Response to Comments for "Representing Lateral Groundwater Flow from Land to River in Earth System Models"

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April 22, 2025

Reply: We thank the editor, associate editor, and reviewers for the positive comments and suggestions. In this response letter, we will use colored text to represent different types of content.

Black text represents the comments by the reviewers.

Red text represents our replies to the comments.

Blue italic text represents the new or updated contents in the revised manuscript.

Figure indices in the response letter are not the same as those in the main text.

Reviewer 1

General comment Reviewer 1 Evaluations:

The paper details a study of preliminary implementation of lateral groundwater flow in the land component of the E3SM model. The goal of the model developments is to allow for subsurface flow along hillslopes to rivers. The formulation of the model allows for water table depth variation such that the slope of the groundwater table may vary in time in response to water infiltration across the land model grid cell and the elevation of water in the connecting river channel segment. Figure 9 of the manuscript highlights the large discrepancy between the default (current) model treatment of groundwater elevations and the observed spatial variability of water table along a hillslope. The ability to more realistically simulation water table depths and seasonally varying lateral groundwater fluxes has the potential to significantly improve the representation of the terrestrial hydrological dynamics in the E3SM model.

The manuscript is well written and clear. I do not have major revisions to request, however, I believe the paper's value could be enhanced with additional details regarding the observed differences in LGFs between some of the cases. For example, case 9 has a high LGF raising the elevation of the downslope boundary would intuitively seem to reduce the gradient of the WTP. However, Figures 9 and 10 show that the water rose significantly and apparently steepened. Is the higher LGF only in response to the increase in water table slope or also due to the thickness of the zone discharge at the river or due to more flow in the shallower soil layers which may have higher Ksat? Is there a strong transient response in this case for the WT to rise?

Reply: Your observation for Case 9 is very accurate, and we also investigated the two factors that affect LGF: the WTG and aquifer interface thickness. When the water level in the river increases, the WTG generally decreases slightly initially, however, as the aquifer thickness also increases, the LGF increases. Our simulation suggests the latter one is the dominant factor. We also need to acknowledge that this process is nonlinear and could vary depending on the configuration of the hillslope elevation profile and WT condition. As for Case 10, it has the smallest hillslope slope, besides, it also has higher macropore flow, therefore its LGF is relatively small compared with other cases. We added more details in the revision.

Line 283:

Case 10 has a relatively gentle slope with increased preferential flow. Therefore, its LGF is even smaller than Case 7 (Table 4).

The plotted slope for case 6 on Figures 9 and 10 is confusing. The plotted slope looks much steeper than all other slopes, but the case is supposed to be the surface slope. On Table 4 the slope is listed as 0.07 which is identical for the other cases.

Reply: Thank you for the comment. The model keeps record of two slopes: surface slope (time invariant) and water table slope (time variant). The surface slope is derived from the hillslope definition process and it is fixed. We also have surface slopes of 0.04 and 0.03 in Cases 3 and 4, respectively, which are used to demonstrate that hillslope definition is very important. In natural conditions, the water table slope is often less than the hillslope. In Case 6, we assume the water table slope (WTG) equals the surface slope (0.07), which is more than double the slope simulated in the other cases, such as 0.028 in case 5. Therefore, Case 6 always has the steepest WTG, serving as a control experiment to test whether it is reasonable to assume that WTG is the same as the surface slope.

Is it possible from the analysis to quantify how including LGF would impact river discharges across a basin seasonally? Or is the most significant potential change related to the discussion of soil moisture and hydrological feedbacks on plants.

Reply: For the analysis on the river component and soil hydrology, we are planning to conduct a more in-depth evaluation in future work. We didn't include them in this study for two reasons: (1) ideally, the two-way interactions between land and river could be included using our approach, but that requires a much larger scale hillslope definition simulation and additionally, we need to run both MOSART and ELM for a watershed; (2) there are already some studies focusing on soil hydrology (soil moisture) using the hillslope approach. Given the critical assumption of using a single hillslope to represent the whole ELM grid cell, we think the uncertainty in soil hydrology will be even larger. Therefore, we decided it is best we improve the multiple hillslope definition in LSM before we dive into more in-depth soil hydrology analyses.

Is there seasonal observational data that can be shown as well? Or is the actual groundwater table at the modeled site truly time invariant. If so, why is the model seasonally responsive but the actual system is not? Can the authors provide any discussion on why all of the modeled cases have WTD much greater than the observed? Is this related to the selection of Ksat and/or the vertical infiltration values?

Reply: Table 4 shows that the modeled WTDs actually change in wet and dry seasons, but the changes range between less than 1 meter and 2 meters. Our observations of WTDs are collected at an actual hillslope, so the scale of the hillslope could be different than the "averaged" conceptual hillslope, as shown in Figure 7. Therefore, the observation data is used for reference and evaluation only; we do not expect to have a one-to-one match between observations and the simulated WTDs.

