egusphere-2026-928 - A non-explicit representation of macropores in the SVS land surface model improves streamflow simulations under frozen soil conditions

Responses to the Anonymous Referee #1

First of all, we wish to thank Referee #1 for providing constructive and insightful comments and suggestions. In addressing these suggestions, along with those from the other two reviewers, we have significantly revised the manuscript. We believe these changes have greatly improved the clarity and focus of our work. In particular, we have reframed the narrative to center on the enhancement of frozen soil infiltration within an operational model, with corresponding revisions to the introduction and discussion. Moreover, we have strengthened the Results section by incorporating land cover- and soil texture-based analyses regarding the calibration and performance of the new frozen soil infiltration configuration. Note that “Macropore configuration”, “Fr-MP” and “a_{MP}” are denoted “Enhance frozen soil infiltration configuration”, “Fr-Inf” and “$a_{no\text{-}imp}$” in this document and in the proposed revised version of the manuscript. Our answers below are in blue, whereas excerpts from the manuscript are in *blue italics* with modifications in ***bold***. In our responses, when referring to other comments from any referee, we use the following terminology: RefX-[Maj or Min]Y where X and Y indicate the referee and comment (major or minor) ID.

Referee comments 1 – egusphere-2026-928

The manuscript addresses a significant and timely topic in cold-region hydrology. The methodology is sound, and the results provide a clear path toward improving operational streamflow forecasting. However, the manuscript requires a more critical discussion regarding the physical basis of the macropore parameterization and a deeper analysis of the spatial variability in model performance. Addressing the major comments regarding the physical justification and the sensitivity of the alpha_MP parameter will significantly enhance the impact and scientific rigor of the work. I look forward to seeing a revised version of this study.

Major Comments :

1. The authors propose a non-explicit, threshold-based representation of macropores. While this is computationally efficient for operational forecasting, the manuscript lacks a robust discussion on the physical limitations of this simplification. Specifically, how does this approach account for the spatial heterogeneity of macropore networks at the grid-cell scale? A more thorough comparison with existing dual-domain or dual-permeability models (e.g., those cited in the introduction) is needed to justify why this simplified approach is sufficient for large-scale hydrological modeling.

Concerns regarding the physical interpretation of the “Macropores configurations” (renamed “Enhanced frozen soil infiltration” in the revised manuscript) were raised by all three referees (see Ref2-Maj2, Ref2-Min4 and Ref3-Maj1). In response, we have thoroughly re-evaluated the physical basis of this configuration and expanded the associated discussion. Detailed modifications are provided in our specific responses to the comments cited above.

We further agree with the referee that a robust comparison with existing dual-domain approaches is necessary to justify our simplified approach for large-scale hydrology. Dual-domain configurations for frozen ground infiltration cover a wide range of complexity levels, from grid-cell permeability fraction (see Niu and Yang 2006) to models that explicitly simulate gravitational macropore flow or derive complex soil freezing curves (see Kurylyk and Watanabe 2013 and Mohammed et al., 2019). While highly accurate, integrating such complex dual-domain approaches into SVS would require a complete reformulation of soil water fluxes, which is beyond the scope of this study given the operational context of the SVS model. Consequently, during the review process, we have considered the simple dual-permeability configuration presented as ‘Option SHP1’ in Agnihotri et al (2023). This approach effectively accounts for permeable and impermeable grid-cell fractions using a freezing factor (F_{frz}), providing a balance between physical representativeness and computational efficiency.:

$$F_{frz} = \left(e^{-a\left(1-\frac{I}{W_{sat}}\right)} - e^{-a}\right)/(1 - e^{-a})$$

where I and W_{sat} are the ice fraction and the water content at saturation, respectively, and a is a scale-dependent parameter ($a = 3$ following Niu and Yang (2006)). More details on this configuration are provided in Agnihotri et al (2023). This approach has been implemented in SVS and we (re-)ran our GEM-Hydro setup in the Great-Lakes and Saint-Lawrence domain for the 2016-2021 evaluation period. Figure R1-1 shows a comparison of performance metrics for streamflow simulation between the AG23 configuration and the noFr, Fr and Fr-Inf configurations:

