

## **Reply to editor**

Thank you for submitting the revised manuscript. Both referees acknowledge that the manuscript has improved substantially, particularly in its organization around the SAP framework and in the expanded discussion of active layer, thermokarst, and groundwater processes.

However, further revision is still required before the manuscript can be considered for final publication. Referee #1 recommends minor revisions, mainly concerning clarification of terminology, figures, tables, and several quantitative statements. Referee #3 also recognizes the improvements but raises more substantive concerns about the transparency of the review methods, the implementation of the evidence synthesis, and the characterization of the 225 studies included in the review.

Please revise the manuscript with particular attention to the following points:

1. Clarify the review methodology, especially how information was extracted, coded, grouped into themes, compared across studies, and synthesized.
2. Strengthen the synthesis throughout the manuscript so that the main findings, mechanisms, boundary conditions, regional contrasts, and uncertainties are more clearly visible to readers.
3. Provide a clearer overview of the literature base, preferably through a supplementary table listing the studies included in the synthesis and their key attributes.
4. Address the specific comments from Referee #1, including clarification of the SAP framework conclusions, the term “large scale,” the treatment of water tracks, Table 1 terminology, figure clarity, and quantitative statements such as the linearity of active-layer effects and the 40% ground-ice threshold.

Please submit a detailed response letter explaining how each referee comment has been addressed. Depending on the extent of the revisions, the manuscript may be returned to the referees for further evaluation.

## **Our response:**

We thank the Editor for handling our manuscript and for the encouraging assessment that both referees acknowledge the substantial improvements. We have addressed all remaining concerns raised by Referee #1 and Referee #3 in the following detailed responses. In particular, we have:

1. Enhanced the review methodology section with a more concrete description of how information was extracted, coded, grouped into themes, compared across studies, and synthesized (all the revisions were marked in Section 2).
2. Strengthened the synthesis throughout the manuscript by adding concise summary tables, structured end-of-section summaries, and clearer articulation of key findings, mechanisms, boundary conditions, regional contrasts, and uncertainties. (Details were in the end of Sections 3, 4, and 5. Marked in Lines 267-274, 405-413, and 739-748, respectively)
3. Prepared a supplementary table 1, which listing the 225 studies included in the synthesis with their key attributes (study region, permafrost type, hydrological focus,

method, spatial scale, and whether quantitative data were reported).

4. Addressed all specific comments from Referee #1, including clarification of the SAP framework conclusions, the term "large scale," the treatment of water tracks, Table 1 terminology, figure clarity, and quantitative statements such as the linearity of active-layer effects and the 40% ground-ice threshold. (The corresponding revisions were detailed described in the following point-by-point response to referee #1 and Referee #3)

## Response to referee #1

### General comments

Thank you for the opportunity to review the revised manuscript again. Compared with the previous version, the manuscript has been improved in several aspects. The overall organization around the proposed Surface Active Layer Permafrost (SAP) framework is clearer, additional conceptual figures have been included, and the discussions of active layer processes, thermokarst, and groundwater processes have been expanded. However, several points still need further clarification.

### Major comments

(1) The Abstract mainly describes the topics covered under the three dimensions, but it does not clearly explain why the SAP framework is used or what conclusions are drawn from this framework.

**Our response:** We agree with the reviewer that the Abstract should more clearly articulate the rationale for the SAP framework and the main conclusions drawn from it. We have revised the Abstract to include a statement on the framework's purpose and its key findings (lines 19-32).

(2) The Abstract refers to "large scale permafrost hydrology", and Section 3.4 also uses the heading "Large scale permafrost hydrological processes". However, the manuscript does not clearly define what "large scale" means. The authors should clarify this term and further explain whether hydrological processes at slope or headwater scales differ from hydrological responses at larger basin or regional scales.

**Our response:** The reviewer raises an important point. We have clarified the definition of "large scale" in both the Abstract and Section 3.4. In the context of this review, "large scale" refers to basin to regional scales (typically  $>10^2$ – $10^4$  km<sup>2</sup>), as distinguished from plot, hillslope, and watershed ( $10^0$ – $10^2$  km<sup>2</sup>) scales. How hydrological processes differ across these scales also was added in the section (lines 234-240).

(3) In the first paragraph of the Introduction, water tracks are highlighted, but they are not adequately addressed later in the manuscript. The paragraph describes water tracks as critical conduits for water and sediment flux across hillslopes, but their role in permafrost hydrological processes is not further discussed.