The observational data show seasonal variability, and the data were collected at a daily time step but do not cover the whole simulation period. In this revision, we modified Figures 9 and 10, each using the corresponding monthly average observational data. The zoomed-in views in Figures 9 and 10 show that the observed WTD in the wet season is shallower than that in the dry season, and the difference is around 1 meter.

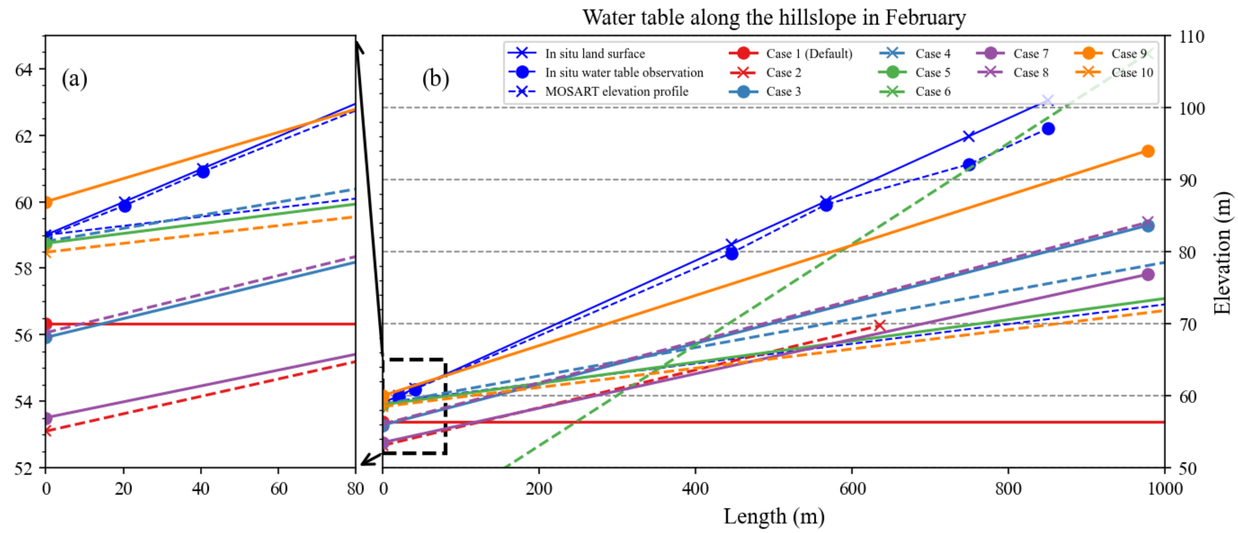

Figure 1: Comparisons of ELM modeled average water table elevation (surface elevation - water table depth) along the hillslope in February from Cases 1 to 10 (Table 3). The blue lines are in situ observational data and the MOSART elevation profile. The x-axis is the distance from the hillslope-river interface (unit: m). The y-axis is the elevation (unit: m). The x-axis is cut off from the actual hillslope distance to 1000 m for better visualization. (a) is a zoomed-in view near the hillslope-river interface of (b).

