Review: *High-resolution mapping of glacial lake expansion in Kyrgyzstan (2016–2024) using Sentinel-2 imagery*
(Manuscript ID: egusphere-2026-1442)

We sincerely thank both reviewers for their careful evaluation of our manuscript and for their constructive comments, which have helped us identify several aspects that would benefit from further clarification and improvement. In response to the comments received, we propose several modifications intended to strengthen the manuscript. The principal planned revisions include:

- Clarification of the inventory scope, terminology, and the use of the 3000 m elevation threshold to delineate high-mountain glacierized and recently deglaciated environments;
- Revision of statements implying direct glacier retreat–lake evolution relationships that were not explicitly evaluated in this study, including the moderation or removal of several causal interpretations in the Abstract, Discussion, and Conclusions;
- Revision of the definition of glacier-detached lakes to better distinguish physical glacier contact from potential hydrological connectivity;
- Addition of supplementary glacier-related contextual information and references, including glacier coverage statistics, glacier–lake distance metrics, and a glacier distribution map derived from RGI v7.0;
- Clarification and restructuring of several methodological aspects, including the distinction between the inventories used throughout the workflow and the introduction of a summary table;
- Clarification of several methodological and statistical aspects, together with revisions to selected figures, captions, and associated discussions to improve readability and facilitate interpretation of the results;
- Addition of references and supporting literature where further context or justification was requested by the reviewers;
- Consideration of a slight revision of the manuscript title to better reflect the inventory-based nature of the study and avoid overstating glacier–lake process relationships.

Detailed responses to each comment are provided below. For clarity, all proposed modifications to the manuscript text are shown in italics.

On behalf of the co-authors,
Valentine Piroton

Referees' Comments to Author:

Reviewing 2

The manuscript by Piroton et al. provides new lake growth evolution data from mid-to-high altitude environment in entire Kyrgyzstan. The study is based on lake contour delineation using Sentinel-2 imagery, conducted either by hand or by NDWI thresholding, in order to create a reference inventory from which machine learning is applied to reconstruct historical lake distribution. The reference and reconstructed datasets are from 2022-2024 and 2016-2017 respectively, corresponding to a 6-8 years evolution time span for this study. The trends described in this manuscript go along with other trends detected across similar high-mountain environments.
The manuscript is well written and provides interesting data on lake evolution in relation to hydro-cryosphere environment. Specific regional aspects are highlighted, following a thorough processing framework.
Overall, the manuscript is technically sound, but several important issues need to be addressed before publication.
We thank Pr. Denis Samyn for the careful assessment of our manuscript and for the positive evaluation of the study. We appreciate the recognition of the methodological framework, the regional perspective provided by the inventory, and the relevance of the results in the context of hydro-cryospheric changes in high-mountain environments.

The comments and suggestions provided have helped identify several aspects of the manuscript that could benefit from further clarification and improvement. They highlight opportunities to strengthen the presentation of the methodology, refine the interpretation of some results, clarify several statements and figures, and provide additional context where needed.

We are grateful for this constructive feedback and address each comment in detail below.

Major comments

• The title suggests high-resolution mapping of 'glacier lake expansion'. On Lines 118-119, the authors write 'The geographic extent of this work corresponds to areas across the territory of Kyrgyzstan at elevations ≥3 000 m to focus on high-mountain glacial lake environments'. On Lines 242-243, they the write 'Polygons were further filtered by proximity to glaciers (within 30 km, based on the RGI v7.0) and by elevation (>3 000 m)'. First, this suggests that the authors consider that all lakes above 3 000 m are glacial lakes. Many lakes above 3 000 m in Kyrgyzstan (and Central Asia) are indeed of glacial origin, but not all high-altitude lakes are "glacier lakes" in the strict sense. There are many lakes of tectonic origin, or which resulted from landslide- or GLOF-damming, especially in this seismically active region of Central Asia. Second, a lake being of glacial origin does not necessarily mean that its formation is related to current deglaciation mechanisms. It is also known that, as a result of climate change, large share of precipitation is currently falling as rain instead of snow, not only at low and mid elevations, but also more and more at higher elevations. This is due to warmer winters and snow season shortening. Some mapped lakes can therefore simply result from the accumulation of higher amounts of liquid precipitation than before. Third, both the temporal and spatial relationships between lake expansion and glacier retreat are not touched upon in this paper. The only argument that the reader gets to know, although from general statistics, is whether the lakes were detached from, attached to, or located on glaciers. How can the authors then claim, for instance, that (see Lines 17-18) 'These results highlight the ongoing influence of glacier retreat on lake formation and expansion in Kyrgyzstan'? Given the strongly oriented scope of the Cryosphere journal, one would expect an in-depth analysis of such 'glacier-hydrology interactions', as argued in the Discussion and Conclusion.

We appreciate the reviewer's important comment and agree that additional clarification regarding the inventory criteria, the potential origin of the inventoried lakes, and the interpretation of the observed changes would strengthen the manuscript.

The primary objective of this study is to produce a high-resolution national-scale inventory of lakes located in glacierized and recently deglaciated high-mountain environments and to document their recent evolution between 2016 and 2024. The study is therefore designed as an inventory and change-detection analysis rather than as a process-based assessment of the genetic origin of each individual lake or of glacier–lake interactions at the lake scale. We recognize that some formulations could be clarified to better reflect this distinction. To address this point, the manuscript will be revised in several ways.

First, we will clarify more explicitly that mountain glacial lake inventories commonly rely either on elevation thresholds or glacier-proximity criteria (often based on RGI outlines) to constrain their spatial extent. In this study, the >3000 m threshold and the glacier-proximity criterion were adopted as methodological selection filters to focus the inventory on glacierized and recently deglaciated high-mountain environments in the Kyrgyz Tien Shan. This threshold is broadly consistent with previous studies indicating that glacierized terrain in the northern Tien Shan is predominantly located above ~3100 m a.s.l., while recent glacial lake changes have been reported to be concentrated at higher elevations (Daiyrov et al., 2022). It also encompasses landscapes that have experienced substantial glacier fluctuations since the Little Ice Age (Sorg et al., 2012). These criteria are not intended to imply that all inventoried lakes are necessarily of glacial origin. The manuscript will be revised to explicitly acknowledge that some lakes may be associated with other geomorphological settings or formation mechanisms, including tectonic or landslide-dammed environments. Lakes occurring below 3000 m a.s.l. appear to be comparatively uncommon in the Kyrgyz Tien Shan and, when present, are often associated with other geomorphological settings, such as tectonic or landslide-dammed basins.