**Our response:** We all agree with the opinion, and we have added a dedicated discussion of water tracks in Section 3.2 (Hillslope hydrological processes), including

their definition, hydrological significance, and relationship to permafrost degradation.

(4) In the second paragraph of the Introduction, the influence of permafrost on hydrological processes is still not sufficiently explained. The paragraph first emphasizes the importance of permafrost for hydrological processes in mountainous basins, but then focuses mainly on estimates of ground ice storage. This may suggest that the hydrological role of permafrost is mainly related to ground ice storage, rather than active layer changes, infiltration processes, and hydrological connectivity.

**Our response:** We thank the reviewer for this observation. We have revised the second paragraph of the Introduction to provide a more balanced presentation of permafrost's hydrological roles, including active layer dynamics, infiltration processes, and hydrological connectivity, in addition to ground ice storage.

(5) The Method column in Table 1 is not consistently defined. It includes specific analytical methods, such as runoff partitioning based on isotopes and electrical conductivity and hydrograph separation, but also includes data sources, such as long term discharge records, and nonspecific entries, such as multiple methods. The authors should clarify the meaning of this column.

**Our response:** We agree that the Method column in Table 1 needs clarification. We have revised the column to consistently describe the analytical approach used to derive the reported contribution value, rather than mixing data sources with analytical methods.

(6) The title of Section 3.3 does not fully match the content of the section. The section is titled “River channel hydrological processes”, but much of the text discusses riverbank retreat, lateral channel migration, floodplain subsidence, channel geometry, and channel morphology.

**Our response:** We appreciate this opinion. We have revised the title of Section 3.3 to “River channel morphology and hydrological processes” to better reflect its content. We have also added a brief introductory sentence to clarify the connection between channel morphology and hydrological processes: Seasonal changes in channel morphology are becoming more pronounced in permafrost-controlled valleys, *with important implications for hydrological connectivity, flow routing, and sediment transport*.

(7) In Section 4.1, the description of active layer hydrological processes appears too deterministic. The authors write that “Groundwater storage and flow capacity increase linearly with active layer depth”. The use of “linearly” implies a strong quantitative relationship. The authors should provide clear evidence for this linear relationship or revise the wording.

**Our response:** The reviewer is correct that the use of “linearly” implies a specific quantitative relationship that may not be universally supported by the literature. We have revised this statement to reflect the more general understanding that groundwater storage and flow capacity increase with active layer depth, while acknowledging that

the relationship may be nonlinear and context-dependent. Lines 295-299: *“Groundwater storage and flow capacity generally increase with active layer depth, although the relationship may be nonlinear and is modulated by factors such as soil texture, organic matter content, and ground ice distribution (Wang et al., 2017; Sjöberg et al., 2021). Consequently, subsurface runoff gradually increases, and surface runoff coefficients decrease as the active layer deepens.”*

(8) In Section 4.1, the wording “active layer functioned as an impermeable barrier” needs clarification. During the early thaw phase, snowmelt infiltration is usually limited by frozen soil rather than by the active layer as a whole. The active layer is a seasonally freezing and thawing soil layer, so this wording may confuse the active layer with the frozen soil that limits infiltration.

**Our response:** We agree that the wording was imprecise. We have revised the relevant sentence to clarify that it is the still-frozen portion of the active layer (i.e., the frozen layer near the permafrost table) that acts as the barrier to infiltration, not the entire active layer. The relevant sentence has been revised to *“During this stage, the still-frozen portion of the active layer acted as an impermeable barrier, leading to high surface runoff coefficients and substantial snowmelt runoff.”* (In line 290)

(9) In Figure 2, the representation of surface soil moisture is ambiguous. The surface soil in the initial thawing stage is shown as wet, whereas the late thawing stage and completely thawed stage are marked as dry soil. However, the soil moisture versus soil depth plot below the figure shows higher surface soil moisture in the late thawing and completely thawed stages than in the initial thawing stage. The authors should check the dry soil and wet soil labels and clarify the correspondence between soil moisture and the different thawing stages.

**Our response:** We thank the reviewer for this careful observation. We have revised Figure 2 to correct the inconsistency between the schematic representation of soil moisture and the soil moisture profiles. The labels have been updated to reflect that surface soil moisture is generally lower in the late thawing and completely thawed stages due to increased drainage and evapotranspiration, while the deeper active layer (near the permafrost table) retains higher moisture.

