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GLOFCA
GLACIER LAKE OUTBURST FLOODS IN CENTRAL ASIA

REDUCING VULNERABILITIES OF POPULATIONS IN THE CENTRAL ASIA REGION FROM GLACIER LAKE OUTBURST FLOODS IN A CHANGING CLIMATE (GLOFCA)

BEST PRACTICE GUIDANCE DOCUMENT ON GLOF RISK ASSESSMENT

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IMPLEMENTING PARTNERS:

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CHAPTER 1

Lake Mapping and Susceptibility Assessment

1: Introduction and framing

1.1 Background, context and motivation

Due to their rich natural resources, unique ecosystem services and spectacular landscapes, mountain regions have always been home to people. However, rough topography, large elevation gradients and steep slopes lead to processes that constitute hazards to downstream communities and infrastructure. Assessing and managing natural hazards and risks has always been an integral part of human activities in mountains.

Since a few decades, high mountain regions all over the world are also increasingly affected by ongoing climate change. Rising temperatures lead to shrinking and eventually disappearing glaciers and warming and degrading permafrost conditions. These changes lead to fundamental and long-term alterations of the landscape and many interconnected systems. Today, the assessment of cryospheric hazards cannot rely on experiences from the past, as conditions and situations are beyond any historical evidence. Therefore, scenario based and future oriented approaches are needed for the evaluation and management of current and potential future hazards and risks.

Outburst floods from glacial lakes can cause damages up to several hundreds of kilometers downstream of their source lakes. Managing risks related to such GLOFs is therefore a transboundary task, requiring regionally coordinated efforts. The GLOFCA project is one of the first regional projects funded by the UN Adaptation Fund and executed by UNESCO, together with the University of Zurich as an international implementing partner. Its main aim is to reduce the vulnerability of people in Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan towards Glacial Lake Outburst Floods (GLOFs). These four Central Asian countries are all heavily affected by climate change, and at the same time have a long history and tradition in disaster risk reduction and management related to mountain processes.

The present document provides a guiding reference to the best-practice for GLOF hazard and risk management in Central Asia, as compiled under the GLOFCA project. It considers procedures and standards for the assessment and management of glacial lakes and related hazards and risks that have been established in the four countries, and combines them with international scientific state-of-the-art approaches. It is a working document that will evolve over the duration of the project. The document is based on contributions from the international and national experts, representing various institutions engaged in the GLOFCA project.

Readers wanting further information about national experiences with GLOF hazard and risk management across Central Asia, may refer to national-level synthesis reports prepared under GLOFCA. These draft reports served as input to the guidance document.

1.2 Terminology & Framework

According to the UNDRR terminology[1], *a **natural hazard** is a natural process or phenomena that may cause loss of life, property damage, social and economic disruption or environmental degradation*. Hazards are characterised by their location, intensity (or magnitude) and probability of occurrence. ***Risk**, on the other hand, considers not only the hazardous event, but also its consequences*. In its Special Report on Risks of Extreme Events and Disasters (SREX)[2], the IPCC defines risk as a function of hazard, exposure, and vulnerability. In the meantime, this is an established standard, and we therefore base our approach on this concept. ***Disaster Risk Reduction (DRR)*** describes efforts aiming at preventing new and reducing existing risks and managing residual risks.

In order to treat GLOF hazards and risks in a comprehensive way for a very large area such as Central Asia, with thousands of glacial lakes, a staggered approach is needed. Potentially critical situations need to be identified with simple but robust approaches at large scale, then detailed in-depth assessments should follow at local scale for hot spot regions and high priority sites (cf. Fig. 1).

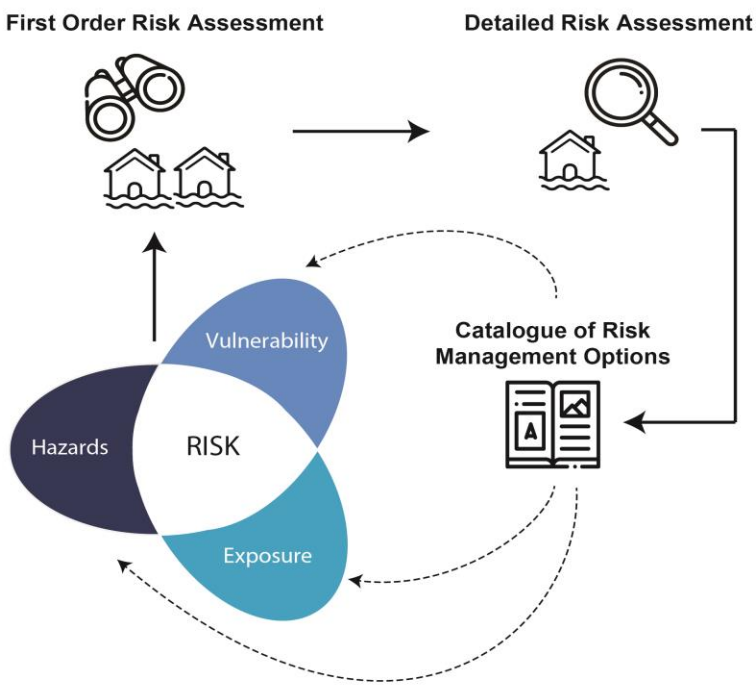

Figure 1: Hazard and risk assessment framework followed in the GLOFCA project

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[1] *https://www.undrr.org/terminology/ (accessed March 2022)*

[2] IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge, UK, 582 pp.

Tasks of the first stage, the first order risk assessment, include remote-sensing based approaches to detect, map, or monitor all glacial lakes over a large area. Simple but robust assessment methods provide first-order insights on the susceptibility or stability of such lakes and their dams, and in some cases, first indications of potential downstream impacts. ***Susceptibility*** *is a relative measure of the likelihood (or probability) that a lake will produce an outburst flood, considering the physical characteristics of the lake and its surrounding environment*.

Glacial lakes identified as potentially critical in this first order assessment are then investigated at detail scale on a case by case basis. In such a detailed risk assessment, lake stability and outburst susceptibility is assessed in more detail, considering the characteristics of the lake, the dam and potential outburst triggers. Based on these outcomes, downstream impacts are modelled by considering outburst scenarios of varying probabilities and magnitudes, using physically-based numerical models. Such model results, in combination with field work, can then be used for the production of detailed hazards maps. In combination with data and information on assets at risk, such hazard maps provide a basis for risk mapping.

For the management of GLOF risks, various Disaster Risk Reduction (DRR) measures exist, which aim at reducing one or more drivers of risk (i.e. hazard, exposure, vulnerability). Here, a special focus is put on comprehensive Early Warning Systems (EWS), which aim at reducing vulnerabilities and exposure of the potentially affected population. EWS are very efficient measures in terms of cost-benefit and are a priority in international policy documents, such as the Sendai Framework for Disaster Risk Reduction or the Sustainable Development Goals (SDG) of the UN. Especially when combined with other risk reduction measures, EWS can significantly contribute to a reduction of GLOF risk.

At the current stage, the present document covers a compilation and recommendation regarding glacial lake mapping and glacial lake susceptibility assessment in Central Asia (Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan) (Chapter 1). Further Chapters will be elaborated during the GLOFCA project.

2: Lake mapping

2.1 International state-of-the-art

2.1.1 Sensors used

Several recent studies on mapping glacial lakes used either selected, cloud-free optical images, or Synthetic Aperture Radar (SAR) data. The optical imagery employed in such studies provides a number of different spectral features for assessment, mostly from top-of-atmosphere reflectance (Pekel et al., 2016; Wangchuk and Bolch, 2020; Zhang et al., 2020b), sometimes after atmospheric correction (Dirscherl et al., 2020; Jha and Khare, 2017). On the other hand, the use of SAR data for water body mapping is based on the low and temporally variable backscattering of surface waters (Santoro and Wegmuller, 2014; How et al., 2021).

2.1.2 Classical approaches

Pure water is among the darkest natural remote sensing targets, and the absorption by pure water increases strongly with wavelength throughout the visible and near-infrared (NIR) spectrum. High loads of suspended particles can counter this dominant property of natural waters, and move the spectral peak in water-leaving reflectance to 600-800 nm for concentrations of several hundred g/m3 (e.g. Figure 3 in Doxaran et al., 2003). Nevertheless, relating relatively high visible to very low NIR and Short-Wave Infrared (SWIR) reflectance remains one of the most powerful approaches to distinguish water from land surfaces.

Zhang et al. (2020b) estimated the robustness of each feature, which resulted in the highest scores for Normalised Difference Water Index-Blue (NDWI-B), Normalised Difference Water Index-Green (NDWI-G) and Enhanced Water Index (EWI). They also found that most widely used indices are strongly correlated, which suggests a limited potential to increase classification accuracy via combinations of optical indices. The most widely used NDWI-G performed best in their analysis and scored compared to and for EWI and NDWI-B, respectively. Zhang et al. (2020b) used Top of Atmosphere (TOA) reflectance and found that normalised indices were consistently more robust means for classification than single bands or band ratios. On the contrary, Dirscherl et al. (2020) found that single atmospherically corrected band reflectances acquired by Sentinel-2 (665 nm, 560 nm, 705 nm, 740 nm, 783 nm in order of importance) represent better classification criteria than indices (TC_{wet}, $AWEI_{nsh}$, $AWEI_{sh}$ ranked 2nd, 5th, 8th). It seems that this difference is primarily related to the application of an atmospheric correction by Dirscherl et al. (2020) as opposed to Zhang et al. (2020b), where absolute TOA reflectance is subject to strong variations in atmospheric scattering that require normalisation with an index. Secondary effects are expected from the pixel composition in the periglacial area, which differs significantly between Antarctica (Dirscherl et al., 2020) and Asian mountain ranges (Zhang et al., 2020b).

