Response letter to reviewer comments

The authors have significantly enhanced their manuscript, providing additional information, reorganizing the paper a bit and clarifying the aims and limits of their work. The newly included Appendixes are of high interest.
Meanwhile, some of my methodological concerns are not fully alleviated. First, the novelty of the proposed pseudo-3D approach for the simulation of coupled water, heat and solute transfer in a real watershed is still not acknowledged, and consequently the need of testing it is still overlooked. Second, the proposed convergence study is only partial, and especially it does not include the main area of interest. Additional numerical experiments must be undertaken for consolidating the methodological aspect of this work.
So I recommend a supplementary revision step for this manuscript.

Response: We thank the reviewer for their careful evaluation of our study, which has provided many useful insights leading to several significant improvements and clarifications. Our intention is in fact not to conduct a site-specific study, instead, we use available site data to design a realistic and reasonable semi-generic model broadly representative of convergent hillslopes, with the aim to investigate the relative differences of transport of solutes and carbon released at different depths in the active layer and permafrost. The question whether a variably width hillslope approximates a 3D catchment is irrelevant in the context of our study and is the result of a miscommunication about what we are trying to accomplish. Our model domain is inspired by the site and captures key physiographic characteristics of the site, but it is intended to be a synthetic domain that is broadly representative of hillslopes in continuous permafrost regions. We are not attempting a case study that would require 3D representation of heterogeneity. The convergent variable-width hillslope is uncontroversial and based on fundamental physics of flow (model sides must correspond to flow streamlines and thus lines of steepest descent of the surface elevation to be no-flow boundaries), and is necessary to preserve the contributing area to a stream segment for a given travel distance to the stream, where distance is defined along the flowpath. Importantly, it ensures the model is consistent with a convergent hillslope conceptualization.

Convergent hillslopes are well understood to be much more common than uniform or divergent hillslopes, so the choice of a convergent hillslope to study is an obvious one. The site which we base the model conceptualisation on corresponds to a small region along one side of a hillslope of Endalen valley in Svalbard. We use this as the basis for design and analysis because it corresponds to a well-defined convergent flow system representative for hillslopes in many valley systems throughout Svalbard and the wider Arctic. To eliminate potential misunderstanding between the hillslope that we conceptualize, versus the much larger Endalen valley catchment, which we do not consider, we have refrained from the use of the term catchment in favor of the term hillslope in our revised manuscript. This change will align better with the terminology commonly adopted in hillslope hydrology and clarify the context of the model intention.

We have clarified the text throughout the manuscript, and especially emphasized the aims of the study, i.e., as a semi-generic representation of a convergent hillslope flow system, in the Introduction section, and clarified the approach in the Methods sections, as well as in Appendix A. Several figures have been improved to help clarify these points and new ones have been added. We have also conducted yet another mesh discretization study, focusing on the transport region (i.e., the main area of interest of the model analysis), demonstrating its robustness, included in the updated Appendix D. Specifics and details are provided in our responses below.

COMMENTS :

1. L 515-523 (problem with lines numbering, I take the manuscript version with apparent modifications as reference): “similar systems are widespread across the Arctic” Please quantify the % of surface coverage of ‘high Arctic hillslope systems underlain by continuous permafrost’ over the total permafrost area, over the continuous permafrost area and over the Arctic region. Please also include the ecotype (bare soil, tundra …?) in the site characteristics.

Response: This prevalence of similar hillslopes in permafrost regions in the Arctic is reported in the reference cited in the text (Hamm and Frampton, 2019). Continuous permafrost is generally accepted to be landscapes underlain by permafrost with 90% or more in extent, and a reference to Brown et al. (2002) has been added to the text which highlights that Svalbard is underlain by continuous permafrost (line 459 of the revised version). While detailed quantification of soil types may be interesting it is unfortunately not realistically possible to provide with reasonable accuracy, but the qualitative description suffices for the purpose of the discussion in our study.

2. L 76: In my opinion it should be at least stated here that considering non-reactive tracer is a simplifying assumption.

