed in more detail below.

Therefore, it becomes evident how the detail of data and its general aggregation to conceptualize an EWS for a location like the Ala-Archa valley in Kyrgyzstan cannot be compared to the data availability of countries like the Unites States or Switzerland. However, based on the given data foundation, a GLOF risk assessment could still be conducted.

6.2 Discussion of Results and Limitations

Based on the research intention of this thesis the overarching research question was formulated as follows:

What kind of an EWS for GLOFs including which components could be implemented at the pilot site in Kyrgyzstan?

This overarching research question was further broken down into four sub-questions in accordance with the internationally recognized main elements of EWSs which served as a structure in the research process to develop a concept for the implementation of an EWS specific to the Ala-Archa research site. The details for each of these components have been elaborated on and the following aims to evaluate some of the results in more detail and address connected areas of limitation.

Concerning risk knowledge, the developed worst case scenario is based on recognized outburst mechanisms (Westoby et al., 2014) which are plausible for the Uchitel lake. Further, the lakes volume as well as the resulting peak discharge which were used for the HEC-RAS simulation are based on field measurement and scientific estimation (Zaginaev et al., 2019). The HEC-RAS model simulation was conducted according to requirements provided in the user handbook (Brunner et al., 2023) and executed with detailed geometry inputs to best of knowledge based of satellite imagery, images from the research area and Google Street view. However, the resulting flooding extents from the simulation are still subject to limitations: As the GLOF sensitivity analysis by Brüniger has shown, the sediment bulking and erosion of a GLOF causes transitions which have implications on the different flow characteristics of the GLOF including velocity and volume. The transitional behavior has been found to be strongest in areas with steep inclination and accordingly high flow velocities (2023). For the study site, the Aksay valley presents the area with steep inclinations while in comparison, the Ala-Archa valley has only a small inclination and therefore the GLOF is likely to have transitioned back to more fluid properties, however the actual flooding extent might still be influenced and thus is subject to limitations.

Further, the GLOF danger assessment based on exposure of buildings and exposed residential population is also subject to limitations: Firstly, although conducted with great attention to detail and wherever possible verified with Google Streetview, the mapping of buildings in the research area based of Google Satellite and ArcGIS World Imagery data may not be fully accurate. In areas with dense vegetation and roof colors which resemble it, distinguishing buildings from each other or identifying them at all, can be a tedious task prone to the chance of errors.

Secondly, the estimation for exposed residential population based on household averages poses further limitations. Although the methodology proposed by Buchanan has been employed in similar contexts of flood risk assessment (2016), the situation in the Ala-Archa valley may impose limitation to the methodology: Some of the buildings mapped may not be residential buildings at all or if they are, they may stand empty, as this area is popular for holding dachas, namely seasonal or year-round second homes to the wealthy inhabitants of nearby Bishkek. Accordingly, the numbers for the vulnerability group of elderly people which were also derived based on the building count are also subject to this limitation.

Third, the population data retrieved from Global Data Lab is for the Chuy region, which is a generally rural region. Comparing the values from the Chuy region to those of the Bishkek region, notable differences in both household size and age distribution appear. The vicinity of the Ala-Archa valley to Bishkek may have an urban influence on the valley which could have implications on the population data when compared to the general region of Chuy. This matter could pose further limitations to the population data.

Finally, concerning the EWS elements of dissemination and warning as well as response capability, this conceptual EWS has major limitations concerning the involvement of the local community. According to Šakić et al., EWS are only effective if they actively put people at the center: Local authorities and communities need to be involved in all aspects of early warning so that the system is designed to be appropriate for community needs and capacities (2022). Due to a language barrier, physical distance to the research area and general circumstances of this thesis, the conceptualization of this EWS for the Ala-Archa valley could not involve the local community. The according limitations to the suggestions for dissemination and warning as well as response capability are inherent. Therefore, the provided conceptualization of an EWS should openly be discussed by the local community of the Ala-Archa valley and the responsible groups and adopted to the local needs and circumstances wherever needed. The EWS conceptualized in this thesis can thus be viewed as a possible starting point which the local community could use for further development which could eventually end in the implementation of a feasible EWS for the Ala-Archa valley.

