A Summary of Revisions and Responses on "Spatially hybrid hydrological modeling based on spatial heterogeneity of watershed characteristics" (Ref: HYDROL55981)

With regards to comments from the Editor:

Although the problems being addressed are potentially of interest to our readership, your manuscript does not meet the required quality standards to be considered for publication.

We thank the editor and the two reviewers for their constructive comments and suggestions. We have made substantial revisions to our manuscript, which we believe improved its quality from multiple aspects and hope to meet the standards of the *Journal of Hydrology*. All comments and suggestion have been responded point-by-point in the rest of this response letter.

The research results reported are too premature for publication. More work is needed to substantiate the conclusions in your manuscript.

The main contribution of this manuscript is to propose an innovative spatially hybrid hydrological modeling approach where compatible spatial units and simulation algorithms can be combined to construct different model structures for each subbasin within the watershed, for example, the lumped conceptual and distributed physically-based model structures. The proposed approach was implemented by extending the Spatially Explicit Integrated Modeling System (SEIMS) and evaluated by a case study in a medium-sized headwater of the Heihe River Basin, China.

To verify the feasibility and effectiveness of the proposed approach and its implementation based on SEIMS, we constructed one distributed physically-based model structure and one lumped conceptual model structure to build two spatially consistent watershed models and one spatially hybrid watershed model for comparisons. It is worth noting that the watershed models constructed in this comparative experiment are not intended to model the hydrological processes in the study precisely nor to enumerate the possible model structures applicable. We believe our proposed approach can obtain reasonable modeling results with sufficient proper modeling simulations of various hydrological processes and expert knowledge in hydrological modeling. The proposed approach can also be implemented in other hydrological modeling frameworks.

In the revised manuscript, we have emphasized the main contribution in the abstract and the last paragraph of the introduction section and clarified the above principles of experimental design in the first paragraph of section 3.2 "Experimental design".

Besides, we have enriched the experimental design and discussion. The comparison experiments between different model structures under different calibration strategies were added (see section 3.2.4 for more details). The section of results and discussions were reorganized from three aspects (see section 4 for more details): 1) the performance of different model structures after automatic calibration under different calibration strategies; 2) the rationality of the constructed spatially hybrid model structure; and 3) the advantage of

SEIMS in implementing the proposed approach.

In summary, the revised manuscript explicitly raised the problem through the literature review, highlighted the main contribution, and sufficiently answered the problem through the proposed approach, the implementation, and the case study.

Authors implemented a flexible model structure approach to simulate hydrologic processes in a watershed in China.

As stated in the response to the above comment, this manuscript aimed to propose an innovative spatially hybrid hydrological modeling approach. The proposed approach was implemented based on the hydrological modeling framework SEIMS and validated by a case study in a watershed in China. The proposed approach can also be implemented based on other proper frameworks. The case study was designed to verify the feasibility and effectiveness of the proposed approach. Therefore, the model structures constructed in the comparative experiments are not intended to model the hydrological processes in the study watershed precisely nor to enumerate the possible model structures applicable. We have clearly stated this point in the first paragraph of section 3.2 "Experimental design" in the revised manuscript.

Although authors indicate that this is an innovative approach, there are a number of approaches in the literature presenting this methodology and even quantifying uncertainty in hydrologic prediction. Introduction lacks enough references and the Methodology lacks sufficient details to assess the performance of the approach.

We would like to briefly present the knowledge system and logic of determining application-specific model structure for hydrological modeling in the introduction section of the revised manuscript. We first clearly defined the hydrological model structure and its two components (i.e., spatial discretization scheme and the representation of hydrological processes) in the first three paragraphs. Then, we categorized existing methods of determining model structures as the spatially consistent method and spatially varying method. The spatially consistent method using fixed or near-fixed model structure cannot accommodate diverse and complex application contexts (i.e., the fifth paragraph), which prompted the developing of modular hydrological modeling frameworks for flexibility (i.e., the sixth paragraph). However, the spatially consistent model structure may be unreasonable and inaccurate to capture the characteristics of the dominant hydrological processes when the application context exhibits significant spatial heterogeneity (i.e., the last sentence of the sixth paragraph). To overcome this limitation, the spatially varying model structure method has developed in two ways: externally integrating multiple individual models manually (i.e., the seventh paragraph) and internally construct and integrate multiple model structures within one modular hydrological modeling framework (i.e., the eighth paragraph). As the state-of-the-art methods, the flexible modular modeling frameworks only support conceptual model structures and cannot integrate physically-based simulation algorithms and spatially explicit distributed simulation units. Here, we finally raised this problem explicitly.