Second, we agree that glacier retreat is only one of several factors that may influence lake formation and evolution. Additional controls, including changes in precipitation phase, snow-cover duration, catchment hydrology, sediment redistribution, and local topographic conditions, may also contribute to the observed patterns. The Discussion will therefore be revised to acknowledge these potential influences more explicitly and to avoid attributing the observed changes to a single process where this has not been directly evaluated.

Third, several statements in the Abstract, Discussion, and Conclusions will be reformulated to avoid implying a direct glacier-retreat-driven mechanism. The interpretation will remain restricted to what is directly supported by the present analyses, namely the spatial distribution, typology, and recent evolution of lakes located in glacierized and recently deglaciated high-mountain environments. Where appropriate, relationships with glaciers will be described as spatial associations rather than demonstrated causal mechanisms. We will also emphasize that a quantitative assessment of glacier–lake interactions would require dedicated glacier-change analyses and falls beyond the scope of the present inventory-focused study.

More specifically, the following modifications will be proposed:

- Section 2 (Study Area) will clarify that the >3000 m threshold represents a methodological selection criterion and does not imply that all inventoried lakes are of glacial origin.
- Section 4.6.3 will revise the definition of glacier-detached lakes to avoid implying complete hydrological disconnection from glacier-fed catchments.
- Statements in the Abstract, Discussion, and Conclusions suggesting direct glacier-driven mechanisms will be reformulated more cautiously.
- Additional contextual information, including glacier distribution, regional glacier-coverage statistics, and lake-to-glacier distance metrics, will be incorporated to better place the observed lake patterns in their regional glaciological context without overstating causal inference.

In addition, we will also consider a slight revision of the manuscript title to better reflect the inventory-based nature of the study and avoid overstating glacier–lake process relationships. One possible revised title under consideration is: "*High-resolution inventories of glacial lakes in Kyrgyzstan (2016–2024) derived from Sentinel-2 imagery.*"

We hope these clarifications will address the reviewer's concerns and improve the overall scope and interpretation of the manuscript.

• Why did the authors conduct a high-resolution mapping of high-environment lakes only between 2016-2017 and 2022-2024? In general, authors generally work specifically by decade(s), allowing for clearly distinguished time periods and for reaching a reasonable minimum number of study years for statistical representativity. Here a maximum of 6 to 8 years of study is proposed. Why did the authors not start in 2015 (when Sentinel-2 first appeared), and why did they stop in 2024, whereas the article was submitted in 2026? As a result, there is already 25-30% of the study period that has become obsolete since the last year of study. I believe the thorough 2024 Randow Forest model could be applied to late 2025 or early 2026 to complement the lake inventory and make it more robust in terms of identified trends.
Thank you for this comment regarding the choice of the study periods. The objective of the present study is not to reconstruct annual lake evolution or to establish long-term temporal trends from a continuous time series. Rather, the aim is to compare two internally consistent national-scale inventories representing the earliest and most recent periods for which complete, high-quality Sentinel-2 coverage could be assembled across Kyrgyzstan and subsequently validated. Consequently, the relevance of the selected periods is primarily linked to inventory consistency and spatial completeness rather than to the duration of the interval itself.

The 2016–2017 period was selected because, although Sentinel-2 became operational in 2015, the first year of the mission does not provide sufficiently complete and homogeneous coverage across the entire study area. The 2016–2017 window therefore represents the earliest period for which a robust country-wide inventory could be produced under consistent conditions.

The 2022–2024 period was selected to construct the most recent inventory possible during the inventory development phase while ensuring complete national coverage, limited cloud and seasonal snow contamination, and imagery suitable for systematic manual verification and refinement. Because the workflow combines automated processing with extensive expert review, image selection was constrained not only by data availability but also by the need to assemble a coherent and visually reliable national mosaic.

While a future extension of the inventory may be considered, such an effort would require the generation, validation, and manual refinement of an additional national-scale inventory and therefore falls beyond the scope of the present study. The objective here is to establish a robust baseline for recent lake-change assessment at the national scale rather than to develop a continuous annual monitoring product.

Furthermore, the development of a national-scale inventory involves multiple successive stages, including image selection, preprocessing, automated mapping, manual verification and refinement, quality control, and subsequent statistical analyses. Consequently, a temporal offset between the most recent observations and the publication of inventory-based studies is inherent to this type of research, particularly when extensive manual validation is performed to ensure consistency, reliability, and national-scale completeness.

To clarify this point, the manuscript will be revised, particularly in Section 3.1, to better explain that the selected temporal windows were chosen to ensure complete and internally consistent national inventories suitable for inventory production, comparison, and validation.

• In last years, various studies involving efficient water surface level monitoring in lakes (e.g. https://iopscience.iop.org/article/10.1088/2515-7620/ad7701; https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL095950; https://www.nature.com/articles/s41598-025-20434-7.pdf) using InSAR (or multi-source data) and machine learning has emerged. The present study does not provide perspective or comparison between their method and the latest advancements (as would be expected in the Cryosphere journal).

We agree that recent developments based on InSAR, radar, and multi-source approaches represent an important advancement in high-mountain lake monitoring, particularly for retrieving water-level changes, surface-elevation variations, or improving observations under persistent cloud cover.

However, the primary objective of the present study differs from that of many investigations focused on water-level monitoring or short-term lake dynamics. The aim of this work is to produce a high-resolution national-scale inventory of glacial lakes and to quantify their spatial and temporal evolution using a consistent methodology applied across Kyrgyzstan. Accordingly, the methodological framework was designed to optimize lake detection, delineation, inventory generation, and change analysis from optical satellite imagery rather than to retrieve lake-level fluctuations or surface-elevation changes.