Response: This part of the text is referring to Jafarov et al. (2022).

3. L 126, Qs in Eq. (1) : OK, then to which physical process is associated Qs? Is Qs set to 0 in your simulations? The reader should be able to understand this after this paragraph.

Response: Qs is a source/sink term. This part of the text has been clarified in the revised manuscript (lines 127-135). The details of solute injection during the transport simulation phase are provided in Section 2.4.

4. L 188-190: “This strategy, together with variable-width elements that preserve flow convergence, provides an accurate representation of catchment-scale processes without

the computational burden of a full 3D model (Appendix A and D).” Please find hereafter my comments on Appendix A and D. Although things are a bit clearer now, I think that there is still some work to be done. Stated here that the representation of catchment-scale processes is accurate still look like an unjustified statement, see my comments on lines 602-606.

Response: Our aim is not to conduct a site-specific study which reproduces a particular hillslope or catchment; rather, we use available site data to design a realistic semi-generic/stylized model representation of the hillslope system, with the objective of investigating solute transport in the active layer. Semi-generic approaches are commonly adopted and often necessary for remote cold regions where data availability is limited (e.g., Lemieux et al. (2024), Lamontagne-Hallé et al. (2020), Walvoord and Kurylyk (2016)). The strategy of studying water and solute movement along hillslopes separately from movement along stream channels is well-established in catchment science and global change research (see, for example, the extensive discussion in the recent review by Fan et al. 2019). We selected this location as the basis for the model design as a representative hillslope for many valley systems throughout Svalbard and the wider Arctic. We have clarified the aims and intentions with the approach throughout the revised text, in particular in the Introduction section (lines 80-89) and Methods section (Section 2.2 lines 113-120, Section 2.3 lines 145-176) as well as Appendix A (lines 536-555) and corresponding figures Fig. 2, 3, and A1. We have also conducted yet another mesh discretization study, focusing on the transport region (i.e., the main area of interest of the model analysis), demonstrating its robustness, included in Appendix D (lines 671-676) and Figs D5, D6.

Lemieux, J., Frampton, A., Fortier, P., 2024. Recent Advances (2018–2023) and Research Opportunities in the Study of Groundwater in Cold Regions. Permafrost & Periglacial ppp.2255. https://doi.org/10.1002/ppp.2255

Lamontagne-Hallé, P., McKenzie, J.M., Kurylyk, B.L., Molson, J., Lyon, L.N., 2020. Guidelines for cold-regions groundwater numerical modeling. WIREs Water 7, e1467. https://doi.org/10.1002/wat2.1467

Walvoord, M.A., Kurylyk, B.L., 2016. Hydrologic Impacts of Thawing Permafrost—A Review. Vadose Zone Journal 15, vzj2016.01.0010. https://doi.org/10.2136/vzj2016.01.0010

5. L 592: Why 1040 m?

Response: This is the length of the model domain representation of the hillslope from the upper boundary to outlet. We have clarified the model design procedure in the Methods section (Section 2.3 lines 145-176) and Appendix A (lines 536-555) and corresponding figures Fig 3 and A1.

6. L 600 : “dominant topographic controls on flow (Dunne and Black, 1970; Anderson and Burt, 1978) “ Why citing experimental studies made in peculiar hillslopes in non-

permafrost areas, as relevant for characterising the flow in this peculiar permafrost watershed? Obviously topography is important for flow in continental surfaces, but why using these references here for justifying this is not clear to me.

Response: Solute transport is driven by surface overland flow and shallow groundwater flow in the suprapermafrost flow system of the active layer during the unfrozen period. The governing physical principles of surface overland flow and groundwater flow during this period are the same as for non-permafrost regions. Indeed, the suprapermafrost flow system in continuous permafrost regions is even simpler than typical non-permafrost locations. In particular, for continuous permafrost environments, topography exerts a strong control on flow in the relatively shallow active layer as permafrost acts as an essentially impermeable boundary inhibiting deep groundwater recharge. The permafrost-specific processes of relevance, heat transport with freeze/thaw and cryosuction, are largely one-dimensional in the vertical direction, and are thus not affected by the spatial structure adopted (column models are adequate in the absence of flow).