In summary, we reviewed existing methods in determining hydrological model structures from the perspective of progressive developments and finally reached one clear problem. In the revised manuscript, we have added some references, such as the works of Knoben et al. (2020) about the uncertainty of model structures, those of Arnold et al. (2010), Dile et al. (2016), Dingman (2015), Fenicia et al. (2011) and Knoben et al. (2019) for better illustration on the concept of model structure. These references have been categorized into the above stated classification system. Although we have carefully searched related literature using keywords like “hydrological model structure”, “integrated hydrological modeling”, and “hydrology spatial heterogeneity", we may missed some importance studies. We appreciate that if the editor and reviewers could provide other key studies that we missed to improve the literature review. Nevertheless, to the best of our knowledge, the problem raised after the literature review has not been addressed.

As responded to the second comments of the editor, to better verify the feasibility and effectiveness of the proposed approach and its implementation based on SEIMS, we added the comparison experiments between different model structures under different calibration strategies (see section 3.2.4 for more details). Further valuable topics such as determining the optimal spatial constitution of the spatially hybrid model structure for specific application contexts and the associated uncertainty analysis could be facilitated following this manuscript as future studies. We have highlighted this point of view in the last paragraph of the conclusion section.

With regards to comments from the Reviewer #1

This paper by Wang et al. describes the development of a hydrologic modeling framework that can simulate a watershed using a hybrid of spatially-distributed, "physically-based" modeling approach, and lumped, conceptual modeling approach. To achieve this, the watershed is first divided into a number of subwatershed, and each subwatershed can be simulated with either a spatially-distributed model, or a lumped model. The subwatersheds connected using a channel routing scheme. The comparison among the hybrid approach, the spatially-distributed approach, and the lumped approach shows that the hybrid approach outperforms the two others at one experimental watershed. The newly developed hybrid hydrologic modeling framework is surely an interesting approach, but I do have some general concerns about the manuscript.

Thanks for the reviewer's approval of the basic idea of our manuscript. We sincerely appreciate the comments from the reviewer and have made substantial revisions to clarify the definitions of related concepts and the primary contribution. We hope the revision can respond to the reviewer's concerns.

1. One thing to be clarified is that the "physically-based" model the authors used in the experiment is not truly "physically-based." I acknowledge that hydrologists have different opinions about what is a physically-based model, but by any means I do not believe the model being used in the paper is a physically-based one, because all the major processes at each model grid (infiltration, percolation, groundwater) are simulated using conceptual approaches. I would categorize it as a spatially-distributed conceptual model, with different model grids interconnected using a kinematic wave routing scheme.

We sincerely appreciate the reviewer's insightful comments. While we acknowledge that the distributed physically-based model structure constructed in our experiment (see section 3.2.1 in the revised manuscript) is not purely physically-based, we maintain that its main modules do have a physical basis, relying on principles of conservation of mass and momentum, and energy, and relying on field measurements for spatial parameters.

We understand the reviewer's rigorous definition of a physically-based model requiring partial differential equations for water movement. MIKE SHE (Graham and Butts, 2005) is indeed an example of such physically-based models. It employs the St. Venant equation for overland and channel flow, the Richards equation for soil water dynamics, and the 3D Boussinesq equation for groundwater. Such models face challenges of data requirements and computational complexity. So, most "physically-based" models today are based on simplified representations and solutions of physical principles. For example, models like SWAT (Arnold et al., 1998), TOPMODEL (Beven and Kirkby, 1979), and WetSpa (Wang et al., 1996), while primarily based on conceptual or empirical formulations, incorporate solving algorithms simplified from physical principles and adhere to mass and energy balance. Also, many parameters (especially terrain and soil attributes) are derived from field measurements and have clear physical meanings. This represents a broad interpretation of "physically-based."