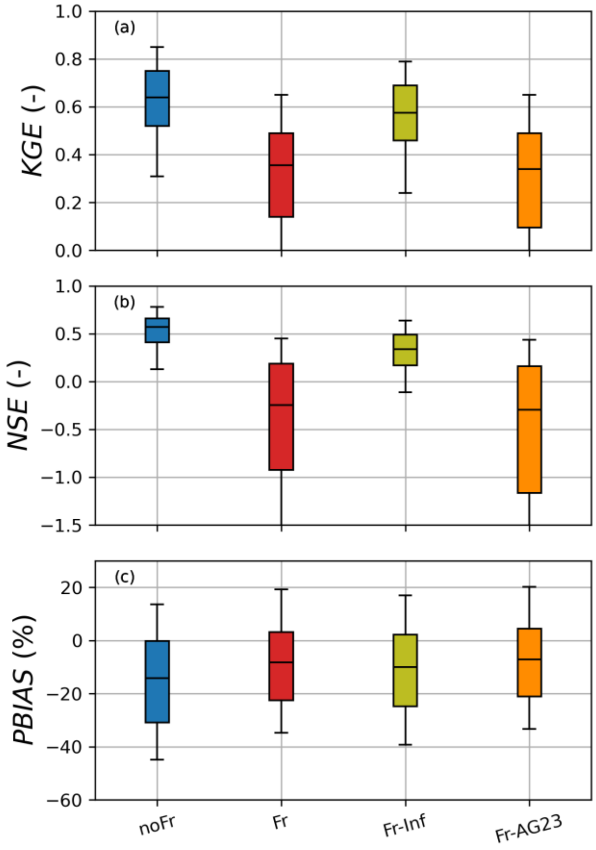

Figure R1-1: Boxplots of streamflow performances (KGE (a), NSE (b) and PBIAS (c)) for the three main configurations (noFr, Fr, Fr-Inf) and the AG23 configuration in the Great-Lakes and Saint-Lawrence domain for the 2016-2021 evaluation period. Details on boxplot representation are given in the legend of Fig. 4 of the manuscript. The target value for the KGE and NSE is 1.0 while the target value for the PBIAS is 0.0.

Our results indicate a clear degradation in performance when using the AG23 configuration compared to the Fr-Inf configuration, which can be attributed to the overly restrictive F_{frz} to infiltration used in AG23. Optimizing the performance of AG23 over the GLSL domain would require a site-specific calibration of the a parameter but it is highly uncertain that performance would reach that of Fr-Inf. Overall, this comparison suggests that the Fr-Inf configuration is better suited for improving frozen soil infiltration at the catchment scale despite not representing the sub-grid heterogeneity of soil water transport regime. We suggest the following modifications to the manuscript and the addition of Figure R1-1 to the Supplementary Materials:

<u>ll. 631-635:</u> "***A configuration of SVS using the dual-permeability approach of Agnihotri et al. (2023) was also evaluated. This simple configuration resulted in a marked degradation in model performance compared to the Fr-Inf configuration (Fig. S6). These results demonstrate that while Fr-Inf does not explicitly account for the spatial***

heterogeneity of subgrid macropore networks, it remains a suitable and effective approach for enhancing frozen ground infiltration and improving streamflow simulations at the catchment scale.”

2. The calibration of alpha_MP is a central component of the study. However, the manuscript does not sufficiently address the potential for equifinality or the transferability of this parameter across different hydro-climatic regions. Are the optimal values of alpha_MP consistent across the diverse landscapes of the Great Lakes and Saint-Lawrence domain? A more detailed analysis of the spatial variability of the optimal alpha_MP and its relationship with soil/land-cover characteristics would significantly strengthen the paper.

This is a very good point. While Figure 4b in the original manuscript illustrates the spatial distribution of the optimal $\alpha_{no\text{-}imp}$ parameter, we agree that the relationship between land surface characteristics and $\alpha_{no\text{-}imp}$ deserved a deeper analysis.