We agree that recent developments based on radar and InSAR observations provide valuable complementary perspectives. These approaches can improve monitoring capabilities in cloud-affected regions, support the analysis of lake-level and volume variations, and provide additional information on lake dynamics beyond areal extent alone. Nevertheless, such applications address different research objectives from those pursued in the present inventory-focused study.

Given the scope of this contribution, submitted to Earth Observation, we consider that the emphasis on the generation of a consistent national-scale inventory from Sentinel-2 imagery remains appropriate. Nevertheless, the manuscript will be revised to provide a broader discussion of recent multi-sensor developments and their potential contribution to future glacial-lake monitoring efforts.

Accordingly, Section 6.4 (Perspectives for Future Monitoring) will be expanded to discuss the potential integration of radar, InSAR, and other multi-source datasets as a logical extension of the present work.

• The reader often finds itself lost through the various inventories and comparison exercises that were conducted. The manuscript would strongly benefit from a clearer unfolding and sequential description of these processing steps, e.g. in the form of a clear descriptive structure (and why not a summary table) between 2024_NDWI, 2024_manual, 2024_corrected, 2016_manual, 2016_corrected, 2024_RFC datasets.
To improve clarity, we will substantially revise the description of the workflow in Section 4 and introduce a new summary table that will explicitly distinguish the inventories used throughout the study, their production methods, and their role in the workflow. This table will be inserted after Sect. 4.1 and before Fig. 4.

The revised workflow will clearly distinguish:

- NDWI_2024: preliminary 2022-2024 lake extraction based on NDWI and topographic filtering;
- Manual_2024: manually refined 2022-2024 inventory used as the reference dataset and training source;
- RFC_2016: Random Forest-based reconstruction of the 2016-2017 lake distribution;
- Manual_2016: manually reviewed and corrected 2016-2017 inventory used for validation and accuracy assessment.

In addition, we will revise the wording throughout Sections 4 and 5 so that each inventory is referred to consistently by name and function. We will also clarify more explicitly that the 2016 reference inventory was obtained after systematic manual review of the Random Forest output against Sentinel-2 imagery, as this was not sufficiently clear in the current version of the manuscript.

We believe that these revisions will substantially improve the readability of the methodological sequence and the distinction between automated outputs, manually refined inventories, and validation datasets.

Table 1. Summary of the inventories used throughout the workflow. (to be inserted after Sect. 4.1 and before Fig. 4).

Inventory name	*Year(s)*	*Method*	*Purpose*
NDWI_2024	2022–2024	NDWI extraction and topographic filtering	Initial lake extraction
Manual_2024	2022–2024	Manual refinement of NDWI_2024	Reference inventory and Random Forest training
RFC_2016	2016–2017	Random Forest classification using training samples derived from Manual_2024	Preliminary reconstruction of historical lake distribution
Manual_2016	2016–2017	Systematic manual review and correction of RFC_2016 using Sentinel-2 imagery	Validation and accuracy assessment

Sect. 4.1: *"We first established a baseline inventory of glacial lakes for 2022–2024 (hereafter NDWI_2024) using Sentinel-2 Level 2A imagery (Table S1)."*

"Spectral and topographic criteria were used to generate preliminary lake outlines, which were subsequently refined and used as the reference dataset (hereafter Manual_2024) for supervised classification."

"We then used these training samples to train and optimize a Random Forest classifier, subsequently applied to 2016 Sentinel-2 imagery to produce a second lake inventory (hereafter RFC_2016)."

Sect. 4.3: *"The second stage of the workflow aimed to produce a glacial lake inventory for 2016 using a supervised classification approach (RFC_2016). The Manual_2024 inventory served as a high-quality reference, providing labeled polygons of lake and non-lake areas."*

Sect. 4.4: *"For the 2016 Random Forest-based inventory (RFC_2016), post-processing focused on threshold optimization and performance assessment. The RFC_2016 inventory was systematically reviewed against the 2016–2017 Sentinel-2 imagery. Missing lakes were added, false positives removed, and lake boundaries corrected, resulting in a manually validated 2016 inventory (hereafter Manual_2016) used as a reference dataset."*

Sect. 5.4: *"The semi-automatic NDWI-based extraction for 2024, when compared to the manually corrected reference inventory of 2 592 lakes (Manual_2024), shows that 1 517 lakes were successfully detected among 5 002 polygons, corresponding to a recall of 69 %, precision of 10 %, and an overall F1 score of 0.18."*

"Across the Manual_2024 inventory, the mean boundary uncertainty was 0.001 96 km^2, with a median of 0.001 33 km^2."

Minor comments

L. 33: Remove 'Indeed', as the previous line is more general.
The word *"Indeed"* will be removed.

L. 45-46: GLOFCA (https://glofca.org/en/) , a new lake monitoring initiative in Central Asia would deserve mentioning, given their strong focus on disaster risk monitoring.
We agree that GLOFCA represents an important recent initiative in Central Asia. We therefore propose mentioning this initiative in the section discussing GLOF hazards and their societal implications, where we believe it fits more naturally within the overall structure of the manuscript.

Sect. 1: *"These challenges have recently led to the development of regional initiatives such as the Glacial Lake Outburst Flood in Central Asia (GLOFCA) project, which aims to strengthen glacial lake monitoring, early warning systems, and disaster risk reduction across Central Asia."*

Figure 1: describe the inset.
Fig. 1: *"The inset shows the location of Kyrgyzstan within Central Asia and the position of the Tien Shan mountain range."*

L. 87-88: 'Mean July temperatures vary from 17–40 °C in valleys to around 4 °C at high altitudes'. This 17-40 range in valleys is rather wide – why not provide an average temperature, like is done at 'high altitudes'?
The reviewer raises a valid point. The original wording combined average July temperatures with locally observed summer temperature extremes, which could be misleading. The paragraph will be revised to improve both clarity and precision.

