Glacial Lake Observatory (GLO): Annual dataset of glacial lakes in Nepal and transboundary catchments (2017–2024)

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Response to Reviewer 1

The authors have responded to all review comments with appropriate and generally concise revisions. I particularly appreciate the inclusion of additional explanatory paragraphs, as well as the newly incorporated section addressing recommended use and detection limits (5.3.2 Recommended use and detection limits), which significantly enhances the practical relevance of the manuscript.

The supplementary material has been notably strengthened through the addition of insightful figures. These effectively illustrate the handling of erroneous detections, provide a comparative assessment of detection performance against existing inventories, and present a clear spatial overview of the validation dataset. Furthermore, the expanded discussion on model training procedures and the rationale behind selecting the DeepLabV3 architecture is well-articulated and adds valuable methodological clarity. Given that all of my previous comments have been addressed thoroughly and satisfactorily, I recommend the revised manuscript for publication.

We thank the reviewer for the time taken to review the manuscript, the overall positive comments to the revised version and recommendation for publication.

Response to Reviewer 2

This research addresses the lack of continually and methodologically consistent mapping of glacial lakes in the transboundary region of the Nepalese Himalaya. Using both Sentinel-1 and Sentinel-2 imagery, they are able to use the strengths of each data source to compensate for the limitations of the other, allowing for better coverage of lake maxima during monsoon season with Sentinel-1 and more precise delineation of small features with Sentinel-2. This method was based on an automatic processing chain using DeeplabV3 deployed in ArcGIS Pro using manual lake delineations as the training reference data.

Overall, this manuscript is well written and thorough, clearly explaining and evaluating various aspects of the dataset. I believe this dataset will be very useful for other researchers assessing GLOF hazard risks and modeling projections of future glacial lake development. From my point of view, the authors have thoroughly and satisfactorily addressed the comments of the reviewers in the first revision round, addressing the majority of my concerns of the first draft as well.

In regards to the revised version, I have one main point I think could be improved upon, as follows. While I understand why the results are discussed considering the two datasets as separate entities (Sentinel-1 and Sentinel-2), it makes it difficult for the reader to gain a holistic overview of the total number lakes and their total area. It is unclear in several sections how many of the lakes reported for Sentinel-1 and Sentinel-2 are actually found in both datasets versus how many are found only in one of the datasets. For example, in Tables 3 and 4, it is interesting to see the differences in how many lakes are found in each sensor's dataset, but it would also be useful to know the combined unique number of lakes (and the total area) across both datasets. This could be accomplished by dividing both of the first two columns in Table 3 (no. of lakes and total area) into three numbers (1. only detected by S1, 2. detected by both, 3. only detected by S2) instead of total values for each sensor. Or perhaps you'd prefer to show that in some other form in a separate table or graph. The other section that could benefit from this additional effort would be in Section 4.3. Here, the statistics for number of lakes over the years are given separately for each dataset, but the combined unique number of lakes (and the *total area) per year within the basins would bring more insight to the overall trend and not just the differences in what the sensors captured.*

We thank the reviewer for their positive comments on our revised manuscript. We are glad to hear we have addressed concerns from the first draft.

In response to the main comment regarding the need for a more holistic view of the Sentinel-1 and -2 results, we have now included a combined analysis of the two sensor inventories. Specifically, overlapping polygons identified independently in Sentinel-1 and -2 were merged for each study year (to avoid duplicate counting) and quantified providing details of the combined number of annual lake detections, unique lakes and cumulative lake area. These additional stats have been incorporated into text within Sect. 4.2 along with an additional table (Table 4), as follows:

'To examine glacial lake detections from both Sentinel sensors collectively, overlapping lake polygons identified independently from Sentinel-1 and -2 imagery were merged within each year. This resulted in a total of 24,925 annual lake delineations across the study period and 4,453 unique lakes between 2017 and 2024. Sentinel-2 detections comprised approximately 90% of all annual lake delineations and 93% of the unique lakes identified through this combined analysis. On average, 3,116 lakes were mapped per year, with annual lake totals ranging between 3,001 (2019) and 3,363 (2024) (Table 4). The mean annual total lake area in the combined inventory was 186.22 ± 4.29 km², with average individual lake size 0.06 ± 0.21 km². Glacially-fed lakes accounted for 59% (n = 14,675) of all lakes captured within the combined dataset.'