The set of indices used by Pekel et al. (2016) differs significantly. The spectral features they used comprise, besides the Landsat input bands in TOA reflectance, the NDVI and Hue-Saturation-Values (HSV) calculated from two different triplets of Landsat spectral bands (referred to as HSV-S and HSV-N). The HSV transformation allows to base classification decisions on a hue value that is, similar to spectral indices, less susceptible to illumination and atmospheric scattering variability than TOA reflectances. However, the existing threshold- and index-based remote sensing approaches have various limitations. The performance of such approaches is affected due to glacial lake turbidity, cloud-and mountain-cast shadows, cloud cover, seasonal snow and freezing-up of glacial lakes. Hence, post-processing steps are often necessary for such methodologies.

Santoro and Wegmüller (2014) used minimum backscatter and temporal variability defined as the standard deviation of the backscattered intensities in the logarithmic decibel (dB) scale to map water extent in the Envisat-ASAR time-series. Using this approach, it was observed that the minimum backscatter of land pixels in rugged areas is reduced and the temporal variability in backscatter is elevated, leading to a reduced separability from water pixels for mountainous areas. Furthermore, wet snow can reduce backscattering in a given pixel temporarily and hence cause, over extended periods, an increased variability. Against this background, and considering the increased temporal resolution enabled by the Sentinel-1 mission, time-series analyses were adopted in place of the temporal variability metric in a study by How et al. (2021). This Greenland-based study used Sentinel-1 Interferometric Wide swath Ground Range Detected (IW-GRD) data for Horizontal-Horizontal (HH) and Horizontal-Vertical (HV) polarisation.

Sentinel-1 C-band backscattering data was also used to create high-frequency glacier outlines for the Southeastern Tibetan Plateau (Zhang et al., 2020a). In this work, an initial lake segmentation based on a backscattering threshold was performed, and the annual median backscattering in each pixel was used for regularisation according to Silveira and Heleno (2009). Similarly, Wangchuk and Bolch (2020) used a backscattering threshold of -14 dB for the Sentinel-1 data used in their classifier.

2.1.3 Machine learning approaches

Wangchuk and Bolch (2020) demonstrated that integrating different data sources in Machine Learning (ML) approaches can significantly improve the robustness of unsupervised land/water classification in high alpine areas. Additionally, Dirscherl et al., (2020) developed a similar method specifically for the Arctic glacier lakes. Wangchuk and Bolch (2020) proposed to use a random forest ML classifier on the data from Sentinel-2 MSI and Sentinel-1 SAR, and a DEM for rule-based glacial lakes segmentation. This ML methodology was validated using the data that captured High Mountain Asia, the Alps and the Andes. This approach performed relatively better compared to various existing methodologies underlining the potential and possibilities of ML-based satellite image analysis for glacial lake monitoring.

2.1.4 Auxiliary information sources

Ancillary information sources were also employed for glacial lakes mapping (Wangchuk and Bolch, 2020; Pekel et al., 2016; Zhang et al., 2020a) mainly to mitigate errors in particular for steep slopes that are subject to cast shadows. The usability of digital elevation models (DEM) for this task depends on their spatial resolution and accuracy for mountainous areas but is very reliable for DEM-derived slopes above 20-30°. The ASTER GDEM V2 was used to identify mountain shadows in SAR data (Zhang et al., 2020a). In addition to a DEM, the perimeters of glaciers, urban areas and lava flows were used by Pekel et al. (2016)which are useful to remove terrain shadows, glacier-related errors, building cast shadows etc.

2.2 National approaches used in Central Asia

Glacial lake inventories in Central Asia are compiled by local authorities and research institutions as well as by international scientists. Local glacier lake inventories are commonly based on freely available remote sensing imagery (Fig. 2). The data base comprises, but is not limited to, ASTER, Hexagon, IKONOS, Landsat 5 (TM), Landsat 7 (ETM+), Landsat 8 (OLI), Sentinel 1 and Sentinel 2B, SPOT5, WorldView-2 (amongst others Mergili et al., 2013, Petrov et al., 2017, Karpitsa et al., 2017, Zheng et al., 2019). In some cases, declassified intelligence data such as Corona have been used to extend the analysis into the past century (Bolch et al., 2011, Mergili et al., 2012).

The inventories are typicall not updated according to a regular schedule, but depend mostly on the initiative of the administrative or research institutions in the region.

In most cases, the outlines of glacier lakes are manually identified and digitised. However, some studies make use of automatic or semi-automatic methods for the detection and delineation by using the normalised difference water index (NDWI) (Bolch et al., 2011, Semakova et al., 2015). The main drawbacks and limitations of such approaches are related to difficulties in the classification of shaded areas, melting ice and turbid lakes (Section 2.1). For these and other possible reasons, manual delineation of lake outlines remains essential. The use of machine learning algorithms and SAR data has the potential to improve the detection of smaller lakes and to allow high temporal resolution analysis even under cloud cover conditions, thus permitting sub-yearly analysis of glacier lakes fluctuations and the detection of potentially dangerous ephemeral lakes.

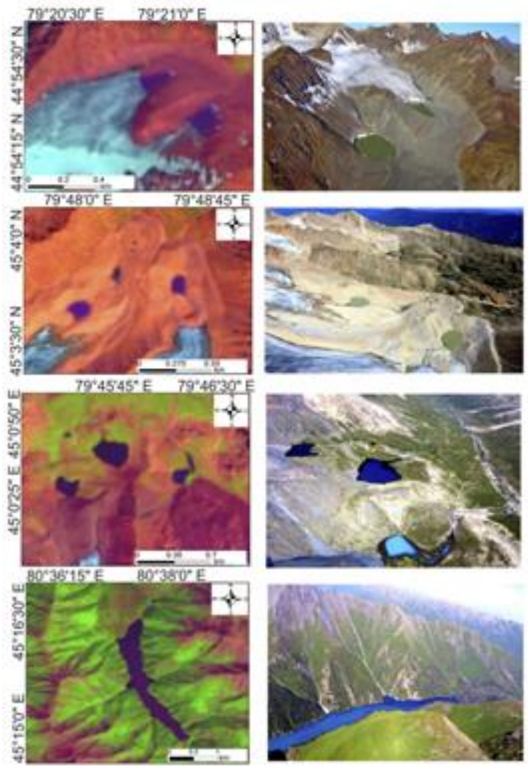

Figure 2: examples of different lake types. Landsat imagery (2014) and oblique aerial photograph (left and right respectively). From Kapitsa et al., 2017

Repeated mapping with annual frequency commonly makes use of imagery from close to the end of the ablation season, i.e. from August or September, to minimise seasonally frozen water, snow cover, and in general the uncertainty associated with seasonal fluctuations (Zheng et al., 2019).

Beside limitations in the visibility and physical changes of the lakes, the coarse spatial resolution of the remote sensing data is the main source of uncertainty, which is usually assessed in local/regional studies. The accuracy of the lake outline depends mostly on the resolution of the data used for mapping (Petrov et al., 2017). According to international best-practice, the relative error is calculated by multiplying the perimeter of the lake by a buffer, representative of the absolute error. This value is taken as half a pixel dimension. Some studies used more elaborate methods for the assessment of the buffer, including the uncertainty due to subjective manual mapping (e.g. Mergili et al., 2013).

Result validation by means of in-situ measurements is beneficial and provides important data on the local characteristics of the glaciers, the lakes and the dam types. Important information about lake bathymetry and ground ice, which are essential for detailed local assessments and calibration of parametric equations for the estimation of lake volumes (Fig. 3) and susceptibility assessment, can only be obtained by detailed in-situ surveys. However, most field sites are difficult to access and fieldwork in this setting is laborious and cost-intensive. Helicopter flights can provide a good compromise between in-situ surveys and satellite remote sensing data only.

Another difficulty can arise in restricted border areas, where it is difficult to obtain permissions to conduct field or helicopter surveys. A major advantage of including field data is, given a proper data integration, the possibility to extend the observation window of several decades in the past by exploiting old field investigations.

For practical reasons, also linked to resolution, the inventories apply a threshold for the glacier lake area, under which the lakes are disregarded. Most studies set this value around 2'000 to 2'500 m^2, but some inventories based on higher resolution imagery have lowered the threshold of digitalization to less than 1'000 m^2 (Petrov et al., 2017, Kapitsa et al., 2017). The use of high-resolution commercial satellite data has therefore the potential to improve both the quality and the accuracy of regional glacier lake inventories.

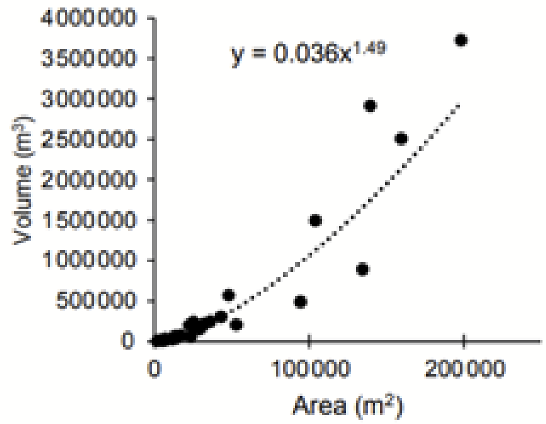

Figure 3: Relationship between lake area and volume in the Zailiiskiy and Djungarskiy Alatau, from Kapitsa et al., 2017.

