Checklist for Glacier Lake Hazard Assessments

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0 Purpose and intention of this checklist

This checklist has been developed in the framework of the S:GLA:MO Project (slope stability and glacier lake monitoring), funded by the European Space Agency (ESA) and executed by Gamma Remote Sensing, Department of Geography of the University of Zurich, Department of Geosciences of the University of Oslo, and ASIAQ Greenland Survey. The main aim of the S:GLA:MO project is to provide an integrated first-order hazard assessment on glacier lakes by using Earth Observation (EO) data such as SAR data and optical high resolution imagery and products derived thereof (namely SAR interferometry).

This checklist is structured and designed accordingly: EO products provide the main source of information, which is used in combination with auxiliary data and mass-movement models for an integrative assessment both the current and potential future hazard situations. Three main actors are included in the procedure, a data producer, specialized and skilled in the procurement, processing and interpretation of EO data; a hazard assessment expert with knowledge and experience in glacier hazard and related interpretation of EO data and mass movement modeling; and a user of the service, which is requesting an assessment of the hazard situation of a specific lake or region.

The purpose of this checklist is to provide a structured guideline for the assessment of glacier lake hazards to the responsible expert. It is designed to be applied for EO-based, first-order hazard assessments, and should help to follow the state-of-the-art and prevent that potentially relevant aspects of an integrated assessment of the current and potential future situations are overlooked or forgotten. However, this checklist does not replace the expertise and experience required for such an assessment.

1 Site description

General description of the lake site: mountain range, location, and setting.

- ❑ Situation of the larger region (sub-catchment containing the lake, from the peaks and glaciers down to the confluence with the main river, settlements and infrastructure along the river which drains the lake; size and depth of the lake (if known))
- ❑ Is the catchment glacierized?
    - ❍ Is the lake still in contact with the glacier (or supraglacial)?

1.1 Historic events

Description of known past events. Not only lake outbursts as such should be considered, but also mass movements that could have acted as lake outburst triggers.

- ❑ Is information on a past lake outburst available?
- ❑ Is information available on mass movements that could affect the hazard situation of the glacier lake?

1.2 Peculiarities

Any site-specific facts, such as, for instance, existing (or planned) special infrastructure (mitigation measures), hydropower plants, protected area / sanctuary, non-structural prevention measures (monitoring, early-warning systems)

1.3 User requirements and responsibilities

Who is requesting the hazard assessment (institution, authority, person, research project)? What is the relation or role of the user with respect to the site/lake (responsible for hazard mitigation, risk reduction, early warning? scientific interest? Involved in development and cooperation? Commercial interests, e.g. hydropower?)

If not the user, then who is responsible and liable for safety issues related to the glacier lake and natural hazards? What is the role of the expert(s) providing the hazard assessment? What is the social, political, and institutional context? What other stakeholders are present (are they involved or not)?

What is expected from the hazard assessment (first-order assessment, focus on current situation or potential future developments and scenarios or both, intention for hazard and risk mapping, planning of early warning installations)? Irrespective of the user request, it is recommended to include in all cases at least an overview of the current situation as well as an outlook on potential future evolutions of the lake and its surrounding.

Data issues: Is the user interested in the EO products used and produced for the assessment (glacier and lake outlines, DEM, landslide inventory)? Can the user provide additional auxiliary data (DEMs, glacier and lake outlines, bathymetry, runoff data, lake level fluctuations, geomorphological and geological maps, information on constructions at the lake, earlier assessments and investigations)?

2 Data

- ❑ Is a suitable DEM available?
    - ❍ If yes: What is the resolution? Acquisition date? Method of generation? Accuracy estimates? Quality (e.g. are there quality issues related to specific surface types such as glaciers, snow covered areas, water bodies, etc.)?
    - ❍ If no: What are the needs to allow a hazard assessment that fulfils the user requirements? Is the data available to produce such a DEM? What data needs to be acquired to produce such a DEM? Time required? Costs?
- ❑ Are lake outlines available?
    - ❍ If yes: Acquisition date? Method of generation? Accuracy estimates? Quality?
    - ❍ If no: Is the required EO data for lake mapping available? If new data needs to be acquired: Time required? Costs? Is other information on the formation of the glacier lake available?
- ❑ Are glacier outlines available (e.g., from the GLIMS (Global Land Ice Monitoring from Space initiative) glacier database / RGI (Randolph Glacier Inventory))?
    - ❍ If yes: Acquisition date? Method of generation? Accuracy estimates? Quality (i.e. mapping of debris-covered glacier parts, separation of individual glaciers)? Are time-series available?
    - ❍ If no: Are glacier outlines required for the hazard assessment? Is EO data for glacier mapping available? Time required?
- ❑ Is data on terrain movements available?
    - ❍ If yes: Acquisition date? Method of generation? Accuracy estimates? Quality (is it pure velocity data or interpreted and commented landslide inventory? Consistence with features visible in high-res optical imagery)?
    - ❍ If no: Is data for deriving terrain displacements available? Time required? Costs?
- ❑ Is glacier velocity data available?
    - ❍ If yes: Acquisition dates? Time lag? Method of generation? How representative is the data? Accuracy estimates? Quality and consistency with terrain information and glacier outlines?
    - ❍ If no: Are glacier velocities required for the hazard assessment? Is EO data for deriving glacier velocities available? Time required?
- ❑ Is a permafrost distribution map available?
    - ❍ If yes: How was the map derived? Accuracy estimates from ground validation? Representativeness for current conditions?
    - ❍ If no: Is the presence of permafrost indicated by typical landforms / features, or the elevation of the site? Are reliable measurements of the MAAT (mean annual air temperature) available?
- ❑ Is a glacier bed topography map available? (Indication of sites with potential future lake formation)
    - ❍ If yes: How was the data derived (which model)? What input data was used? Quality (consistency with the geometry of the glacier surface and the surrounding terrain)?