7. L 602-606 : Fan and Bras 1998 proposed 1D analytical solutions for flow in and over a hillside with a Darcy-type equation for either divergent, convergent or uniform hillslopes. Then, for applying these analytical solutions at the catchment scale, they suggested to divide the complex topographical surface of the catchment in elementary hillslopes of one of these three basic types. Troch et al. 2003 then extended this approach to nine basic plan shape / Curvature profile types hillslopes, and by using a numerical resolution of Boussinesq equation for flow on the obtained 1D domains. Paniconi et al., 2003, made a comparative study of the results of this approach with the one obtained with fully 3D Richards equation-based flow simulation, once again only for basic hillslope types. Finally Hazenberg et al., 2015 apply this approach for LSM simulations. On the other hand If I understand correctly what you do is to approximate the whole catchment as a kind of convergent hillslope with the thalweg topographical line as longitudinal profile, then to approximate this 3D convergent hillslope as a 2D transect with variable width of the unique y-axis cell, and then to apply a numerical resolution of variably saturated flow and transport with freeze/thaw to the obtained pseudo-3D representation of the watershed. This would be significantly different from the developments cited above, although directly inspired by them. I would recommend this new approach to be explained and tested. If I correctly understood, in Gao and Coon 2022, a basic geometry in the style of Troch et al. 2003 was dealt with, without studying whether or not such a simplified geometry allows to catch the dynamics in real, complex watersheds, but rather for giving a theoretical test case for evaluating relative importance of various processes in the numerical simulation of permafrost dynamics. And no comparison with full 3D results was proposed in this later paper. So I think that this new approach is potentially promising, but should be carefully assessed, from at least two points of view :

- Is the simplified approach developed in Fan and Bras 1998, Troch et al., 2003, Paniconi 2003 and Hazenberg et al., 2003 for Boussinesq equation applicable to the modelling of permafrost dynamics + solute transport, i.e. for 3D simulations of coupled flow, heat transfer and solute transfer?
- Is this simplified approach applicable to the considered watershed, given its complex morphological structure ? I Guess that this approach could not always be successfully applied, for peculiar watershed topologies for instance. Furthermore, I wonder whether or not the proposed methodology for building the y-axis width along slope does conserve the properties of the hypsometric curve of the watershed? I think this point could be important for properly handle the altitudinal distribution of contributing areas, and thus for the time of concentration.

Such an assessment would likely request large computational means, which should not be a problem given the High Performance Computing capabilities of ATS.

Response: It is important to make the distinction between a catchment with a “complex morphological structure” and a hillslope. The strategy of studying hillslope processes separately from stream processes is well-established in catchment science and global change research (see, for example, the highly cited review paper of Fan et al. 2019); we are taking this standard approach. Granted, our convergent hillslope has some internal structure, but variation in elevation within grid cells is small compared with variation across the grid cells, as is obvious from our revised Fig 2. More to the point, we emphasise again that our aim is not to create a site-specific model that reproduces the “complex morphological structure” of that site; this would be outside of the scope and aims of our study and would also require field measurements that are not available. In our opinion, such place-specific case studies like that would be less interesting scientifically because it would tell us much about the single site but would be less generalizable because of uniqueness of place.

Instead, we use information from the hillslope site in Endalen as a representative site for design of a semi-generic model, with the aim to study the relative impact of solute transport released from different depths in the active layer and permafrost. For this, it is not necessary to capture the precise or absolute timing of seasonal events as our findings are not dependent on those specifics. Further, the hillslope that we use as the basis for model design is a topographically well-defined convergent flow system. Even though our aim is to construct a representative semi-generic mode, we adopt a variable width approach as it preserves the contributing area to a stream segment for a given travel distance to the stream, where distance is defined along the flowpath, which ensures the model design is consistent with convergent hillslopes. As noted in our previous responses, the plan shape and profile (and thus the hypsometric curve) are preserved by construction. This greatly simplifies the model representation in terms of its applicability in allowing for topography-controlled runoff and adopting lateral no-flow boundary conditions. The approach using a surface energy balance model also simplifies the implementation of surface boundary conditions, which can be based on readily available hydro-meteorological data from weather stations, avoiding the uncertainty of imposing surface temperature-based boundary conditions.