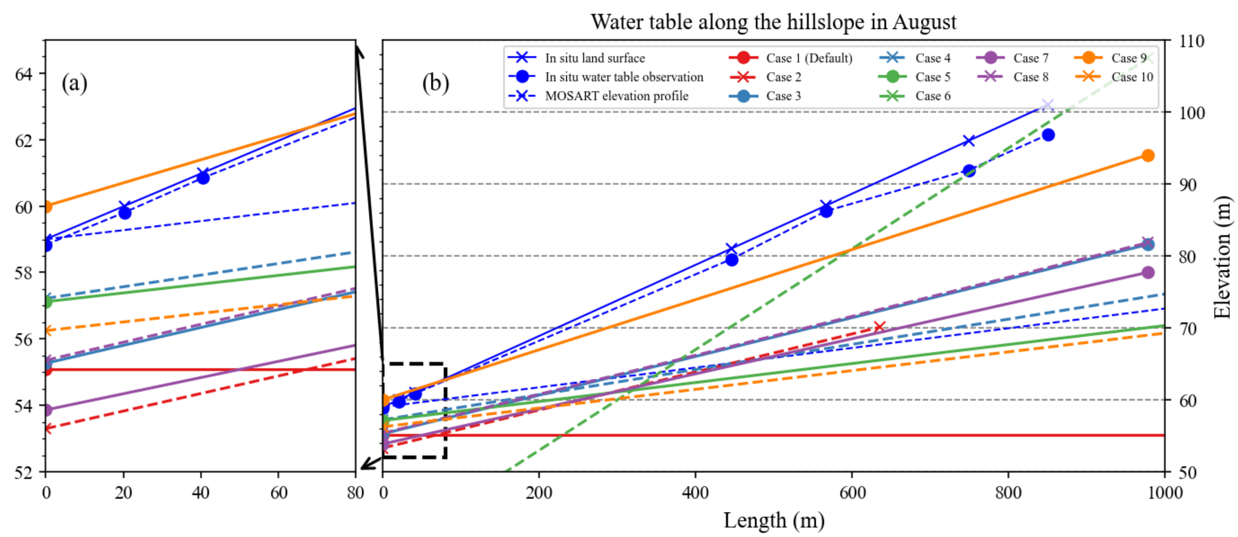

Figure 2: Comparisons of E3SM land model (ELM) simulated average water table elevation along the hillslope in August from Cases 1 to 10 (Table 3). The blue lines are in situ observational data and the MOSART elevation profile. The x-axis is the distance from the hillslope-river interface (unit: m). The y-axis is the elevation (unit: m). The x-axis is cut off from the actual hillslope distance to 1000 m for better visualization. (a) is a zoomed-in view near the hillslope-river interface of (b).

Minor comments:

Q 1.1 *Line 91: WTD not defined yet.*

Reply: Thank you for the comments. Water table depth was defined at line 44:
Line 44:

Instead, some LSMs use empirical functions to estimate the within-cell or intra-grid LGF as a function of Water Table Depth (WTD) and surface topography

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Q 1.2 *Line 291: "Case 6 produced the largest WTD (19.9m) due to its large LGFs (caused by high WTG, 0.07)I" Can more detail be provided? The WTG for case 6 is the same for 3, 7, 8, 9, and 10.*

Reply: Thank you for the comments. For Case 6, see Table 3 "6 HLGF HexWatershed-based 1.73×10^6 surface slope 0.1 time-variant", therefore the water table gradient is set as the surface slope, which is defined by the hillslope definition (time-invariant). In other cases, the WTG is time-variant and modeled based on intermediate WTD. The surface slope is usually higher than the WTG, therefore, Case 6 has the largest LGFs, resulting in the largest WTD. This case is used to demonstrate that if the WTG is not modeled accurately, it will overestimate LGF and therefore WTD. The cases related to WTG, i.e., Cases 3, 7, 8, 9, and 10, are slightly different, where WTD is caused by the combined effects in the case configuration (hillslope, macropore, and river condition) in Table 3. The column "Average slope" in the Table means the hillslope, not the WTG, which is the last column, we updated the table to avoid confusion.

Line 292:

Case 6 produced the largest average WTD ($\sim$ 19.9 m) due to the simulated large LGFs ($\sim 5.0 \times 10^{-5}$ mm s^{-1}), which itself is caused by high WTG (0.07, equal to surface slope) (Figure 8 and Table 4).

Q 1.3 *Figure 10: the title at the top says February but the results are for August.*

Reply: Thank you for the comments. There was a mistake in the code that produced this figure. We fixed it in the revision. It is indeed for August. The updated figure is:

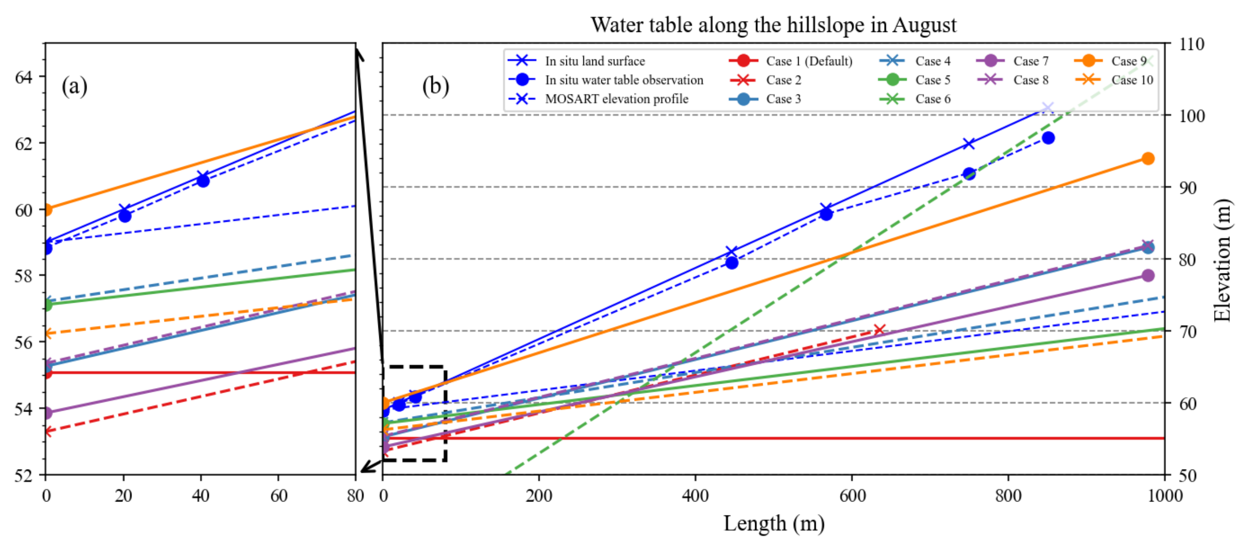

Figure 3: Comparisons of E3SM land model (ELM) simulated average water table elevation along the hillslope in August from Cases 1 to 10 (Table 3). The blue lines are in situ observational data and the MOSART elevation profile. The x-axis is the distance from the hillslope-river interface (unit: m). The y-axis is the elevation (unit: m). The x-axis is cut off from the actual hillslope distance to 1000 m for better visualization. The (a) is a zoomed-in view near the hillslope-river interface of (b).