Sect. 2: *"The country experiences hot, dry summers in the lowlands, where summer temperatures may locally exceed 40 °C, and cold, snowy winters nationwide (Kulikov and Schickhoff, 2017). Alpine conditions prevail in high mountain regions. Mean July temperatures vary from about 27 °C in low-elevation valleys to around 4 °C at high altitudes (Kulikov and Schickhoff, 2017). In contrast, severe frosts occur throughout the country in winter, particularly in mountain valleys and depressions (Tomaszewska and Henebry, 2018)."*

L. 95-96: Provide references.
This point was also raised by Reviewer 1. Additional references will therefore be incorporated to support the statements related to glacial retreat and associated slope hazards.

Sect. 2: *"The steep and rugged terrain further shapes local microclimates and contributes to hazards such as landslides, avalanches, and rockfalls, particularly in areas experiencing active glacial retreat (**Bolch et al., 2011; Huggel et al., 2012**)."*

L. 101-103: Idem.
Consistent with a similar comment raised by Reviewer 1. References supporting the importance of meltwater resources for regional hydrology, agriculture, and rural livelihoods in Kyrgyzstan will be added.

Sect. 2: *"Rural livelihoods and national agriculture depend heavily on meltwater availability (**Sorg et al., 2012; Shahgedanova et al., 2020**), making the stability of glaciers and glacial lakes a central concern for both environmental and socio-economic resilience. Kyrgyzstan hosts several thousand glaciers, particularly in the northern and central Tien Shan; these glaciers continuously feed glacial lakes, which play a critical role in regional hydrology by supplying meltwater to major rivers such as the Naryn, a key tributary of the Syr Darya (**Kriegel et al., 2013**)."*

L. 118-119: 'The geographic extent of this work corresponds to areas across the territory of Kyrgyzstan at elevations ≥3 000 m to focus on high-mountain glacial lake environments'. Does this mean that the presented inventory is not a complete inventory of what they call 'glacial lakes'? How many of these lakes are located below 3 000m?
The reviewer raises an important point. As discussed in the major comments above, mountain glacial lake inventories commonly rely either on elevation thresholds or glacier-proximity criteria to constrain their spatial extent. In this study, a threshold of 3000 m a.s.l. was intentionally adopted to focus on glacierized and recently deglaciated environments in the Kyrgyz Tien Shan. This threshold broadly encompasses landscapes affected by glacier fluctuations since the Little Ice Age and elevations where recent glacial lake changes are

predominantly observed. This criterion does not imply that all lakes above 3000 m a.s.l. are necessarily of glacial origin, and lakes occurring below this elevation appear to be comparatively uncommon and are often associated with other geomorphological settings, such as tectonic or landslide-dammed basins. A clarification regarding the spatial scope and intended focus of the inventory will therefore be added to the manuscript.

Sect. 2: *"The inventory is restricted to lakes located above 3000 m a.s.l. to focus on glacierized and recently deglaciated environments in the Kyrgyz Tien Shan. This threshold is broadly consistent with previous studies indicating that glacierized terrain in the northern Tien Shan is predominantly located above ~3100 m a.s.l., while recent glacial lake development and changes have been reported to be concentrated at higher elevations (Daiyrov et al., 2022). It also encompasses landscapes that have experienced substantial glacier fluctuations since the Little Ice Age (Sorg et al., 2012). This elevation threshold was adopted as a methodological inventory criterion and does not imply that all lakes above this elevation are necessarily of glacial origin."*

L. 126-128: 'Two distinct temporal windows were considered: […] (2) July to October of 2022–2024, representing recent conditions for our glacial lake inventory'. Why extend the reference period across two years? This is not discussed. See Major Comments on time period limitations for trend robustness.
We agree that the justification for using a multi-year period was not sufficiently explained. As discussed in the major comment on the selected study periods, a clarification will be added to the manuscript to explain that the 2022–2024 window was selected to obtain complete national coverage from high-quality Sentinel-2 imagery and generate a robust reference inventory suitable for subsequent manual inspection.

Sect. 3.1: *"(2) July to October of 2022–2024, selected to obtain a complete and internally consistent national mosaic from cloud-free Sentinel-2 imagery suitable for glacial lake inventory generation and subsequent manual inspection."*

L. 133-134: 'In areas where a single tile did not meet these conditions, multiple adjacent Sentinel-2 tiles were merged to obtain optimal coverage, minimizing both cloud contamination and residual snow'. How were these tiles merged?
Thank you for this comment. Additional details regarding the mosaic generation procedure will be added to the manuscript. When multiple Sentinel-2 scenes were available for the same area, the scene providing the best visual quality (i.e., minimal cloud cover, limited snow cover, and favorable illumination conditions) was retained. The selected scenes were then mosaicked to generate a seamless national raster for each spectral band before producing the final multi-band composite.

Sect. 3.1: *"When multiple Sentinel-2 scenes were available for the same area, the image providing the best visual quality (i.e., minimal cloud cover, limited snow cover, and favorable illumination conditions) was retained. The selected scenes were then mosaicked in ArcGIS Pro to generate a seamless national raster for each spectral band (blue, green, red, NIR and SWIR), which were subsequently combined into a multi-band composite."*

Figure 3 caption and L. 186: why were Sentinel 2-A images only used? This is not discussed.
We believe there may be a misunderstanding regarding the terminology used. The term "Level-2A" refers to the processing level of the Sentinel-2 imagery (i.e., atmospherically corrected bottom-of-atmosphere reflectance products) and not to the Sentinel-2A satellite

platform. Both Sentinel-2A and Sentinel-2B acquisitions were used in this study, as detailed in Table S1 and described in Section 3.1. Level-2A products were selected because they provide atmospherically corrected surface reflectance data, which are more suitable for spectral index calculations and image classification. To avoid potential confusion, this distinction will be clarified in the manuscript.