In response to this comment and Ref2-Maj2, we extracted the dominant land surface types and average sand/clay fractions for the catchments associated with each hydrometric station. We then analyzed these characteristics in relation to the optimal $\alpha_{no\text{-}imp}$, as shown in Figure R1-2:

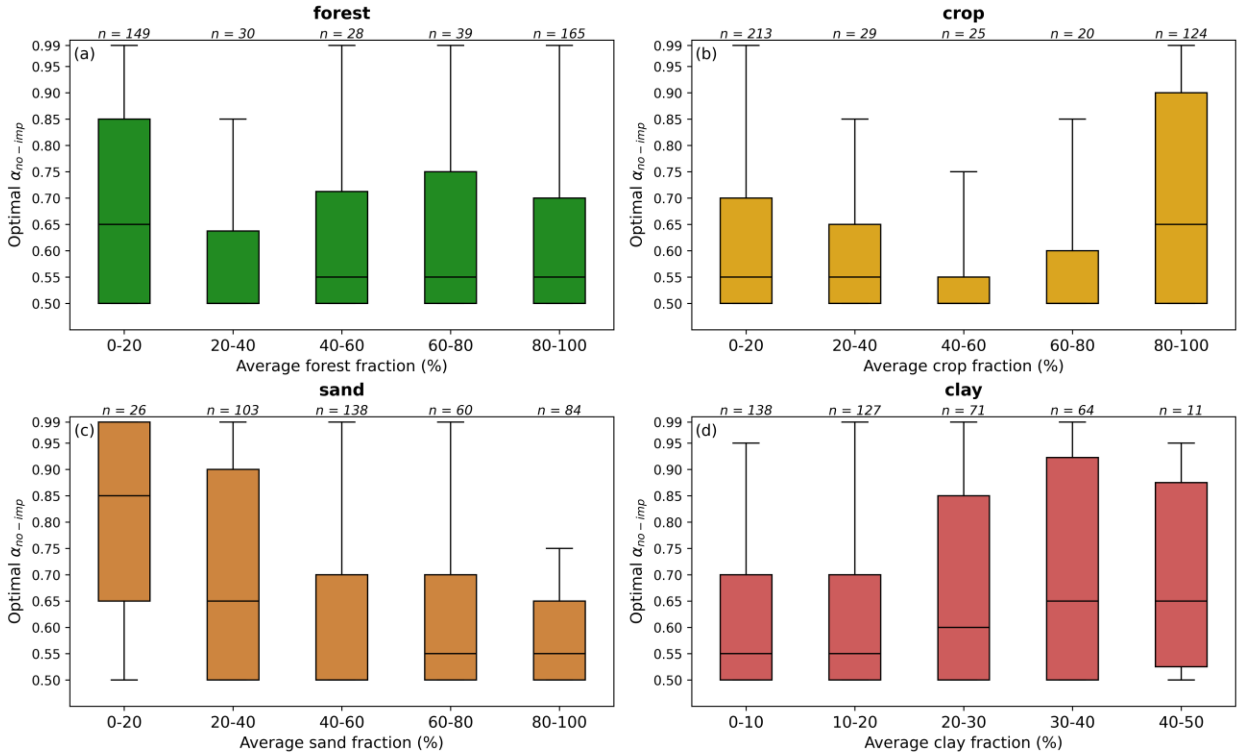

Figure R1-2: Boxplots of the optimal $\alpha_{no\text{-}imp}$ value in relation to the average forest (a), crop (b), sand (c) and clay (d) fractions for the enhanced frozen soil infiltration configuration (Fr-Inf). Simulations were performed using values of $\alpha_{no\text{-}imp}$ from 0.5 to 0.99 with increments of 0.05 on the Great-Lakes and Saint-Lawrence domain from 1 September 2016 to 31 August 2018. Details on boxplot representation are given in the legend of Fig. 4 of the main manuscript. The number of catchments for each surface cover fraction bin (n) is indicated on top of the boxes.