Reviewer 2

Reviewer 2 Evaluations:

The manuscript by Liao et al. presents the implementation of a lateral groundwater flow model coupled with a component of the E3SM model. The objective of the model developments is to account for groundwater flow along hillslopes down to rivers. The hillslope definition is based on watershed delineation at subgrid spatial scales, and a physics-based lateral groundwater flow model is implemented using Darcy's Equation. The model is coupled with the land component (ELM) and river component (MOSART) in the Energy Exascale Earth System Model (E3SM). Tests are conducted on the hillslope definition, lateral groundwater flow, and sensitivity using different configurations, with the model's application demonstrated in the Amazon basin.

The main results show that the subsurface processes are significantly improved using this hillslope approach. Figures 9 and 10 clearly demonstrate the benefits of the implementation compared to Case 1 (without the hillslope method).

The manuscript is well-written and easy to read. No major revisions are required for this manuscript. However, I believe the manuscript could be further improved. First, some figures could be enhanced for better visibility (see minor comments below). It could also be useful to clearly identify the domain of applicability of this model (e.g., shallow groundwater systems, etc.).

Moreover, the model introduces a subgrid heterogeneity definition to resolve lateral groundwater flow (LGF), and the analysis of results has primarily been conducted on an averaged state of the system. It is unfortunate to present a model with hillslope-based resolution without offering an analysis of the results at the same resolution. For example, adding a spatial comparison of simulated river discharges (and/or the contribution of LGF) across the domain (Figure 5) would have provided a more in-depth analysis of the results. Is there observed discharge data available for this domain to compare with the model results?

Also, it would be interesting to understand how the model handles a hillslope domain spanning multiple grid cells of the land surface model (LSM).

Reply: Thank you for the comments. In this revision, we updated several figures as suggested (see below). We also clarify that the model we developed only considers the unconfined shallow groundwater:

Line 153:

In a normal scenario, when the shallow groundwater table along the hillslope is below the land surface, the subsurface lateral groundwater flows through the "downslope end" into the river channel.

We appreciate the reviewer's insightful comments regarding the model's spatial resolution. Although the model introduces a subgrid heterogeneity framework to address lateral groundwater flow (LGF), we are currently limited by the implementation that uses a single "averaged" hillslope representation coupled with an averaged river stage (via MOSART). In other words, our current configuration does not incorporate multiple lateral columns along the slope, which prevents us from performing a detailed spatial analysis of simulated river discharges or the specific contribution of LGF at a finer resolution. Currently, there is no direct way to obtain the river gage condition at the subgrid scale except through (incomplete) observations. In our study, we made an assumption that an "averaged" hillslope is coupled with an "averaged" river stage from MOSART. We plan to improve the analysis in a future study that allows river routing at the subgrid level so each hillslope is linked to a unique river segment.

We agree that a hillslope can span across an LSM grid cell. Because the natural landscape does not conform to the existing structured LSM grid, it is likely that many hillslopes may occupy multiple grid cells, and there is no easy solution to address this issue. In the future, we plan to use an unstructured mesh-based approach to better capture the land surface so we can describe the hillslope more realistically.

Minor Comments

Introduction

Q 2.1 *- Lines 35–38: What about the following reference: J. Marçais, J.-R. de Dreuzy, J. Erhel. (2017) Dynamic coupling of subsurface and seepage flows solved within a regularized partition formulation.* `https://doi.org/10.1016/j.advwatres.2017.09.008`*. Upon reading your manuscript, the description of your model reminded me of this reference, which is not cited in your work.*

Reply: Thank you for the suggestion. We reviewed the suggested reference and realized we missed it in the previous literature review. We have added it in the revision.

Line 36:

Besides the 3D modeling approach, regional hydrologic models also use the two-dimensional (2D) approach to simulate the LGF along hillslopes, as many studies recognized its impacts on the belowground water table and soil moisture along the hillslope [3–5].

Q 2.2 *- Figure 1: The color of the left hillslope appears more yellow than orange, as mentioned in the caption. This could be confused with other orange polygons in the figure.*

Reply: Thank you for the comments. Indeed, the color is closer to yellow. We updated both the color hex code and caption to avoid confusion.