Sect. 4.1: *"We first established a baseline inventory of glacial lakes for 2022–2024 using Sentinel-2 Level 2A imagery (Table S1). Level-2A products were selected because they provide atmospherically corrected surface reflectance data, which are more suitable for spectral index calculations and image classification."*

L. 156-157: 'The DEM was generated from optical stereo images acquired by the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) between 2006 and 2011'. Since the DEM used was created in 2006-2011, could the time difference with the study period affect the precision of altitudes provided in this work given the rather intense and rapid glacier environment evolution that is discussed?
The reviewer raises a valid point. Although local topographic changes may have occurred between the DEM acquisition period (2006–2011) and the study periods, the AW3D30 DEM was used only to derive topographic parameters (elevation and slope) and not to quantify elevation changes. Moreover, the same DEM, acquired prior to both study periods, was used consistently for both inventories. Consequently, any potential influence of the time difference between DEM acquisition and the study periods is expected to be limited and unlikely to significantly affect the reported temporal trends at the national scale.

Sect. 3.2: *"The DEM was generated from optical stereo images acquired by the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) between 2006 and 2011 and served as a static topographic reference throughout the study."*

L. 166-167: 'This dataset offers global coverage of linear hydrographic features that are too narrow to be represented as polygons'. Please add ', including those' after 'features'.
Sect. 3.2: *"This dataset offers global coverage of linear hydrographic features including those that are too narrow to be represented as polygons."*

L. 179-180: 'to accurately map glacial lakes in Kyrgyzstan and analyze their spatio-temporal evolution'. This is very redundant across the manuscript and most likely not needed.
Thank you for this suggestion. We agree that the recurring emphasis on glacial lake mapping and spatio-temporal evolution is somewhat redundant throughout the manuscript. The following passages will therefore be revised to improve conciseness and reduce repetition.

Sect. 1: *"These limitations underscore the need for updated, high-resolution glacial lake inventories to enable national-scale monitoring of lake dynamics and GLOF hazards."* replaced by *"These limitations highlight remaining gaps in the current representation of glacial lakes in Kyrgyzstan and motivate the development of an updated national-scale inventory."*

"In addition, we evaluate the extent to which large-scale automated glacial lake inventories can accurately capture lakes at risk of GLOFs. By comparing our results with global datasets, we demonstrate the added value of expert-guided refinement within automated classification workflows, which remains essential for achieving the level of detail and accuracy required for hazard-oriented inventories." revised to *"We further compare the*

resulting inventory with existing large-scale datasets to evaluate their representation of potentially hazardous glacial lakes and to assess the benefits of expert-guided refinement."

Sect. 3.1: *"This dual-period dataset provides consistent, high-resolution coverage of Kyrgyzstan's alpine regions, enabling robust delineation of glacial lake boundaries and detection of subsequent changes."* simplified to *"This dual-period dataset provides consistent high-resolution coverage of Kyrgyzstan's alpine regions for subsequent inventory generation and comparison."*

Sect. 3.2: *"Together, these datasets—including glacier outlines, the DEM, administrative boundaries, rivers, and major lakes—establish a comprehensive spatial framework that supports high-resolution mapping, temporal analysis, and visualization of glacial lakes in Kyrgyzstan."* replaced by *"Together, these datasets provide the spatial context required for inventory generation, filtering, interpretation, and regional analyses."*

Sect. 4.1: *"The methodological workflow of this study, implemented within Python-based environments, was designed to accurately map glacial lakes in Kyrgyzstan and analyze their spatio-temporal evolution. It follows a two-step approach combining expert-based manual refinement with automated machine learning techniques (Fig. 4)."* revised to *"The methodological workflow of this study, implemented within Python-based environments, follows a two-step approach combining expert-based manual refinement with automated machine learning techniques (Fig. 4)."*

"This approach provides robust training samples while maintaining reproducibility and scalability, essential for consistent temporal comparisons and quantitative assessments of lake changes." simplified to *"This approach maintains both reproducibility and scalability."*

"Nonetheless, our comparison between the two inventories enabled quantitative assessment of the spatial and temporal dynamics of glacial lakes across the Kyrgyz mountains." deleted for conciseness.

Sect. 4.4: *"Together, these post-processing and validation steps support the refinement and expert-checked comparison of automated and manual inventories, providing a robust methodological framework for analyzing glacial lake dynamics across the Kyrgyz mountains."* replaced by *"Together, these post-processing and validation steps ensure the consistency and reliability of the final inventories."*

Sect. 4.6.3: *"Detailed results, including spatial patterns and temporal changes, are presented in the following section."* simplified by *"Detailed results are presented in the following section."*

Sect. 6.2: *"Overall, the manually refined 2016 and 2024 inventories constitute a robust reference for national- and sub-regional-scale glacial lake monitoring, with polygon metrics confirming the high reliability and spatial completeness of the dataset."* revised to *"Overall, the inventories provide a detailed reference for national- and sub-regional-scale analyses."*

Sect. 7: *"Beyond simple mapping, it provides new insights into the spatial, typological, and temporal evolution of glacial lakes in a rapidly changing cryospheric environment."* Deleted to avoid repetition.

These revisions reduce repeated references to glacial lake mapping and spatio-temporal analysis throughout the manuscript while preserving the methodological and scientific context of the study.

L. 186-189: 'Spectral index and topographic constraints were used to generate preliminary lake outlines, which were then carefully refined through extensive manual editing to ensure accurate delineation. This manually corrected inventory provided a consistent set of reference polygons, serving as training samples for supervised classification'. Idem – reduce redundance across the manuscript.
We recognize that some aspects of the workflow description are repeated across the manuscript. The corresponding passages will therefore be shortened where appropriate.

