Response to comments on Manuscript egusphere-2025-6543 (RC2)

Reply on RC2:

Many thanks for taking the time and effort to review our paper. All comments from Referee #2 are addressed below with point-by-point responses.

For better readability, our replies are prefixed with "**R/**". The original reviewer comments are prefixed with "**RC-n/**" and are presented in **bold**. The revisions to be added into the revised manuscript is highlighted in red. The important parts are highlighted in blue. The quoted content is displayed in *italics*. All references cited in this response are listed at the end of the reply. Line numbers from the unrevised manuscript are provided where relevant.

Point-to-point response:

RC1-1/ Overall, I thought this was a well-designed study with a well written manuscript. The results demonstrated that spatially explicit parameterization and multi-gauge calibration increased overall accuracy of the VIC model simulated streamflow.

R/ Thank you for your positive and encouraging comments. Your comments are valuable for revising and improving our paper. Below, we provide detailed responses to each of your concerns. The corresponding revisions will be incorporated into the subsequent revised manuscript.

I have a few suggestions below:

RC1-2/ Introduction: The introduction needs a justification and explanation of the VIC model at the beginning or after line 70. The introduction, as it is currently, provides a specific, detailed explanation of spatial explicit parameterization without discussion, in detail, the implementation within VIC, despite the objectives detailing the application of MPR and VIC-refinements. I recommend at least one paragraph specifically justifying the use of VIC as the hydrologic model in this study.

R/ Your suggestion was very helpful in addressing the gaps in our introduction. Since the VIC model forms the foundation of this study, further clarification was indeed valuable. Accordingly, we have added additional explanation after line 70. We also supplemented a paragraph after line 91 to clarify the reasons for selecting the VIC model and the corresponding implementation approach in this study. The relevant revisions are provided below for your convenience.

Line 70:

Of particular concern, the pathway poses a major challenge in estimating spatially explicit parameters and ensuring their transferability across scales, notably for distributed hydrological models such as the Variable Infiltration Capacity (VIC) model (Sun et al., 2023). Despite the widespread development and application of such models~~distributed hydrological models have been widely developed and applied worldwide~~, th~~is~~e challenge remains unresolved, with many modelling studies—even recent ones—still rely on spatially uniform parameters derived from calibration (Yousefi Sohi et al., 2024; Shrestha et al., 2025).

Line 91:

Although MPR has been implemented in a series of distributed hydrological models, the VIC model is adopted as the modelling framework in this study. This choice is motivated by the long-standing challenges in estimating spatially distributed parameters of VIC, which remain an active research topic. Recent studies have explored different strategies, including surrogate-based approaches (e.g., Sun et al. 2023) and MPR-based parameter estimation (e.g., Gou et al. 2021). In this context, the increasing use of spatially distributed parameters in VIC applications mirrors a broader shift towards spatially explicit parameterizations in modern hydrological modelling. In addition, recent developments in VIC, particularly the transition to version 5, enable all model parameters to be handled through a unified NetCDF-based I/O framework, thereby facilitating spatial parameter estimation (Hamman et al., 2018). To support the MPR-based spatial parameter estimation using distributed information (e.g., soil and vegetation properties), our team has developed an open-source Python-based deployment framework for VIC-5 (https://github.com/XudongZhengSteven/easy_vic_build). The framework integrates a range of transfer functions and offers an object-oriented, modular workflow for parameter estimation, providing the flexibility to implement and systematically compare spatially explicit and uniform parameterizations within a unified framework. We further anticipate that this framework will contribute to broader applications of the next-generation VIC-5.

RC1-3/ I think the explanation of multi-gauge in nested catchment systems needs more explanation than the one sentence provided in line 105. I recommend expanding this to a full paragraph.

R/ Following your suggestion, we have expanded the explanation of multi-gauge calibration in nested catchments (originally in line 105) into a new paragraph. The revision is provided below for your convenience.

