Global lake-terminating glacier classification: a community effort for the Randolph Glacier Inventory (RGI) and beyond

Illustrated Guidelines

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Knowledge about the existence of lakes which are in contact with glaciers is a fundamental importance to understand as the lakes increase glacier mass loss due to calving, dynamic thinning and increased mass loss at the ice-water interface (King et al. 2019; Tsutaki et al. 2011; 2019; Pronk et al. 2021; Main et al., 2023). Moreover, they impact geodetic mass balance calculations as the satellites cannot measure subaqueous mass loss (Zhang et al. 2023).

Motivation:
The main aim of this effort is to determine whether or not a glacier is lake-terminating for the general attribute table of the Randolph Glacier Inventory. Uncertain (in case the existence is possible but cannot be determined due to unsuitable images) or specific cases (e.g. if a lake is only in contact with a small part of the lake termini) shall also be documented. In cases where a glacier is found to be lake-terminating, we seek to provide a qualitative “connectivity level” evaluation (akin to Rastner et al., 2012) that users can further parse depending on their needs.

Secondary aims that can partially addressed with this inventory are a classification of morphologies of lake-terminating versus non-lake-terminating glaciers and the provision of a baseline to identify hotspots where cryosphere risks related to potentially expanding lakes (e.g. glacial lake outburst floods) as well as changing aqueous ecologies should receive future attention.

These illustrated guidelines will describe the general methodology and provide information about how to decide whether a glacier is lake-terminating and how to assess connectivity level to provide consistent attribution for the RGI table.

1. Definition and categories of lake-terminating glaciers

For determining whether a glacier is lake-terminating, your guiding question should be “does the glacier end in a lake(s) large enough to have the potential to significantly increase the glacier’s mass loss and/or alter glacier dynamics?”. This is an inherently subjective determination, and we have developed three confidence levels (or ‘categories’, described below) to promote consistent determination of lake-terminating status across contributors. If you answer “definitely”, “probably”, or “possibly” to the question above, you will place it in one of the lake-terminating glacier confidence levels. If you answer “no” or “not likely”, this glacier should be considered land- or marine-terminating.

Lake-terminating glacier Category 3:

The glacier is definitely in direct contact with a large lake that spans at least ~50% of the glacier terminus. Lakes smaller than 0.01 km^2 should not be considered. Glaciers in this lake-terminating confidence level will have a lake that is large enough (relative to the glacier width/terminal perimeter) that it very likely is capable of affecting upstream glacier mass loss and flow dynamics. See examples Figures 1-4.

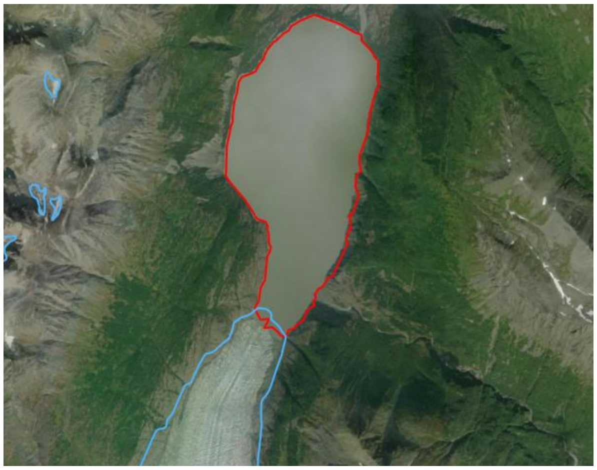


Figure 1: Category 3 lake-terminating glacier, example 1: Skilak Glacier in Alaska. The RGI 7.0 outline (blue) intersects the 2000 lake outline (red), with the entire terminus in contact with the proglacial lake. The base image is from 2018 and the lake outline is from Rick et al. (2022)