Sect. 4.1: *The methodological workflow of this study, implemented within Python-based environments, was designed to accurately map glacial lakes in Kyrgyzstan and analyze their spatio-temporal evolution. It follows a two-step approach combining expert-based manual refinement with automated machine learning techniques (Fig. 4). By manually correcting the inventory from 2022–2024, we ensured a high-quality reference dataset because spectral indices alone (e.g., NDWI, normalized difference snow index) are often insufficient to reliably delineate lakes in complex mountainous terrain (Shugar et al., 2020). This approach provides robust training samples while maintaining reproducibility and scalability, essential for consistent temporal comparisons and quantitative assessments of lake changes."* revised to *"The methodological workflow of this study, implemented within Python-based environments, follows a two-step approach combining expert-based manual refinement with automated machine learning techniques (Fig. 4). As spectral indices alone (e.g., NDWI, normalized difference snow index) are often insufficient to reliably delineate lakes in complex mountainous terrain (Shugar et al., 2020), the 2022-2024 inventory was manually refined and used as a reference dataset for classifier training. This approach maintains both reproducibility and scalability."*

"Spectral index and topographic constraints were used to generate preliminary lake outlines, which were then carefully refined through extensive manual editing to ensure accurate delineation. This manually corrected inventory provided a consistent set of reference polygons, serving as training samples for supervised classification." simplified to *"Spectral and topographic criteria were used to generate preliminary lake outlines, which were subsequently refined and used as reference data for supervised classification."*

Sect. 4.4: *"This semi-automated workflow ensured a high-quality reference inventory suitable for subsequent training of the 2016 classification model."* revised to *"This semi-automated workflow ensured a reliable reference inventory."*

L. 193: 'our comparison between the two inventories'. Add 'already existing' or so after 'two'. See Major Comments of clarity between the various processing steps.
The corresponding sentence has been removed from the manuscript to improve conciseness and avoid redundancy.

L. 257-258: 'whereas the Random Forest-based inventory was compared to the manual 2016 inventory'. It is rather unclear to figure out how this 2016 inventory was created and compared to. See Major Comments on processing steps clarity.
Thank you for highlighting this point. The distinction between the Random Forest-derived inventory and the manually corrected 2016 inventory was not sufficiently explicit in the

original manuscript. As discussed in response to the major comment regarding workflow clarity, a summary table describing the different inventories and their role within the workflow will be added. The text will also be revised to clarify that the 2016 reference inventory was obtained through systematic manual review and correction of the RFC_2016 inventory using the 2016–2017 Sentinel-2 imagery and subsequently used for accuracy assessment.

Sect. 4.4: *"For the 2016 Random Forest-based inventory, post-processing focused on threshold optimization and accuracy assessment. Model performance was evaluated by comparing predicted lake locations to the manually mapped reference polygons."* completed by *"For the RFC_2016 inventory, post-processing focused on threshold optimization and performance assessment. The RFC_2016 inventory was systematically reviewed against the 2016–2017 Sentinel-2 imagery. Missing lakes were added, false positives removed, and lake boundaries corrected, resulting in a manually validated 2016 inventory used as a reference dataset. Model performance was then assessed by comparing predicted lake locations to this reference inventory."*

"Specifically, the NDWI-based inventory was assessed against the manual 2024 inventory, whereas the Random Forest-based inventory was compared to the manual 2016 inventory." revised to *"Specifically, the NDWI-based inventory was assessed against the manually refined 2022-2024 inventory, whereas the RFC_2016 inventory was compared with the manually validated 2016 inventory."*

L. 285-289: Several statistical aspects are vaguely described and should deserve more attention and detail. I also propose to create a special table to highlight the main findings in this regard.
We agree that some aspects of the statistical methodology can be described more explicitly. The corresponding section will therefore be revised to better explain the purpose of the Hartigan's Dip Test and the use of CCDF analysis for characterizing glacial lake size distributions. Additional clarification regarding the interpretation of the power-law exponent (α) will also be added.

Sect. 4.6.1: *"Hartigan's Dip Test (Hartigan and Hartigan, 1985)* ***was used to test whether the lake-size distribution deviated from unimodality. A high p-value indicates that the null hypothesis of unimodality cannot be rejected. In this case, the test indicated a unimodal distribution (D = 0.0041, p = 0.9951), supporting the interpretation of the inventory as a continuous size spectrum rather than as distinct lake-size populations****. The interquartile range was additionally used to detect potential extreme values. Complementary cumulative distribution functions (CCDFs) of lake areas were computed in RStudio using the poweRlaw package. The CCDF represents the probability that a lake has an area greater than or equal to a given value x and* ***is commonly used to characterize highly skewed size distributions because it reduces noise in the upper tail and facilitates the identification of scaling relationships.*** *This approach is suitable for highly right-skewed distributions dominated by small lakes, as is the case here (see Sect. 5.1). Scaling behavior was quantified by fitting a power-law model to the CCDF for lakes exceeding an empirically determined minimum area threshold (x_{min}):*

$P(x) \propto x^{-\alpha}, x \geq x_{min}$ *(3)*

where $P(x)$ is the probability of observing a lake of area x and α is the scaling exponent describing the decrease in lake frequency with increasing size. ***Higher values of α indicate a more rapid decrease in lake frequency with increasing lake size."***

Sect. 5.1: *"This α value indicates a rapid decline in lake frequency with increasing size, reflecting the strong dominance of small lakes within the inventory."*

L. 370: 'Inventoried lakes were classified as supraglacial, proglacial, or glacier-detached (Fig. 8a)'. These classifications were already illustrated in Fig. 6C. Should Fig. 8a come before the latter for figure order coherence?
Thank you for this suggestion. However, Figure 6C provides a schematic illustration of the classification criteria used in the workflow, whereas Figure 8a presents the resulting spatial distribution of the classified lakes. We therefore prefer to retain the current figure order, which follows the progression from methodology to results.

L. 371-372: 'whereas glacier-detached lakes are no longer directly affected by glacier ice or meltwater'. This is not entirely true from a glacio-hydrological perspective. It is not because a glacier becomes detached from its original lake that they get disconnected flow wise. Caution should be taken in the discussion on this kind of hydro-topographical considerations.
Thank you for this important clarification. We agree that glacier-detached lakes may remain hydrologically connected to glacierized catchments through meltwater-fed drainage systems despite the absence of direct contact with glacier ice. The wording will therefore be revised to avoid implying a complete loss of glacier influence.

