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 #2

We thank the referee for carefully reading the manuscript and for providing valuable feedback. We are pleased that the referee appreciates the relevance of our work in the context of operational hydrological forecasting. Based on comments from Referee #2 and those from two other anonymous reviewers, we propose significant modifications to the original manuscript, which we believe will improve the paper. Specifically, concerns about the narrative/physical interpretations (also explicitly raised by another referee) were addressed by extensively reformulating the narrative to avoid overstating the physical meaning of the structural changes brought to the model. While we respond to Referee #2 point-by-point here, an exhaustive breakdown of this restructuring can also be found in our response to Referee #3. Major changes also include the addition of two new analyses of model calibration and performance based on land surface characteristics. 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 2 – egusphere-2026-928

General comment:

This study presents a computationally efficient approach to improve infiltration under frozen soil conditions in a land surface model. The manuscript clearly demonstrates that the current soil freezing formulation leads to unrealistic runoff responses and that increasing infiltration can substantially improve streamflow simulations at large spatial scales. The topic is highly relevant, particularly in the context of operational hydrological forecasting, and the study provides a valuable and pragmatic contribution in this regard.

However, the proposed "macropore representation" is, in its current form, a conceptual parameterization that mimics the effect of preferential flow rather than explicitly representing macropore processes. The implementation effectively removes the ice-induced hydraulic impedance once a soil moisture threshold is exceeded and additionally modifies the runoff generation scheme. As such, the approach represents a combined structural modification of flow partitioning rather than a direct representation of macropore flow.

1. In its current form, the manuscript does not sufficiently disentangle these effects. A clearer separation of the impacts of the increased vertical hydraulic conductivity and the modified runoff generation would be necessary to properly attribute the improvements in model performance.

This point aligns with the concerns raised in Ref3-Maj1. To address this, we have conducted two additional SVS-Watroute coupled experiments over the GLSL domain between 2015-2021 to isolate the effects of the two structural modifications:

- Fr-SATSFC0: This experiment is identical to the default soil freezing configuration (Fr) but disables the subgrid-scale saturation mechanism for surface runoff generation.
- Fr-Inf-SATSFC1: This experiment utilizes the enhanced frozen soil infiltration configuration (Fr-Inf) but removes the modification to surface runoff generation.

Figure R2-1 presents the KGE, NSE, and PBIAS for the primary experiments (noFr, Fr, and Fr-Inf) alongside these two intermediate configurations. The results show that while the intermediate configurations offer marginal improvements in KGE and NSE compared to the baseline Fr configuration, they are significantly outperformed by the Fr-Inf configuration.

