

**A Summary of Revisions and Responses on “A spatially hybrid hydrological modeling approach based on spatial heterogeneity of watershed characteristics”
(Ref: HYDROL70533)**

With regards to comments from the Reviewer #1

This manuscript represents the authors' second revision, and they have made substantial improvements. All of my previous concerns have been thoughtfully addressed, and I find that the conclusions are now well supported by the revised results. While I remain interested in the development of a hybrid modeling framework that enables simultaneous integration of conceptual and fully physically-based components, the current approach presented by the authors offers a valuable contribution to the field. Additionally, the comparative performance of the hybrid model against both conceptual and what the authors describe as "semi-physically-based" models could stimulate meaningful discussion within the community.

We sincerely thank the reviewer's positive feedback. We're also grateful for the reviewer's interest in the potential of our modeling framework to integrate fully-physically-based simulation modules. We agree that the framework can serve as a useful platform for supporting multiple working hypotheses and advancing hydrological understanding. This is precisely the direction of our continued efforts.

In the revised manuscript, we added a clear description of our future work to integrate fully-physically-based simulation modules in the second paragraph of Section 4.3 “Limitations and future directions”: “We plan to gradually implement a variety of fully-physically-based simulation modules, such as a 2D hillslope overland flow module inspired by FullSWOF, and a fully coupled 3D module of overland flow, subsurface flow, and groundwater flow following approaches from SHUD and ParFlow.”

With regards to comments from the Reviewer #2

The work proposes a hybrid modelling framework that enables the integration of different modelling approaches, at varying spatial scales, to solve for liquid discharge within a basin. This framework is designed to allow the application of different hydrological models to different areas or sub-basins, integrating their hydrological responses through the channel network. In my view, however, the study lacks a deeper discussion of scale-related issues and does not thoroughly assess the uncertainties arising from scale integration. As a result, the work presents the novelty of a new modelling platform, but without sufficient theoretical grounding and testing to substantiate the authors' conclusions.

I agree with the perspective of the former reviewer regarding the definition of physically-based models. Furthermore, the heterogeneity of characteristics and processes at the model scale can result in what is essentially a conceptual application of the model, through the use of representative parameters, even when fundamental physical laws are applied via differential equations, particularly due to the absence of a clearly defined upscaling law. The atomistic concept of physically-based models, as defined here, assumes that an adequate representation of each process at the grid scale, at which the model's equations are solved, will collectively yield an accurate representation of the basin-scale hydrological response. Conversely, in hydrological calibration based on observed discharge time series, we often make the inverse assumption: if the model adequately reproduces the observed discharge at the basin scale, it is taken as evidence that the processes at the scale of the physical equations are well represented. On the other hand, conceptual models aim to capture response patterns at the basin, or hydrological response unit, scale by applying representative parameters that integrate heterogeneity occurring at lower (sub-grid) scales. Thus, beyond the debate over the definition of physically-based versus conceptual models, I believe there is another unresolved issue in the work: the discussion ventures into the domain of hydrological scale problems, which have been extensively explored by authors from Dooge to Beven, Sivapalan, and many others. Nevertheless, the text does not examine in depth the coupling of processes across spatial and temporal scales within the model, nor the transfer of uncertainties between those scales. The integration of scales is reduced to the aggregation of discharges within the drainage network, effectively forcing spatial and temporal scales into congruence. The case studies presented, evaluated primarily through the fit of simulated and observed discharge series, do not, in themselves, seem sufficient to enable the authors to address these scale-related questions.

We sincerely thank the reviewer's insightful comments. We have carefully revised the manuscript to address these concerns, which we summarized into four key points below.

(1) Definitions of conceptual and physically-based representations

We agree that the classification of hydrological process representations is not absolute. Even fully-physically-based models, as defined in the Introduction section of this manuscript, may lose some of their physical grounding when applied at coarse spatial scales. This is due to the generalization of watershed spatial heterogeneity through "representative parameters," which renders physically-based models into an effective conceptual application of the underlying equations. This issue arises largely from the absence of well-established upscaling

laws in hydrology (Dooge, 1986; Beven, 1989, 2000; Sivapalan et al., 2003), i.e., theoretical methods for transferring physical equations derived at a fine scale to a coarser scale.

