

Response to Reviewer Comments

Manuscript: egusphere-2025-1198

Introducing a new normalized cryospheric index (NCI) to categorize sub-watersheds on arid environments

Christopher Ulloa, Ayon García, Anouk Beniest

Dear Editor and Reviewer,

We sincerely thank the Reviewer and the Editor for the thorough and constructive evaluation of our manuscript. The comments have been instrumental in improving the clarity, structure, and internal consistency of the paper. Below, we provide a detailed point-by-point response to each comment raised by Reviewer 1. All changes have been implemented in the revised manuscript and are highlighted using track changes. Reviewer comments are presented in italics, and our responses are in regular text. Specific changes to the manuscript are indicated in blue.

Response to Editor

Thank you very much for the careful revisions. I am in line with the reviewer that the study has clearly improved, but that there are still several issues left. Please address all comments and suggestions in the revised manuscript carefully and provide a detailed point-to-point reply to each comment along with a track changes version of the manuscript. Please make sure that the response letter and the manuscript are consistent, i.e. that the information in the reply is also considered in the revised version of the manuscript as highlighted by the reviewer.

We thank the Editor for their guidance. We have carefully addressed all comments from Reviewer 1 and ensured full consistency between this response letter and the revised manuscript. A track changes version of the manuscript is provided alongside this response. Below we detail each modification.

Response to Reviewer 1

Comment 1: Overall structure and organization

The authors have substantially improved the manuscript by incorporating state-of-the-art datasets, including ice thickness and volume estimates. This clearly strengthens the study. The manuscript also presents valuable data that could make an important contribution and is likely worthy of publication. However, the paper still lacks a clear overall structure and better organization. At present, several sections appear disordered, and some information is repeated across the manuscript. This affects the readability and makes it difficult to follow the main narrative and identify the key contributions of the study. In particular, the authors should do more to highlight the most relevant findings and better separate background information, methods, and results.

We thank the Reviewer for acknowledging the improvements and for this important feedback. We agree that the manuscript required a substantial reorganization. In the revised version, we

have implemented a comprehensive restructuring of the manuscript following the Reviewer's specific suggestions. The revised structure is as follows:

The manuscript has been reorganized into the following structure: 1. Introduction (unchanged in scope) 2. Regional Setting 2.1 Study Area (moved from Section 3.1 of the Methodology) 2.2 Hydrological background of the cryosphere and conceptual framework for ice-volume estimation 2.3 Glacier and Periglacial Environment Mapping (moved from Results Section 4.1, as these are pre-existing inventories that form the foundation for the volume estimations) 3. Methodology 3.1 Survey of cryospheric water reserves (previously 3.2) 3.2 Survey of cryospheric resources: MODIS-derived snow permanence (previously 3.3) 3.3 Field work for ground truthing (previously 3.4) 3.4 DInSAR kinematic analysis (previously 3.5) 3.5 Calculation of ice volume and uncertainty (previously 3.6) 3.6 Normalized Cryospheric Index (NCI) formulation (previously 3.7) 4. Results 4.1 Snow permanence results 4.2 Analysis of runoff 4.3 Field survey observations 4.4 Geophysical results 4.5 Thickness estimations on periglacial environment 4.6 Ice volumes, snow area and NCI for sub-watersheds 5. Discussion 6. Conclusions.

We have also carefully reviewed the entire manuscript to eliminate redundancies and repeated information across sections. Background information has been consolidated in the Regional Setting section, while Methods and Results are now clearly separated.

Comment 2: Justification for “reservoir” and “reserve” concepts

I also still do not see a strong justification for introducing the concepts of reservoir and reserve in this context. It is unclear what these terms add to the analysis. Why not simply refer to cryospheric landforms and snow, which seem more direct and consistent with the rest of the manuscript?

We thank the Reviewer for this valuable comment. We agree that the introduction of the terms “cryospheric reserves” and “cryospheric resources” may add unnecessary conceptual complexity and could be perceived as inconsistent with standard terminology used in cryospheric and hydrological studies.

Following the Reviewer's suggestion, we have revised the manuscript to adopt more direct and widely used terms. Specifically, we have replaced:

“cryospheric reserves” → cryospheric landforms (including debris-free glaciers, debris-covered glaciers, rock glaciers, gelifluction taluses, and protalus lobes), and

“cryospheric resources” → snow (or seasonal snow, where appropriate).

These changes have been applied consistently throughout the manuscript.

Importantly, this modification does not affect the conceptual framework of the NCI. The distinction between long-term ice storage and seasonal snow contribution is still preserved in the formulation of the index through the independent weighting of each component. However, this distinction is now expressed explicitly in terms of cryospheric landforms versus snow, avoiding the introduction of additional terminology.