(10) The title of Section 5.1 does not fully match the content of the section. The section is titled “Transformation relationships between surface water and groundwater in permafrost regions”, but the discussion mainly focuses on water age determination and geophysical exploration. The section currently emphasizes methods rather than the related hydrological mechanisms.

**Our response:** We all agree the reviewer’s opinion, and the Section 5.1 have been rewritten. In the revised section, the content was focused on the hydrological mechanisms of “Transformation relationships between surface water and groundwater”. All the revisions were marked in lines 462-523.

(11) In the third coupling point of Section 6, the basis and applicability of the 40%

ground ice content threshold need further clarification. The authors use a volumetric ice content of approximately 40% as a key threshold affecting hydraulic conductivity, but this is a strong quantitative statement. If the authors consider this threshold applicable to other permafrost regions, they should provide additional references or further discuss its applicability across different permafrost catchments.

**Our response:** The reviewer raises an important point. We have revised the discussion of the 40% threshold to acknowledge that this value is derived from specific field and may not be universally applicable across all permafrost regions (Lines 764-768).

#### Detailed comments

(1) Some lines in Figures 2, 3, and 4 are not sufficiently clear. The authors should improve the figure resolution and make the arrow lines easier to distinguish.

(2) In Figure 2, the meaning of the dark blue water body is not clear. Does it represent groundwater storage? No corresponding legend is provided in the figure. In addition, from the mid thaw stage to the completely thawed stage, the dark blue water body appears to decrease. The authors should clarify whether this indicates a decrease in groundwater with active layer deepening.

(3) The terminology in Table 1 is not fully consistent. For the same reference, the Huangheyan station is described as “Permafrost thaw water contribution to annual runoff”, whereas the Tangnaihahai station is described as “Permafrost meltwater contribution to annual runoff”. The authors should check the use of “melt” and “thaw” throughout the manuscript and standardize the related terminology.

(4) In Section 7.2, the relationship between active layer hydrological processes and suprapermfrost hydrological processes needs further clarification. The manuscript discusses active layer hydrological processes and then refers to the suprapermfrost water system. The authors should clarify whether these terms refer to the same type of process or to different processes within the active layer and the suprapermfrost water system.

**Our response:** (1) we have regenerated all these figures at higher resolution and have enhanced the contrast of arrow lines and labels. The revised figures have been uploaded with the manuscript. (2) We have revised Figure 2 by enhancing the contrast of arrow lines and labels. The dark blue water body represents suprapermfrost groundwater within the active layer. The apparent decrease in this water body from the mid-thaw to the completely thawed stage reflects the fact that as the active layer deepens, stored water is gradually released as subsurface flow, leading to a decline in the suprapermfrost water table. This is consistent with the hydrological dynamics described in the text. In addition, we also have added some sentences to clear the meaning in the first paragraph of Section 4.1 (Lines 304-308). (3) We have standardized the terminology in Table 1 and throughout the manuscript to consistently use “thaw” for the process of permafrost ice converting to liquid water and “melt” for the corresponding water released. The Huangheyan and Tangnaihahai entries have been unified as “Permafrost thaw water contribution to annual runoff.” (4) We thank the reviewer for this clarification. Active layer hydrological processes and

suprapermafrost hydrological processes are closely related but not identical. The active layer is the seasonally thawed soil layer above the permafrost table, and active layer hydrological processes refer to water movement within this layer (infiltration, soil moisture dynamics, interflow). Suprapermafrost hydrological processes refer more specifically to the behavior of the groundwater system that sits immediately above the permafrost table (the suprapermafrost aquifer), which is recharged from the active layer and discharges to streams. The active layer provides the conduit and storage medium for suprapermafrost water. We have added a clarifying sentence in Section 7.2 (Lines 874-877).

### **Response to referee #3**

I did not participate in the first round of review for this manuscript, so I have tried to focus my assessment primarily on whether the authors have adequately addressed the concerns raised by the two original reviewers, rather than introducing an extensive set of new issues at this stage. At the same time, after reading the revised manuscript and the response letter, I found that some of the remaining issues identified by the first-round reviewers also correspond to my own reading experience. In particular, I still feel that the manuscript would benefit from greater methodological transparency, clearer synthesis of the reviewed evidence, and a more informative overview of the literature base.