7. Conclusion and Future Work

The intention of this thesis has been to conceptualize an EWS for the GLOFCA pilot site of the Aksay and Ala-Archa valleys in Kyrgyzstan. Based on the internationally recognized main components for EWSs, a concept including the components of risk knowledge, monitoring and warning, dissemination and communication and response capability was developed to contribute to DRR and DRM measures in the region.

Regarding risk knowledge, it was found how the Uchitel glacial lake could be affected by different mechanisms triggering an outburst flood which poses a hazard to the valleys below. Based on the possibility of a moraine-dam breach different worst-case scenarios were developed with peak discharges between 300 m^3/s and 900 m^3/s that were used to simulate the flooding extent of a GLOF in the HEC-RAS program. Working with detailed geometry input to the HEC-RAS model, generated building maps as well as residential population data, the general GLOF danger for the Ala-Archa valley could be assessed based on flooding extent maps.

Different GLOF danger hotspots were identified: From the national park infrastructure, over an outer quarter of Kashka Su, to the structural flood mitigation measure of the Kashka Su dam exposures and vulnerabilities of infrastructure and residential population could be assessed for the three different peak discharge scenarios. Depending on the scenario a total of 61 to 99 buildings were found to be impacted by the GLOF danger, indicating the exposure of 251 to 407 residents along the Ala-Archa river channel.

Based on the aggregated risk knowledge different suggestions were made for the remaining three main EWS components. Regarding monitoring and warning, different possibilities for the monitoring of the Uchitel glacial lake were proposed, including that of a local monitoring approach through the use of drones. For the warning system, an arrangement including two detection stations and several warning distribution stations was proposed. Emphasis was put on the redundancy of the system as well as simplicity and cost effectiveness. The suggested detection system includes possible locations and two different detection sensor systems with the according benefits and downsides. For the warning system the use of air or electrical horns was suggested depending on the location and access to electricity. The system overall orientates itself on other existing EWSs for GLOFs and state-of-the-art technology from the private sector which have been implemented in different places around the world.

For dissemination and communication, the proposal includes general suggestions for the warning message communication and suggests a possible implementation of signposts along the river channel and especially in the national park, while the resident population could be addressed through a leaflet and be involved in risk education and evacuation training.

For the response capability, the proposal includes the suggestion for the establishment of evacuation training as well as an emergency plan for first responders in case of a GLOF event.

The emergency plan includes proposals for access strategies, resource allocation and dam relief response.

Based on the GLOF danger analysis and the results discussed in this thesis for the conceptual development EWSs in the Ala-Archa valley, different aspects were identified which would benefit from future studies and research that could contribute to gain further understanding and thereby help towards the implementation of an EWS at the GLOFCA pilot site in Kyrgyzstan:

- Since a major limitation of this conceptual EWS includes the lack of community involvement, further research is needed to understand and include the different stakeholders in the Ala-Archa valley which are concerned by early warning in the region. Such efforts may include studies with the local population to assess risk awareness and preparation as well as institutional framework analysis for EWS implementation with the Kyrgyz Ministry of Emergency Situations and the Kyrgyz Ministry of Natural Resources Ecology and Technical Supervision to coordinate institutional responsibilities.
- For the technical implementation of the monitoring and warning components of the EWS, further research could refine and evaluate the precise locations and needed engineering solutions to locate the EWS detection and warning stations. This research may include working with national and local authorities and institutions as well as professional partners from the private sector with experience in the implementation of EWS technology.
- A detailed case study in the field of hydraulic construction could provide further knowledge on the Kashka Su dam concerning its vulnerability to failure when its basin is filled and consequently overtopped. Further, the possibilities of enhancing the dam’s capacity through water deviation or dam and basin enlargement could be assessed. A cost to benefit analysis could be beneficial in this context.
- Concerning dissemination and communication of GLOF hazards, interdisciplinary research could compose a GLOF specific guideline for the communication of GLOF warning messages to exposed communities. Results from case studies evaluating different warning communication approaches for existing GLOF EWS from around the world could be compiled to make an effort in this direction.

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Personal Declaration

I hereby declare that this thesis is the result of my own, independent work.

All external sources are explicitly acknowledged in the thesis.

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Nussbaumen, 30.

30.09.2023