The results indicate that the optimal $\alpha_{no\text{-}imp}$ value varies according to both vegetation and soil texture. While the influence of land cover (forest vs. crops) is less pronounced, a clear pattern emerges regarding soil texture: the optimal $\alpha_{no\text{-}imp}$ decreases when the average sand fraction increases at the expense of clay fraction. This explains why the Fr-Inf configuration (using the default $\alpha_{no\text{-}imp} = 0.55$) performs better in catchments with higher sand fractions (see revised Figure 7 in the response to Ref2-Maj2). We have updated the manuscript to include this analysis and have added the supporting figure to the Supplementary Materials (Fig. S1):

ll. 398-403: "***However, the optimal $\alpha_{no\text{-}imp}$ varies considerably with land surface characteristics (see Fig. S1) as shown by generally larger optimal $\alpha_{no\text{-}imp}$ value in catchments of low forest fraction (0–20%) and high crop fraction (80-100%). Nonetheless, the optimal $\alpha_{no\text{-}imp}$ parameter exhibits greater sensitivity to soil texture. In particular, catchments for which low $\alpha_{no\text{-}imp}$ performs better are also characterized by a higher sand fraction. In contrast***, *the few areas where larger values of $\alpha_{no\text{-}imp}$ perform better* ***are characterized by a higher clay fraction.***"

ll. 469-470: "***This aligns with the use of a fixed $\alpha_{no\text{-}imp}$ of 0.55 in Fr-Inf, which performs optimally in catchments with higher sand and forest fractions (Fig. S1).***"

ll. 649-650: "***Better performance achieved in forested and sandy catchments is attributed to the calibration of the $\alpha_{no\text{-}imp}$ parameter to 0.55, which is more representative of these specific landscape characteristics.***"

3. The results indicate that the Fr-MP configuration performs differently in agricultural areas compared to forested catchments. The authors attribute this to the interaction between tile drainage and frozen soil. I suggest a more in-depth analysis of this interaction. Does the current model structure adequately decouple the effects of macropores from those of anthropogenic drainage systems? This is crucial for the model's reliability in human-altered landscapes.

The need for a deeper analysis of the relationship between land cover, soil texture, and model performance was also raised by Referee #2. We have performed this analysis and thoroughly revised Section 3.3, including an updated Figure 7. We invite the Referee to refer to our responses to Ref2-Maj2 and Ref2-Min18 for the full details of these changes.

Regarding the representation of tile drainage and ploughing, these are currently implemented as multiplicative factors applied to the unfrozen soil hydraulic conductivities ($K_{sat,v}$ and $K_{sat,h}$) of specific soil layers. For ploughing, a multiplicative factor ($m_v = 10$) is included in the calculation of the ice impedance effect ($K_{sat,v,fr}$) when resolving the Richards equations for vertical soil water fluxes. However, in the calculation of $K_{sat,h}$, which is derived from $K_{sat,v}$, the 'natural' value of $K_{sat,v}$ (unaffected by ploughing) is used to ensure that ploughing does not artificially amplify lateral flow in the top three soil layers.

Similarly, the effect of tile drainage, which occurs in the fifth soil layer, is applied to the $K_{sat,h}$ value adjusted for the presence of soil ice. When the enhanced infiltration condition is met in agricultural areas ($W > \alpha_{no\text{-}imp} W_{sat}$), $K_{sat,v}$ is restored to its unfrozen value and amplified by the ploughing multiplicative coefficients. To avoid any confusion, we suggest the following modifications to the manuscript:

ll. 404-407: "***Additionally,*** *these stations are all located at the outlet of highly agricultural catchments (see Fig. 2), where* ***the land surface is modified by agricultural tile drainage and often result in flashy runoff response. This behavior is more accurately captured by model configurations that are more restrictive to infiltration, even when accounting for amplified coefficients used to represent the effects of ploughing and tile drainage.***"

ll. 517-519: "***In this specific catchment, the multiplicative factors of $m_h = 500$ and $m_v = 10$ may be insufficient to adequately represent the effects of agricultural drainage, highlighting a limitation of this non-explicit approach (Gaborit et al., 2025).***"

4. While the authors evaluate the impact on TT and TD, the improvements are described as "slight" or "neutral." Given that the primary goal is to improve streamflow, the authors should clarify whether these meteorological improvements are statistically significant and if they have any meaningful impact on the broader numerical weather prediction (NWP) performance at ECCC.