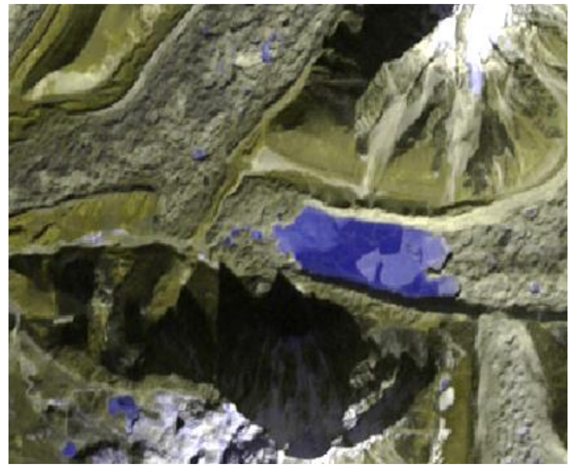


Figure 2: Category 3 lake-terminating glacier, example 2: Imja/Lhotse Shar Glacier, Khumbu Himalaya.

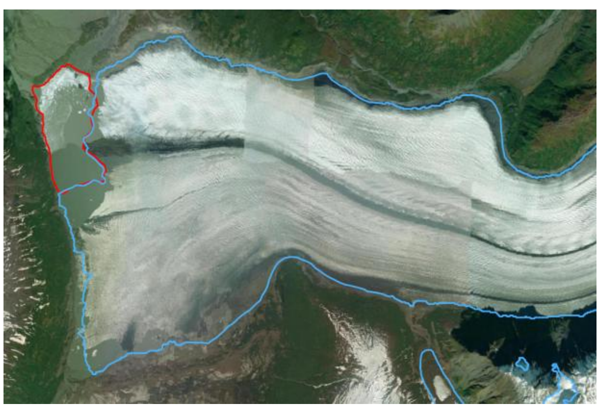


Figure 3. A Category 3 lake-terminating glacier (Knik Glacier, Alaska), where ~50% of the glacier terminus is in visible contact with a proglacial lake. The terminus appears fairly flat, features prominent rifts extending from the lake, and further glacier retreat seems likely to result in lake expansion, suggesting a deep and dynamically-relevant lake.

Figure 4. A collection of Category 3 lake-terminating glaciers ending in Alsek Lake, Alaska. The entirety of each glacier's terminus is in contact with lake water.

Lake-terminating glacier Category 2:

The glacier is definitely in direct contact with a lake that spans only a smaller part (clearly less than 50% but more than 10%) of the terminus, or with one or more lakes that occur at the side. Glaciers in this lake-terminating confidence level will have terminal lakes that may be relevant for upstream glacier mass loss and flow dynamics, but it is less certain than in Category 3 cases. See examples Figures 5 - 7.

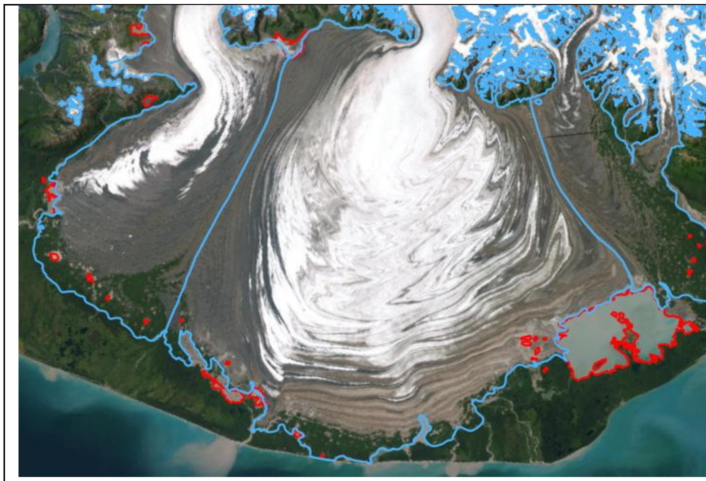


Figure 5: Malaspina Glacier (Alaska) has several lakes at the terminus, but the majority of the terminus is in contact with land.

Figure 6: Southern Inylchek Glacier, Kyrgyzstan. The end of the tongue is land-terminating. However a large part of the active tongue is flowing towards a lake impacting the glacier behavior.

