

Dear editor and the two reviewers,

We sincerely thank you for your hard work and constructive comments which have significantly helped us improve our manuscript. We have carefully considered all comments and have prepared a revision that addresses each point raised. Below, we provide a point-by-point response to the comments, describing the changes made in the revised manuscript.

Reply to reviewer 1

Comment 1: In Section 2.1 Impact of freeze-thaw cycles on surface runoff, the manuscript mainly discusses processes such as infiltration, active-layer storage, and subsurface runoff. Much of this discussion focuses on hydrological processes within the active layer, rather than surface hydrological processes. In addition, this section partly overlaps with Section 3.

Response: We have addressed this by reorganizing content so that new Section 3 (previous Section 2) focuses specifically on surface hydrological processes, including Snowmelt and rainfall surface runoff generation, hillslope hydrological processes, river channel processes, and large-scale surface water connectivity. In addition, we have moved active layer-specific discussions to new Section 4 (previous Section 3), where they belong. We also have eliminated overlap by ensuring that each process is discussed in only one location, with clear cross-references where integration is needed.

Comment 2: In Section 4.3 Impact of climate change on hydrology in permafrost regions: Increasing discharge and recharge to surface runoff, the section still focuses mainly on changes in baseflow and ground ice, while surface runoff is not analyzed in sufficient detail.

Response: Thanks and we agree with the comment. In the revised manuscript, new Section 5.3 now provides balanced coverage of both surface runoff and baseflow responses: (1) Temporal increasing in winter runoff (subsection 5.3.1): retains and enhances the previous baseflow discussion; (2) the spatial patterns and controls of surface runoff (new subsection 5.3.2): discusses increasing discharge and recharge to surface runoff, and add a new Table 2 shown quantitative synthesis of permafrost thaw contributions to runoff ; (3) Integration (subsection 5.3.3): discuss how surface and subsurface responses are linked through permafrost degradation. In the revisions, we have added some new references of surface runoff studies from the Arctic and Tibetan Plateau to strengthen this section.

Comment 3: In the Introduction, lines 49–64, the authors emphasize the impacts of permafrost degradation on ecosystems and hydrology, while the topics of this manuscript—surface runoff processes and the role of the active layer in runoff generation—are briefly addressed. In addition, the Introduction first discusses permafrost

degradation and then introduces surface runoff and active layer, which does not fully match the structure of the manuscript.

Response: We agree with the editor and have rewritten the Introduction to better balance the discussion of permafrost degradation impacts with the manuscript's core topics, and align the flow with the manuscript structure. In the revised Introduction, the impacts of permafrost degradation on ecosystems in previous lines 49–64 have been deleted.

Comment 4: The manuscript discusses baseflow changes in different regions under permafrost degradation. However, the discussion mainly focuses on describing findings from the literature, while the mechanisms controlling baseflow change are not sufficiently analyzed. For example, Line 152 suggests that permafrost degradation leads to increased runoff in the Arctic, whereas Line 514 reports a decreasing runoff trend in the Yarlung Zangbo River region. The manuscript does not sufficiently discuss the conditions under which different runoff trends occur.

Response: We have substantially strengthened the mechanistic analysis of baseflow changes. In the revised manuscript, we have added a new subsection (Section 5.3.3: "Mechanisms controlling baseflow responses") that systematically discusses active layer thickening and permafrost table lowering, talik formation and expansion, changes in subsurface hydraulic connectivity, ground ice melt contributions, and interactions with precipitation and evapotranspiration. We also explicitly addressed the contrasting trends noted by the reviewer. Arctic increases: attributed to widespread permafrost degradation, talik formation, and enhanced groundwater connectivity in low-relief landscapes; Tibetan Plateau decreases (in some basins): attributed to (a) complex topography limiting new flow path formation, (b) competing effects of warming on evapotranspiration, (c) possible groundwater depletion where recharge is limited, and (d) methodological differences in baseflow separation

Comment 5: Sections 4.2 and 4.3 partly overlap, as both address mechanisms of baseflow increase associated with permafrost degradation. Although Section 4.2 focuses on temporal trends and Section 4.3 emphasizes spatial variability related to permafrost coverage, the distinction between these perspectives is not always clear. Further clarification or synthesis of regional baseflow responses would improve the presentation.