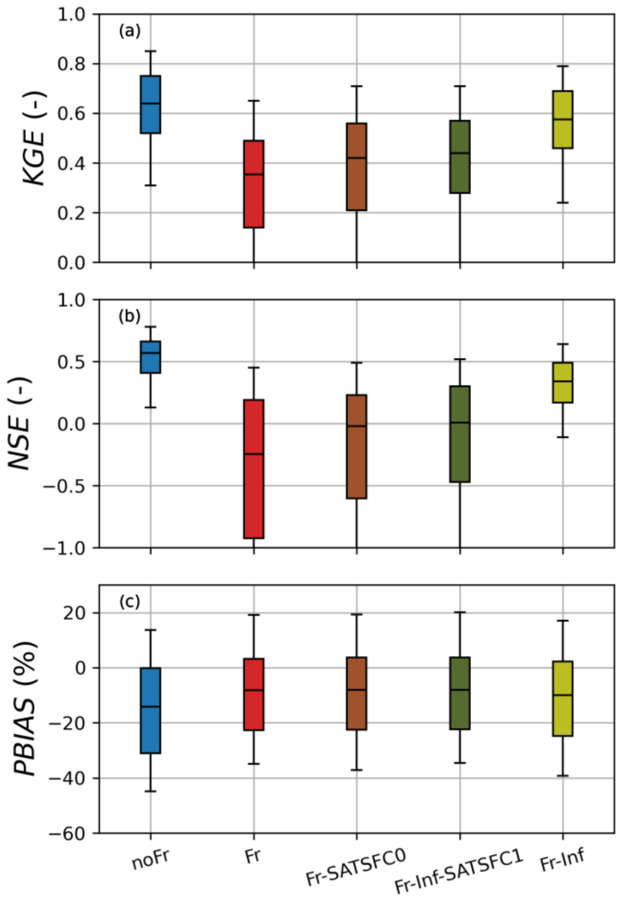

Figure R2-1: Boxplots of streamflow performances (KGE (a), NSE (b) and PBIAS (c)) for the three main configurations (noFr, Fr, Fr-Inf) and the two intermediate configurations (Fr-SATSFC0 and Fr-Inf-SATSFC1) in the Great-Lakes and Saint-Lawrence domain for the 2016-2021 evaluation period. Details on boxplot 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.

This demonstrates that the combination of both structural modifications, namely the relaxation of ice impedance on vertical flow and the restriction of saturation excess for surface runoff generation are required to achieve a reasonable improvement in streamflow simulations when soil freezing is enabled. Based on this analysis, we suggest the following modification to the discussion of the manuscript and the addition of Figure 2-1 to the Supplementary Materials as Figure S7:

ll. 677-685: "***To isolate the effects of each modification, we conducted two intermediate frozen soil sensitivity experiments (Fig. S7). Disabling the subgrid-scale surface runoff generation as the sole modification resulted in only slight improvements over the default soil freezing configuration (Fr). Similarly, applying the Fr-Inf configuration while restoring the surface runoff generation mechanism yielded only minor performance gains compared to Fr. These tests demonstrate that both modifications are necessary to meaningfully improve model performance under frozen soil conditions and should therefore be implemented together in SVS. However, while these combined changes successfully reduce rapid-response fluxes, the Fr-Inf configuration still overestimates mid-winter runoff peaks (Figs. 8 and 9). This can be partly explained by*** *the near-surface anisotropy ratio ($K_{sat,h}/K_{sat,v}$)****, which*** *is of the order of 1000* ***and*** *strongly promotes lateral flow over infiltration.*"

2. Furthermore, the physical interpretation of the results could be strengthened. In particular, the manuscript would benefit from a more explicit discussion of:

- the conceptual nature and limitations of the parameterization,
- the implications of representing subgrid-scale preferential flow using a bulk threshold formulation,
- the spatial variability in model performance, especially in relation to land use, soil texture, and the exclusion of stations from the evaluation.

We agree that the physical interpretation of our conceptual approach to enhanced frozen soil infiltration required a more in-depth discussion. In the revised manuscript, we have reframed the narrative to clarify the structural changes made to the runoff/infiltration partitioning and to explicitly address the inherent limitations of this configuration (as also suggested in Ref3-Maj1).

To address concerns regarding the representation of subgrid preferential flow, we implemented a dual-domain approach based on Agnihotri et al. (2023). Our comparison (detailed in the response to Ref1-Maj1) indicates that this subgrid approach did not yield clear performance improvements. This suggests that a bulk threshold formulation remains a suitable and computationally efficient alternative for representing macro-scale frozen soil processes in large-scale hydrological simulations. Following Ref2-Min4, we have also added a more explicit discussion of these conceptual limitations to the manuscript.