SWAT claims to be physically-based because it "*requires specific data on weather, soil* *properties, topography, vegetation, and land management practices, directly modeling physical processes associated with water and sediment movement, crop growth, and nutrient cycling*" (Neitsch et al., 2011). WetSpa is considered to be physically-based because "*its mathematical models describe components based on principles like conservation of mass and momentum*" (Liu and Smedt, 2004). Similarly, TOPMODEL describes its parameters as physically-based because "*they can be directly determined by measurement and applied at ungauged sites*" (Beven and Kirkby, 1979).

Therefore, we regarded the model structure constructed in our experiment as physically-based primarily for two reasons. Firstly, the model structure includes simulation algorithms based on physical laws. The algorithms of percolation and interflow are based on Darcy's law. The percolation is calculated as the product of hydraulic conductivity and the gradient of the hydraulic potential, and the interflow is calculated from the kinematic approximation of Darcy's Law and, with the hydraulic gradient equal to the slope at each grid cell. These two methods are the same as those used in WetSpa [for more details, please refer to Liu and Smedt (2004) and Safari et al. (2012)]. Secondly, the soil data used for infiltration, depression, percolation, and interflow are derived from field measurements and have clear physical meanings. The geomorphology-based unit hydrograph is also derived from terrain data.

From another perspective, we adopted module integration to develop the hydrological modeling framework in this study. We did not intend to claim all the modules included in a model structure are physically based. Therefore, instead of emphasizing the entire model structure as "purely" physically-based, we highlighted that our approach supports the integration of modules based on different principles (both physically-based and conceptual) and different forms of simulation units in a watershed as an overall watershed model structure.

In summary, we have revised the manuscript to clarify the definition of "physically-based representation of hydrological processes (i.e., the simulation algorithm)". In the third paragraph of the introduction section, it was defined as "a physically-based representation uses known scientific principles to model water movements in vertical or lateral directions by the partial differential equation representing the mass, momentum, and energy balance that solved by finite difference approximations or empirical equations." The above explanation of the constructed distributed physically-based model structure has been added to the first paragraph of section 3.2.1. We hope the revisions are acceptable for the reviewer.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large Area Hydrologic Modeling and Assessment Part I: Model Development. JAWRA Journal of the American Water Resources Association 34, 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin 24, 43–69. https://doi.org/10.1080/02626667909491834

Graham, D.N., Butts, M.B., 2005. Flexible, integrated watershed modelling with MIKE SHE. Watershed models 849336090, 245–272.

Liu, Y.B., Smedt, F., 2004. WetSpa Extension, A GIS-based Hydrologic Model for Flood

Prediction and Watershed Management. (Attached)
Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute.
Safari, A., Smedt, F., Moreda, F., 2012. WetSpa Model Application in the Distributed Model Intercomparison Project (DMIP2). Journal of Hydrology 418–419, 78–89. https://doi.org/10.1016/j.jhydrol.2009.04.001
Wang, Z.M., Batelaan, O., De Smedt, F., 1996. A distributed model for water and energy transfer between soil, plants and atmosphere (WetSpa). Physics and Chemistry of the Earth, 21, 189–193. https://doi.org/10.1016/S0079-1946(97)85583-8

2. This then raises the major concern: this modeling framework, at least as of now, uses only conceptual models, but can handle different subwatersheds with different spatial resolutions (spatially-distributed model grids or HRUs or subwatersheds) and modeling equations. Then how different is the authors' newly developed framework from other existing hydrologic modeling frameworks?

After clarifying the term of "physically-based" model structure, our innovation could be clearer. As stated in the seventh paragraph of the introduction section in the revised manuscript, existing frameworks, including the FLEX-Topo, SUPERFLEX, and airGR, primarily support lumped or semi-distributed conceptual model structures for hydrological modeling in a spatially varying manner, but not supporting distributed physically-based model structures, nor the spatially hybrid model structures. To overcome this limitation, we proposed the spatially hybrid hydrological modeling approach where compatible spatial units and simulation algorithms can be combined to construct different model structures, including lumped conceptual and distributed physically-based model structures, for each subbasin within the watershed. Model structures in each subbasin can be integrated to perform the entire watershed simulation.