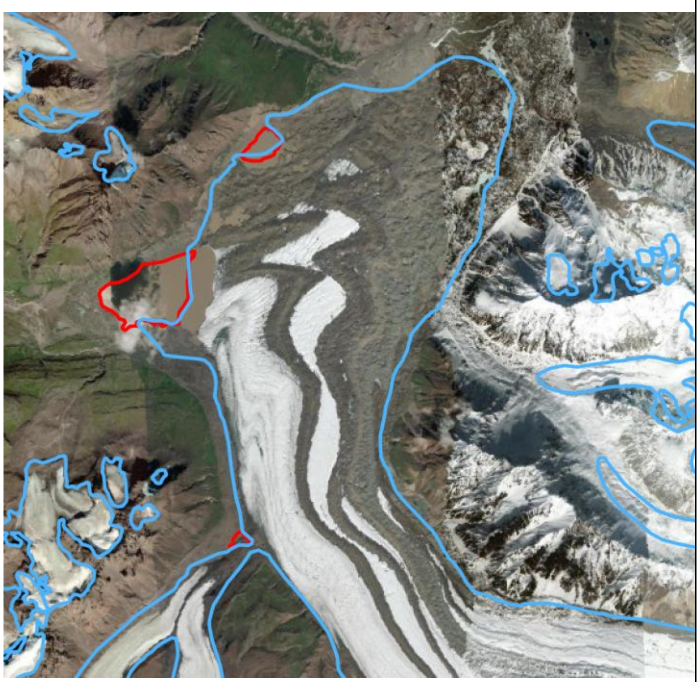


Figure 7. Russell Glacier (Alaska) has a large (relative to the glacier width) lake near the terminus that spans <50% of the terminal perimeter.

Lake-terminating glacier Category 1:

The glacier tongue is in contact with one or more small lakes (area >0.01 km²) that collectively are in contact with < ~10% of the terminal perimeter. Glaciers in this lake-terminating confidence level will have a lake(s) that likely play a relatively minor role in affecting glacier mass loss and flow dynamics. Unclear but likely cases should be included in this category. See example Figures 8 and 9.

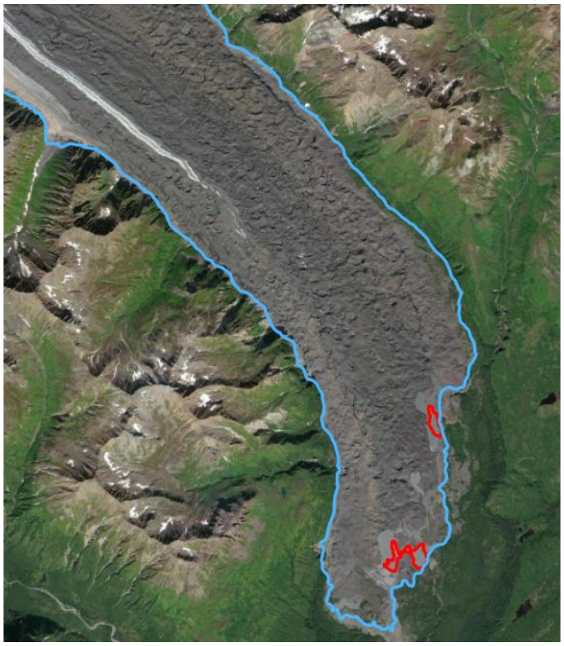


Figure 8: Scattered supraglacial lakes across the terminus area of an Alaska glacier (RGI2000-v7.0-G-01-04360), some of which have merged to form larger lakes.

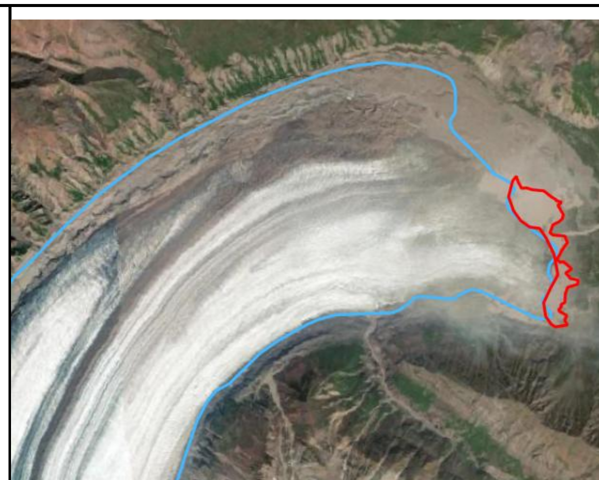


Figure 9: Alaska's Chisana Glacier has a small lake at its terminus, but it appears fairly shallow (terminus has convex shape into lake) and to be minimally impacting glacier behavior.