We also thank the Referee for the suggestion regarding spatial variability. We have performed a detailed analysis of model performance in relation to land cover (forest vs. crop fraction) and soil texture (sand vs. clay fraction). These findings have led to significant insights, and we have entirely revised the latter half of Section 3.3, including a modified Figure 7, to reflect these new results. We believe that this addition addresses several comments from the Referee and strengthens significantly the manuscript:

ll. 463-499: “*__Figure 7 illustrates the spatial distribution of KGE, NSE, and PBIAS for the Fr-Inf experiment, alongside the corresponding forest-crop and sand-clay fractions for each catchment.__ A **distinct** spatial pattern emerges **across** the GLSL domain **with the Fr-Inf configuration reaching its** highest **scores** for **all** three metrics in the Saint-Lawrence valley and north of Lake Superior and Lake Huron. **These regions are characterized by a predominance of evergreen and mixed forests (Fig. 2) and sandy soils. Stations yielding KGE scores above 0.8 (yellow dots on Fig. 7a-c) are consistently associated with higher forest and sand fractions. Conversely, performance declines to approximately 0.4 in the regions between Lake Huron, Lake Ontario, and East of Lake Erie, which are areas dominated by crops and higher clay content.** 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). The lowest **KGE (< 0)** are obtained in the northern region between Lake Michigan and Lake Huron, and West of Lake Michigan, **regions with a high concentration of stations excluded from the experiment comparisons (red crosses on Figs. 3 and 5). One must note that the noFr and Fr experiments also exhibit better KGE in forested and sandy areas compared to agricultural and clayey regions (Figs. S2 and S3). This suggests that while activating soil freezing with enhanced infiltration modulates the KGE magnitude, it does not fundamentally drive the underlying spatial variability in model performance.***

*The spatial pattern of the NSE closely follows that of the KGE, with the best results obtained in the northern and eastern parts of the GLSL domain (NSE > 0.5), and the worst scores obtained in the southern and western parts of the domain (NSE < 0.2). **Accordingly, the NSE is better at stations associated with high forest and sand fractions.** The similarity between the KGE and the NSE implies that the KGE can be explained by its variability component at most stations**. Interestingly, the Fr experiment performs poorly (NSE < 0) across the majority of the domain, with the exception of the region bounding Lake Erie (Figs. S3). Specifically, the Fr configuration yields higher NSE values in catchments characterized by clay-rich soils, a trend that contrasts with the results of the noFr and Fr-Inf***

experiments (Figs. S2 and 7). This suggests that the NSE, which reflects the ability of the model to capture the timing and amplitude of discharge peaks, is more sensitive to soil texture characteristics than the KGE.

*In line with the KGE and NSE criteria, the absolute PBIAS is minimal (absolute values below 10%; pale blue or red on Fig. 7c) for many stations located in the Saint-Lawrence Valley and North of Lake Superior and Lake Huron****, where the soil tends to be sandy rather than clayey.*** *In these regions, the* ***Fr-Inf*** *experiment* ***slightly*** *overestimates streamflow (blue dots)* ***in general****, though it tends to* ***result in strong underestimations*** *elsewhere. The positive bias is attributed to the soil freezing configuration that remains too restrictive to infiltration despite* ***the increase of infiltration****. Consequently, most stations in the eastern part of the domain, where the bias is positive, are also stations where the* ***Fr-Inf*** *degrades the KGE compared to noFr (Fig. 5b). The overall negative bias in the rest of the domain can be explained by an underestimation of streamflow during periods of low-flow regime. As the available pore space for liquid water decreases with growing soil ice, lateral flow likely prevails over soil drainage. This reduces the liquid water that contributes to support base flow.* ***This behavior is consistent across all model configurations but is particularly pronounced in soils with higher clay fractions.***