In the revised manuscript, we have clarified the definitions of spatial discretization scheme and the representation of hydrological processes in the second and third paragraph of the introduction section. We have emphasized the above stated innovation in the abstract and the last paragraph of the introduction section.

3. There is the possibility that the framework can handle true "physically-based" models, but the authors did not demonstrate the uses. I am curious then how different subwatersheds can be connected. This is more than just using a routing scheme to connect the generated runoff from each subwatershed. If a Richards-equation based subsurface model is used in one of the subwatersheds, how can the boundary conditions be set for the subwatershed, and be connected to the adjacent physically-based subwatersheds or conceptual subwatersheds?

The basic idea of designing a spatially hybrid hydrological modeling approach is constructing and executing different model structures on relatively independent areas within the watershed in a divide-and-conquer way. The design of the hydrological modeling framework SEIMS meets the need to implement the proposed approach. We have rewritten section 2.2.1 to briefly introduce the design of SEIMS from three aspects: the spatial discretization scheme, the modular modeling design, and the parallelization strategy.

For short, SEIMS takes each subbasin as independent modeling unit to executing the configured model structure. The watershed would be divided into subbasins connected by drainage network, and each subbasin is then divided into grid cells on which to execute hillslope simulation modules. The data exchange happens at the outlet of each subbasin from upstream to downstream in sequence after executing the channel simulation modules. Each simulation module is responsible for the simulation of one or several hydrologic processes on corresponding simulation units in different orders. Each module should handle its required simulation conditions. Users should decide the feasibility of the module combinations to meet the requirements of each module, including the boundary conditions when calculating vertical and lateral water movements. For example, to implement a physically-based interflow module based on the Darcy's Law, the boundary condition could be set either with the hydraulic gradient equal to the slope at each cell, or with the output of previous or subsequent modules.

Therefore, boundary conditions for physically-based modules can be set independently in each subbasin model structure, and are mainly on the in-out relationships between grid cells. Take the simulation modules of percolation and interflow processes in SEIMS as an example, the initial conditions are set by estimation on field capacity based on soil data (i.e., the HWSD soil dataset). The lateral boundary conditions on each grid cell within a subbasin are provided by adjacent grid cells at each time step (based on soil moisture and hydraulic conductivity). The upper boundary conditions are provided by the net precipitation data output from the other module. As for the bottom boundary conditions, the groundwater recharge velocity would be determined by both the soil moisture and the reservoir volume. The discharge at subbasin outlet would be the summary of surface runoff, interflow, and groundwater baseflow.

Considering the modular modeling design of SEIMS, the tighter coupled simulation methods of several hillslope hydrological processes using rigorously physically-based algorithms could be possibly implemented as one simulation module. We added this point as one future direction in the last paragraph of the conclusion section.

4. The comparison among the hybrid, physically-based, and lumped approaches is the key part of the manuscript. However, the description of the calibration process is not very clear to me. What is the calibration unit? Are subwatersheds being calibrated separately in all three cases? What parameters are being calibrated?

Thanks for this constructive comment. We have made overall improvements to our experimental design based on this feedback and revised the text in section 3.2.4 "Comparative experiments of parameter calibration".

In the original manuscript, the entire watershed was considered as a calibration unit. Parameters were calibrated collectively for the entire watershed, meaning that one parameter of a module were the same globally and changed simultaneously across different subbasins. In the revised manuscript, we have improved the calibration strategies by considering the subbasins with the same model structure as a calibration unit. That is, during calibration, the parameters for the same model structure (or, in one calibration unit) in one experiment would be simultaneously changed by addition, multiplication, replacement by a specific value. Such changes are made based on their distributed initial values derived from soil and land use data. For example, for a certain land use parameter in a calibration unit, its value would be *a* for forest cells, and *b* for grass cells. During calibration, these values can be changed to *ax* and *bx* (multiply *x*), or *a*+*x* or *b*+*x* (add *x*).

We added the comparative experiments between this new calibration strategy and the watershed-level calibration strategy. Please refers to section 3.2.4 for more details.