Digital Elevation Models (DEM) are used for imposing a minimum threshold on lake elevation to be included in the inventory. This value is commonly set to 1'500 m a. s. l. in Central Asian countries. Digital elevation products are also useful to quantify lake susceptibility to outburst floods and can be used to assess the flow path and magnitude of possible mass movements. Freely available data products are the ASTER DEM and the SRTM with a resolution of 30 m. The vertical uncertainty has been evaluated by Kapitsa et al. (2017) as ±10m for the region of Djaungarskiy Alatau in Kazakhstan. High-resolution DEMs are used in particular circumstances, but the spatial extent of a GLOF is such that the calculation of the necessary data can be very time and resource consuming. Elevation models can also support the calculation of future evolution of glacier lakes size and number. For Central Asia, such an evolution is evaluated by different authors on the basis of glacier thickness modelling and identification of overdeepenings (e.g. Kapitsa et al., 2017, Zheng et al., 2021).

In the regional literature, similar to the international scene, there is no consensus on the classification of glacier lakes. Kapitsa et al. (2017) combine the approaches of Popov (1986) and Medeu et al. (2013) and develop a new classification scheme differentiating: contact lakes developing at glacier tongues, proglacial morainic lakes forming on the 20th to 21st century moraines (within 500 m) but with no contact with a glacier, morainic lakes positioned in the LIA or older moraines, and dammed lakes forming due to damming of rivers and streams. Petrov et al. (2017) suggest a geometrical criterion for lake type classification based on the relative position of lakes to glaciers: supraglacial lakes are positioned on the glacier surface, proglacial lakes are situated at the margins of a glacier and in direct connection to it, periglacial lakes are defined within 2 km of distance from the glacier terminus, and finally, extraglacial lakes represent the rest (Fig. 4). The possibility of a consensus approach for a regional study is envisaged by several authors and appears feasible in a practical sense given the large overlaps between different approaches.

Along with basic detection, many inventories also provide information useful for the application of hazard criteria, such as lake type, dam type, presence of cascading lakes, lake area, freeboard height, distance to infrastructure, average slope and slope in proximity of the lake dam. This point is further discussed later in chapter 3.2.

3: Susceptibility Assessment

3.1 International state-of-the-art for susceptibility assessment

This section focuses on the susceptibility assessment of the lake. Some scientists refer to this step as the lake hazard assessment, or danger assessment. We here use the term “susceptibility assessment”, but regardless of the terminology used, it is important to distinguish this step from the downstream hazard assessment, which then considers how the outburst event will propagate downstream, and what the impacts (flow heights, velocities, etc.) will be to infrastructure and communities. This aspect of downstream hazard modelling and mapping will be covered separately in Chapter 2 of the guidance document.

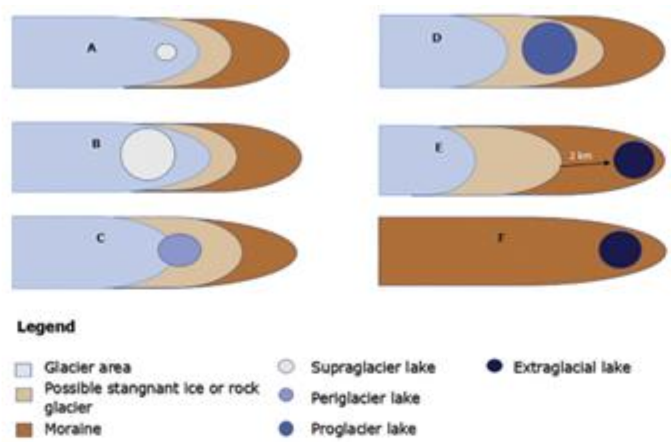

Figure 4: Lake positions in relation to glaciers and their evolution over time, from Petrov et al., 2017.

Lake susceptibility assessment) involves identifying from which lakes, how likely, and how large an event could be, based on analyses of wide-ranging triggering and conditioning factors driven by interlinking atmospheric, cryospheric, geological, geomorphological, and hydrological processes. Conditioning factors encompass static and inherent characteristics of the site, but also dynamic factors that gradually increase the susceptibility of a site over time (e.g., dam characteristics, lake size). Triggering factors are thereby reserved for those processes that directly initiate an outburst or transform a site from a stable to unstable state (e.g., extreme melt or rain event, rockfall into a lake, earthquake). How relevant certain factors are for susceptibility or stability will vary from one region to another, and expert judgement is needed to determine whether or not more emphasis (weighting) should be applied to some factors in the local assessment of susceptibility.

Various schemes have been proposed for assessing the susceptibility levels of glacial lakes, mostly drawing on remotely sensed information to characterise semi-quantitatively the cryospheric environment, lake and dam area, and other geotechnical and geomorphic characteristics of the upstream catchment area of the lake (e.g., Huggel et al., 2002; McKillop and

Clague, 2007; Worni et al., 2013). In mountain regions of the Himalaya and Andes, where much research has focused, classification schemes have tended to emphasise the role of rock/ice avalanches as a primary trigger. The potential for unstable rock and/or ice to impact into a lake can be determined based on worst-case runout distances. Assessment approaches have mostly been developed and tailored towards regional implementation, and in particular for moraine dammed lakes, for which McKillop and Clague (2007) provided an early comprehensive overview of many of the relevant susceptibility factors that may condition or trigger an outburst event (Fig. 5). Since this early work, a fuller range of factors relevant for the destabilisation of ice, moraine, and bedrock dammed lakes has emerged.

Various lake susceptibility or hazard assessment procedures have been presented in the literature (Kougkoulos et al., 2018), building on early systematic approaches (Huggel et al., 2002; McKillop and Clague, 2007), and regional scale studies (Ives et al., 2010). The final susceptibility rating (sometimes called danger level) for any given lake is typically based on a simplified empirically-based classification scheme (e.g., decision tree), or based on an index that mathematically combines multiple factors. For sub or englacial drainage of ice-dammed lakes, or complex ice-moraine structures, process understanding remains rather limited on an international level and robust assessment criteria are lacking.

3.1.1 Cryospheric Factors

Key overarching determinants of GLOF susceptibility and the resulting event magnitude are the size of the glacier lake, the outburst mechanism (and related hydrograph), and the characteristics of the downstream torrent (determined by channel inclination and debris availability) (Emmer, 2017). Large lakes can produce potentially greater flood magnitudes, but larger lakes also are more susceptible to impacts from rock and ice. **However, if too much weighting or attention is applied to absolute lake size, dangerous situations involving smaller lakes or rapidly changing lakes can be missed.** International best-practices for monitoring of lake area and changing lake size have been presented in Section 2. Direct measurements of lake volumes remain rare owing to the difficulties and danger involved in surveying lake bathymetries in remote regions. Approaches using small unmanned boats with sonar instrumentation provide a safe and cost-effective option for surveying critical lakes, providing detailed bathymetries. For regional to basin scale studies, a first-order estimate of lake volume can be derived from empirical equations that link mean lake depths with lake area (Fujita et al., 2013; Huggel et al., 2002; O'Connor et al., 2001). Consideration of the geomorphological context (e.g., moraine-dammed, supraglacial, or ice-dammed) has been shown to considerably improve such first-order estimates of lake volume (Cook and Quincey, 2015). Future threats can be anticipated where lakes expand or newly develop within depressions in the glacier bed. Possible locations where lakes may develop in the future can be established from morphological criteria (Frey et al., 2010) or derived from modelled bed topography (Farinotti et al., 2019; Linsbauer et al., 2016), although future lake volumes can only be estimated to within an approximate order of magnitude.

Glacier dynamics (advance, retreat, calving, downwasting, and surging) can be monitored over large areas using remote sensing and photogrammetry, and should be combined with regular monitoring of lake development and updating of the lake inventory. Permafrost conditions need to be characterised for both the surrounding steep bedrock slopes, but also for the dam area of the lake to infer the presence and likely condition of any ground ice in the dam structure (ice-cored moraine or rock glacier) that may be highly susceptible to further warming and melting. For critical dam structures, geophysical techniques can then be employed to more precisely determine the subsurface thermal conditions. Whereas supraglacial drainage networks can be observed at the surface, the connectivity of lakes to a sub or englacial system can only be established through observation of past drainage events, field experimentation (e.g., dye-tracing) or modelling.

3.1.2 Geotechnical and geomorphic factors

For lake susceptibility assessment, a distinction is made between those factors that are critical to the stability of the lake dam and those that influence the potential for an external triggering event, such as those factors that trigger a rock or ice avalanche, or debris flow (for a full discussion see Emmer, 2017). Additionally, studies have highlighted the hydro-geomorphic characteristics of the lake catchment area, which may influence the susceptibility to precipitation or melt-triggered outburst events.

With high resolution optical imagery (such as available from google earth) and corresponding high quality digital terrain models, it has become possible to quantify various physical characteristics of the dam and catchment area remotely over large spatial scales (Allen et al., 2019; Dubey and Goyal, 2020; Rounce et al., 2016). However, precise geometric measurements (e.g., dam freeboard, or dam height) and in situ characteristics (e.g., ice-core, lithology) are still best obtained through local site investigations.

Geographical information system (GIS) tools can be used to determine the upstream catchment area of each glacial lake, and quantify key hydrological characteristics therein (Allen et al., 2015). While empirical evidence linking catchment characteristics with GLOF susceptibility remains limited, it can be assumed that lakes fed by a steep, fast-draining catchment area are more susceptible to rapid inflow from precipitation or snowmelt. The same tools may be used to assess the topographic and geomorphological characteristics of the downstream flood path below the lake.