Several studies consider variable-width hillslopes in addition to the ones we have already cited. Although the specific goals and methods differ, the conceptualization of variable width hillslopes to preserve the area-distance relationships is the same for all. Studies on hillslope representation using the Boussinesq approximation for different hillslope width functions include Paniconi et al. (2003), Troch et al. (2004), Hilberts et al. (2004), Hsieh and Huang (2023). Indeed, although Hazenberg et al. (2015) apply variable-width hillslopes to Earth System Models, Hazenberg et al. (2016) evaluates the approach with site measurements from a well-characterised catchment, albeit for uniform width conceptualizations. Fan et al. (2019) again highlights the use of a variable width concept, and Chaney et al. (2018) perform large-scale analyses of variable width hillslopes at a relatively coarse scale, collapsing those into a few canonical simulations using statistical analyses of the resulting hillslopes. Loritz et al. (2017) conceptualize and parameterize representative 2D hillslope models against two monitored catchments of widely differing sizes (~300 km^2 and ~20 km^2), showing good agreement with discharge, but highlight some variability depending on seasonal variability. Another useful review summarising hillslope catchment research which includes these and many other studies is provided by Paniconi and Putti (2015).

We have clarified the text in the Introduction section (lines 80-89) and Methods section (Section 2.2 lines 113-120, Section 2.3 lines 145-176) and also revised Fig 2 to include topography elevation contours, which now helps clarify the convergent nature of the hillslope, and updated Fig 3 with additional panels to show the domain and mesh discretization more clearly. Also, the more detailed description of the model design in Appendix A (lines 536-555) has been rewritten with further clarification both in text and with an additional figure Fig A1 which shows the convergent nature of the hillslope and model domain representation.

Paniconi, C., Troch, P.A., van Loon, E.E., Hilberts, A.G.J., 2003. Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 2. Intercomparison with a three-dimensional Richards equation model. Water Resources Research 39. https://doi.org/10.1029/2002WR001730

Troch, P.A., Van Loon, A.H., Hilberts, A.G.J., 2004. Analytical solution of the linearized hillslope-storage Boussinesq equation for exponential hillslope width functions. Water Resources Research 40, 2003WR002850. https://doi.org/10.1029/2003WR002850

Hilberts, A.G.J., Van Loon, E.E., Troch, P.A., Paniconi, C., 2004. The hillslope-storage Boussinesq model for non-constant bedrock slope. Journal of Hydrology 291, 160–173. https://doi.org/10.1016/j.jhydrol.2003.12.043

Hsieh, P.-C., Huang, T.-T., 2023. Modelling of hillslope storage under temporally varied rainfall recharge. Math. Model. Nat. Phenom. 18, 9. https://doi.org/10.1051/mmnp/2023009

Hazenberg, P., Fang, Y., Broxton, P., Gochis, D., Niu, G.-Y., Pelletier, J.D., Troch, P.A., Zeng, X., 2015. A hybrid-3D hillslope hydrological model for use in Earth system models. Water Resources Research 51, 8218–8239. https://doi.org/10.1002/2014WR016842

Hazenberg, P., Broxton, P., Gochis, D., Niu, G.-Y., Pangle, L.A., Pelletier, J.D., Troch, P.A., Zeng, X., 2016. Testing the hybrid-3-D hillslope hydrological model in a controlled environment. Water Resources Research 52, 1089–1107. https://doi.org/10.1002/2015WR018106

Chaney, N.W., Van Huijgevoort, M.H.J., Shevliakova, E., Malyshev, S., Milly, P.C.D., Gauthier, P.P.G., Sulman, B.N., 2018. Harnessing big data to rethink land heterogeneity in Earth system models. Hydrology and Earth System Sciences 22, 3311–3330. https://doi.org/10.5194/hess-22-3311-2018