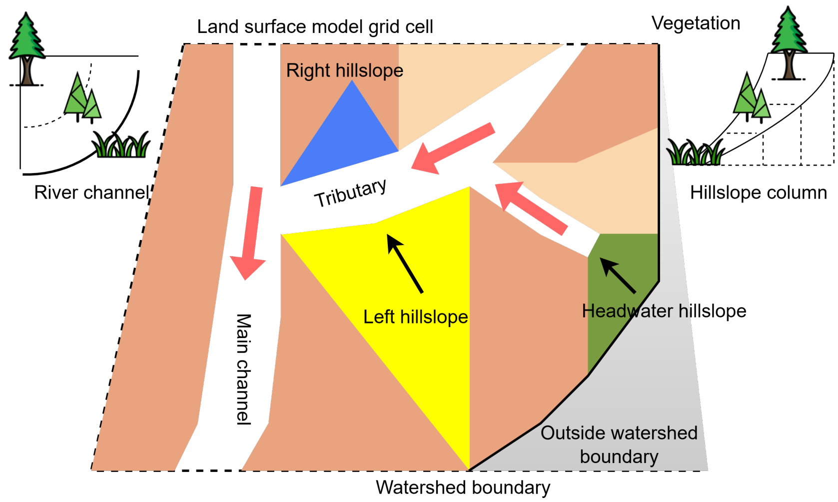

Figure 4: Illustration of the land surface with river channels and hillslopes within a land surface model (LSM) grid cell. The river channels include the main channel and tributaries. Colored polygons are conceptual hillslope types. The yellow, blue, and green polygons are left, right, and headwater hillslopes, respectively. Red arrows are the flow direction in the channels. Black arrows are the flow direction along the hillslope. The area marked in grey represents the portion that does not belong to this watershed. The upper left and right mini plots illustrate the left/right(divergent) and headwater (convergent) hillslopes along a river channel or headwater with different vegetation distributions. Sizes are not drawn to scales.

Method Description

Q 2.3 *- Line 91: What does WTD stand for? I understand that it means "Water Table Depth," but it is not clearly stated. Please define it earlier in the text.*

Reply: Thank you for the comments. WTD was defined around Line 44: as a function of Water Table Depth (WTD) Line 44:

Instead, some LSMs use empirical functions to estimate the within-cell or intra-grid LGF as a function of Water Table Depth (WTD) and surface topography.

Q 2.4 *- Line 150: This sentence might be better placed in the legend of Table 1, or the sentence could be adapted to explicitly reference Table 1 (Table 1 is not referenced in the text).*

Reply: Thank you for the suggestion. We moved the sentence into the table caption.

Line 44:

Definition of hillslope characteristics based on MOSART elevation profile [2]. $Area_g$ and $Length_{cell}$ are the area and length of an ELM grid cell; $Elev_{max}$ and $Elev_{min}$ are the maximal and minimal elevation from the MOSART elevation profile [1].

Q 2.5 *- Line 168: Could you provide more details to define K0, K1, and K2? Additionally, using the symbol "K" for shape parameters may be confusing, as it is commonly associated with hydraulic conductivity. Consider changing the notation for the shape parameters.*

Reply: Thank you for the comments. We renamed these three shape parameters to λ_0, λ_1, and λ_2 to avoid confusion. We provided a short explanation for each shape parameter. Additionally, we have included more details in the supplementary material.

Line 165:

The first shape parameter λ_0 (Equation A1) defines the water table slope when the lower end of the water table meets the lower end of the hillslope, which is the transition scenario between with and without a seepage (Brown line in Figure 5). The second λ_1 (Equation A7) and third λ_2 (Equation A16) shape parameters each describe the nonlinear change of the water table slope based on the transition slope and surface or bedrock slope (Green and blue lines in Figure 5). More details of this design are illustrated in the supplementary materials.