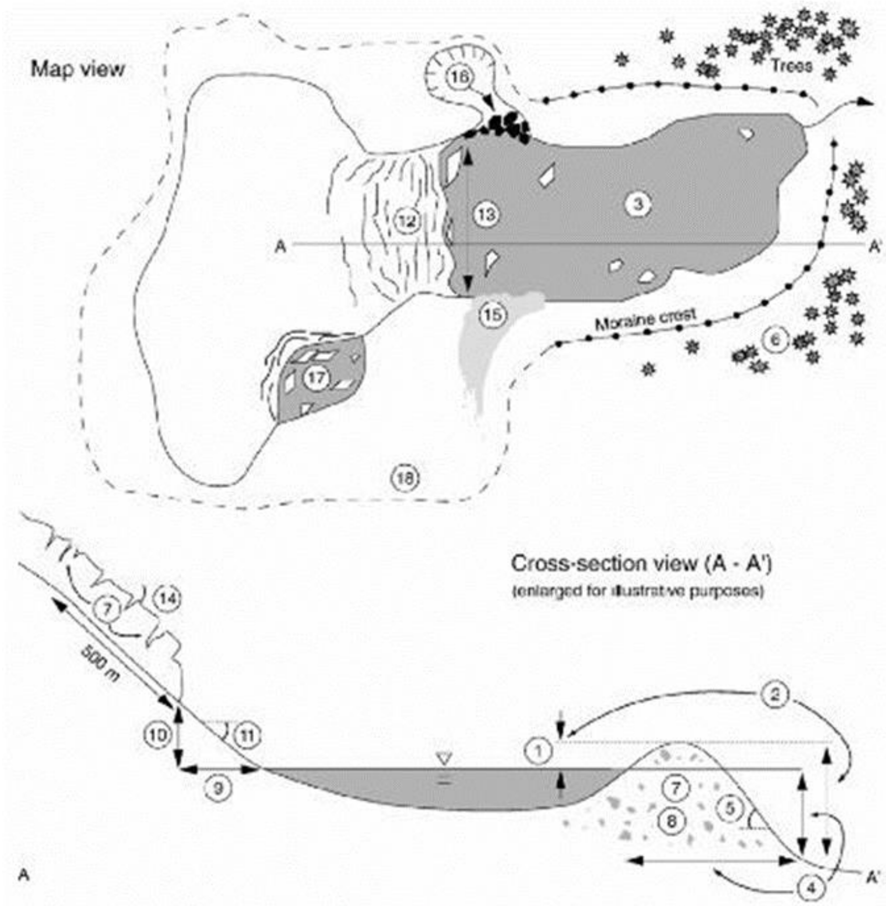

Figure 5: Summary of factors relevant to the stability of moraine dammed glacial lakes, as presented by McKillop and Clague (2007). These include: (1) lake freeboard, (2) lake freeboard-to-moraine crest height ratio, (3) lake area, (4) moraine height-to-width ratio, (5) moraine downstream slope steepness, (6) moraine vegetation coverage, (7) ice-cored moraine, (8) moraine lithology, (9) lake–glacier proximity (horizontal distance), (10) lake–glacier relief (vertical distance), (11) slope between lake and glacier, (12) crevassed glacier snout, (13) glacier calving front width, (14) glacier snout steepness, (15) snow avalanches, (16) landslides, (17) unstable lake upstream, and (18) watershed area.

3.2 National approaches used for susceptibility assessment

Most of the Central Asian literature and assessment approaches refer to the term lake hazard assessment rather than the term of lake susceptibility assessment which is used more often in international literature. Here we maintain the original wording of the national approaches and understand both lake susceptibility assessment and lake hazard assessment as synonymous.

In the first step, it is decided which lakes will be assessed in detail. In the Republic of Uzbekistan, based on Petrov et al. (2017), a detailed hazard assessment is made for all lakes at altitudes above 1500 m a.s.l. that exceed an area of 100 m^2 and drain into Uzbekistan. In the Republic of Kazakhstan, the most dangerous lakes, and since 2015, all moraine lakes, are assessed. In the Republic of Kyrgyzstan, a detailed annual assessment and categorization is conducted for lakes that are susceptible to GLOFs. Those lakes are listed in a national lake atlas that is updated regularly and serves as a basis for lake monitoring and assessment. In the Republic of Tajikistan, hazard assessments are conducted in three stages, including firstly a preliminary hazard analysis, and secondly, the identification of possible hazard sequences, and thirdly an analysis of the consequences.

For the detailed lake susceptibility assessment, all four countries refer to hazard categorization based on different types of characteristics of varying detail influenced by atmospheric, cryospheric, geological, geomorphological, and hydrological processes. Lakes are assigned to one of 2 hazard categories in Kazakhstan, one of 3 categories in Uzbekistan and Tajikistan, or one of 4 categories in Kyrgyzstan. Detailed hazard assessments and categorization are based on ground surveys (e.g. bathymetry), airborne surveys and interpretation of space and aerial photographs. They are conducted based on expert judgement and considering a catalogue of criteria. Parameters for hazard categorization are defined qualitatively (visually) and quantitatively based on long-term field observations of local processes, condition of lakes and surroundings, and records of past events.

Figure 6: Ground observation works at the Lake No. 1 in the Turgen River Basin, Ile Alatau, 2020

In Kazakhstan, lakes are assigned to one of the two categories of high or low hazard potential, based on criteria for the lake, the dam, and the glacier. These include lake type, lake volume, filling mode, basin geomorphology, runoff, and drainage channel, for the lake criteria; dam type, composition, dimensions, state, and location, for the dam criteria; and type, dimensions, and location, for the glacier criteria. Qualitative expert judgement, as well as hard/absolute values are used in some of the criteria for categorization (for the latter: e.g., dam width or height of >10m or <10m; location of the dam relative to the lake of <500m or >500m; location of the glacier relative to the lake of <500m or >500m; or glacier dimensions of >0.5 km2 or <0.5 km^2) (for details see table 1).

Stationary and non-stationary lakes are distinguished. Even though the number of non-stationary lakes is much lower than the number of stationary lakes, they account for >50% of the catastrophic GLOFs. Non-stationary lakes fill up at the very beginning of the ablation period up until the pre-winter period. The filling of lakes occurs as a result of the blocking of ice tunnels and their outburst is most often a result of the opening of such underground runoff channels. Lakes of 20 or more years of age are considered to pose a minimal threat of outburst. In Kazakhstan most of the moraine dammed lakes have dams made by moraine materials containing buried ice cores or permafrost. Main causes of lake outbursts are thought to be the degradation of dams due to soil thawing and rapid filling up of the lakes in summer and subsequent dam erosion through surface drainage channels, as well as intra-morainic runoff channels.

In the Republic of Tajikistan, glacial lakes are classified into three hazard categories, namely (1) lakes at outburst stage, (2) lakes that are approaching outburst stage, but pose no immediate threat yet, and (3) lakes with the potential for an outburst in the future, but at present are safe. While category (3) lakes should be surveyed annually, category (2) lakes should be observed, and for category (1) lakes protective and preventive measures are required to prevent possible catastrophic consequences. For Tajikistan the only study with a detailed assessment of glacial lakes has been carried out in 2009-2010 and published by Schneider et al., (2010). However, it mainly addresses GLOF scenario modelling, rather than specific criteria for lake susceptibility assessment.

In Kyrgyzstan, mountain lakes are classified based on geological factors of their formation, namely the genesis of their dams and the peculiarities of the structure and composition of these dams. According to the genesis, nature of the structure and composition of their dams, the outburst-prone mountain lakes are divided into the following types: glacial, moraine-glacial, moraine, moraine-dammed and landslide; and subtypes (see Figure 7). Lakes of each type and subtype have their own characteristic features that have to be considered in their outburst susceptibility assessment. For the hazard classification, the same hazard categories as in Tajikistan are used, but with an additional category (4) with lakes that have burst already, but still retaining a significant amount of water, and in the case of cardinal changes in natural conditions (e.g., an earthquake, landslide, slope failure, mudflow, etc.) could burst again. The most important criteria that has been used for categorization are lake type, nature of filling, nature of runoff, position of glaciers, activity of thermokarst processes and lake feeding conditions, as well as changing conditions (e.g., in temperature, precipitation, earthquakes), and accumulation of loose detrital materials on steep slopes. More recently the most important criteria have been adjusted to: filling of the lake, nature of lake runoff, nature of the dam and evidence of dam destruction, and contact with the glacier. For example, moraine-glacial lakes are considered to be the most outburst-prone lakes in Kyrgyzstan, and lakes with underground flow are found to be the most prone to outburst. Lakes are most prone to outbursts between May and September when lake level and volume increases, depending on the type of lake. A detailed list of criteria for outburst susceptibility assessment and categorization for different lake types is shown in Table 2.