The parameters used for calibration were priority selected based on parameter sensitivity analysis, which is out of the scope of this manuscript. We have added an explanation of the sensitivity analysis step in the revised manuscript, along with a description of the selected parameters in sections 3.2.1 and 3.2.2.

5. In addition, the authors claimed that "the calibration objectives are maximum NSE, minimum absolute values of RSR and PBIAS." Are weights assigned to NSE, RSR, and PBIAS to generate an objective function, or some other approach was applied?

Thanks for pointing out this unclear statement. The parameter calibration was conducted using the NSGA-II (non-dominated sorting genetic algorithm-II; Deb et al., 2002) integrated in the SEIMS framework. The objection function for parameter calibration is maximum NSE, minimum absolute values of RSR and PBIAS, each component has the same weight. We have added the two sentences in the last paragraph of section 3.2.4 in the revised manuscript.

6. The terms "uniform" and "model structure" should be defined. It is not clear whether they are referring to equations to be used, or spatial discretization, or some other modeling approaches. For example, in the Highlights, the authors stated that "the spatially hybrid model outperformed two conventional uniform models." It gave me the impression that the authors were comparing the spatially hybrid model with two spatially uniform, i.e., lumped models. Without a clear definition of "model structure," the introduction section is hard to follow.

We agree that the definition of "model structure" is of vital importance for our manuscript. We have rewritten the introduction section to clearly define the model structure in the first paragraph and then explain the two components of the model structure in the following two paragraphs, i.e., spatial discretization scheme and the representation of hydrological processes.

Regarding the term "uniform", we have changed it to "consistent" for better clarity. A "consistent" (or "uniform" in the original manuscript) model structure uses the same spatial discretization scheme and combination of simulation algorithms in the whole watershed, while the spatially varying model structure includes different model structures for different regions within the watershed.

The fourth highlight was revised as "The spatially hybrid model structure outperformed two spatially consistent ones." We designed one distributed physically-based model structure (section 3.2.1 in the revised manuscript) and one lumped conceptual model structure (section 3.2.2) to build two spatially consistent watershed models and one spatially hybrid watershed model (section 3.2.3) for comparison. We have added this sentence in the first paragraph of section 3.2 “Experimental design”.

7. Some acronyms need to be defined, for example, SUMMA, MARRMoT, ESMF, and OpenMI.

We have checked the entire manuscript and added the full name of acronyms when first mentioned, such as SUMMA (Structure for Unifying Multiple Modeling Alternatives), MARRMoT (MARRMoT (Modular Assessment of Rainfall–Runoff Models Toolbox), ESMF (Earth System Modeling Framework), OpenMI (Open Modeling Interface), and others.

8. Line 385: "However, since the lack of modules for permafrost and glaciers in SEIMS, a purely physically-based model, if applied, may be confronted with inaccuracies in representing certain processes." I don't quite understand why this problem is specific to physically-based models. Do the authors imply that the conceptual models can overcome this with over-calibration or over-parameterization?

Thanks for pointing out this confusing statement. We consider the advantage of conceptual models like GR4J to lie in their generalized and averaged representation obtained from fitting numerous catchments with various climatic and landscape conditions, as it is developed through testing on 429 catchments (Perrin et al., 2003). This characteristic enables them to perform relatively well in simulations when physical processes are not fully represented. Thus, we would like to attribute this advantage to the inherent structure of conceptual models, rather than over-calibration or over-parameterization.

We have rewritten the reasonable analysis of constructing the spatially hybrid model structure in the first paragraph of section 3.2.3 in the revise manuscript: “Ideally, a physically-based model could better simulate hydrological processes with explicit physical meaning. While limited to the insufficiency of the cognization of hydrological processes and difficulty of implementing complicated simulation algorithms, a conceptual model could be a valuable complementary, which is often come up with mathematical fitting under some degree of generalization. Therefore, a spatially hybrid model structure (referred to as the HybM) combining both physically-based and conceptual models were constructed in this case study.”

9. Line 400–402. Can the authors provide equations for those indices (NSE, RSR, PBIAS, R-square)?

We have added the equations of these indices in section 3.2.4 of the revised manuscript.