We believe that this revision improves the clarity, consistency, and accessibility of the manuscript while maintaining its physical and hydrological interpretation. We have also removed the term “reservoir” from the abstract and main text to prevent confusion, replacing it consistently with “cryospheric landforms”. The manuscript thus uses “cryospheric landforms” for the long-term ice-storage component and “snow” (or “snow permanence”) for the seasonal component, in agreement with the Reviewer’s suggestion to adopt direct, widely used terminology.

Comment 3: Duplication and inconsistency in section organization

There is also some duplication and inconsistency in the organization of the regional setting, study area, methods, and results. For example, the study area is currently presented in the methodology section, while the manuscript uses previous inventories that are later presented in the results section under Glacier and Periglacial Environment Mapping. If these inventories are primarily the basis for the analysis, they would fit better in an earlier section.

We agree entirely with this observation. In the revised manuscript, we have implemented the following changes: (a) **The Study Area** (previously Section 3.1 within Methodology) has been moved to become Section 2.1 under the Regional Setting. This provides the reader with the geographic and physiographic context before any methods are introduced. (b) **The Glacier and Periglacial Environment Mapping** (previously Section 4.1 in Results) has been moved to become Section 2.3 under the Regional Setting. As the Reviewer correctly identified, this section primarily describes pre-existing inventories (García et al., 2017; RGI v6.0) that form the foundation for the volume estimations. Presenting them before the Methodology provides the reader with the necessary base information to understand the subsequent analytical steps. [The revised Regional Setting section now follows this order: 2.1 Study Area 2.2 Hydrological background of the cryosphere and conceptual framework for ice-volume estimation 2.3 Glacier and Periglacial Environment Mapping.](#)

We have also carefully reviewed the entire manuscript to remove duplicated information that previously appeared in multiple sections. Descriptions of cryoform types, for example, are now consolidated in Section 2.3 and not repeated in the Results.

Comment 4: Inconsistencies between the response letter and the manuscript

In addition, there seem to be inconsistencies between the response letter and the manuscript itself. In the response letter, the authors state that they follow the Kirkbride definition, but this is not clearly reflected in the main text. They also mention that the approach was modified or adjusted to the RGIK framework, yet this is also not clearly explained in the manuscript. These conceptual and methodological aspects should be explicitly stated in the paper, not only in the response letter.

We sincerely apologize for this oversight. The Reviewer is correct that these conceptual aspects were mentioned in our previous response letter but not adequately reflected in the manuscript. We have now rectified this by explicitly incorporating these definitions into the revised text. Specifically: (a) **Kirkbride definition:** We have added an explicit statement in Section 2.2 (Hydrological background of the cryosphere and conceptual framework for ice-volume estimation) clarifying that our classification of debris-covered glaciers follows the Kirkbride (2011) definition, in which a debris-covered glacier is defined as a glacier whose ablation zone is

largely or entirely covered by supraglacial debris. This distinguishes them from rock glaciers, which are permafrost landforms with internal ice deformation. Added text in Section 2.2: “The classification of debris-covered glaciers adopted in this study follows Kirkbride (2011), who defines them as glaciers whose ablation zone is largely or entirely mantled by supraglacial debris. This distinction is important in the study area, where debris-covered glaciers occur in close spatial association with rock glaciers but represent fundamentally different cryospheric processes.”

We thank the Reviewer for raising the question of consistency with the RGIK (Rock Glacier Inventories and Kinematics) framework. The inventory of García et al. (2017) was carried out and published before the RGIK guidelines (developed by the IPA Action Group from 2020 onwards) became available, so the inventory cannot strictly follow RGIK protocols by date of publication. Nevertheless, an a posteriori comparison shows that García et al. (2017) is methodologically coherent with the principles later formalized by RGIK, with three substantive extensions:

(i) Mapping workflow. García et al. (2017) combined medium-resolution multispectral imagery (Landsat 4–5 TM, 7 ETM+, 8 OLI), high-resolution satellite imagery (Quickbird, IKONOS via Google Earth/ESRI), and the ASTER GDEM v2 with field reconnaissance — the same multi-source approach recommended by RGIK for rock-glacier inventories.

(ii) Diagnostic criteria and activity status. The identification of rock glaciers in García et al. (2017) relied on standard geomorphological indicators (front-ramp angle $>30^\circ$, longitudinal furrows and ridges, lobate/tongue-shaped outlines), and only "active" rock glaciers were retained. This is consistent with the RGIK distinction between active and relict landforms, although a continuous activity scale (active / transitional / relict) following RGIK had not yet been formalized.

(iii) Database structure. Polygons were given unique identifiers following the GLIMS convention and stored with the morphometric attributes required by RGIK (area, perimeter, centroid coordinates, mean slope, aspect, mean elevation).