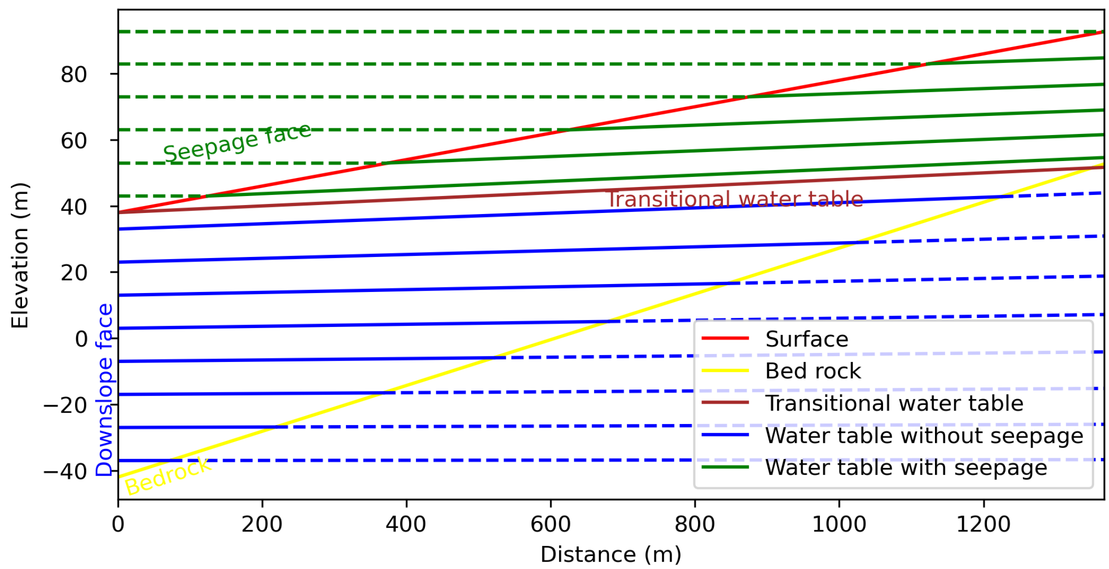

Figure 5: Illustration of water table dynamics along the hillslope. Solid green, brown, and blue lines represent the water table under different scenarios. Dashed lines are used to illustrate the slope and position only. Elevation and distance are not drawn to scale.

Model Application and Evaluation

Q 2.6 *- Figure 4: Is it possible to add the watershed delineation in this figure? This would help to better situate the results shown in Figure 5.*

Reply: Thank you for the suggestion. We added the HydroSHEDS basin datasets in the figure to illustrate the watershed boundaries. Because our workflow only supports one watershed, which is also the largest watershed (upper left) in this grid cell, we only added the boundaries in Figure 4.

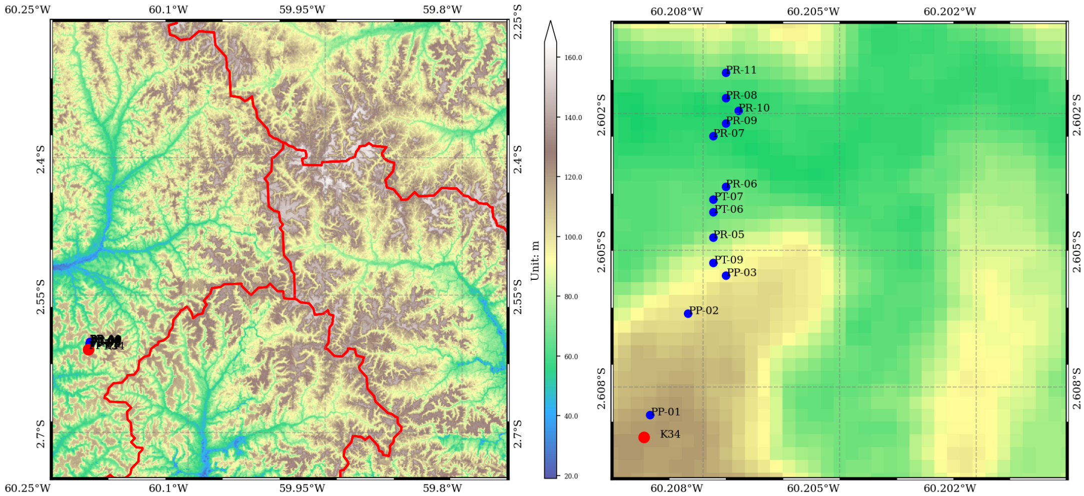

Figure 6: Surface elevation of the study area (unit: m) and locations of in situ measurement sites. (a) is the 30 m resolution surface elevation of the 0.5° × 0.5° ELM grid cell. The red lines are watershed boundaries. (b) is a zoomed-in view of the hillslope transect.

Q 2.7 *- Figure 8: The placement of the zoomed-in plot makes the figure appear cluttered. Moving the zoomed-in plot outside the main figure could make the visualization clearer. Same comment for Figures 9, 10, and 11.*

Reply: Thank you for the comments. We redesigned Figure 8 into two subfigures to describe the model results. For example, Figure 8 is updated as