10. Figure 4: The ranges of y-axes in the subfigures are different, which makes it difficult to compare the performances of the three models. Can the same y-axis range be used for all subfigures?

We have redrawn the simulation results of different model structures in one figure (i.e., the Figure 4 in the revised manuscript) to make them comparable.

11. Table 1: The first row "conceptual and comprehensive surface runoff." Should it be "runoff" instead of "surface runoff?" I also feel references could be provided to the processes listed.

We have taken this suggestion and revised as "Conceptual and comprehensive hillslope runoff", since the "runoff" generated by GR4J does include the subsurface.

The simulation algorithm used in constructing the distributed physically-based model structure and the lumped conceptual model structure were listed in Table 1 and Table 2, respectively. More details of these included and other available simulation modules implemented in SEIMS were provided in Table S1 of the supplementary material, primarily including the reference and brief introduction.

With regards to comments from the Reviewer #2

This paper represents a significant advancement in hydrological simulation by integrating physical-based and conceptual models. This approach enhances the accuracy of the simulation by leveraging the strengths of each model type while effectively overcoming their individual limitations. Particularly noteworthy is the paper's ability to address the challenges posed by spatially varied watersheds, where the applicability of a single-model approach may be hindered due to inherent assumptions. Such an integration offers a more robust and versatile framework for hydrological modeling, making it a valuable contribution to the field. Given these considerations, I believe this paper merits publication. Its approach and findings have the potential to offer meaningful insights and advancements in hydrological research. Having acknowledged the paper's significant contributions, I would like to offer a few questions and suggestions for improvement to further enhance the quality and impact of the work.

Thanks for the reviewer's approval of the basic idea of this manuscript. We sincerely appreciate the comments from the reviewer and have made revisions accordingly.

1. I noticed that you have employed two different evapotranspiration models in your study: the Penman-Monteith model for physically based modeling and the Hargreaves model for conceptual modeling. I am curious about the rationale behind choosing these distinct models for different parts of your analysis. Additionally, could you clarify if, in your hybrid modeling approach, you maintained consistent algorithms for each model - Penman-Monteith for the physically-based modeled part of the watershed (mountainous region) and Hargreaves for the conceptually modeled part (central part)?

We thank the reviewer for bringing up this point. Our choice of different evapotranspiration (PET) modules was not based on their suitability, as both the Penman-Monteith (PET_PM) and Hargreaves (PET_H) modules are commonly used algorithms, and their simulation performance was validated through the results obtained. The decision to use different modules was determined by the input requirements of other modules in a model structure. In the original "physically-based" model structure, evapotranspiration is simulated by soil evaporation module (SET_LM), which necessitates the use of PET_PM for transpiration simulation. However, in the conceptual model GR4J, there is no explicit simulation of transpiration, and only the PET from the Hargreaves model is required. In the spatially hybrid model, we maintained these pairings, with the conceptual model's sub-basins using PET_H and the physically-based model's sub-watersheds using PET_PM. We have added explanations of this point in the Section 3.2 of our manuscript.

2. I am interested in understanding the approach you took regarding the parameterization of models for the different subbasins in your study. Did you apply a set of common parameters across all subbasins, or were specific parameters calibrated for each individual subbasin?

As responded to the fourth comment of Reviewer #1, we have improved our calibration strategy from watershed-level to subbasin-level. Please refer to that response for more details. The manuscript has also been revised accordingly, i.e., section 3.2.4 "Comparative experiments of parameter calibration".

3. In your discussion, particularly in lines 453-459, your insightful analysis could potentially be further enhanced with additional visual representation. I would recommend considering the inclusion of panels for the other experiments, similar to those presented in Figure 4, to accompany this section.

We have taken this suggestion and revised the "Results and discussion" section of the revised manuscript. The simulation results of the three model structures were combined into one figure for clearer comparison (Figure 4). Please refers to section 4.2 "The rationality of the spatially hybrid model structure" for more details.

4. Line 235: In the text at line 235, I would suggest either replacing 'relative' with 'relatively' for grammatical correctness or considering the removal of 'relative' altogether to enhance the clarity of the sentence.

We have taken this suggestion and used "relatively" in the revised manuscript.