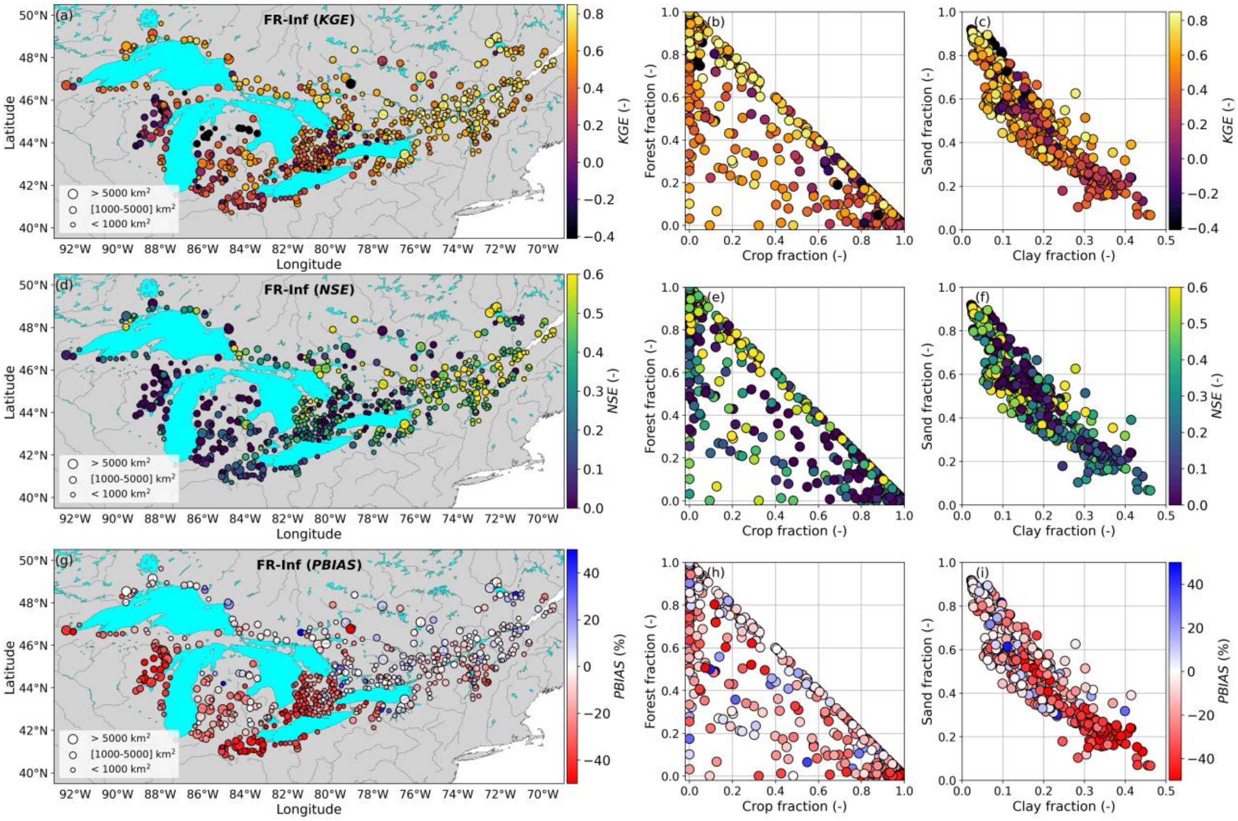

Figure 7: ***Spatial performance and catchment characteristics for the Fr-Inf experiment (2016–2021). Left panels (a, d, g) show the Great Lakes and St. Lawrence domain with KGE, NSE, and PBIAS at each station. Right panels (b, c, e, f, h, i) show corresponding forest-crop and sand-clay fractions categorized by performance scores.*** *In (a) to (f), a good performance of the model is represented by yellow shades. In (g) to (i), underestimation of streamflow is shown by red colors while an overestimation is shown by blue colors with pale red and blue dots show a low absolute bias.*"

Figure S1 will also be replaced by Figures S2 and S3 which are similar to Figure 7 but for the noFr and Fr configuration, respectively.

With respect to these changes, we also suggest the following addition to the methods:

ll. 309-311: "***For the upstream catchment related to each station, we extracted the corresponding land surface types and the depth-averaged soil texture (to 3 m) from the geophysical field dataset.***"

3. Finally, the transferability of the calibrated parameter α_MP within and beyond the study domain is not addressed and should be discussed.