Loritz, R., Hassler, S.K., Jackisch, C., Allroggen, N., van Schaik, L., Wienhöfer, J., Zehe, E., 2017. Picturing and modeling catchments by representative hillslopes. Hydrology and Earth System Sciences 21, 1225–1249. https://doi.org/10.5194/hess-21-1225-2017

Paniconi, C., Putti, M., 2015. Physically based modeling in catchment hydrology at 50: Survey and outlook. Water Resources Research 51, 7090–7129. https://doi.org/10.1002/2015WR017780

8. L 630-643: Hard to follow. A schematic figure presenting which slope is dealt with etc would probably be helpful.
   Response: The model design in Appendix A has been rewritten and the part this comment refers to was deemed unnecessary and has been removed. A new figure Fig A1 has been introduced to clarify the site location with a map view and view of the model domain. Fig 2 and A1a show elevation bands, which map directly to grid cells in our semi-generic hillslope model shown in Fig 3 and A1b.

9. L 646-647: "At the top boundary (surface), a surface energy balance, which serves as a source and sink for water and energy in the subsurface, is derived from site-specific weather data." How is this SEB derived? This should be explained.
   Response: The SEB refers to the surface energy balance model used, which has been described in detail in previous publications. This has been clarified in the main text in the Methods section 2.3 (lines 168-173) and in Appendix A (lines 583-592), and relevant references have been added.

10. L 659-661: "By using a frequency-density function, the resulting distribution more closely resembles natural rainfall variability, ensuring a realistic representation of precipitation events. This precipitation model plays a critical role in shaping the hydrological and thermal balance within the soil." Interesting. If I understand correctly the used precipitation distribution is a realization of a random process with prescribed statistical moments? Then I think that it would be interesting to test the variability of the

output results of this study when using different precipitation distributions obtained by different realization of this random process.
Response: While exploring different precipitation patterns would be an interesting avenue for future research, it falls outside the scope of this study and does not align with our current aims. The use of the variable frequency-density function is intended to represent realistic precipitation variability based on the available 10-year hydro-meteorological weather dataset, with an approach based on our previous research.

11. L 662-665: Table 1 should be inserted here, or this paragraph moved in the body of the text as a comment of this table. This should be also more precise : why these peculiar values has been chosen ? Saying 'to resemble highly water-conductive material' is not specific enough. You did not invent these value I guess, the abaqus from where they were extracted or whatever should be mentioned.
Response: These values are consistent with qualitative observations of soil textures on site. The revised version has a reference to Table 1 (page 9), which is updated with relevant sources.

12. L 703-709: Figure D3 should be cited here.
Response: Done.

13. L 716: Figure D4 is not displayed in the Appendix.
Response: Figure D4 is included in Appendix D.

14. L 716-728: The convergence study, showing dependency of the results on mesh refinement, is done only for the upper part of the domain. It should be done for the whole domain, especially in the Main Area of Interest. Another comment related to the answer of the authors regarding my comments 32 : "energy- and mass conservation apply to these cells in the same way that it does in the contemporary active layer cells. The mesh resolution is therefore adequate." Please do not forget that energy and mass conservation is necessary but not sufficient for obtaining converged numerical results ; truncation errors must also be assessed.
Response: The text in the Appendix and corresponding text in the Methods section has been improved to clarify the modeling approach, please see our previous responses. We undertook another mesh convergence study in response to this comment, increasing the mesh resolution in the transport region, i.e., the main area of interest for the analysis. Numerical differences were negligible and further confirms the model robustness. We note the original mesh with spacing of 0.5 m was already overly refined based on our experience with these types of simulations, so it is no surprise that results from a superfine mesh with 0.25 m spacing was virtually indistinguishable. We have added new figures Fig D5 and D6 showing temperature and Darcy velocity for comparing the original

fine mesh of the seasonal simulations and our new superfine mesh. We also added text to in Appendix D describing the result (lines 671-676).