Our objective in presenting these results was to demonstrate that the inclusion of soil freezing processes (with or without enhanced infiltration) does not degrade the ability of the model to predict near-surface temperature and humidity. As our primary goal was not to optimize these specific variables, we did not initially perform rigorous significance testing on the Fr-Inf configuration for these metrics.

However, to address this comment, we have provided a figure generated by our internal EMET evaluation tool (Fig. R1-3). The results indicate that improvements in near-surface air temperature (TT) bias primarily occur during nighttime hours (UTC-5). Furthermore, the 90% confidence intervals remain above zero, suggesting that these gains are statistically significant (Fig. R1-3b). This example illustrates the difference between the Fr-Inf and noFr configurations for air temperature bias over the period from March to July 2018. While these secondary improvements are encouraging, we have kept the focus of the manuscript on the hydrological impacts. Nonetheless, we propose the following addition to the manuscript:

ll. 571-572: "***In general, improvements are statistically significant during nighttime (not shown).***"

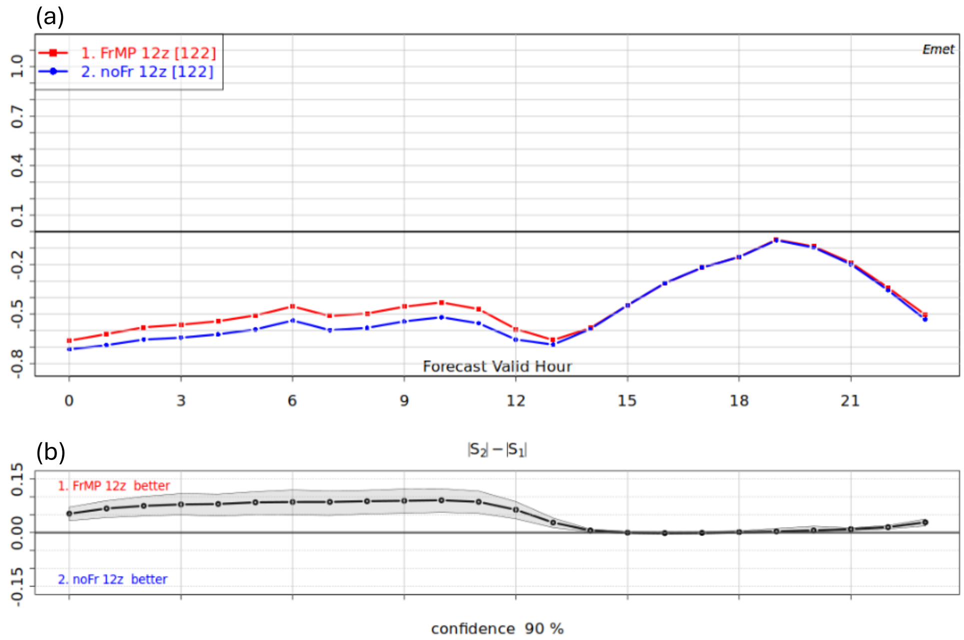

Figure R1-3: (a) Mean near-surface (2-m) temperature bias of the Fr-Inf (FrMP) and the noFr experiments for the period between 2018-03-01 and 2018-06-30. (b) Bias difference between both experiments with the gray shading showing the 90% confidence interval. The x-axis shows daily hours at UTC + 0.

Minor Comments :

1. Page 2, Line 40: The term "discrepancy" is used well here; ensure this is consistently linked to the scale-dependency of the processes throughout the discussion.