In response to Ref1-Maj2, we conducted a detailed analysis of catchment characteristics (forest-crop and sand-clay fractions) relative to the optimal $\alpha_{no\text{-}imp}$ values identified in Section 3.2. This analysis reveals that a calibrated $\alpha_{no\text{-}imp}$ to 0.55 is particularly well-suited for catchments dominated by sand and forest, rather than those with high agricultural and clay content. This explains the superior model performance in these specific environments. Detailed revisions to the manuscript and Supplementary Materials are outlined in our responses to Ref1-Maj2.

Regarding the transferability of the calibrated $\alpha_{no\text{-}imp}$ beyond the GLSL domain, an essential next step is to evaluate the Fr-Inf configuration across other large-scale hydrological domains. Assessing the robustness of this approach and its calibration across diverse geographic regions is a prerequisite for its implementation into our operational forecasting systems.

4. Overall, I consider the manuscript suitable for publication after revision. The proposed approach is particularly interesting from an operational perspective, as it provides a simple and efficient way to improve infiltration under frozen conditions. I am especially interested to see how this concept will evolve in future work toward more physically based representations of preferential flow processes.

We thank the referee for showing interest in our work. We believe that the revised version manuscript, based on comments from all three referees, will strongly improve and tighten the manuscript.

Minor comments and technical notes:

1. L. 44: The sentence is difficult to follow. Consider restructuring it for clarity (e.g. "This makes the representation … complex and challenging.").

This sentence will be removed from the revised version of the introduction (see Ref3-Maj1)

2. L. 87, 204, 250, 273, Figure 1 caption: The manuscript frequently refers to a "macropore representation" or "macropore configuration". Given that the approach does not explicitly represent macropore flow but rather mimics its effect on infiltration, I suggest using a more precise terminology (e.g. "conceptual macropore parameterization" or "macropore flow correction") consistently throughout the manuscript.

References to "macropores" when describing the new configuration will be replaced by "enhanced frozen soil infiltration" in the revised version of the manuscript (see Ref3-Maj1).

3. L. 150: The statement that a unique residual unfrozen water content is assigned independently of soil temperature is somewhat unclear, as Eq. (1) explicitly includes temperature. I may be misinterpreting the formulation. However, it would be helpful to clarify whether this temperature dependence is averaged out to obtain a constant value for each soil type.

Indeed, the residual unfrozen water content corresponds to the average of W_{res} estimated with temperature (T_i) values of 263.15 K to 271.15 K by increments of 2 K. We suggest the following modification to the manuscript:

ll. 176-179: "*It corresponds to the average of the values obtained from Eq. (3) of Niu and Yang (2006) for* ***soil temperatures (T_i) from 263.15 to 275.15 K by increments of 2 K***:

$$W_{res} = \frac{W_{sat} \sum_{i=1}^{n=5} \left[\frac{10^3 L_f (T_i - T_{ref})}{g T_i \psi_{sat}} \right]^{-1/b}}{n} \quad (9)$$

where L_f and g are the latent heat of fusion (334 J kg^{-1}) and the gravitational constant (9.81 m s^{-2}), respectively."

4. L. 214: The proposed parameterization represents a strong simplification of preferential flow processes. In particular it does not account for dynamic effects such as refreezing or the dependence of macropore flow on soil type and saturation. Some experimental studies even suggest that preferential flow can decrease at high saturation levels or vary significantly with soil structure. A short discussion (maybe later in the manuscript) of these limitations would strengthen the manuscript.

In the revised manuscript, we have reframed the proposed configuration as a structural modification designed to enhance frozen ground infiltration, rather than an explicit representation of macropore preferential flow. Section 2.1.3 (ll. 223–245) has been updated to reflect this change in terminology (see Ref3-Maj1).