Line 105:

In practice, streamflow is often used as a reliable and informative calibration target, as it integrates both surface and subsurface hydrological response over the entire basin. The presence of multi-gauge in nested catchment systems, measuring streamflow from different sub-basins, thus provides a suitable setting for multi-objective calibration of hydrological models (Liu et al., 2024). Such strategy offers two advantages. First, neighboring sub-basins constitute comparable (often paired) units that support parameter estimation and comparative analyses (Vinogradov et al., 2011; Argentin et al., 2025). Second, the implied hydrological connections among sub-basins motivates joint calibration, which provides a broader, system-wide view and allows spatial relationships across the network to constrain shared parameters and improve identifiability. For example, parameter sets that reproduce outlet streamflow equally well can differ substantially at interior gauges, helping to discriminate among competing solutions. Quantifying the extent to which multi-gauge calibration improves model realism is therefore particularly relevant for models with spatially explicit parameters, where the nested structure reflects hierarchical hydrological responses.~~There is considerable value in evaluating the benefits of multi-gauge calibration for enhancing model realism, especially for models with spatially explicit parameters, where the nested sub-basin structure captures the hierarchical patterns of hydrological responses.~~

RC1-4/ In objective 3 – Its unclear what you mean by cross-benefits between the two approaches. Can you expand on this by specifically defining the two approaches and generally discussing the expected cross-benefits?

R/ Thank you for pointing out this lack of clarity. We have revised the objectives section to explicitly define the two approaches (strategies) and have expanded description of Objective 3, highlighting the **potential sources of the expected cross-benefits**. The corresponding revisions are provided below for your review.

Line 111:

Prompted by pressing issues in contemporary hydrological modelling, we examine two modelling strategies—spatially explicit parameterization and multi-gauge calibration—against to a baseline of spatially uniform parameterization and single-gauge calibration. Specifically, this study aims to address three critical questions: (1) How spatially explicit parameterization, compared with spatially uniform parameterization, can enhance the realism of hydrological models while introducing additional equifinality; (2) To what extent multi-gauge calibration strategies in nested catchments can better constrain parameter identifiability; and (3) Whether cross-benefits exist between these two strategies~~approaches~~ and, if so, in what form. Notably, most previous studies have focus on individual strategies, potentially overlooking the cross-benefits that may emerge from their combination. We stress that relying on a single strategy alone may impose a practical limit on model improvement; for example, simply increasing model complexity without complementary constraints can lead to under-constrained parameter estimation, a limitation that is expected to be alleviated through the introduction of multi-gauge calibration.