In response to Ref3-Maj1, we have reframed the narrative of the study and thoroughly revised the Introduction. In the revised manuscript, the term "discrepancy" is used only once (in the Results section) to specifically describe model performance degradation.

2. Page 7, Eq. 9: Please clarify if alpha_MP is a static parameter or if it could be dynamic based on seasonal vegetation growth.

In the model development presented here, $\alpha_{no\text{-}imp}$ is a static parameter. We have clarified this in the revised Section 2.1.3). It should be noted that while this parameter is currently fixed, the Fr-Inf configuration may be further refined in future iterations of the SVS model to include more dynamic representations of frozen soil infiltration (as discussed in our response to Ref2-Min18).

3. Page 8, Figure 1: The conceptual diagram is excellent. Please ensure the legend clearly distinguishes between the "matrix flow" and "macropore flow" pathways in panel (c).

We thank the reviewer for this remark. In SVS, vertical soil water fluxes are consistently simulated as matrix flow. Under the “enhanced frozen soil infiltration” condition ($W > W_{no\text{-}imp}$), the parameterization effectively eliminates the ice-impedance effect on these fluxes. We have modified Figure 1c to more clearly illustrate this process and to ensure that the distinction between standard matrix flow and the enhanced infiltration configuration is clear.

4. Page 10, Section 2.4.1: The exclusion criteria for stations (NSE < 0 or KGE < -0.41) are reasonable, but please provide a brief justification for why these specific thresholds were chosen over others.

We received a similar remark from Referee #2. The suggested correction is presented in our response to Ref2-Min5.

5. Page 13, Line 355: The mention of the "perched aquifer" in Michigan is interesting. Could the authors provide a bit more detail on how this specific geological feature might be better represented in future iterations of the model?

There is no plan on the short-term to better represent complex aquifers in Watroute, which currently relies on a simple conceptual reservoir with a power law function to simulate baseflow (this is also the case for the Raven model). This simple representation is generally enough to represent the effect of superficial (free surface) aquifers on river flows, even with static parameters for the power law function for most basins across Canada.

To better represent complex aquifers, one could use a hydro-geological model instead of this simple conceptual reservoir. However, such a model is not trivial to setup and would add significant complexity to the current hydrological forecasting system, possibly increasing computation time and latency of the forecasts.

One relatively easy solution could be to try to determine climatological baseflows from applying a digital filter to the observed streamflow for regions where complex (confined) aquifers exist, and use the climatological baseflow instead of the baseflow computed from the simple conceptual reservoir. Indeed, even if the interaction between different aquifers of a region can be complex, the effect of confined aquifers on streamflow can sometimes be fairly simple to represent, since such confined aquifers can have a very slow response time to meteorology and their contribution to baseflow can remain quite constant through time. But this would still require quite some work, and the methodology is not fully clear either, especially with regard to the interpolation of such climatological baseflows or their extrapolation to ungauged areas.

Finally, in the real-time hydrological forecasting system used at Environment and Climate Change Canada named NSRPS (National and Surface River Prediction System), a baseflow assimilation procedure is currently in place, allowing to correct the state of the simple conceptual reservoir based on estimated baseflow derived from filtered observed flows. These corrections have a long inertia in terms of their effect on forecasts, that can generally last up to more than 10 days. Therefore, it is not even sure if putting more efforts into better representing baseflow in areas with complex aquifers would actually have a strong impact on the flow forecasts of such regions, compared to the current strategy involving the correction of the simple conceptual reservoir.

6. Page 16, Line 411: The observation that only 4 stations show a Delta KGE < -0.5 is a strong point. Please emphasize this in the abstract as a measure of the model's robustness.

We suggest the following addition to the abstract:

ll.17-19: “***Strong degradations relative to the no freezing configuration (ΔKGE < –0.5) are observed only at 4 stations with Fr-Inf (< 1%) as opposed to 172 stations under the Fr configuration (33%), highlighting the robustness of the approach.***”

7. Page 23, Line 495: The authors mention that wetlands and meanders are not fully represented in Watroute. It would be beneficial to include a brief sentence on how the transition to the "Raven" routing scheme might specifically address these limitations.