We acknowledge that the literature presents complex findings on this topic. While some studies suggest that preferential flow is more prevalent in dry soil conditions (e.g., Merdun et al., 2008; Hardie et al., 2011), research specifically investigating frozen soils (e.g., Demand et al., 2019; Bauer et al., 2026) indicates that high antecedent moisture can actually facilitate rapid infiltration. This occurs because water in smaller pores may freeze first, leaving larger pores available for water transport. By reframing our approach as a structural enhancement to the infiltration partitioning, we maintain the physical reasoning backing the Fr-Inf configuration while acknowledging these complex subgrid processes.

We propose the following addition to discussion:

ll. 640-645: "***While some studies have shown that preferential flow is favored under low antecedent soil moisture (Hardie et al., 2011; Merdun et al., 2008), the approach proposed here relies on the exceedance of a threshold, derived from sensitivity analysis, to increase frozen soil infiltration. This is supported by empirical evidence suggesting that water may freeze preferentially in smaller pores, leaving larger pores available for rapid infiltration (Demand et al., 2019; Mohammed et al., 2019; Bauer et al., 2026). Nevertheless, this remains a structural modification to the SVS soil freezing scheme which does not explicitly account for the subgrid physical processes that drive frozen ground infiltration, such as macropore preferential flow.***"

ll. 659-660: "***Finally, given the reliance of the SVS vertical flux scheme on Darcian flow (Alavi et al., 2016), we tried to mimic preferential flow*** *to increase vertical hydraulic conductivity ($K_{sat,v}$)* ***but this*** *resulted in numerical instabilities.*"

5. L. 311: The exclusion of stations based on NSE/KGE thresholds is understandable. However, it would be helpful to briefly explain the choice of the KGE threshold (-0.41) and its interpretation, as this value is not immediately intuitive for the readers.

We suggest the following modification to the manuscript:

ll. 330-332: "*When comparing two or more experiments for a given station, we decided to exclude the station from the analysis if the NSE or KGE of at least one experiment was lower than 0 and –0.41, respectively,* ***indicating that the mean of the observations is a better predictor of streamflow than the model (see Eq. 11 and 12 and*** *Knoben et al., 2019).*"

6. L. 359: There appears to be a missing "Fr-" before the word "experiment".

Thanks for raising this up. This will be corrected.

7. Figure3/Figure 5: The spatial distribution of excluded stations (red crosses) shows a pronounced clustering in specific regions rather than a random pattern. While the manuscript discusses potential causes for poor model performance in these areas, it remains unclear whether the station filtering systematically removes specific hydro-climatic or physiographic conditions from the evaluation. Please clarify how this affects the representativeness of the results.

In Figure 3, 5a and 5b, clusters of red crosses appear west of Lake Michigan and between Lakes Michigan and Huron, These markers indicate that none of the tested model configurations resulted in a NSE > 0 or a KGE > –0.41. This poor performance by all three configurations may be attributed to the fact that surface-ground water exchanges, flow regulations and wetland processes are not currently represented in SVS or Watroute.

Moreover, in Figure 5a, a third cluster of red crosses emerges northwest of Lake Ontario, indicating that only the noFr configuration meets the inclusion criteria in this area. This suggests that even with the enhanced frozen soil infiltration configuration, infiltration remains overly restricted in this specific region. We propose adding the following sentences to the manuscript:

ll. 378-379: "***This may also explain the emergence of excluded stations (red crosses) northwest of Lake Michigan and between Lakes Michigan and Huron.***"

ll. 435-437: "***The concentration of excluded stations northwest of Lake Ontario suggests that infiltration is still insufficiently captured in this area, even with the Fr-Inf configuration, indicating that the model remains too restrictive to frozen ground infiltration in certain localized conditions.***"

ll. 689-691: "*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).***"

8. L. 372: Please consider using more precise terminology such as "macropore parameterization" instead of implying an explicit representation.

As for Ref2-Min2, this will be revised in the revised manuscript.

9. L. 406: Please clarify whether this statement applies to all stations or only the majority of them.

This applies to the majority of stations. It will be corrected

10. L. 408: The underlying reasons for the observed behavior are not entirely clear. Additional explanation would improve the interpretation.