Sect. 4.6.3: *"(iii) glacier-detached lakes, which include lakes that are no longer in direct physical contact with glacier ice but may remain indirectly influenced through glacier-fed catchments."*

Sect. 5.1: *"Glacier-connected lakes (supraglacial and proglacial) are likely still influenced by glaciers, whereas glacier-detached lakes are no longer in direct physical contact with glacier ice, although indirect hydrological connections may still persist."*

L. 375: 'consistent with its high glacier fraction (9.34 %)'. Add a table, map and/or graph for highlighting such relationships with glaciers (distance, density, glacier coverage etc). The RGI contains all the necessary information for this. See Major Comments on this.
Thank you for this suggestion. To provide additional context regarding glacier–lake relationships, we will add supplementary material including (i) a map showing the RGI v7.0 glacier distribution across Kyrgyzstan, (ii) regional glacier coverage statistics together with the distribution of glacier-connected and glacier-detached lakes, and (iii) summary statistics of lake-to-glacier distances for the different lake types. These additions will provide complementary information while keeping the main focus of the manuscript on inventory generation and comparison.

TableXX.:

Region	Glacier coverage (%)	Total lakes	Glacier-connected lakes	Glacier-detached lakes	Mean lake elevation (m)

Table YY.:

Lake type	Median glacier distance (m)	Q1	Q3

L. 376-377: 'Despite their different regional sizes, this result suggests that glacier size rather than regional area primarily limits lake formation'. Is this relevant to the discussion? If yes, this should be clarified.
This interpretation is not sufficiently supported by the analyses presented in the manuscript. As the relative influence of glacier extent and regional area on lake formation was not explicitly assessed, the corresponding statement will be removed.

Sect. 5.1: *"Despite their different regional sizes, this result suggests that glacier size rather than regional area primarily limits lake formation."* deleted.

Figure 9 caption: do the 'a)' and 'b)' correspond to the 'A)' and 'B)' of the graph? Also, why not add letters to the left part of the graph, as the figure design is not particularly clear on how to read this part.
Thank you for this comment. The panel labels follow the convention used throughout the manuscript, where panels are identified by uppercase letters in the figures (A, B) and referred to using lowercase letters in the captions (a, b). We therefore prefer to retain this consistent formatting.

L. 422 vs L. 431: 'Over half of all lakes (54 %) remained stable over the study period' vs 'Stable lakes accounted for about 20.7 %'. Please explain why these 'stable lakes' differences appear here. Please also be more specific when describing such trends.
The reviewer raises an important point. The two percentages refer to different definitions of stability. The value of 54 % refers to lakes that persisted between 2016 and 2024 regardless of changes in their surface area, whereas the value of 20.7 % refers only to lakes classified as stable with respect to area change. This distinction was not sufficiently clear in the original text. The corresponding paragraphs will be revised to explicitly distinguish persistence dynamics (appearance, disappearance, fragmentation, fusion, persistence) from lake-area change categories (gain, loss, stable area).

Sect. 5.2: *"Over half of all tracked lakes (54 %)* ***persisted between 2016 and 2024****, whereas 23.9 % newly appeared and 15 % disappeared. Fragmentation and fusion represent minor processes (5.3 % and 1.9 %, respectively)."*

Sect. 5.2: *"Lakes exhibiting stable surface areas accounted for about 20.7 %, whereas 38.8 % could not be assigned to an area-change category because they either newly emerged or vanished during the study period."*

Figure 10: It is not clear from these maps where most changes occur, given the large number of points, diameters and classes. How about producing maps with continuous changes, where colours directly define gradients?
We appreciate this suggestion. While Figure 10 was intentionally designed to distinguish discrete categories of lake evolution (emergence, disappearance, stable lakes, gains, and losses), we agree that the large number of individual lakes may make it difficult to identify regions exhibiting the strongest overall changes. To facilitate the interpretation of the spatial patterns, we therefore propose adding a supplementary map showing the major regions defined in Fig. 5 colored according to their relative change in lake number (%) between 2016 and 2024. We believe that this additional visualization will complement the categorical representation of Fig. 10 while preserving its original objective of illustrating individual lake trajectories.

L. 485-486: why referencing ‘low FP’? Shouldn’t the false positives only be described (as e.g. simply ‘FP’) before being discussed?
This is a valid point. The terms FP and FN are already defined in the preceding sentence, and the additional references to “low FP” and “low FN” are not necessary at this stage. To avoid mixing metric definitions with their interpretation, the sentence will be revised accordingly.

Sect. 5.4: *“Precision indicates the proportion of detected lakes or pixels that correctly match reference lakes, recall measures the proportion of reference lakes or pixels that are captured, and F1 provides a balanced measure of both.”*

L. 486: ‘recall’. It has already been mentioned earlier on several occasions (e.g. L. 230, 250 etc). It should be defined earlier on these first instances (and not here).
The term “recall” is indeed introduced earlier in the manuscript before being formally defined in Sect. 5.4. To improve readability, a brief definition will be provided at its first occurrence in Sect. 4.3.

Sect. 4.3: *“Hyperparameters were optimized to maximize recall (i.e. the proportion of reference lakes successfully detected) for the lake class while maintaining overall accuracy, reflecting our priority of detecting all possible glacial lakes in the study area.”*

L. 526-527: ‘This reflects the progressive development of new depressions exposed by glacier retreat’. See Major Comments: these glacier-lake relationships have not been properly argued through this discussion.
This comment is consistent with the reviewer’s major remarks regarding glacier–lake relationships. As the present study does not explicitly quantify glacier retreat or glacier-lake interactions at the individual-lake scale, the original interpretation may overstate the causal relationship. The corresponding discussion will therefore be revised to focus on observed spatial and temporal patterns rather than on glacier-driven mechanisms that were not directly evaluated.

Sect. 6.1: *“This pattern is particularly evident in the Terskey and Kyrgyz ranges, where numerous newly detected lakes occur in high-elevation environments.”*

“Regions with extensive glacier coverage, such as Issyk-Kul, continue to host numerous small glacier-connected lakes, indicating a close spatial association between glacierized terrain and the occurrence of glacier-connected lakes.”