Response: We have merged and reorganized these sections to eliminate overlap. In new Section 5.3 now comprehensively addresses permafrost degradation impacts on runoff, with clear subsections: 5.3.1: Temporal trends in runoff components (integrating previous Section 4.2 and parts of 4.3); 5.3.2: Spatial patterns and controls (focusing on permafrost coverage and regional variability); 5.3.3: Mechanistic synthesis (integrating both temporal and spatial perspectives). This structure maintains the distinction between temporal and spatial perspectives while clearly showing how they complement each other.

Comment 6: Although many studies are cited in Sections 2.1 and 4.2 to support the effects of permafrost degradation on surface runoff and baseflow, it would be helpful to include figures of runoff changes from typical catchments or analyses based on observation data. This would strengthen the conclusions and improve reader understanding.

Response: We thank the reviewer for this thoughtful suggestion. In the revised manuscript, we have added a new Table 1 to quantitative synthesis of permafrost thaw contributions to runoff and baseflow based on different typical catchments. In addition, we strengthen the manuscript through enhanced textual synthesis and more detailed discussion of existing observations. Specifically, we have: (1) Enhanced the quantitative and qualitative synthesis in new Sections 3.1 and 5.3 by providing more detailed descriptions of key observational studies, including explicit reporting of trend magnitudes, temporal patterns, and catchment characteristics. (2) Improved the narrative integration of observational findings by explicitly connecting them to the mechanistic processes discussed throughout the manuscript. For example, we now more clearly link observed baseflow trends in specific catchments to active layer thickening, talik development, and changes in subsurface connectivity. (3) Strengthened the discussion of regional patterns by synthesizing findings from multiple studies in a more structured and comparable manner within the text. This helps readers understand both the consistency and variability of observed responses across different permafrost environments.

Comment 7: In Section 5.1, the authors provide a future direction on the development of many observation approaches. However, the manuscript does not clearly identify which key hydrological fluxes remain poorly observed within the proposed framework, what the main limitations of current observational methods are, or how future techniques are expected to address these core challenges.

Response: We all agree with the reviewer's comments, and revised the new Section 7.1. We have substantially revised this part by addressing the key hydrological fluxes remain poorly observed within the SAP framework, and adding the method limitations and future expected techniques. This revision transforms the section from a general listing of methods to a targeted research agenda grounded in identified knowledge gaps.

Detailed Comments

Comment 8: In Lines 204–206, the authors refer to data from 2011–2012, but it is not clear what these data represent. The author should clarify these data and include an appropriate figure to help readers better understand their significance.

Response: We apologize for the lack of clarity. These lines referred to the research highlighted that permafrost melt contributing to the water in thermokarst lakes by Yang et al. (2016). To clear it, we have carefully revised these sentences in this part.

Comment 9: Line 110: The statement that "Increased spring-summer runoff is primarily driven by snowmelt and active layer thaw, whereas permafrost limits deep infiltration, leading to an increased groundwater contribution during thaw" is confusing. The manuscript suggests that limited infiltration under permafrost conditions leads to increased groundwater contribution. However, it is unclear whether "groundwater" here refers to shallow suprapermfrost water or deeper groundwater systems. The authors should clarify the hydrological compartment and explain the physical mechanism.

Response: We thank the reviewer for identifying this confusion. We have rewritten the section (now in Section 3.1) and that sentences have been deleted.

Comment 10: Line 134: The introduction of aufeis (icing) in this paragraph appears abrupt. While aufeis is an important indicator of winter groundwater discharge and water storage, there is not clearly direct relevance to the channel morphology and lateral migration. The authors should clarify the connection.