Overall, the authors have clearly made substantial revisions. They have added a new Review Methods section, reorganized several major sections, introduced a quantitative summary table, and strengthened the discussion of mechanisms and boundary conditions. These changes have improved the manuscript and show that the authors have taken the first-round comments seriously. However, in my view, several aspects of the response remain only partially satisfactory.

**Our response:** We thank the reviewer for the thoughtful assessment and the constructive suggestions for improving methodological transparency and synthesis. Below we address each comment in turn.

First, the newly added Review Methods section is a useful improvement, but I still find the description of the evidence extraction and synthesis procedure somewhat general. The authors state that key information was extracted into a standardized spreadsheet and that a narrative synthesis approach was followed. However, as a reader, I cannot clearly see how this narrative synthesis was actually implemented. For example, it remains unclear how the extracted information was coded or grouped into themes, how conflicting findings were compared or interpreted, how qualitative evidence was integrated with quantitative evidence, and whether any cross-checking was conducted during study selection or data extraction. This concern is related to the first-round request for more reproducible review-method details, but I also think it is important for the readability and credibility of the manuscript itself. I recommend that the authors provide a more concrete description of the synthesis workflow, rather than only referring to a general narrative synthesis approach.

**Our response:** We thank the reviewer for this important suggestion. We have

substantially expanded the Review Methods section to provide a more concrete and transparent description of the synthesis workflow, including coding procedures, thematic grouping, handling of conflicting findings, integration of qualitative and quantitative evidence, and quality assurance measures. A new section “2.4 Synthesis workflow” was added in the manuscript.

Second, I have some concerns about the way Table 1 is introduced and about the broader presentation of synthesis throughout the manuscript. In Section 2, the authors directly refer to Table 1 when describing the review method. In my opinion, the methods section should describe the general procedure for compiling comparable evidence, rather than pointing to a specific result table at this early stage. More importantly, although the addition of Table 1 partly responds to the previous reviewer’s comment, I do not think the issue is limited to that specific table or to the previous Section 4.3 alone. My own impression is that many parts of the manuscript still read as long narrative compilations of individual studies, while the key take-home messages are not always sufficiently visible. The manuscript would be strengthened if the authors added concise summary tables, synthesis boxes, or more structured end-of-section summaries where appropriate. These do not need to be limited to quantitative contribution rates; they could also summarize key mechanisms, boundary conditions, regional contrasts, methodological limitations, and remaining uncertainties across the major sections. Such additions would help the review move further from a literature listing toward a more synthetic and reader-friendly contribution.

**Our response:** We thank the reviewer for this constructive criticism. We have made several changes to address these concerns. (1) We have revised the reference to Table 1 in Section 2. The methods section now describes the general procedure for compiling comparable evidence without pointing to the specific result table. The revised sentence “Where multiple studies reported comparable metrics (e.g., ground ice melt contribution to runoff), we compiled the values to identify ranges and patterns. These compiled results are presented in a summary table (Table 1) in the results section” were marked in Line 154-156. (2) We have revised structured end-of-section summaries for Sections 3, 4, and 5, each highlighting key take-home messages, mechanisms, boundary conditions, and remaining uncertainties. (Lines 267-274, 405-413, and 739-748)

Third, I think the manuscript should provide a clearer overview of the studies included in the review. The revised manuscript states that 225 records were retained for the final synthesis, but it does not sufficiently characterize this body of literature. For a manuscript presented as a comprehensive systematic review, readers should be able to understand what these included studies are, when they were published, which journals or source types they came from, which regions and permafrost types they cover, and what methods or hydrological processes they address. I therefore recommend that the authors include a supplementary table listing the studies retained for the synthesis. This list should be distinct from the general reference list, because not every cited reference necessarily represents an included study used in the evidence

synthesis. The supplementary table could include, at minimum, author/year, title, journal or source, study region, permafrost type, hydrological focus, method, spatial scale, and whether quantitative hydrological data were reported.

**Our response:** We agree with the reviewer that a comprehensive overview of the included literature would significantly enhance transparency and credibility. We have prepared a Supplementary Table S1 listing all 225 studies retained for the final synthesis, with the following columns: author/year, title, journal/source, study region, permafrost type, hydrological focus, method, spatial scale, and whether quantitative hydrological data were reported.