The current main limitation of Watroute with regard to meanderous rivers and relatively flat regions in general, is that the model assumes the same overbank slope (1%) everywhere. Therefore, it cannot represent what happens when a river floods and water spreads in large areas along the river. This tends to significantly decrease peak flow magnitude and lengthen the response time of the flood. Even if a spatially-varying overbank slope could be used based on DEMs, we still wouldn't fully capture the impact that wetlands can have during river floods, in such regions.

Raven includes more options to represent these processes, for example by defining some subbasins as "wetlands" that can capture part of a river flow through lateral transfer of water. See this citation of the Raven Manual 4.0 at page 95, paragraph 5: "larger lakes or wetlands systems could be more explicitly represented by abstracting laterally to WETLAND HRUs via, e.g., the :LateralFlush process, and there conditionally applying seepage, evaporation, and overflow. The benefit that Raven could have in such flat or wetland areas, compared to Watroute, has not been assessed yet, to the extent of our knowledge. This will be an interesting thing to assess when comparing both routing schemes in the context of open-loop runs.

We suggest the following revisions to the manuscript:

ll. 688-693: "***By design, Watroute cannot explicitly represent lateral spreading of water in flat areas adjacent to the river, as the model assumes a uniform overbank slope of 1%.*** *This likely contributes to the poor performance observed in the region bounded by the five Great Lakes (Fig. 7) and the exclusion of several stations for analysis in this region (Figs. 3 and 5). The envisioned transition in NSRPS from Watroute to the Raven routing scheme,* ***which includes an explicit representation of wetlands*** *(Craig et al., 2020), in the coming years may help alleviate these issues.*"

8. Clarity of Figures: In Figure 4 and Figure 5, the color scales are effective, but please ensure that the symbols for different drainage areas are easily distinguishable in the printed version.

We appreciate the suggestion to use varying symbol sizes to represent catchment scale. We tested using different symbols and larger markers, but we found that these changes significantly reduced the readability and clarity of Figures 3 and 5, particularly in areas with a high density of stations. As for Figure 4b, the discrete color-scale makes it fairly easy to distinguish between stations of low and high optimal $\alpha_{no\text{-}imp}$ values.

Since the primary objective of these figures is to illustrate spatial patterns through the color-coded performance metrics, we have opted to retain the original symbol size to ensure the maps remain legible. Additionally, as Figure 7 has been resized in the revised manuscript (in response to Ref2-Maj2), the original symbol size was found to be the most effective for maintaining clarity across all map-based figures.

9. References: Ensure that all cited preprints (e.g., Bauer et al., 2025) are updated to their final publication status if available by the time of revision.

The manuscript of Bauer et al. 2026 has just been published in its final form in *The Cryosphere* (TC) at the time of submitting this document (17 June 2026). We suggest citing the TC publication in the revised manuscript. Note that the manuscript of Khedhaouiria et al. (2026) is still only published as a preprint. When submitting the final version of our manuscript, we will cite the most up-to-date version of this article.

Cited References:

Agnihotri, J., Behrangi, A., Tavakoly, A., Geheran, M., Farmani, M. A., and Niu, G.: Higher Frozen Soil Permeability Represented in a Hydrological Model Improves Spring Streamflow Prediction From River Basin to Continental Scales, Water Resour. Res., 59, e2022WR033075, https://doi.org/10.1029/2022WR033075, 2023.

Kurylyk, B. L. and Watanabe, K.: The mathematical representation of freezing and thawing processes in variably-saturated, non-deformable soils, Adv. Water Resour., 60, 160–177, https://doi.org/10.1016/j.advwatres.2013.07.016, 2013.

Mohammed, A. A., Pavlovskii, I., Cey, E. E., and Hayashi, M.: Effects of preferential flow on snowmelt partitioning and groundwater recharge in frozen soils, Hydrol. Earth Syst. Sci., 23, 5017–5031, https://doi.org/10.5194/hess-23-5017-2019, 2019.

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