Response: We agree that the connection was unclear. We have restructured the paragraph (now in Section 3. 3) to first establish the channel morphology context, then introduce aufeis as a related but distinct phenomenon. We also added explanatory text: "Although aufeis is primarily a winter phenomenon, its spring melt can contribute to channel scour, sediment transport, and modification of channel geometry (Yoshikawa et al., 2007). For example, winter aufeis volumes account for 27–30% of the annual groundwater discharge in the Arctic Kuparuk River (Yoshikawa et al., 2007), representing a substantial water flux that, when released in spring, can affect channel stability and floodplain inundation. ". In addition, we have moved detailed aufeis discussion to Section 5.1 (groundwater-surface water interactions), where it is more logically placed, with a brief mention and cross-reference in the channel morphology section

Comment 11: Line 281: The manuscript states that permafrost type, underlying surface characteristics, topography, and soil composition are key variables controlling hydrological process. However, the subsequent discussion focuses mainly on soil and vegetation. The roles of permafrost type, underlying surface characteristics, and topography are not sufficiently analyzed. The authors should expand the other factors.

Response: We have significantly expanded new Section 4.2: "Key factors controlling hydrology processes in the active layer" to address all identified variables. (1) Permafrost type: Discusses differences between continuous, discontinuous, sporadic, and isolated permafrost in terms of active layer thickness, thermal regime, and hydrological behavior. Includes synthesis of comparative studies (e.g., Evans et al., 2020; Song et al., 2022). (2) Topography: Addresses slope effects on flow paths, aspect effects on solar radiation and thaw depth, and landscape position effects on water accumulation. Includes

examples from hillslope studies (Sjoberg et al., 2021; Chiasson-Poirier et al., 2020). (3)
Underlying surface characteristics, including surface geology and sediment type, presence of organic layers and land cover heterogeneity.

Comment 12: Lines 240~254, the authors describe runoff generation during freeze thaw cycles. However, this discussion is not supported by appropriate references. The relevant citations should be added in this section. Section 5.2 also lacks the related references.

Response: We have thoroughly added citations throughout.

Comment 13: Some technical terms are used inconsistently throughout the manuscript. For example, Line 24, it is unclear whether active layer thawing refers to the same process as the freeze–thaw cycle discussed later. Similarly, in Line 27, the relationship between permafrost thawing and permafrost degradation is not clearly defined. The authors are encouraged to review the manuscript and standardize the terminology where appropriate to avoid confusion.

Response: Thank you for your patient help and suggestions. We have conducted a thorough terminology review and standardized usage throughout. We have revised all instances to ensure consistent usage:

- "Freeze-thaw cycle" used for seasonal dynamics
- "Active layer thaw" or "thaw progression" for the warm-season deepening
- "Permafrost degradation" for long-term climate-driven changes
- "Permafrost thaw" as a general term but clarified in context

In previous Line 24: "The active layer thawing" was deleted, so as that sentence focusing on describing the hydrological influences more clear.

Comment 14: The heading structure is inconsistent across the manuscript. Subheadings in Section 3 line 241~254 lack numbering, whereas subheadings in other sections are numbered. A consistent heading numbering scheme is recommended.

Response: We have standardized the heading numbering scheme throughout the manuscript.

Reply to reviewer 2

Comment 1: Please clarify what "integration" means in this review—primarily a mechanistic synthesis (linking surface-active layer-permafrost processes and feedbacks),

a quantitative evidence synthesis (comparable summary of key hydrological responses), or both (with a clear hierarchy and organization). At present, the level of technical/quantitative detail is uneven across sections, with some parts highly detailed while others remain largely conceptual, which makes the main narrative and the added value of the proposed framework difficult to follow. A brief positioning statement (in the Introduction or framework section) and a consistent section-end summary template (mechanisms, comparable quantitative evidence where available, and uncertainty/boundary conditions) would substantially improve clarity.