Table 4. Summary statistics of the combined Sentinel-1/ Sentinel-2 lake analysis for the Nepal-transboundary region (2017-2024). Lake polygons derived from Sentinel-1 and Sentinel-2 datasets were spatially merged to remove duplicate detections but retain the maximum mapped extent of each lake.

Year	No.Glacial Lakes (>0.001 km^2)	Glacial Lake Total Area (km^2)	Mean Glacial Lake Area (km^2)	Max Glacial Lake Area (km^2)
2017	3104	182.69	0.059	5.52
2018	3006	182.84	0.061	5.55
2019	3001	181.86	0.061	5.47
2020	3174	187.16	0.059	5.49
2021	3119	186.30	0.060	5.47
2022	3060	185.48	0.061	5.53
2023	3098	188.29	0.061	5.55
2024	3363	195.19	0.059	5.60

It is also mentioned that Sect. 4.3 would benefit from this combined analysis. In response, we have now expanded this section to include additional analyses of combined annual lake abundance and cumulative lake area across the three basins of the Nepal-transboundary region. We have also expanded Fig. 6 by adding two new panels (Fig. 6e–f), which present the annual number of lakes and cumulative lake area by basin for the combined Sentinel-1/-2 analysis.

We have also extended the elevation analysis within Sect. 4.3 and provided an additional supplementary figure (Fig. S3) to include the combined Sentinel-1/-2 elevation distributions of glacier-fed and non-glacier-fed lakes.

See additional text and figures for Sect. 4.3 below:

‘Consistent with the Sentinel-2 inventory, the combined Sentinel-1/-2 detections showed significant increases in both lake number and total cumulative lake area only in the Koshi Basin (Fig. 6e-f). The Koshi basin accounted for 59% of all lakes mapped across the eight-year period (n = 14,624) and 70% of the total cumulative lake area across the Nepal-transboundary region, increasing from 1,746 in 2017 to 1,881 in 2024, with the largest count occurring in 2021 (n = 1,905). Total cumulative area increased by 7% from 126.8 km^2 to 135.6 km^2. Basin-scale trend analysis confirmed that the number of mapped lakes increased significantly only in the Koshi Basin (22.8 lakes yr^{-1}, $R^2 = 0.71$, $p = 0.008$), whereas no significant trends were detected in the Gandaki or Karnali basins. Similarly, total lake area increased significantly in both the Koshi (1.19 km^2 yr^{-1}, $R^2 = 0.96$, $p < 0.001$) and Gandaki (0.27 km^2 yr^{-1}, $R^2 = 0.63$, $p = 0.018$) basins, while no significant change was observed in the Karnali Basin (0.03 km^2 yr^{-1}, $R^2 < 0.01$, $p = 0.925$). Mean lake area remained stable in all three basins, with no significant temporal trends detected (all $p \geq 0.278$). In contrast, maximum lake area increased significantly only in the Gandaki Basin (0.041 km^2 yr^{-1}, $R^2 = 0.55$, $p = 0.036$), whereas no significant changes were observed in the Koshi or Karnali basins.

Collectively, these results indicate that recent changes in Nepal–transboundary glacial lakes have been concentrated in the Koshi Basin, where both lake number and total cumulative lake area increased significantly between 2017 and 2024. In contrast, the Gandaki Basin exhibited a significant increase in total lake area without a corresponding increase in lake number, while no significant temporal trends were detected in the Karnali Basin.