The inventory differs from a strict RGIK rock-glacier inventory in that it explicitly includes two additional ice-rich permafrost landforms — gelifluction taluses and protalus lobes — which are not part of the RGIK rock-glacier scope but constitute the dominant cryospheric components of the arid Atacama cryosphere (97% of the total ice-bearing periglacial area in the region). This extension is therefore a deliberate adaptation to the regional cryosphere, not a deviation from RGIK methodology, and we have made this distinction explicit in the revised Section 2.3 of the manuscript. Added text in Section 2.3 “The regional inventory of García et al. (2017) predates the RGIK (Rock Glacier Inventories and Kinematics; IPA Action Group) guidelines, but its mapping workflow, multi-source satellite photo-interpretation supported by field reconnaissance, identification of active rock glaciers from diagnostic geomorphological criteria (frontal ramp, furrows and ridges), and a GLIMS-compatible attribute database, is methodologically consistent with the principles later codified by RGIK. The inventory extends this scope to include gelifluction taluses and protalus lobes, two ice-rich permafrost landforms that dominate the arid Atacama cryosphere but fall outside the RGIK rock-glacier framework”.

Comment 5: Suggested restructuring of the manuscript

I would suggest restructuring the manuscript, particularly the regional setting and methodological framework, in the following order: Regional setting: Study area (currently placed in the methodology section); Hydrological background of the cryosphere and conceptual framework for ice-volume estimation; Glacier and Periglacial Environment Mapping (If this section mainly summarizes previously developed inventories that form the basis of the volume estimations, it would be more appropriate to place it before the results section). More generally, Sections 3.2 to 3.6 should be reorganized, especially if the inventories constitute the foundation for the volume estimations. At present, the logic of the manuscript is difficult to follow because the base information for the analysis is introduced too late.

We fully agree with this suggestion and have implemented the restructuring exactly as proposed by the Reviewer. The revised manuscript now follows this order: **Section 2: Regional Setting** 2.1 Study Area – Moved from Section 3.1 (Methodology). This section now opens the Regional Setting by providing the geographic context, the definition of sub-watersheds, and the criteria for identifying cryospheric sub-watersheds. 2.2 Hydrological background of the cryosphere and conceptual framework for ice-volume estimation – Remains in its original position but now includes the explicit references to the Kirkbride definition and RGIK framework (see Comment 4). 2.3 Glacier and Periglacial Environment Mapping – Moved from Section 4.1 (Results). This section describes the pre-existing cryoform inventories that serve as the foundation for the ice-volume estimations, and is therefore presented before the Methodology. **Section 3: Methodology** Sections 3.1 through 3.6 now follow a logical sequence: (1) survey of cryospheric reserves, (2) survey of cryospheric resources (snow), (3) field validation, (4) DInSAR kinematic analysis, (5) ice-volume calculation, and (6) NCI formulation. The base information (inventories, study area) is now presented before the methods, so the reader understands what data are being used before the analytical procedures are described. **Section 4: Results** The Results section now begins with new results (snow permanence, runoff analysis, field observations, geophysical surveys, thickness estimations, and NCI calculation), without repeating background information on the inventories. [This restructuring ensures that the logical flow of the manuscript proceeds from context \(Regional Setting\) → base data \(inventories\) → methods → results → discussion → conclusions, directly addressing the Reviewer's concern that the base information for the analysis was introduced too late.](#)

Comment 6: Overall assessment and internal consistency

Overall, the manuscript has clear potential and includes valuable information, but substantial improvements in structure, clarity, and internal consistency are still needed before publication.

We thank the Reviewer for this overall assessment and for the specific and constructive suggestions provided. We believe that the comprehensive restructuring implemented in this revision, together with the explicit incorporation of the Kirkbride definition and RGIK framework references, has substantially improved the manuscript's structure, clarity, and internal consistency. We have also ensured that all information presented in this response letter is fully reflected in the revised manuscript, as requested by the Editor. A summary of all major changes implemented: 1. Complete restructuring of the manuscript following the Reviewer's suggested order. 2. Study Area moved from Methodology to Regional Setting (new Section 2.1). 3. Glacier

and Periglacial Environment Mapping moved from Results to Regional Setting (new Section 2.3). 4. Explicit incorporation of the Kirkbride (2011) debris-covered glacier definition in Section 2.2. 5. Explicit incorporation of the RGIK framework reference in Section 2.3. 6. Clearer justification for the reserve/resource distinction in Section 2. 7. Elimination of duplicated information across sections. 8. Full consistency between this response letter and the revised manuscript.

We hope that the revised manuscript now meets the standards of the journal. We remain available to address any additional comments or suggestions.

Sincerely,

Christopher Ulloa, Ayon García, and Anouk Beniest