“One possible explanation is the generally faster response of smaller glaciers to climatic forcing, although this relationship was not explicitly evaluated in the present study.”

“Such changes may reflect the progressive redistribution of supraglacial water bodies at higher elevations.”

“The strongest changes were observed among glacier-connected lakes, whereas glacier-detached lakes remained comparatively stable throughout the study period.”

“Similar patterns have been reported in other glacierized mountain regions, where recent lake changes are often concentrated among small, high-elevation lakes, while larger lakes tend to remain comparatively stable (e.g., Wang et al., 2020; Izagirre et al., 2025).”

Sect. 6.2: *"Overall, the inventories provide a detailed reference for national- and sub-regional-scale analyses."*

Sect. 7: *"These small lakes, though individually minor, represent the most dynamic and numerous components of Kyrgyzstan's glacial lake."*

"Overall, lake expansion exceeded shrinkage during the study period."

"The subtle increase in supraglacial lake size and upward shift in elevation suggest ongoing changes within high-elevation glacierized environments. Such changes further highlight the sensitivity of small lakes to micro-topographic and hydrological conditions."

"Our analysis revealed that the smallest and most numerous glacial lakes exhibited the most pronounced changes between 2016 and 2024, while also being the most challenging to detect automatically."

"These inventories provide a valuable basis for improving automated mapping approaches and for supporting future investigations of cryospheric change in Central Asia."

L. 526: 'progressive development of new depressions'. The depressions were already present before the glacier retreat. 'development' should be replaced e.g. by 'exhumation'.
The original sentence has been removed and replaced by a more descriptive interpretation. This revision avoids assumptions regarding the origin of the depressions while remaining consistent with the observed spatial patterns and the reviewer's previous comments regarding glacier–lake relationships.

Sect. 6.1: *"This pattern is particularly evident in the Terskey and Kyrgyz ranges, where numerous newly detected lakes occur in high-elevation environments."*

L. 529: 'highlighting the role of glacier retreat in creating new depressions'. Idem, please replace 'creating' by e.g. 'liberating'.
As discussed above, the original statement implying the creation of new depressions has been removed. The revised text instead focuses on the observed spatial association between glacierized terrain and glacier-connected lakes without inferring a specific geomorphological mechanism.

Sect. 6.1: *"Regions with extensive glacier coverage, such as Issyk-Kul, continue to host numerous small glacier-connected lakes, indicating a close spatial association between glacierized terrain and the occurrence of glacier-connected lakes."*

L. 535-536: 'Supraglacial lakes showed slight increases in median area and an upward shift in elevation, consistent with the retreat of ice surfaces'. Can this be clearly related to the respective 2016 and 2024 glacier status (e.g. using the RGI)? If not, this is speculative.
We agree that the original statement may be overly speculative, as glacier changes between 2016 and 2024 were not explicitly quantified in the present study. The corresponding sentence will therefore be revised to avoid implying a direct relationship between the observed changes in supraglacial lakes and glacier retreat.

Sect. 6.1: *"Supraglacial lakes showed slight increases in median area and an upward shift in elevation. Such changes may reflect the progressive redistribution of supraglacial water bodies at higher elevations."*

L. 537-538: 'gains from supraglacial-to-proglacial transitions were broadly balanced by losses as some proglacial lakes became glacier-detached'. Idem – this is to be demonstrated. See Major Comments on this, as well as comment on L. 371-372 as rivers could flow out of the lake, keeping the water level balanced.
We agree that this interpretation remains speculative, as transitions between lake categories were not explicitly tracked. The corresponding sentence will therefore be modified as follows:

Sect. 6.1: *"Proglacial lakes remained relatively stable in both size and elevation despite substantial changes observed in the other lake categories."*

L. 540: please add 'lake' before 'expansion'.
Sect. 6.1: *"In general, lake expansion dominated over shrinkage, suggesting that ongoing glacier retreat continues to foster the formation of new lakes in supraglacial and proglacial settings, and that losses are spatially localized."*

L. 544-545: 'topography becomes the key limitation, as observed for example in the Tropical Andes where glaciers have lost more than 50 % of their LIA area and the topographic potential for new lake formation is now fairly limited (Emmer et al., 2020)'. I do not see why this reference is used in this Central Asian context, and how this related to this part of the discussion. Should another reference be used? Is this sentence necessary?
We agree that this example is not essential in the present context and we will remove it from the revised manuscript.

L. 573-574: 'This is reflected by the high precision and recall values'. How can this be reflected if some lakes were not detected in the other datasets? Or is this related to the efficiency of the Random Forest classification? Please clarify.
Thank you for this clarification request. The original wording was indeed ambiguous and could incorrectly suggest that the larger number of lakes detected in our inventories was demonstrated by the precision and recall metrics. The corresponding paragraph has therefore been revised for clarification.

Sect. 6.2: *"This difference is primarily attributable to the systematic manual refinement of lake boundaries and the inspection of the entire study area. Despite these differences in lake counts, the inventories show relatively high precision and recall values (up to 0.85 and 0.73, respectively), together with the high percentages of reference lakes covered, and compared lakes matched."*

L. 660: 'The original manuscript was refined using ChatGPT'. For transparency, please explain in which ways.
For transparency, we will clarify that ChatGPT was used exclusively for language editing, grammar correction, and improvement of readability. All scientific analyses, interpretations, results, and conclusions were developed and validated by the authors.

Acknowledgments: *"The original manuscript was refined using ChatGPT for language editing, grammar correction, and readability improvements. All scientific analyses, interpretations, results, and conclusions were developed and validated by the authors. The* *revised manuscript was later checked by a native English speaker. The authors would like to thank Robert Dennen for proofreading the article.”*

Given the comments above, my overall impression is that this manuscript is not yet mature for publication and should be resubmitted after major revision.
We appreciate the detailed comments and have carefully considered all suggestions to improve the clarity, methodology, and interpretation of the manuscript.