RC1-5/ Study Area: Can you provide a land use analysis on the Upper Han River Basin to visualize the amount of anthropogenic vs natural landscape? Please include an explanation of the presence or absence of impoundments, dams, or reservoirs in the watershed.
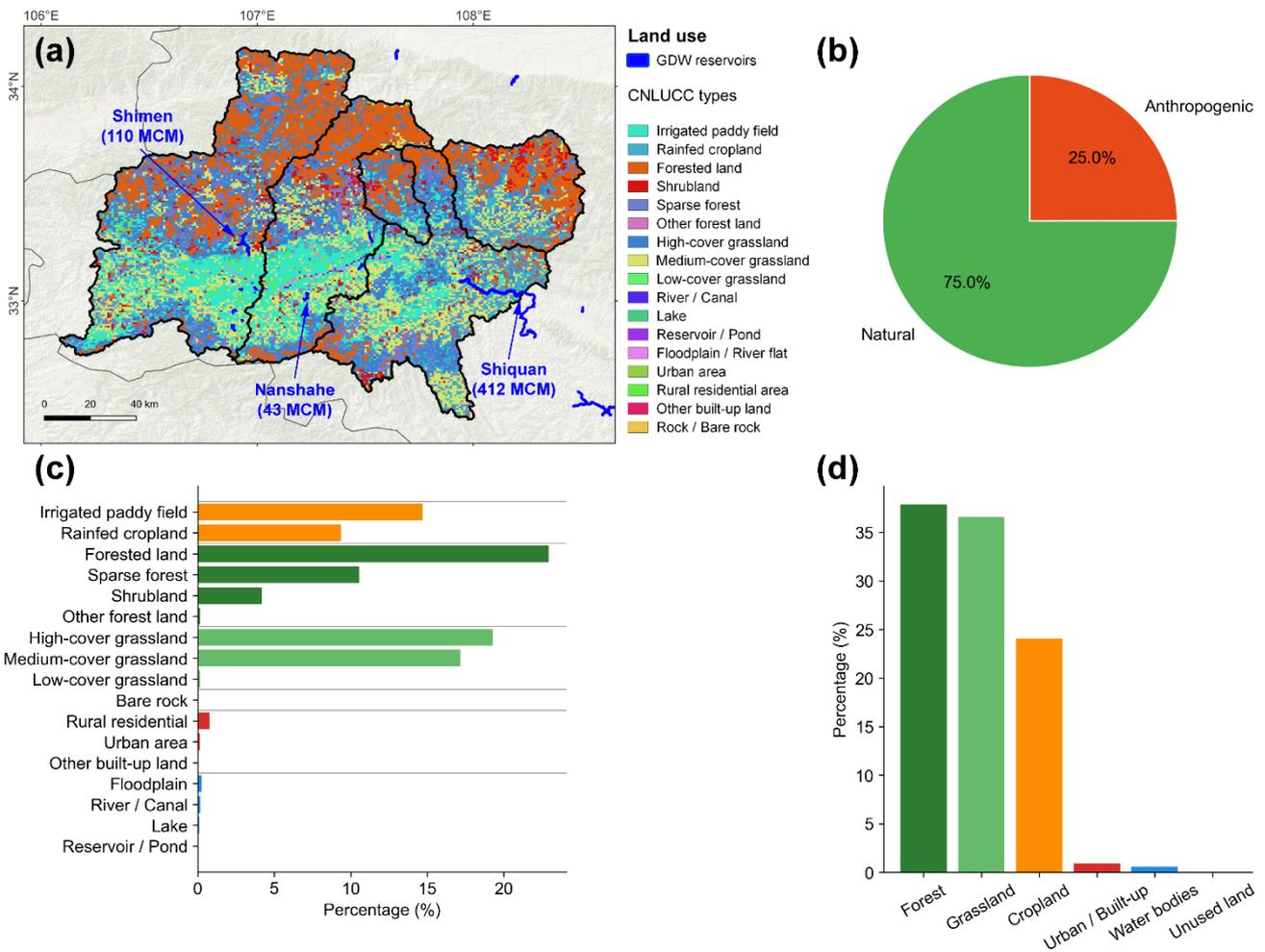
R/ We thank you for this valuable comment, which is very helpful for clarifying the characteristics of the study basin. In response, we have collected data from **CNLUCC (China multi-period land use remote sensing monitoring; Xu et al., 2018) and GDW (Global Dam Watch; Lehner et al., 2024) datasets** to conduct a land use analysis and spatial visualization, as shown in Fig. S1.

Our analysis shows that **natural land use dominates** the basin, accounting for approximately 75% of the area. Anthropogenic hydraulic structures are scarce, with only three reservoirs: Shimen and Nanshahe, located in the upper and mid-reaches, have maximum storage capacities of 110 and 43 MCM (million cubic meters), respectively, which are negligible for hydrological modelling. The only potential source of uncertainty is the Shiquan reservoir, with a maximum storage of 412 MCM, situated near the basin outlet. However, it **operates on a daily regulation scheme** and is primarily used for hydropower generation and flood control. As the model aims to simulate daily streamflow, **its impact on the simulated discharge is expected to be minimal**. This is further supported by **the large annual runoff at the station (~10.8 billion cubic meters), which substantially exceeds the reservoir storage capacity**. In light of these considerations, the reservoir is not explicitly represented in the model, and its influence is assumed to be negligible. It is worth noting that, compared with the UHRB, the Han River basin downstream of Shiquan contains many hydraulic structures along the mainstem, such as Xihe, Ankang, Dongwuyan, and Danjiangkou reservoirs, whereas anthropogenic impacts in the UHRB are comparatively minimal.