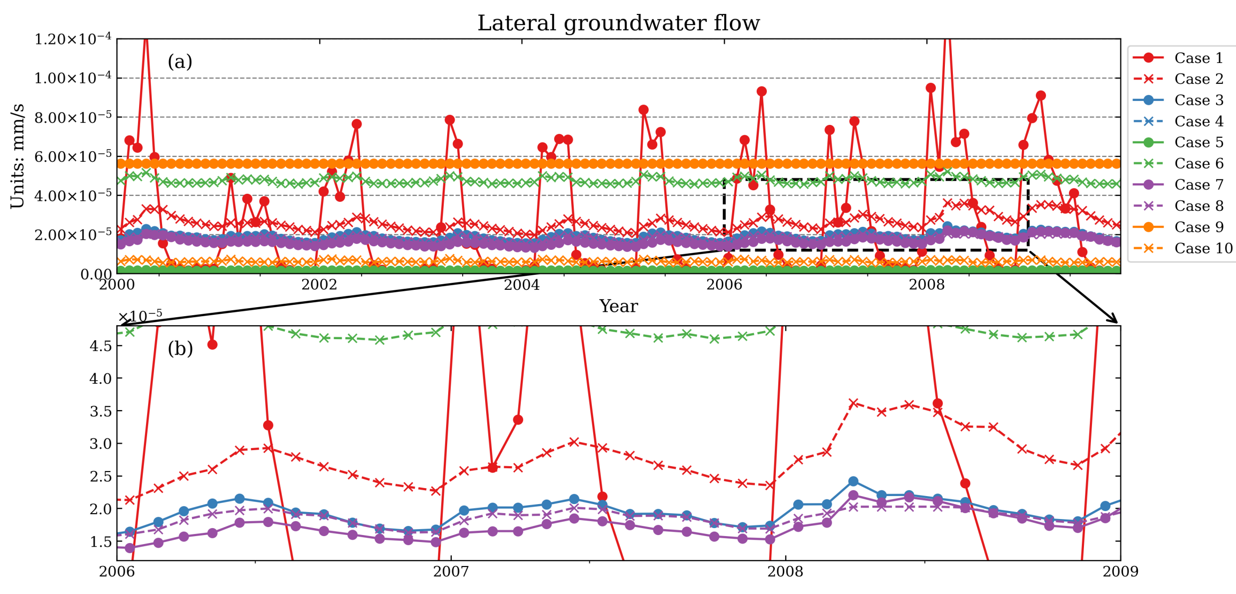

Figure 7: Comparisons of E3SM land model (ELM) simulated monthly lateral groundwater flow from the year 2000 to 2009 from Cases 1 to 10 (Table 3). The x-axis is time. The y-axis is the lateral groundwater flow (units: mm s^{-1}). The (b) subplot is a zoomed-in view of (a) from 2006 to 2009.

Figure 9 is updated as:

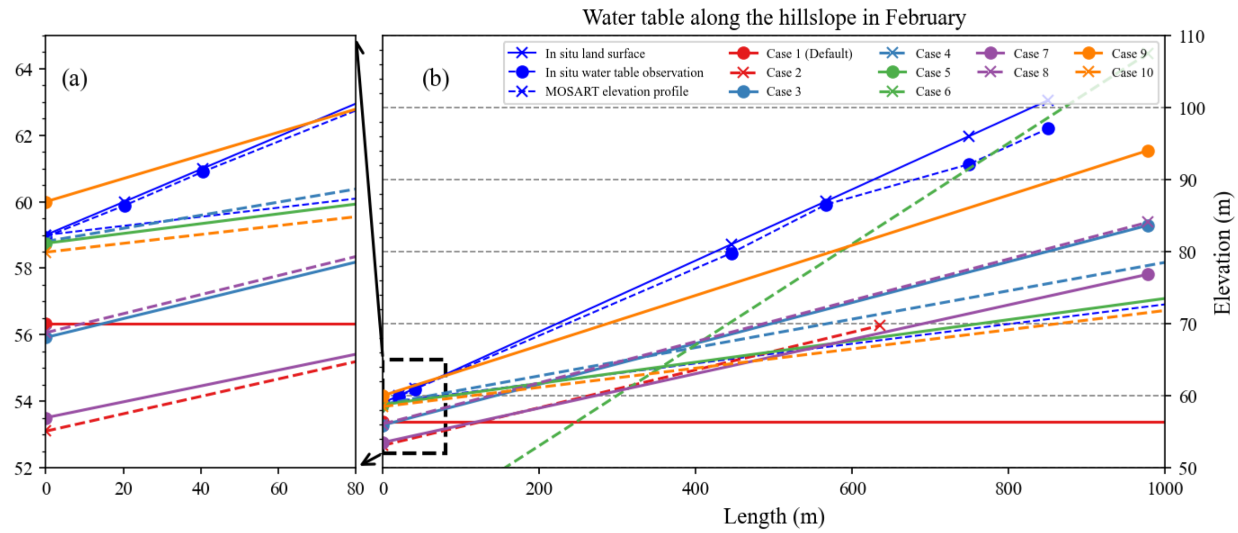

Figure 8: Comparisons of ELM modeled average water table elevation (surface elevation - water table depth) along the hillslope in February from Cases 1 to 10 (Table 3). The blue lines are in situ observational data and the MOSART elevation profile. The x-axis is the distance from the hillslope-river interface (unit: m). The y-axis is the elevation (unit: m). The x-axis is cut off from the actual hillslope distance to 1000 m for better visualization. The (a) is a zoomed-in view near the hillslope-river interface of (b).