Predictably, glacier-fed lakes occurred at significantly higher mean elevations than non-glacier-fed lakes (Fig. 7). Independent two-sample t-tests confirmed that these differences were statistically significant ($p < 0.001$) across all basins in both the Sentinel-2 inventory and the combined Sentinel-1/Sentinel-2 analysis. The largest mean elevation differences were observed in the Koshi Basin (406 m), followed by Gandaki (354 m) and Karnali (126 m)’

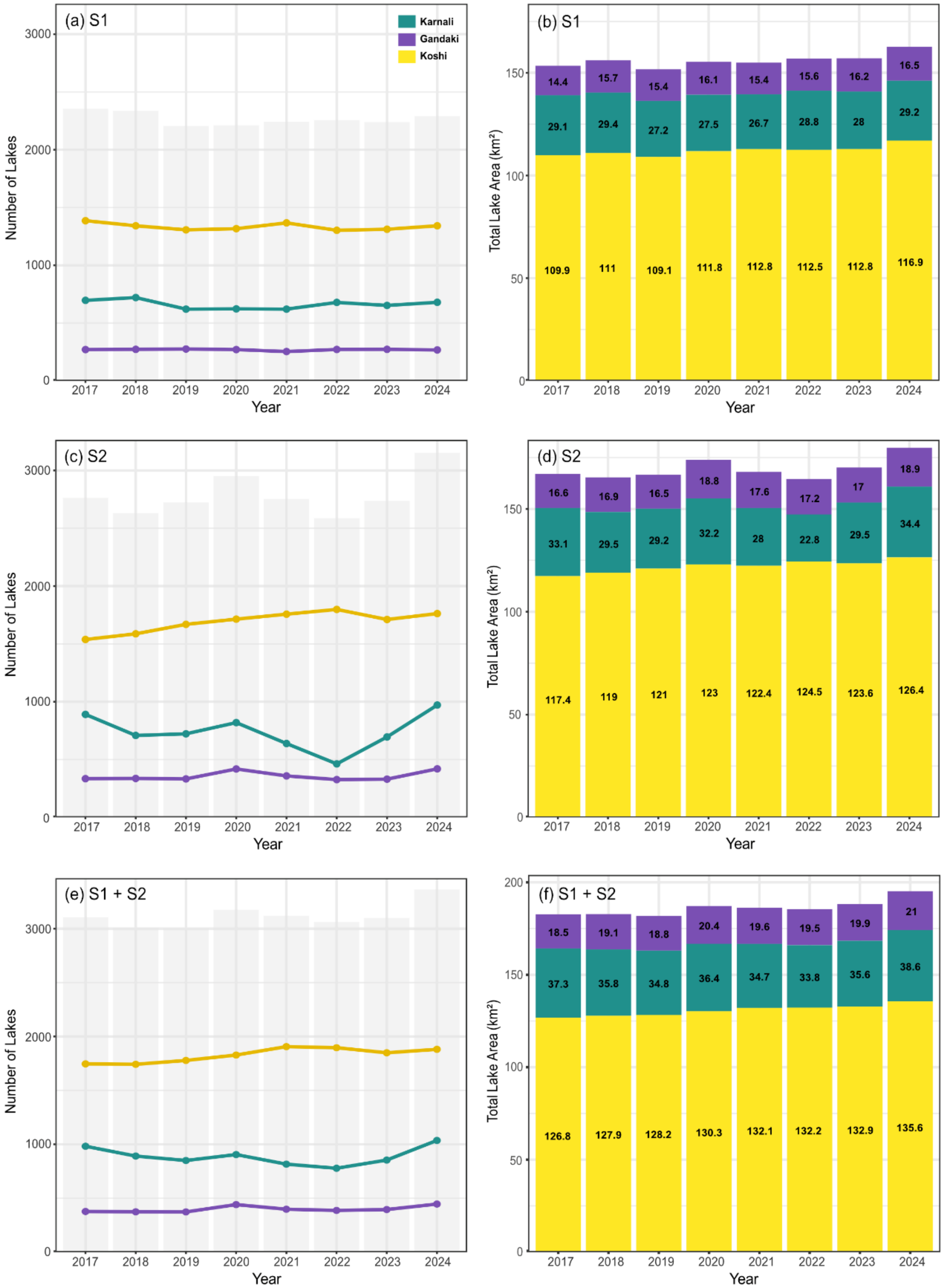

Figure 6: Annual glacial lake statistics for the Nepal-transboundary region (2017–2024) derived from Sentinel-1, Sentinel-2 and combined Sentinel inventories. Panels show the annual number of lakes (a, c, e) and total lake area (km²; b, d, f) by basin for Sentinel-1 (a–b), Sentinel-2 (c–d) and the combined Sentinel-1/ Sentinel-2 inventory (e–f). The combined inventory integrates overlapping Sentinel-1/ Sentinel-2 lake detections within each year. Grey bars indicate the total number of lakes mapped each year.