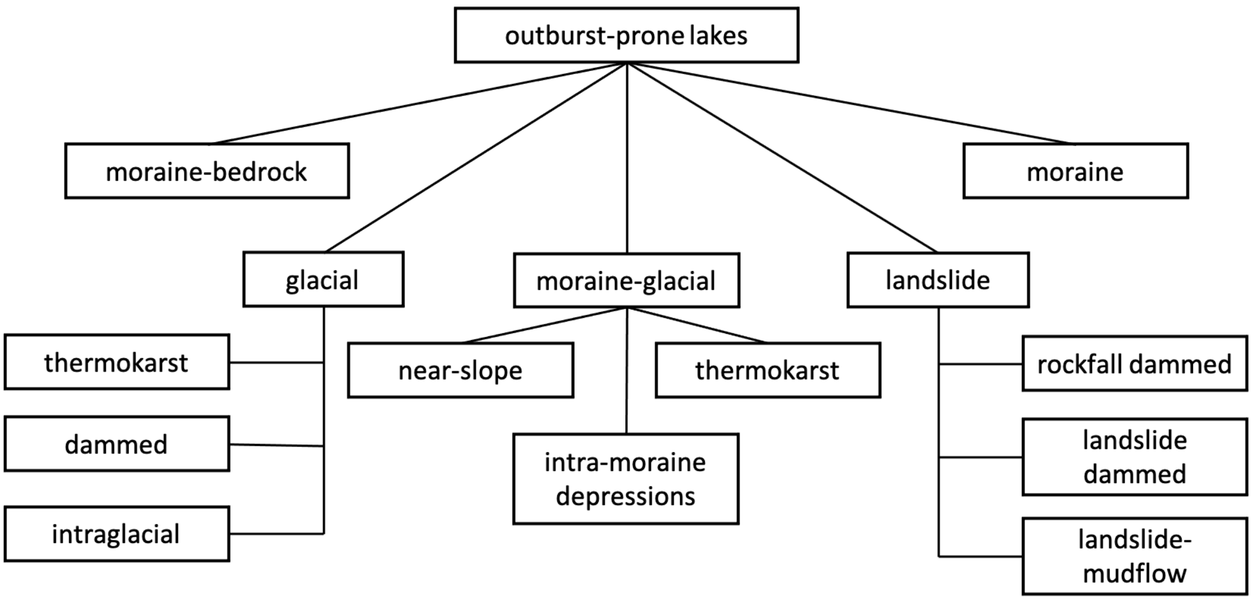

Figure 7: Classification system of hazard-prone mountain lakes in Kyrgyzstan (S.A. Erokhin, thesis).

In Uzbekistan, lakes for which a hazard assessment is conducted, are assigned one of three outburst potential categories (low, medium, or high) based on the lake type, the dam type, the freeboard, the connection, the drainage type, and the possible potential for an impact into the lake (see Figure 8).

In all countries, the monitoring of lakes and their changes (e.g., lake size, or volume) is based on remote sensing methods through analysis of space imagery data, on field observations, and on daily synoptic forecasts. Special importance is given to non-stationary lakes. Those dynamic lakes are in most cases monitored annually. Lake inventories and the lakes' hazard potential are then reassessed.

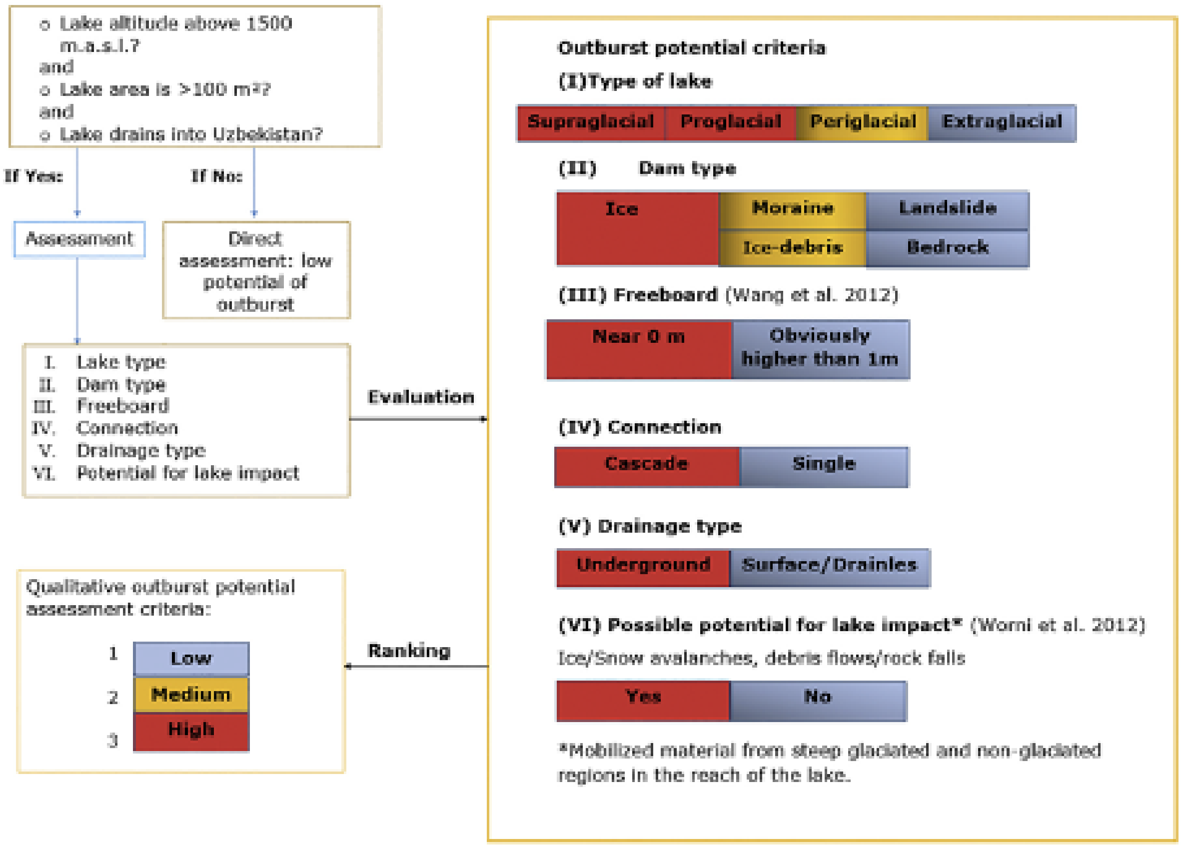

Figure 8: Flow chart illustrating the framework used for the creation of the inventory of mountain lakes of Uzbekistan and for the classification of lake outburst potential (Petrov et al., 2017)

Table 1: Criteria used for lake hazard assessment in Kazakhstan, summary based on tables provided by Dr. Kassenov (Kazselezaschita)

Lake						
Type	***Volume***	***Filling mode***	***Basin***	***Runoff***	***Runoff channel***	***Hazard category***
Non-stationary	> 40'000 m^3	Sudden filling of a previously empty basin in the current year (at the beginning of a mudflow hazardous season)	Steep sheer sides of the runoff channel and lake basin Areas with exposed buried ice. Bottom slope towards the bulkhead	Absent	Not detected	hazardous

	> 50’000 m^3 greatest depth in the center or near the bulkhead			underground	possibly blocked by the collapse of soil	potentially hazardous
	<40’000 m^3 greatest depth in the center or on the opposite side of the bulkhead	lack of volume growth over the past 10 years or degradation of the lake basin	flat sides. weak bottom slope towards the bulkhead	underground	there is no possibility of overlapping by soil collapse	Non-hazardous
	30x50 m with significant development potential		Steep sides. Areas with exposed buried ice. Steep bottom slope towards the bulkhead	underground	possibly blocked by the collapse of soil, ice	developing
Stationary	>40’000 m^3 greatest depth at the bulkhead or in the central part	Intensive growth in volume over the past 2-10 years - (from tens to hundreds of thousand $m^{3)}$	Steep sheer sides. Areas with exposed buried ice. Bottom slope towards the bulkhead	Partially superficial (over a short distance) underground	Easily eroded Easily blocked by the collapse of soil, ice, snow	hazardous
Stationary (landslide, chocked)	> 50’000 m^3 greatest depth in the center or near the bulkhead	Slow volume growth over the past 10 years (from tens of thousands of m^3)	Not steep sides. Areas with exposed buried ice. Weak bottom slope towards the bulkhead	partially superficial (over a short distance)	eroded	potentially hazardous

Stationary (landslide, tarn)	<40’000 m^3 greatest depth in the center or on the opposite side of the bulkhead	lack of volume growth over the past 10 years or degradation of the lake basin	flat sides. weak bottom slope towards the bulkhead	partially superficial underground	not eroded there is no possibility of overlapping by soil collapse	Non-hazardous
	> 5’000 m^3	Intensive volume growth over the past 1-3 years to tens of thousands m^3)	Steep sides. Areas with exposed buried ice. Steep bottom slope towards the bulkhead	Partially superficial (over a short distance) or the complete absence of runoff	Eroded or unorganised runoff channel without a laid natural armoring channel Possibly blocked by the collapse of soil, ice.	developing
Lake Bulkhead						
Composition	***Sizes***	***Condition***				***Hazard category***
Frozen breccia Ice	<10 m in width	Soil subsidence. Voids, grottoes. Superficial runoff. Leakage water outlets to the surface in the tail bay of the bulkhead.				hazardous
Frozen breccia Ice	>10m in width	separate voids, grottoes. superficial runoff or leakage water outlets to the surface in the tail bay of the bulkhead				potentially hazardous
compacted soils	<10m in width	Superficial runoff is absent or insignificant. There are no leakage water outlets to the surface. Outcrops of bedrock are observed in the lake bulkhead.				Non-hazardous
Moraine						
Condition						***Hazard category***