Non-lake-terminating glacier (land-terminating) (Category 0):
A glacier that is not in direct contact with a lake. A glacier is also NOT lake-terminating, despite there being a "glacial lake" close by (i.e., the lake found in landscape formerly covered by and formed glacier ice. These kinds of lakes are included in several inventories).

A glacier with supraglacial lakes that have not amalgamated to form one lake that spans the majority of the glacier's terminus should not be considered lake-terminating. Glaciers with proglacial water bodies smaller than 0.01 km² should not be considered lake-terminating.

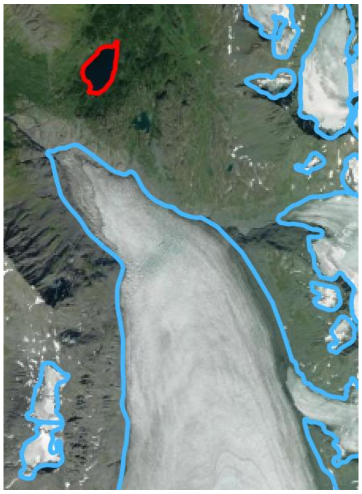


Figure 10: A lake which is in the vicinity of the glaciers but not in contact with the ice. Harris Glacier, Alaska.

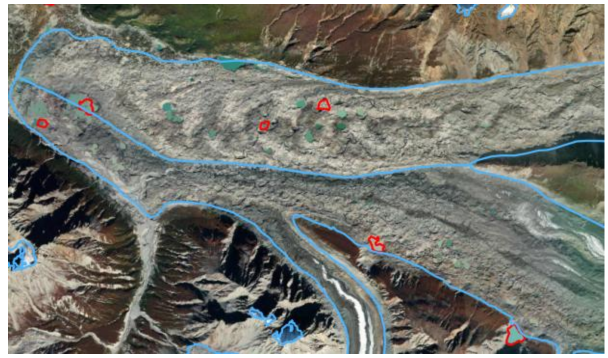


Figure 11. Small supraglacial ponds do NOT make a glacier lake-terminating unless they have coalesced into a one or more lakes that are large relative to the glacier width and located at or very near the terminus. Walsh and Logan glaciers (Alaska).

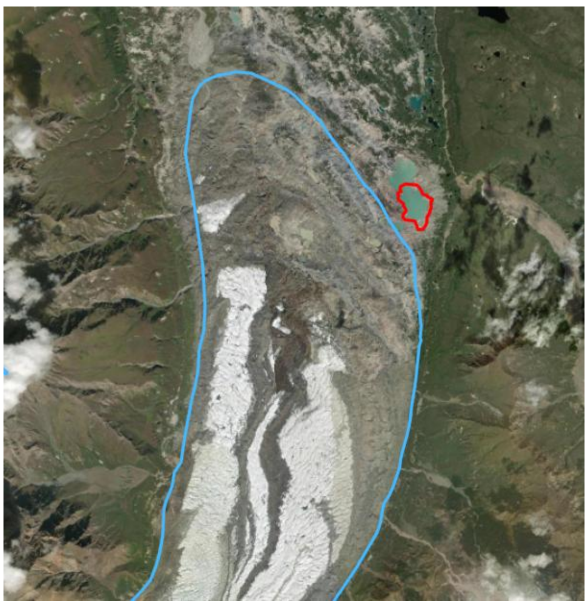


Figure 12. The Yukon's Klutlan Glacier would not be considered lake-terminating. It has a small lake beyond its RGI terminus that does not appear to be in direct contact with glacier ice.