Q 2.8 *- Line 270-308: Clearly mention in the text, at the start of paragraphs 3.2.3 and 3.2.4, that the modeled data (LGF, WTD and WTG) presented are averages.*

Reply: Thank you for the comments. Indeed, the average was used in the analyses, we revised the text when it may cause confusion.

Q 2.9 *- Figure 10: The title of the figure mentions data presented for the month of February, whereas the legend indicates it is for the month of August.*

Reply: Thank you for the comments. We realized that there was a mistake in our plotting script. It should be August. We regenerated and replaced the figure.

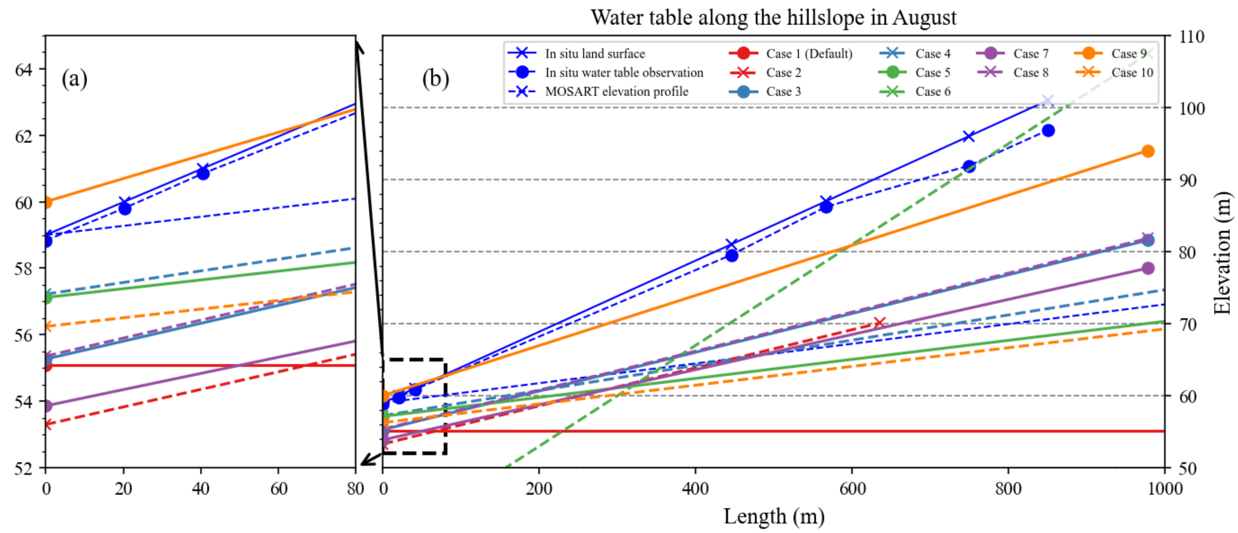

Figure 9: Comparisons of E3SM land model (ELM) simulated average water table elevation along the hillslope in August from Cases 1 to 10 (Table 3). The blue lines are in situ observational data and the MOSART elevation profile. The x-axis is the distance from the hillslope-river interface (unit: m). The y-axis is the elevation (unit: m). The x-axis is cut off from the actual hillslope distance to 1000 m for better visualization. The (a) is a zoomed-in view near the hillslope-river interface of (b).

References

[1] Hongyi Li, Mark S Wigmosta, Huan Wu, Maoyi Huang, Yinghai Ke, André M Coleman, and L Ruby Leung. A physically based runoff routing model for land surface and earth system models. *Journal of Hydrometeorology*, 14(3):808–828, 2013.

[2] Xiangyu Luo, Hong-Yi Li, L Ruby Leung, Teklu K Tesfa, Augusto Getirana, Fabrice Papa, and Laura L Hess. Modeling surface water dynamics in the Amazon Basin using MOSART-Inundation v1. 0: impacts of geomorphological parameters and river flow representation. *Geoscientific Model Development*, 10(3):1233–1259, 2017. Publisher: Copernicus GmbH.

[3] Jean Marcais, J-R De Dreuzy, and Jocelyne Erhel. Dynamic coupling of subsurface and seepage flows solved within a regularized partition formulation. *Advances in Water Resources*, 109:94–105, 2017. Publisher: Elsevier.

[4] Peter A Troch, Claudio Paniconi, and and E Emiel van Loon. Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 1. Formulation and characteristic response. *Water Resources Research*, 39(11), 2003. Publisher: Wiley Online Library.

[5] Xue-Yan Zhang, Yuanhao Fang, Guo-Yue Niu, Peter A Troch, Bo Guo, L Ruby Leung, Michael A Brunke, Patrick Broxton, and Xubin Zeng. Impacts of Topography-Driven Water Redistribution on Terrestrial Water Storage Change in California Through Ecosystem Responses. *Water Resources Research*, 60(2):e2023WR035572, 2024. Publisher: Wiley Online Library.