Presence of traces of the local and micro mudflows passage. Cracks, subsidence, sinkholes, grottoes, thermokarst funnels with distinct water supply runoff channels. Significant watering of the moraine.			hazardous
Minor subsidence, small cracks. Traces of the micro mudflows passage, Process of forming a runoff channel. Average water cut.			potentially hazardous
Absence of subsidence and cracks. Lack of traces of the micro mudflows passage, The process of formation of the runoff channel has been completed or absent. Average or low water cut.			Non-hazardous
Moraine ledge			
Parameters	***Condition***	***Location of the lake relative to the moraine ledge***	***Hazard category***
Height ≥10m	Heterogeneity of particle size distribution Intra soil water outlets Landslides, landslide funnels High water cut	at a distance of ≤ 300m	hazardous
Height ~10m	Heterogeneity of particle size distribution Individual landslides, landslide funnels Average water cut	At a distance of ~500m	potentially hazardous
Height <10m	Heterogeneity of particle size distribution Individual landslides, landslide funnels Average water cut	At a distance of ≥ 500 m	Non-hazardous
Glacier			
Type	***Sizes***	***Location of the lake relative to the glacier***	***Hazard category***
valley hanging	≥ 0.5 km^2 ~ 0.25 km^2	≤ 0.5 km	hazardous

valley hanging	≥ 0.5 km^2 ~ 0.25 km^2	> 0.5 km	potentially hazardous
valley, tarn, hanging	< 0.5 km^2	> 0.5 km	Non-hazardous
Risk zone			**Hazard category**
with the presence of people located in the mudflow risk zone with a population of more than 50 people			highly hazardous
lack of engineering mudflow protection structures			highly hazardous

Table 2: Updated criteria for the categorization of outburst susceptibility of lakes in the Kyrgyz Republic. Source: Erokhin, S. A., & Zaginaev, V. V. (2020b). Trends of outburst hazard for the dynamics of mountain lakes in Kyrgyzstan. In S. S. Chernomorets & K. S. Viskhadziev (Eds.), Debris Flow: Disasters, Risk, Forecast, Protection. Proceedings of the 6th International Conference (Tajikistan) (Vol. 1, pp. 194–207).

Genetic class of lake	**Subclass**	**Outburst susceptibility criteria**	***Hazard category**
Ice-dammed	Supraglacial Englacial Glacier dammed	· Rapid lake level rise in melting season · Outburst events in the past	1, 2
		· Lake level is stable or gradually increasing · Outburst events in the past	3, 4
Moraine-dammed (Ice-cored)	Intra-moraine depressions	· Direct contact with glacier · Underground · Gullies and piping on the downstream dam face · Signs of dam subsidence along underground channels · Lake water level fluctuation up to several metres; · Rapid lake filling (weeks, months); potential overflow	1

		· Direct contact with glacier · Underground · Signs of dam subsidence along underground channels · Gullies and piping observed at the dam footslope · Lake water level fluctuation up to several metres; · Gradual lake filling (1-3 years);	2
		· Underground/combined outflow · Signs of dam subsidence along underground channels · Gullies and piping observed at the dam footslope · Amplitude of lake water level fluctuation is insignificant; stable regime of water inflow and outflow · Gradual lake filling/lake level is stable;	3
		· Underground/surface (stable overflow)/combined outflow (stable) · Gradual water level decrease	4
	Thermokarst	· Underground outflow · Signs of dam subsidence along underground channels · Ice outcropping along the lake banks · Intensive subsidence of lake basin banks and bottom; subsidence cracks · Rapid lake filling (weeks, months);	1
		· Underground outflow · Signs of dam subsidence in individual parts of lake basin banks · Gradual lake filling	2
		· Underground outflow · Insignificant lake filling	3
		· Lake level is stable or decreasing	4
Bedrock- and moraine-dammed	-//-	· Direct contact with glacier · Underground/combined outflow · Gullies and piping on the downstream dam face · Signs of dam subsidence along underground channels · Lake water level fluctuation up to several metres; · Rapid lake filling (weeks, months); potential overflow	1

		· Direct contact with glacier · Underground · Signs of dam subsidence along underground channels · Gullies and piping observed at the dam footslope · Lake water level fluctuation up to several metres; · Gradual lake filling (1-3 years);	2
		· Underground/combined outflow · Signs of dam subsidence along underground channels · Gullies and piping observed at the dam footslope · Amplitude of lake water level fluctuation is insignificant; stable regime of water inflow and outflow · Gradual lake filling/lake level is stable	3
		· Underground/surface (in case of stable overflow) /combined outflow (stable) · Gradual water level decrease	4
Moraine-dammed (Ice-free)	-//-	· Underground outflow · Gullies and piping on the downstream dam face · Lake water level fluctuation up to several metres; · Rapid lake filling	1
		· Underground outflow · Gullieson the downstream dam face · Gradual lake filling	2
		· Underground outflow/stable surface outflow · Gullieson the downstream dam face · Graduallakefilling · Insignificant amplitude of lake water level fluctuation · Stable regime of water inflow and outflow	3
		· Underground outflow · Gradual water level decrease	4
Landslide-dammed	Rockslide-dammed	· Underground outflow · Intensive erosion, gullies and piping on the downstream dam face · Rapid lake filling	1
		· Underground outflow · Gullies on the downstream dam face · Gradual lake filling	2

		· Underground outflow/stable surface outflow · Gullies on the downstream dam face · Insignificant amplitude of lake water level fluctuation · Stable regime of water inflow and outflow	3
		· Underground outflow · Gradual water level decrease	4
	Debris-flow-dammed lake	· Absence of water outflow · Rapid water level rise/possible water overflow	1
		· Underground outflow · Gradual water level increase	2
		· Underground outflow/stable surface outflow · Insignificant amplitude of lake water level fluctuation · Stable regime of water inflow and outflow	3
		· Underground outflow · Gradual water level decrease	4
	Landslide-dammed lake	· Absence of water outflow · Rapid water level rise/possible water overflow	1
		· Underground outflow · Gradual water level increase	2
		· Underground outflow/stable surface outflow · Stable regime of water inflow and outflow	3
		· Underground outflow · Gradual water level decrease	4

* Hazard category 1 is assigned to the lakes with highest outburst susceptibility and hazard category 4 is assigned to the lakes with lowest outburst susceptibility.

4: GLOFCA contribution to regional best practices

In this section, we draw on learnings from international state-of-the-art, and current national approaches, to introduce recommended approaches and new tools being developed under the GLOFCA project for lake mapping and susceptibility assessment.

4.1 GLOFCA contribution to lake mapping

A comprehensive and up-to-date inventory of glacial lakes nationally, and regionally is a key first step for monitoring changes over time and identifying potentially dangerous lakes. Particularly in Central Asia, experience has shown that new lakes can develop extremely rapidly, and non-stationary lakes can expand or regrow over weeks to months. This requires that lake mapping is repeated regularly, including (and perhaps more importantly) during time periods when bad weather may prevent field access or availability of cloud-free optical satellite imagery.

Therefore, we are developing the Glacial Lakes Inventory (GLI) toolbox for mapping and monitoring the glacial lakes in Central Asia (Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan) using the python Tkinter library. This library is used to construct the Graphical User Interface (GUI) for the toolbox. Tkinter is available on operating systems such as Linux, MacOS, and Windows. More details on the library can be accessed from the Tkinter official online documentation page, see https://docs.python.org/3/library/tkinter.html. The toolbox will monitor the dynamics of the lakes and will provide statistics such as the changes in surface area, appearance of new and disappearance of existing lakes. In our toolbox, we use the Sentinel-2 Normalised Difference Water Index (NDWI) to detect the glacial lakes. Given the fact that machine learning is a promising research direction (refer to section 2.1.3), we are developing a deep learning-based methodology that makes use of the complimentary information in Sentinel-1 Synthetic Aperture Radar (SAR) and Sentinel-2 optical satellite data. This approach allows high temporal resolution, while SAR can penetrate cloud cover and allow year-round monitoring.

However, there are several underlying challenges. Most of these lakes are very small in area, and frozen for a large part of the year, making the mapping and monitoring using satellite sensors challenging. Additionally, observing such lakes using optical satellite imagery such as Sentinel-2 becomes challenging due to the inability of the sensor to penetrate clouds. Moreover, cast and cloud shadows, and increasing lake and atmospheric turbidity pose further hurdles that need to be tackled. On the other hand, for monitoring using SAR satellite sensors (e.g. Sentinel-1 SAR), handling the cases of windy scenarios along with cast shadows and backscattering variations due to changes in turbidity are the main difficulties.

A snapshot of the GLI toolbox prototype (version 0.0) that was presented during the Regional Exchange Workshop (Tashkent, Nov 2021) is shown in Figure 9.