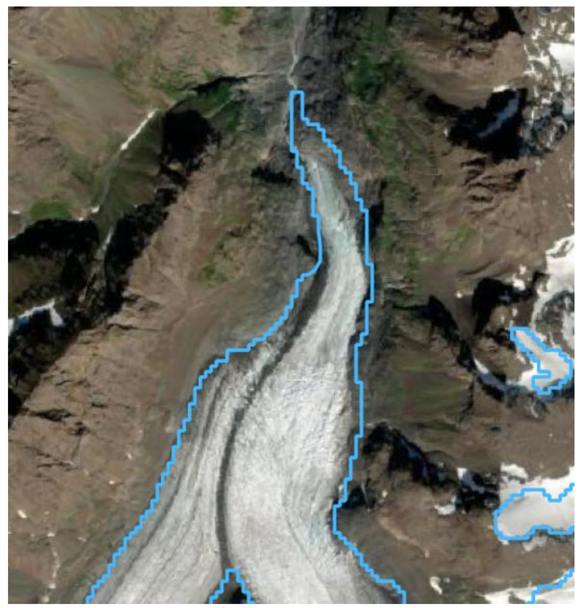
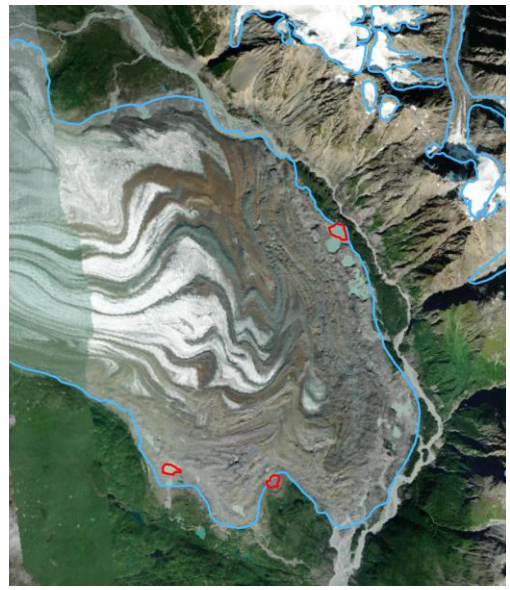


Figure 13. For completeness sake, the only water body near Alaska's Eklutna Glacier's terminus is its proglacial stream. It is thus not considered a lake-terminating glacier.

Ambiguous lake termini:

Streams cutting across termini are Category 2 in case the stream has a clear impact on ice melt, otherwise it should be Category 1.

	
Figure 14. The terminus of Childs Glacier (Alaska) is cut across by the Copper River, featuring embayments where calving seems to occur. This would be considered a Category 2 lake-terminating glacier.	*Figure 15. The terminus of Tweedsmuir Glacier (Yukon) is cut across by the Alsek River, but there appears to be limited interaction between the river and glacier. This would be a Category 1 lake-terminating glacier.*

2. Methodology:

We rely on the best possible existing lake inventory for any region that is most closely matching the 2000 time stamp. If an inventory is lacking or too far removed in time from 2000 (>10 years away) the classification is done manually based on satellite imagery from 2000. If neither of these approaches are taken, all glaciers in that region are flagged as 'not assigned' terminus type (term_type = 9).

Important note: When in doubt, put the glacier in the higher number connectivity level (i.e., higher relevance; Category 2 instead of Category 1).

Important note: If you reviewed a glacier or region and determined that certain glaciers are definitely NOT lake-terminating (Category 0), please indicate that on your data submission (Section 3). A list that included exclusively glaciers that are definitely not lake-terminating is helpful in its own right.

Workflow using existing lake inventory

We have provided a Python script (linked below – use and modify as you see fit) that utilizes an existing ice-marginal lake inventory to produce a limited subset of RGI glaciers that should be manually verified for lake-terminating status. We have compiled a list of known datasets here.