Response: We thank you for this important clarification. In the revised manuscript, we now explicitly define "integration" as a dual approach: (1) mechanistic synthesis that links surface-active layer-permafrost processes and feedbacks, and (2) quantitative evidence synthesis that provides comparable summaries of key hydrological responses where available. We have added a positioning statement in the revised Introduction and at the beginning of the Framework section (new Section 6) to clearly establish this dual focus. Additionally, we have implemented a consistent section-end summary template throughout Sections 3-5 (original Sections 2-4). This structure improves the narrative flow and highlights the added value of our integrated framework.

Comment 2: The manuscript is framed in the Abstract and Introduction as a "systematic analysis", but it does not provide reproducible review-method details (e.g., databases and time span searched, core search terms, inclusion criteria, the number of screened/included studies, and how evidence was categorized). This limits the traceability and credibility of the synthesis and the proposed framework. I recommend adding a standalone "Review Methods" section that reports at least these minimum items; if the work is intended as a narrative/comprehensive review, please adjust the "systematic" wording accordingly and clarify the coverage and organization of the literature.

Response: We agree that methodological transparency is essential for credibility. In the revised manuscript, we have added a standalone "Review Methods" section (new Section 2) that details: Databases searched, Time span, Core search terms, Inclusion criteria, and Number of studies. In addition, Evidence categorization was pointed out that studies were categorized by (a) spatial scale (plot, hillslope, watershed, regional), (b) permafrost type (continuous, discontinuous, sporadic), (c) hydrological process focus (surface runoff, active layer processes, permafrost thaw impacts), and (d) methodology (field observations, modeling, isotope tracers, geophysics). We have also adjusted the wording in the Abstract and Introduction from "systematic analysis" to "comprehensive systematic review" to accurately reflect our methodology while maintaining the rigor of our approach.

Comment 3: The Introduction concludes by summarizing permafrost hydrology into three dimensions (Hydrological Effect of the Surface Underlying Layer, Regulatory Role of the Active Layer on Runoff, and Water Supply Function). However, the subsequent Sections

2-4 (and their subsections) do not consistently map onto this three-part structure, with several topics appearing to cross these categories. Could the authors clarify how each section/subsection corresponds to the three dimensions (e.g., via an explicit roadmap at the start of Sections 2-4 and brief "take-home messages" that link back to the stated framework)? As written, this misalignment makes the narrative harder to follow.

Response: We thank the reviewer for identifying this structural inconsistency. In the revised manuscript, we have:

- 1) Restructured the main sections to directly correspond to the three dimensions: Section 3: Surface hydrological processes in permafrost regions (Dimension 1); Section 4: Hydrological functions of the active layer (Dimension 2); Section 5: Hydrological effects of permafrost change (Dimension 3). Titles of the three sections directly reflect the three dimensions, which also were clearly pointed out in the Introduction (Paragraph 4).
- 2) Included "take-home messages" at the end of each subsection that explicitly link back to the framework. For example, at the end of new subSection 5.3.3, we state: "Thus, while permafrost degradation generally enhances baseflow and winter runoff, the magnitude and even direction of change are modulated by permafrost type, topography, geology, and climate. Quantitative synthesis reveals that permafrost thaw contributes measurably to river discharge in many basins, but large uncertainties remain due to observational limitations and regional heterogeneity."
- 3) Reorganized content to minimize cross-categorization. Topics that inherently cross categories (e.g., thermokarst) are now explicitly discussed as integrative elements with clear cross-references between sections.

Comment 4: Thermokarst is primarily a consequence of permafrost degradation (ground ice melt) and is therefore closely tied to the "hydrological impacts of permafrost change" discussed in Section 4. Would it be more appropriate to place the thermokarst subsection under Section 4 (or, at minimum, explicitly frame it as a cross-cutting topic with clear cross-references between Sections 2 and 4)? In its current placement under Section 2, the thematic alignment is not entirely clear.

Response: The reviewer raises an excellent point. In the revised manuscript, we have moved the thermokarst discussion to Section 5 (formerly Section 4), where it now appears as Section 5.2: "Thermokarst as a manifestation of permafrost degradation and its hydrological impacts". This placement better aligns with the framework's third dimension (hydrological effects of permafrost change).