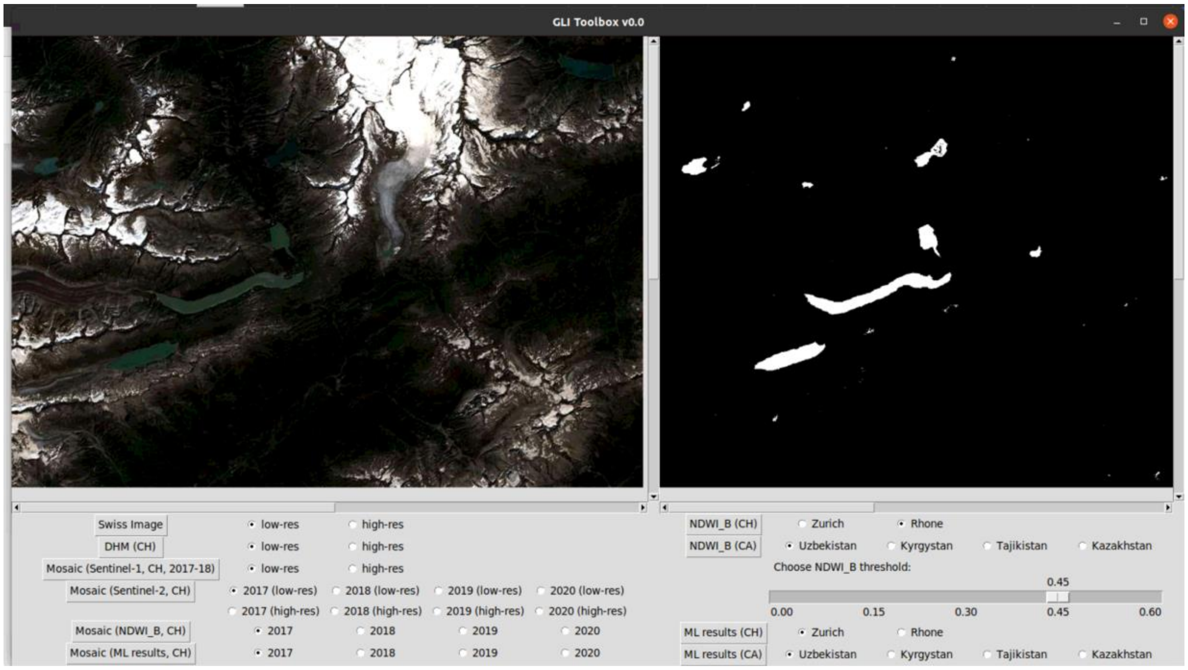

Figure 9. A screenshot of the Glacial Lakes Inventory (GLI) Toolbox prototype (version 0.0).

Some selected features of the current version of the toolbox (version 0.0) are as follows:

1) Our toolbox offers the possibility to select and visualise various maps (Sentinel-1 and -2, NDWI etc.)
2) In the Graphical User Interface (GUI), a satellite image and corresponding water body map can be visualised side by side.
3) The toolbox is equipped with buttons to navigate between various maps (including the sub-buttons to choose the year, region of interest etc.).
4) Functionality to zoom (in and out) and translate the map is a feature of the toolbox.
5) There is a sliding bar to vary the NDWI threshold and see the corresponding effect on the water body maps in real-time.

The toolbox version 0.0 will be updated and optimised considering the suggestions of the local partners, following training and hands-on experience with the toolbox.

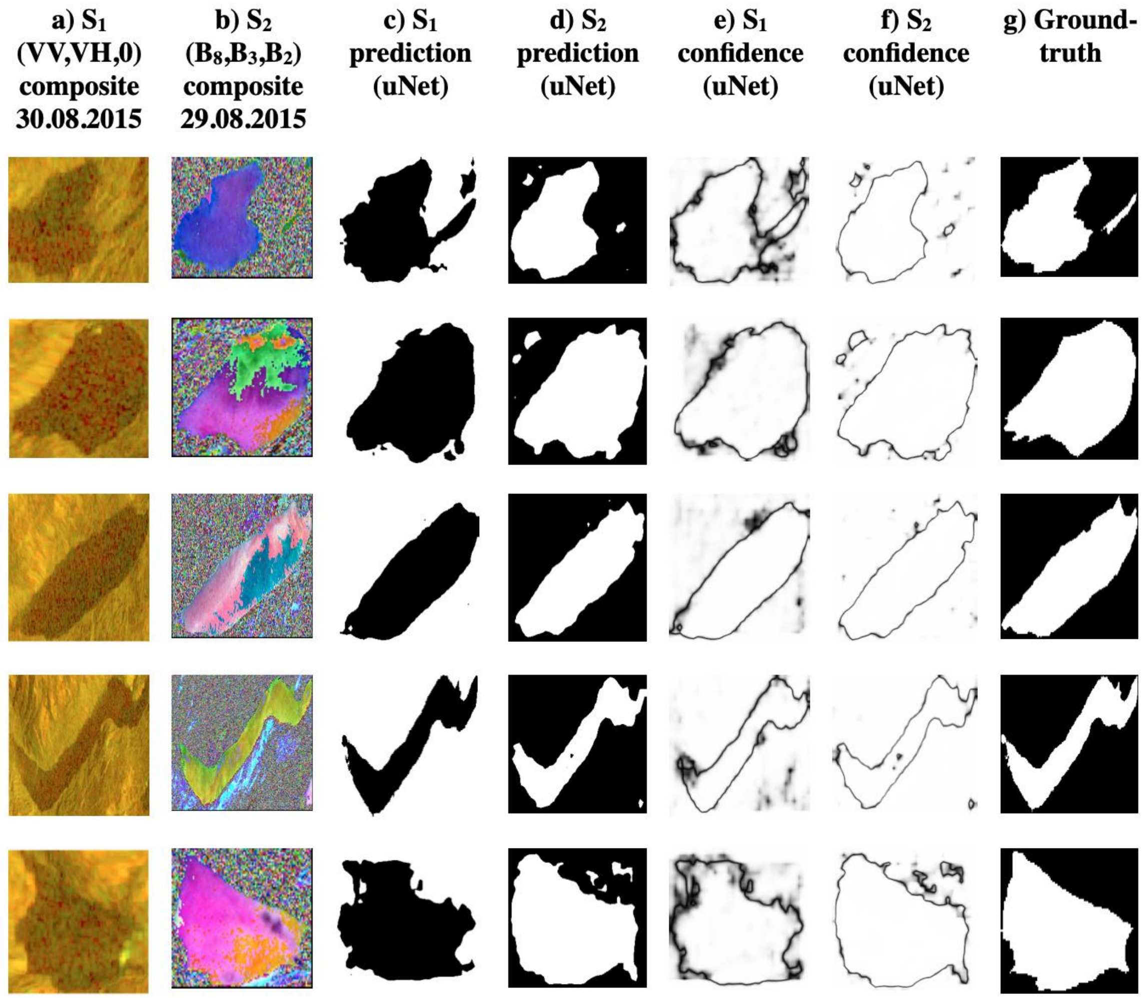

Figure 10. Preliminary results of the GLM network (U-Net encoder) on Sentinel-1 (S_1) and Sentinel-2 (S_2) data for some glacial lakes in Switzerland. The first and second columns show the S_1 RGB composite from 30.08.2015 and the S_2 composite from 29.08.2015, respectively. The third and fourth columns display the prediction results for the S_1 and S_2 branches, respectively. The fifth and sixth columns show the corresponding per-pixel confidence scores (the more white the more confident the classifier is). The final column shows the per-pixel ground-truth labels (reference data). In column 3, each predicted lake pixel is labelled as black and the background pixel as black. In columns 4 and 7, each lake pixel is labelled as white and the background pixel as black.

As a next step, we will identify the limits (especially the size of the smallest glacial lake that can be detected with high confidence) of our algorithm. More importantly, we will adapt the deep learning algorithm (developed for Swiss glacial lakes) for Central Asia. Fine-tuning of the methodology might be needed to equip our approach with the lake conditions in Central Asia. Some ground truth data from Central Asia will be needed for this. However, over-tuning the approach for each target country (or even for each lake) will be time-consuming and hence will not be done. We will finalise a set of parameters for our approach that are viable for all the four target countries in order to merge everything together into a consolidated regional inventory. Furthermore, this will increase the generalisability of our methodology which will be useful when a glacial lake from a different geographical region needs to be mapped without much re-tuning of the parameters.

The spatial resolution of Sentinel-1 SAR is approximately 20m, and for Sentinel-2 is 10m. The machine learning approach of Wangchuck and Bolch (2020) (which also used Sentinel-1 and Sentinel-2 data) detected lakes as small as 0.01 km^2 (surface area). At the moment, we tested the algorithm on bigger glacial lakes only. We also speculate that our algorithm will be able to detect small lakes that are around 0.01 km^2 in area. However, this can be confirmed only after the model testing is complete. Still, monitoring small lakes (< 0,01 km^2 area) and subglacial events) using remote sensing seems challenging which underlines the importance of field campaigns for such scenarios. Note that, for fine-grained monitoring, the proposed deep learning algorithm could be adapted for RGB images, freely available high-resolution images, UAV images etc. However, the network parameters need to be re-trained on the new data modality, which is processing-heavy and time-consuming. Additionally, sufficient annotated reference data (from Central Asia) is needed. Hence, this investigation will not be performed. Theoretically, a glacial lake extent can be detected using our algorithm, whenever a Sentinel-1 or a cloud-free Sentinel-2 data captures the region of interest. However, we expect the temporal resolution of the final product to be less since we foresee some multi-temporal smoothing steps that need to be done. However, at least one detection per month seems feasible.

4.2 GLOFCA contribution to susceptibility assessment

Here we combine regional experience with international best practices (GAPHAZ 2017) to provide experts with an overview of all factors that should be considered in a comprehensive assessment of GLOF susceptibility for any given lake. From Section 3, it is clear that there are many commonalities to the national approaches used across Central Asia, particularly with regards to rapidly changing non-stationary lakes, and lakes forming in complex moraine structures, and thermocast environments. Institutions in Central Asia have unique and world-leading experience with these types of lakes, and can contribute to improved understanding of these lakes in other similar mountain regions. Some other glacial lake outburst processes, particularly cascading events involving catastrophic rock or ice avalanches striking large proglacial lakes, have been rarely observed in Central Asia, but appear more common in, e.g, the Andes or Himalaya. Under GLOFCA, an opportunity exists to combine knowledge from these different regions, to ensure that assessment approaches are comprehensive for all lake and GLOF types.