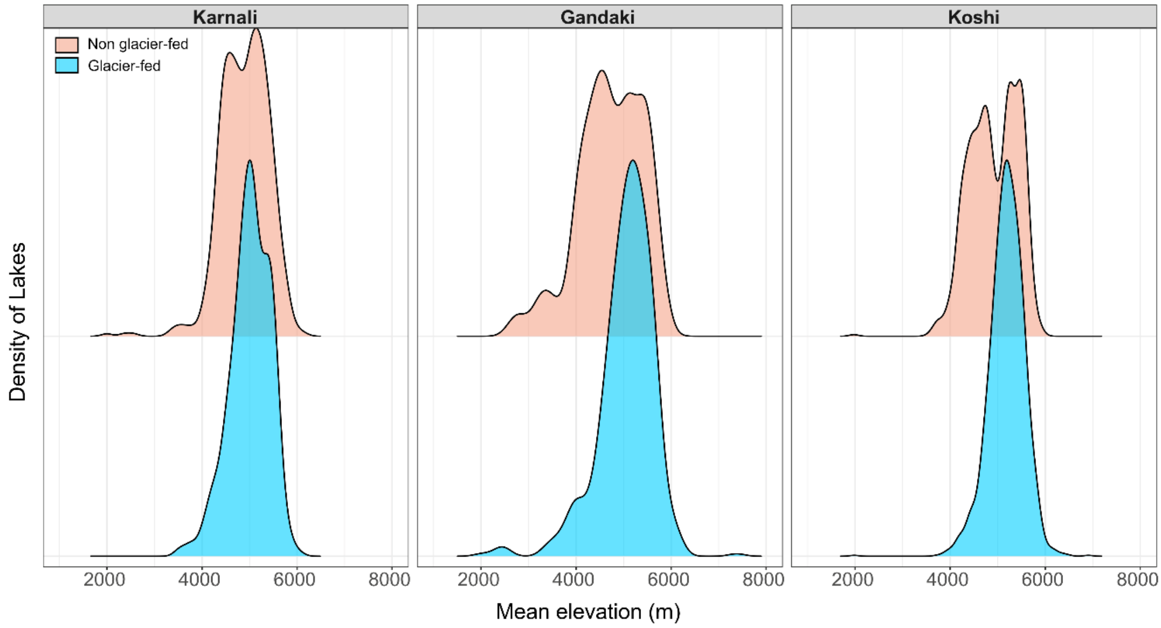

Figure S3: Density distribution of glacier-fed and non-glacier-fed lakes from the combined Sentinel-1/-2 delineations across mean elevation (m) within the three major Nepal-transboundary river basins: Karnali, Gandaki, and Koshi. Shaded areas represent the relative density of lakes by elevation, highlighting the elevational preferences of glacier-fed (blue) and non–glacier-fed (orange) lakes in each basin.

Finally, we have acknowledged this combined sensor analysis in the abstract and expanded the Discussion Sect 5.2 to consider the combined analysis, highlighting the contribution of Sentinel-2 to the overall lake detections while recognising the complementary role of Sentinel-1.

See added discussion text below:

'When detections from both sensors were combined, Sentinel-2 accounted for 90% of all annual lake delineations and 93% of unique lakes, indicating that the optical dataset captured the vast majority of mapped glacial lakes, while Sentinel-1 primarily contributed additional detections where optical observations were limited.'

We hope these additions satisfactorily address the reviewer's comment and provide a clearer overview of glacial lake abundance and area across both Sentinel sensors.

Specific comments:

Table 4: It is not mentioned in the caption which number is bold (S1 or S2)

This has now been updated (Table 5 in revised manuscript).