    - ❍ If no: Is a glacier bed topography map required for the hazard assessment? If glacier outlines and a DEM are available (see above), glacier bed topography can be modelled with the GlabTop model (UZH).

- ❑ Is a geological map available?
    - ❍ If yes: What is the date of the map? How was the map derived? What is represented in the map (lithology, structure, failure zones)? Quality?
- ❑ Is any other auxiliary data available that might influence the hazard assessment? Such data may include bathymetric surveys, infrastructure data, meteorological observations, runoff and lake level measurements, or information on preventive measures (structural or non-structural) related to the glacier lake.

3 Assessment of the current hazard

Aspects to be assessed by using the data listed above. If not available, information from other sources such as field visits, GoogleEarth, or literature should be considered.

3.1 Dam

- ❑ Characteristics
    - ❍ Material
    - ❍ Formation
- ❑ Conditions
    - ❍ Freeboard
    - ❍ Width-to-height ratio
    - ❍ Lake level stable or fluctuating?
    - ❍ Surface outlet existing? Potential for blocking of outlet by ice blocks or floating snow?
    - ❍ Indication of percolation through dam?
    - ❍ Permafrost conditions in dam? Presence of dead ice or buried ice bodies? Cavities?

3.2 Surrounding

- ❑ Geology (lithology, geological structures, failure zones)?
    - ❍ Are there oversteepened bedrock parts that might be affected by debuttressing due to glacier retreat since the ice age / little ice age?
- ❑ Is permafrost present or likely in the surrounding of lake or influencing processes that affect the hazard situation?
- ❑ Terrain displacements observed in the lake surrounding?

3.2.1 Relation to glacier

- ❑ Glacier in direct contact with the lake?
    - ❍ Dammed by glacier ice? Supraglacial lake?
    - ❍ Glacier terminus in the lake? Is calving observed? (Floating ice blocks?)
    - ❍ Is the glacier known to have surged in the past?

3.2.2 Upstream situation

- ❑ Are other lakes present further upstream?
- ❑ Is unstable terrain identified upstream of the glacier lake?
- ❑ Are steep glaciers or glacier parts present in the upstream region of the lake (with potential avalanche trajectories towards the glacier lake?)
- ❑ Can regions with susceptibility for rock falls be observed upstream? (Traces from events (changes in colour, depositions), records of past events, visual observations?)
- ❑ Is there an indication of permafrost?

3.2.3 Downstream situation

- ❑ Availability of erodible sediment (as part of the moraine dam of further downstream)
- ❑ Situation at transition to less inclined terrain: potential consequences of material deposition?
- ❑ Potential for chain reactions and cascading processes? (e.g., impact on another lake, damming of the main river?)

3.3 Potential lake outburst triggers

- ❑ Possibility for…
  - ❍ … rock/ice avalanches impacting the lake? (indicated by steep hanging glaciers, unstable rock formations)
  - ❍ … debris-flow or GLOFs from upstream regions impacting the lake?
  - ❍ … rapid landslides impacting the lake? (indicated by terrain displacements)
  - ❍ … low freeboard (due to high water level; e.g. caused by intense precipitation, intense snow melt, blockage of the lake outlet, or reduced outflow)

4 Potential future developments

4.1 Lake development

- ❑ Potential for area/volume increase due to
  - ❍ …glacier retreat (proglacial lakes)?
  - ❍ … glacier melt and downwasting (supraglacial lakes, growth in all directions)?
  - ❍ … changes at the dam (e.g., temporarily dammed lakes)?
- ❑ Potential for changes of the freeboard? (increasing lake level or dam erosion)?
- ❑ Potential for changes of the dam geometry (width-to-height ratio, e.g. due to erosion at the dam)?
- ❑ Potential for changes in the hydraulic regime? (e.g. increase of the hydraulic gradient due to lowering of the water level of a connected lake or the aquifer below the lake)?
- ❑ Degradation of dead-ice / permafrost in moraine dams?