Comment 5: Taking Section 4.3 as an example, the current compilation of quantitative results from multiple basins (e.g., the Yellow River source region and the Yarlung Zangbo River) reads largely as a listing rather than a cohesive synthesis. To improve comparability, I recommend adding a summary table that explicitly details the values, metric definitions, spatiotemporal scales, methods, and associated uncertainties. Finally, a

process-based synthesis should be included to explain which boundary conditions and key controlling factors drive the large inter-basin differences in the reported contribution rates.

Response: We fully agree that the quantitative synthesis needed improvement. In the revised manuscript (now Section 5.3), we have added a comprehensive summary table (Table 1) that systematically presents study location and basin, reported contribution values (with ranges where available), metric definitions (e.g., % of annual runoff, % of baseflow, absolute volume), spatiotemporal scales (time period, basin area), methods used (isotope tracing, modeling, hydrograph separation), and key references. In addition, we have added a process-based synthesis subsection (Section 5.3.3: "Mechanisms controlling baseflow responses and regional variability") that discusses: Permafrost type and coverage as primary controls, topographic and geological boundary conditions, climate regime (precipitation seasonality, temperature trends), vegetation and soil characteristics, and methodological differences contributing to apparent variability. This revised structure transforms the section from a listing to a true synthesis that highlights both patterns and controlling factors.

Comment 6: There are noticeable issues in wording and consistency within Figure 4. For instance, "Active layer" is misspelled as "Activity layer," and terminology should be standardized across the diagram and the main text. Furthermore, the figure assigns "Spring: Dunne runoff" and "Fall: Horton runoff" in a rigid, one-to-one manner. I question whether this seasonal attribution is too absolute given the complexity of the region. It would be necessary to clarify the boundary conditions, potential exceptions, or provide supporting references to justify this classification.

Response: We apologize for these errors and oversimplifications. In the revised manuscript, Figure 4 (now Figure 5) has been completely redrawn, including: Corrected terminology (now consistently "active layer" throughout), standardized terminology matching the main text, and more nuanced representation of seasonal runoff mechanisms. In addition, we have added a discussion in new Section 6 that explicitly addresses the boundary conditions and exceptions to these generalized patterns.

Comment 7: If Figure 4 is intended to be the core "SAP integrated hydrological system" framework of the review, the manuscript appears to position itself as an "impact chain" synthesis (i.e., freeze–thaw and degradation alter connectivity and hydraulic properties, thereby reshaping runoff partitioning and baseflow). However, the current text provides limited mechanistic integration and evidence synthesis to substantiate this framework, and some links within the diagram seem directionally unclear or potentially contradictory (e.g., the sign of freeze–thaw impacts on runoff coefficients; the logical bridge between increased storage capacity and increased discharge). Clarifying the causal chain, key

couplers, and boundary conditions and aligning the depth of synthesis accordingly would strengthen both the framework and the narrative.

Response: This is a critical observation. We have substantially revised the framework presentation. We have revised Figure 4, and added a new Section 6 “Framework of SAP integrated hydrological system”, so that: (1) Articulates the full causal chain: "Climate warming → permafrost change → altered hydraulic properties → hydrological responses"; (2) Addresses the apparent contradiction noted by the reviewer: increased storage capacity can lead to increased discharge through enhanced connectivity and groundwater drainage, particularly when permafrost thaw opens new flow paths (we now cite Walvoord et al., 2012; Kurylyk & Walvoord, 2021); (3) Clarifies that freeze-thaw impacts on runoff coefficients are bi-directional: during thaw periods, coefficients decrease (more infiltration); during freeze periods, coefficients increase (reduced infiltration). In addition, we have strengthened the evidence synthesis throughout Sections 3-5 to substantiate each link in the causal chain, with particular attention to mechanistic understanding and quantitative support.

We believe these revisions have substantially improved the manuscript's clarity, scientific rigor, and contribution to the field. We thank you for your insightful comments and hope that the revised manuscript meets your expectations. We look forward to your further consideration.

Sincerely,

Jia Q. on behalf of the authors.