Additional explanation will be added (see Ref2-Min7)

11. L. 414: Could the observed spatial variability in model performance be linked to differences in land use or soil properties? While some aspects are discussed, it might be helpful to further elaborate on the controlling factors (e.g. soil texture, land cover, or hydrological regime).

This point was addressed in response to Ref2-Maj2.

12. L. 418: The results indicate substantial performance degradations associated with the soil freezing configuration in some regions. While general limitations of the freezing scheme are discussed later, it would be helpful to more explicitly link these limitations to the observed regional patterns in model performance.

In the revised section 3.3, we provide a deeper interpretation of the poor performance of the Fr experiment (especially with respect to the NSE). Please refer to Ref2-Maj2 for the proposed modification.

13. L. 421: The influence of station exclusion on the interpretation of PBIAS should be clarified, especially since different configurations are evaluated on different subsets of stations. This may affect the comparability of the reported bias between experiments. In addition, the use of the term "demonstrates" appears too strong in this context. Given the differences in station subsets and the indirect nature of the comparison, "suggests" may be more appropriate.

In Figure 6, we compare the three experiments using a consistent subset of 521 stations where at least one configuration achieved an NSE > 0 or a KGE > –0.41. This subset includes several stations where the Fr experiment exhibits poor performance in terms of KGE and NSE, often due to the generation of unrealistic mid-winter and spring discharge peaks. These overestimations in peak flow effectively compensate for the model's general tendency to underestimate baseflow as a result of the lack of a water table representation. This phenomenon of compensating errors explains why the Fr experiment may appear to outperform the noFr configuration in terms of PBIAS, despite significant degradations in KGE and NSE scores. We suggest the following precision added to the manuscript:

ll. 450 to 455: "*The noFr and the Fr experiments result in the largest and the smallest negative biases, respectively (Fig 6c),* ***contrasting with the KGE and NSE****.* ***This may be caused by the multiple unrealistically high mid-winter and spring peaks of streamflow which tend to compensate for SVS general tendency to underestimate baseflow.*** *More interesting, however, is that the PBIAS of the Fr-MP experiment is nearly equal to that of the Fr experiment. It* ***suggests*** *that the large improvements in KGE and NSE resulting from the addition of* ***the enhanced frozen soil infiltration*** *configuration do not exacerbate the general underestimation of streamflow.*"

14. L. 439: While some explanations are provided, the underlying drivers of the observed spatial patterns are not fully clear. Could these patterns be more explicitly linked to dominant hydrological processes (e.g. snowmelt dynamics, flow partitioning, or model structural limitations)?

The analysis of performance scores based on dominant land cover and soil texture provides a clearer understanding of the spatial variability in model performance. We have linked these results to the soil water balance of SVS under each model configuration. Full details of this analysis and the associated revisions are provided in our response to Ref2-Maj2.

We did not perform a specific analysis of the relationship between hydrological regimes and spatial performance patterns because several key hydrological processes (e.g., surface-groundwater interactions, wetland processes) are not yet represented in SVS or Watroute. Consequently, any conclusions drawn from such an analysis would remain largely speculative. We have chosen to focus our discussion on the land surface and soil texture characteristics, for which we have robust data and direct model sensitivities.

15. Figure 8: Adding a finer temporal reference (e.g. months or seasons) to the x-axis would improve readability and help distinguish between winter, snowmelt, and summer events.

We will modify the x-axis of Figures 8, 9a and S4 to show a finer temporal resolution.

16. Furthermore, differences between the model configurations appear to persist during summer periods, when soil freezing should not play a significant role. This may be related to the modified runoff generation scheme introduced together with the macropore parameterization. Please clarify whether such differences under unfrozen conditions are expected within the current model formulation.