4.2 Developments in the lake surrounding

4.2.1 Glacier changes

Expected glacier fluctuations:

- ❑ Retreat

- ❍ Lake expansion?
- ❍ Changes of calving activity?
- ❍ Formation of new ice avalanche starting situations (e.g., retreat of the glacier tongue into a steep terrain step above the glacier)?
- ❍ Potential for the formation of new glacier lakes?
- ❍ Changes of conditions for avalanche-prone hanging glaciers (changes in the thermal regime at the base of a hanging glacier (cold or temperate bed) can alter the stability)?
- ❍ Exposition of unconsolidated material (potential starting zones for debris flows)? Exposition of new bedrock (thermal changes, changes of mechanical stress fields)?

- ❑ Advance, including surges and surge-type movements
  - ❍ Formation of new glacier-dammed lakes?
  - ❍ Changes of calving activity?
  - ❍ Formation of new ice avalanche starting situations (e.g., retreat of the glacier tongue into a steep terrain step above the glacier)?
  - ❍ Reduction of lake area?
  - ❍ Increase of lake level?
  - ❍ Changes of conditions for avalanche-prone hanging glaciers?

4.2.2 Changes in the surrounding terrain

- ❑ Changes in the availability of loose material (either new depositions or removal of existing deposits)?
- ❑ Activation / acceleration of landslides?
- ❑ Potential evolution of the permafrost conditions?

5 Modelling potential outburst scenarios

Depending on the data availability, potential GLOF scenarios can be modelled. For existing lakes, physically based dynamic models can be used for this task. For situations with less detailed information, as it is typically the case for potential future lakes, more robust results can be obtained by employing more simple, empirical models.

5.1 Scenario definition

Based on data and analyses described above, different scenarios should be elaborated, including at least a small scenario and a worst-case scenario.

In the best case, return periods or probabilities of occurrence can be defined. If this is possible, scenarios should include events with a 'high', 'medium', and 'low' probability, that could corresponding to different return periods, even though return periods might be difficult to define. The large scenario should correspond to a worst-case scenario.

Records of past events might help to define such scenarios. However, glacier lakes often constitute new situations beyond historical experience. Thus, no experience exists that could be used for establishing, for instance, frequency-magnitude relations.

5.2 Model results

Critical examination of model results is necessary. In consultation with local experts (e.g., the user of the service) or field visits, critical points along the trajectory should be revised. Such critical points include locations where the flood potentially leaves the channel or infrastructure objects (such as bridges) that are not represented in the DEM but might influence the behaviour of the flow.

If needed by the user, model results of different scenarios can eventually be merged generalized into a synthesized map (e.g., a hazard map).

6 Monitoring strategy

Based on the assessment of the current situation and the anticipated potential future developments, a monitoring strategy is set up, aiming at providing the information required for a continued update of the hazard assessment. Such a monitoring strategy can have a stepped design, i.e. include changes in the monitoring based on observed changes of the situation.

For each aspect and suggested data product of the monitoring strategy the duration of the suggested update cycle and timing, the reason and purpose of using this product, and a cost estimation for the acquisition and production of the product should be given in order to provide a basis for decision-making.

Product	**Update cycle / timing**	**Purpose / remarks**	**Costs**

Monitoring items that need to be processed by specialists, i.e. EO-derived products such as DEMs, glacier and lake outlines, glacier velocities, a landslide inventory, etc. should be separated from aspects that need to be monitored by the user, such as measurements of the lake level, runoff, on-site inspections, etc. This depends as well on the type of user and its skills.

7 Conclusions and recommendations

Based on the model results and in consultation with local experts, recommendations for hazard prevention and risk reduction measures (both direct engineering measures and indirect warning and prevention measures) as well as for the design and setup of a monitoring strategy, as described above, should be given to the user.

8 Final remarks

Explicit statement that the presented analysis is related to GLOF hazard, possibly for only a specific lake, and that other hazardous processes are not treated explicitly. If possible, an indication to other potentially critical aspects can be given.

9 Expert validation

An independent expert should check any assessment. This section should reflect who is the reviewing expert, what aspects of the assessment are addressed, what are the comments or suggestions for changes related to this aspect, and what are the changes finally applied to the document by the responsible expert. Discussions or differing opinions should be reflected here as well, also comments and remarks on points that were not incorporated in the assessment.

The expert validation process can also be represented in a table.