In the revised manuscript, we have added a paragraph after the classification of hydrological process representations in the Introduction section to explicitly state this viewpoint. For the purpose of this study, we follow our defined classification and primarily focus on conceptual and semi-physically-based representations.

(2) “Atomistic forward modeling concept” vs. “inverse calibration assumption”

We agree with the reviewer’s argument regarding the potential conflict between these two perspectives. In principle, the proposed spatially hybrid modeling approach adheres to the atomistic forward modeling concept: each subbasin-level model structure is determined based on the appropriate representation of hydrological processes and available data, ensuring a physically reasonable and practically executable watershed model. Ideally, model calibration should utilize multi-scale observations (e.g., at subbasin and watershed outlets) to avoid relying solely on the inverse calibration assumption that successfully watershed-scale reproduction validates subbasin-scale model structures.

In the absence of multi-scale observations, it is a common practice in current hydrological modeling to calibrate based solely on the watershed outlet data. In this case study, only the watershed outlet discharge data was available. To partially mitigate this limitation, we designed two calibration strategies (i.e., universal and regional). The universal calibration strategy involves a uniform adjustment of parameters for all subbasin models, while the regional calibration strategy applies separate parameter sets to models of mountainous subbasins and gently sloping subbasins. It’s important to note that while we applied the inverse assumption in our case study, we do not support using such a calibration approach exclusively. Furthermore, our modeling framework can serve as an effective tool for conducting comparative studies of different calibration methods.

In the revised manuscript, we have added the above two paragraphs in Section 3.2.4 “Comparative experiments” to clarify this design rationale and have further emphasized the importance of multi-scale observations in the last paragraph of Section 4.3 “Limitations and future directions.”

(3) Hydrological scaling issues

We argue that this study does not intend to resolve the fundamental hydrological scaling issues, nor to ignore their existence, but rather to provide a practical and flexible modeling approach under current knowledge gaps. We believe that our modeling framework can serve as an effective tool for investigating these theoretical issues, provided that it incorporates diverse hydrological simulation algorithms across spatial and temporal scales and has access to multi-scale data.

In the proposed approach, subbasins serve as consistent modeling units for appropriate model structures. The channel routing components of each subbasin model structure (e.g., the Muskingum method) are used to couple with their upstream and downstream subbasins. This ensures a coherent integration of different subbasin model structures across the watershed. Therefore, the inter-subbasin coupling operates at a consistent subbasin scale through the same or different channel routing algorithms. This study did not explicitly address the

coupling of processes across nested spatial and temporal scales within each subbasin and the transfer of uncertainties between them. We agree that this issue is worth addressing in future work. The proposed approach and its implemented framework are extensible to support such research when new theories and data become available.

We have revised Section 4.3 “Limitations and future directions” in the revised manuscript to discuss this limitation and highlight the potential future work.

(4) Case study limitations

We agree that multi-scale observation data are more sufficient than only watershed outlet data to evaluate the rationality of the watershed model. The case study was intended as a simplified proof-of-concept application to demonstrate the integration feasibility and simulation effectiveness of the proposed approach based on a relatively simplified application context. In the absence of multi-scale observation data, the regional calibration strategy provides a useful method to compare the model performance.

We have clarified this point in Section 4.3 “Limitations and future directions”. Future work should conduct more comprehensive case studies in watersheds with multi-scale observation data and diverse geographic characteristics to further evaluate the robustness, generalizability, and uncertainty implications of the spatially hybrid modeling approach.

In summary, this study does not aim to solve the fundamentally theoretical issues in hydrology, but rather to provide a pragmatic, flexible, and extensible framework that enables the integration of existing hydrological modeling methods at the subbasin scale. The implemented modeling framework holds the potential to support future investigations into these theoretical issues. We have explicitly clarified the methodological design, acknowledged theoretical limitations, and outlined future directions in the revised manuscript. We hope these revisions and explanations have now adequately addressed the reviewer’s concerns.