Therefore, what follows is a check-list (Table 3), providing a resource to guide local experts in their assessment. ***The check-list is intended to cover all lake types and the wide-ranging factors that can contribute to or trigger an outburst event. Therefore, the table provides overarching guidance and is intended to compliment, but not replace the detailed classifications systems used nationally or by different institutions (eg. Tables 1and 2).*** The checklist contains all factors that are commonly assessed under the national approaches, but also contains additional factors that may be less commonly observed in the central Asian context. **The practitioner is encouraged to consider all factors, even if certain GLOF types or triggering processes have rarely been observed in the past – rapid environmental changes can lead to surprises and new, even unprecedented situations are emerging**.

The check-list can support both the large-scale, remote-sensing based prioritisation of glacial lakes, but clearly indicates the importance of local field studies to fully investigate important factors that determine GLOF susceptibility.

The check-list does not on its own lead to a final decision about the susceptibility level of a lake. As demonstrated in Section 3, various classification schemes are used internationally and nationally to determine the hazard level of a given lake (e.g. high, medium or low), and no single scheme is appropriate for all processes and lake types. Therefore, **after considering all factors that contribute to GLOF susceptibility, the skill and experience of the local experts remain most important for deciding whether or not the lake requires further monitoring and/or immediate action**.

As a general guiding principle, the more factors identified in the check-list table that are indicative of higher GLOF susceptibility, the higher the overall susceptibility of that lake will be. However, **international and regional experience shows that some factors are more important than others, and may be given a higher weighting by the expert. These factors are indicated with an asterisk (*) in the table**. For example, a lake that shows rapid expansion over the order of weeks to months, could be considered in the highest susceptibility category, regardless of the assessment from other factors. This shows the importance of establishing lake mapping and monitoring procedures at high temporal resolution to support the susceptibility assessment.

Finally, the urgency and type of response action required for a highly susceptible lake will strongly depend on the hazard and risk to downstream infrastructure and communities (to be described under Chapter 2 of this guidance document).

Table 3: Checklist for the assessment of the susceptibility of a given lake to GLOF. Factors may be relevant for conditioning (Con.), triggering (Trig.), and/or the magnitude (Mag.) of any GLOF. An asterisk (*) indicates those factors that have been shown across multiple studies to be important for GLOF susceptibility.

Susceptibility factors for GLOFS	***Relevance***			***Key Attributes***	***GLOF Susceptibility***		***Assessment Methods***
	Con.	*Trig.*	*Mag.*		***Lower***	***Higher***	
Meteorology							
Long-term temperature trends	+			*Increasing mean temperature*	No trend ☐	Strong trend ☐	*Station-based or gridded climate analyses*
				Increasing intensity and frequency of extreme temperatures	No trend ☐	Strong trend ☐	
Long-term precipitation trends	+	+		*Increasing Intensity and frequency of extreme precipitation events*	No trend ☐	Strong trend ☐	
*Seasonal temperature extremes**		+		*Unusually warm temperatures over period of weeks to months*	Not unusual ☐	Unusually warm ☐	
*Seasonal precipitation extremes**		+		*Unusually heavy precipitation over period of weeks to months*	Not unusual ☐	Unusually wet ☐	

Cryosphere and lake							
Permafrost conditions	+			*Thermal state of permafrost; distribution and persistence within lake dam area and surrounding slopes*	No permafrost or cold permafrost ☐	Warm (melting) permafrost. ☐	*Model-based (indirect) Geophysical (semi-direct) Geomorphic evidence (deformation and slumping).*
Glacier retreat and downwasting	+		+	*Retreating tongue destabilizing adjacent slopes; retreat directly destabilizing the lake dam (relevant for ice-dammed lakes or lakes dammed at the side a glacier moraine)*	No retreat or impact on surrounding slopes or dam stability ☐	Significant retreat and impact on surrounding slopes or dam stability ☐	*Remote sensing*
*Advancing glacier (incl. surging)**	+			*Potential formation of ice-dammed lakes*	No glaciers advancing and no record of surging ☐	Advance occurring or surging possible ☐	*Remote sensing Evidence from past events*
*Ice avalanche potential**		+	+	*Steep unstable ice masses; changes in ice velocity of crevasse patterns; evidence of past events*	No or minimal potential ☐	Potential for frequent and/or large ice avalanches ☐	*Remote Sensing Fieldwork Modeling*
Calving potential		+	+	*Glacier in contact with glacier; width of glacier calving front; activity; crevasse density*	No contact or minimal potential ☐	Large and frequent calving possible ☐	*Remote sensing and field studies.*
*Englacial or subglacial water pockets**	+	+	+	*Presence of or potential for englacial water pockets*	No likely water pockets ☐	Known or likely water pockets ☐	*Past evidence (repeat events), Geophysical monitoring, Modeling of bedrock topography*
Lake size	+		+	*Area or volume; potential for future growth*	Small or no potential to grow ☐	Large or with potential to significantly grow ☐	*Remote sensing, modelling of bed topography, field studies*

*Past outburst events**	+	+	+	*Magnitude and frequency of past events (only relevant where water remains or could refill)*	No past events ☐	Past events occurred ☐	*Remote sensing, historical records, local knowledge.*
Long term lake growth	+		+	*Annual to decadal growth of lakes*	No or minimal change ☐	Lake growing ☐	*Remote sensing*
*New lakes or rapid lake expansion**	+	+	+	*Change in water level and lake area over weeks to months*	No or minimal change ☐	Significant change ☐	*Remote sensing Field monitoring*
Lake depth	+		+	*Larger lake depth exerts hydrostatic pressure on lake dam*	Shallow ☐	Deep ☐	*Field studies (sonar measurements of lake bathymetry)*
Lake bed topography	+		+	*Bed togography influences avalanche displacement wave propagation and run-up*	Becoming deeper towards lake dam ☐	Becoming shallower towards lake dam ☐	*Field studies (sonar measurements of lake bathymetry)*
Outflow from lake	+			*Type of outflow (surface, underground); stability of drainage channels*	Stable surface outflow ☐	No outflow or underground (en- or subglacial) outflow ☐	*Remote sensing Field studies*
Lake water temperature		+		*1. Increase of water temperature in the moraine glacier lakes impact on the melting of buried ice in the moraine.* *2.Hydrothermal gradient – increasing a water temperature for each 1 meter of depth impact on the melting of ground channels in the moraine on the certain depth*	No trend ☐	Strong trend ☐	*Remote sensing Field studies*

Lake dam							
Type	+		+	*Bedrock; moraine; ice*	Bedrock ☐	Ice, moraine, or mixed ☐	*Remote sensing Field studies*
*Ice-cored moraine or thermocast**	+		+	*Visible ice lens in dam; thickness; persistence; thermal condition (linked to permafrost)*	No ice-core ☐	Potential or observed ice core ☐	*Remote sensing Geomorphic mapping Geophysical field studies*
Dam width to height ratio	+		+	*Width across the dam crest relative to the dam height (see (4) in figure 5)*	Wide, low dam ☐	Tall, narrow dam ☐	*DTM analysis, field studies*
*Freeboard**	+		+	*Elevation difference between lake surface and lowest point of moraine crest*	Large ☐	Small or no freeboard ☐	*Remote sensing, DTM analysis, field studies*
Lithology	+		+	*Large blocky material; presence of fine-grained material (including downstream of the dam)*	Coarse material predominant ☐	Fine-grained material predominant ☐	*Field studies*
*Subsidence of dam**		+		*Subsidence and cracks as a result of piping beneath dam; evidence of thawing permafrost within dam*	No subsidence ☐	Subsidence visible ☐	*Remote sensing, DTM analysis, field studies*
Downstream slope	+			*Mean slope on downstream side of lake dam*	Gentle slope ☐	Steep slope ☐	*DTM analysis, field studies*
*Erosion on downstream slope**	+	+		*Gullies, cracks and piping observed on downstream slope*	No erosion ☐	Erosion visible ☐	*Remote sensing, DTM analysis, field studies*
Vegetation	+			*Density and type of vegetation (grass, shrubs, trees)*	Widespread ☐	Absent or sparse ☐	*Remote sensing, field studies*
Hydrology (influencing runoff into the lake)							
Catchment area upstream of the lake	+		+	*Total size of drainage area upstream of catchment*	Small catchment ☐	Large catchment ☐	*DTM analysis*

Mean slope of upstream catchment area	+			*Steepness of catchment area*	Gentle slope ☐	Steep slope ☐	*DTM analysis*
Drainage density	+			*Density of the stream network in catchment area*	Low density ☐	High density ☐	*DTM analysis*
Stream size draining into lake	+			*Presence of large fluvial streams, facilitating rapid drainage into lake*	No streams or small streams only ☐	Large streams evident ☐	*Remote sensing, DTM analysis of stream order*
Upstream lakes	+	+	+	*Presence and susceptibility of upstream lakes that could cause cascading processes*	Absent ☐	One or more susceptible lakes ☐	*Remote sensing*
Geotechnical factors							
*Rock avalanche potential**		+	+	*Steep slopes; highly fractured bedrock; warm permafrost; deformation or movement; evidence of past events*	No or minimal potential ☐	Potential for frequent and/or large rock avalanches ☐	*Remote sensing Geotechnical survey and analyses, modelling*
*Lateral moraine instabilities**		+	+	*Steep lateral moraines surrounding lake; warm permafrost; erosion and gullies; deformation or movement; evidence of past events*	No steep moraine slopes adjacent to lake ☐	Steep, unstable moraine slopes adjacent to lake ☐	*DTM analysis, remote sensing, field work, geophysical investigations*
Seismicity		+		*Potential magnitude & frequency, ground acceleration*	Low seismicity ☐	High seismicity ☐	*Geological mapping & modelling.*

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