Script for subsetting the RGI to glaciers within 1 km of a previously mapped lake:
https://drive.google.com/drive/folders/1SZjsD_OEUuq_bnAhcyrKSP_i3qSFw7mn?usp=sharing

The general workflow implemented in this script is to:

1) create a geodatabase of terminus locations, pulling the term_lat & term_lon fields from the RGI
2) buffer the terminus positions by 1 km
3) spatial join the existing lake dataset and buffered RGI terminus positions (these assigned term_type = 2)

Contributors should then manually verify the collection of lake-terminating glaciers and assign lake-terminating relevance levels, based on the examples above and following general criteria:

- Lake-terminating Category 3: >~50% of terminus is adjacent to lake; the lake(s) is definitely relevant for glacier mass loss & dynamics
- Lake-terminating Category 2: ~10 - ~50% of terminus is adjacent to lake; the lake(s) is probably relevant for glacier mass loss & dynamics
- Lake-terminating Category 1: <~10% of terminus is adjacent to lake, but there is some reason to think the lake is possibly dynamically relevant.
- Not lake-terminating, Category 0: The glacier is not lake-terminating; its terminus is almost exclusively in contact with land (or the ocean), or has a terminal water body that is so small as to seem inconsequential for its mass loss/dynamics

- Supraglacial lakes (lakes forming entirely on top of glacier ice) should not to be considered unless they have coalesced into large water bodies than span the majority of the terminus
- Lakes <0.01 km^2 should not be considered
- Glaciers with terminus cut across by a stream should be labeled as Category 2 or 3 (see guidance under "ambiguous termini" above)
- When in doubt whether the glacier is in contact with a lake or not use Category 1 or if it seems more likely that the glacier is not in contact but you cannot verify from the utilized image or any other image source (e.g. because of clouds, snow cover, cast shadow) use the 'not assigned' category (term_type=9)
- Recall that a list of definitively not lake-terminating glacier (lake Category = 0) is very useful in its own right

We strongly urge contributors to use the 0 - 3 lake-terminating categories defined above, but will accept binary submissions as well. If you are performing a binary (yes/no) lake-terminating classification, please consider the above-defined Categories 2 & 3 as "yes", and please make it clear in your contribution that you did a binary classification.

Workflow without existing lake inventory

In cases where no prior ice-marginal lake dataset exists, the user will have to manually inspect the termini of glaciers in your region to determine whether the glacier is lake-terminating, using the examples above the general criteria summarized in the preceding section. The Randolph Glacier Inventory Version 7 should be used as a starting point for glacier extents, and satellite imagery used to determine lake-terminating status should come from as close to the year 2000 as possible (within 10 years at most).

3 Output data format:

The contributors to the lake inventory should provide a csv file with the following structure (download a template here).

rgi_id	lake_cat	image_id	image_date	inventory_doi	contributor
RGI2000-v7.0-G-01-08604	1	LT50660171999270PAC02	1999/09/27	https://doi.org/10.18739/A2MK6591G	Armstrong
…	…	…	…		…

The fields are defined below:

rgi-id: This is the glacier ID from the Randolph Glacier Inventory Version 7
lake_terminating_category: This is the lake-terminating category as defined above
image _id: The id of the image used to verify or and/or decide about the lake-terminating level. For Landsat imagery, please use the Product ID.

image_date: The date of the image used to verify or and/or decide about the lake-terminating level. Please use YYYY/MM/DD date format.
inventory_doi: doi of the lake data set used (if existing), otherwise include n.a.
contributor: Name of the person who checked the lake-terminating category. You can also include more than one person. However, it is important that the person who checked the category is mentioned and not or not only the supervisor or data provider.

We strongly urge contributors to use the 0 - 3 lake-terminating categories defined above, but will accept binary submissions as well. If you are performing a binary (yes/no) lake-terminating classification, please consider the above-defined Categories 2 & 3 as "yes", and please make it clear in your contribution that you did a binary classification.

These regional tables will be merged to produce a global table of lake-terminating glaciers that will then be merged with the existing RGI tables and shapefiles.

Thank you for your time and effort! Please contact William Armstrong (armstrongwh@appstate.edu) and/or Tobias Bolch (tobias.bolch@tugraz.at) with any issues or questions.

4 References:

King, Owen, Atanu Bhattacharya, Rakesh Bhambri, and Tobias Bolch. 2019. "Glacial Lakes Exacerbate Himalayan Glacier Mass Loss." *Scientific Reports* 9 (1): 18145. https://doi.org/10.1038/s41598-019-53733-x.
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