Thank you for raising this up. Indeed, it is possible that differences arise in summer (i.e. under unfrozen conditions) due to modifications brought to surface runoff generation mechanism. However, since subgrid-scale surface layer interflow only happens when the surface layer is saturated, which seldom occurs when the surface layer is unfrozen, this situation is fairly rare. The following modifications will be added to the revised manuscript.

l. 240: "***This seldom occurs in the absence of ice in the topmost soil layer.***"

ll. 522-524: "***On both Figs. 8 and S4, differences between the assessed SVS configuration under unfrozen soil conditions arise due to the structural modification to surface runoff generation. These differences remain uncommon since it necessitates the saturation of the surface layer, which rarely occurs without modelled soil ice.***"

17. Figure 9: Please clarify whether the improved agreement is related to specific freezing conditions during the selected period.

We selected the hydrographs for station 02HL001 during the 2018–2019 winter because they effectively illustrate the primary impacts of the Fr-Inf configuration. Specifically, Fr-Inf attenuates unrealistically high mid-winter peaks produced by the Fr configuration and provides a more accurate representation of both the timing and magnitude of the spring freshet. While specific meteorological and freezing conditions in any given year inevitably influence model performance, the 2018–2019 period is representative of the general behavior observed across the domain. In most cases, the Fr-Inf hydrograph sits between the noFr and Fr simulations regarding baseflow and rapid-response fluxes (surface runoff and lateral flow), providing a more physically consistent agreement with observations than the default Fr experiment.

We suggest the following addition to the manuscript:

ll. 558-559: "***One must also note that the impact of the Fr-Inf configuration on streamflow simulations varies among stations and years depending on the prevailing soil freezing conditions which differ spatially and inter-annually.***"

18. L. 610: The influence of soil type on the presented results could be discussed in more detail, as it may significantly affect the applicability and transferability of the parameterization. In particular, experimental studies suggest that the role of preferential flow under frozen conditions can vary with soil properties and saturation state. A brief discussion of this variability would strengthen the manuscript.

Following the land cover- and soil texture-based performance and calibration analysis, as presented in responses to Ref2-Maj2 and Ref1-Maj2, we will provide additional interpretations in the discussion. We propose the following modifications to Section 4.2 (Limitations):

ll. 645-655: "***Moreover, the proposed parameterization*** *does not currently rely on land cover characteristics* ***neither on soil texture*** *to modulate infiltration,* ***despite well-documented effects on frozen soil hydraulic behavior*** *(Ala-Aho et al., 2021; Jarvis, 2007; Mohammed et al., 2019; Zhang et al., 2021).* ***Our results suggest that the observed spatial variability in model performance is influenced by land use and, to a larger extent, by soil texture (Fig. 7).*** *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.* ***However, to maintain model parsimony and avoid introducing additional free parameters, the current Fr-Inf configuration does not explicitly account for varying surface characteristics. Despite this simplification, the approach performs reasonably well across the Great Lakes and St. Lawrence domain. In the future, the calibration of*** $\alpha_{no\text{-}imp}$ ***is likely to be reviewed*** *when applying the model* ***across other large domains*** *in Canada and this approach may be revised* ***to include a root-depth or a soil-texture dependency.***"

Regarding the relationship between soil moisture and preferential flow dynamics, please refer to the response to Ref2-Min4 for the proposed modification to the manuscript.

19. L. 615: The macropore configuration is implemented together with a modification of the runoff generation scheme by disabling the subgrid-scale interflow routine at the surface. This represents an additional structural change to the model. It would be helpful to more clearly separate and discuss the respective impacts of this modification and the macropore parameterization on the results.

The respective impact of disabling subgrid-scale saturation surface runoff generation and favoring vertical soil fluxes under frozen soil conditions was already briefly addressed in Section 3.4. The revised version of the manuscript will further include a clearer separation of both structural changes to the model (see Ref2-Maj1, Ref3-Maj1 and Ref3-Maj2).

Cited References:

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