We have added the corresponding analysis and figure in the revised manuscript, attached below for your review.

RC1-6/ Methods: Figure 2: Could you add the additional steps of RVIC parameter refinement using MPR technique here?

R/ Thank you for your valuable suggestion. We recognize that the lack of a schematic illustration may reduce the transparency of the RVIC parameter refinement regionalization. To address this, we have included a schematic diagram to better clarify the methodology. To maintain the clarity and independence of the figures, this addition is presented as Fig. S2 in the Appendix rather than being incorporated into Figure 2. The newly added figure and the revised description are provided below for your review.

Line 248:
Nonetheless, we use the MPR technique here to enhance the spatial representation of these two parameters by linking them to topography (Fig. S2~~Table. 2~~).
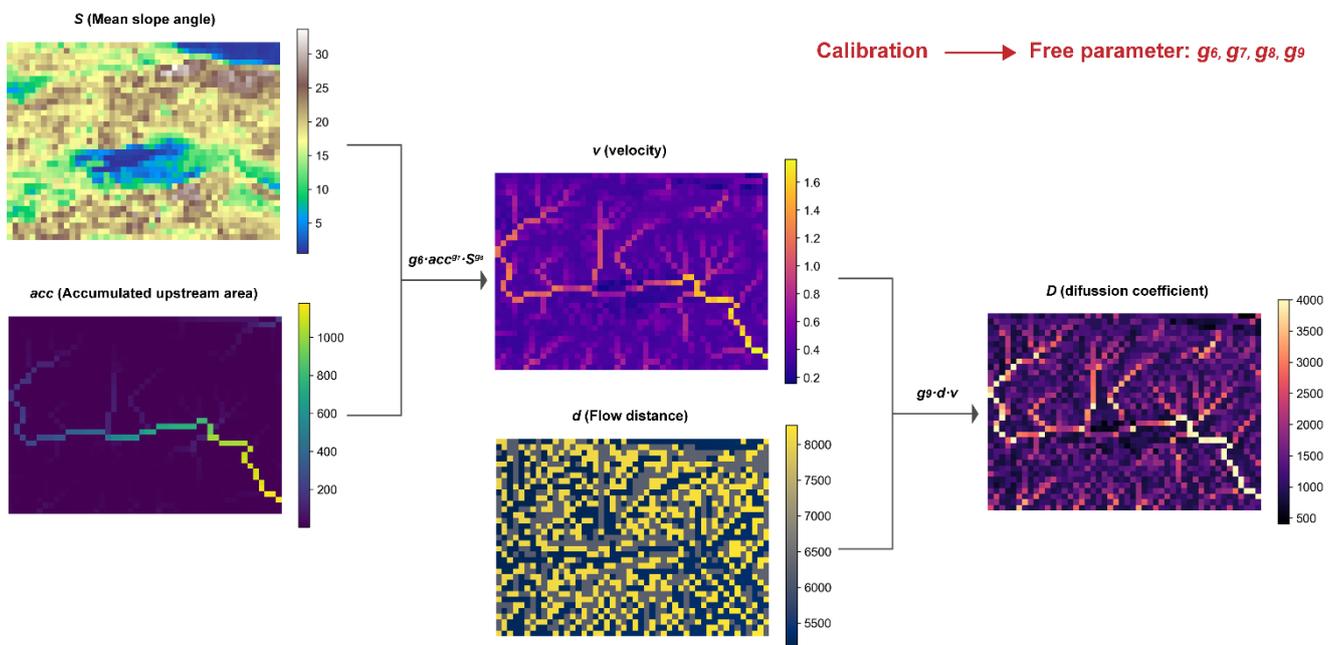
Figure S2. Refinement of the MPR-based regionalization of RVIC parameters. Spatially distributed velocity and diffusion coefficients are estimated using transfer functions (Table 2) driven by topographic attributes and calibratable g-parameters.

RC1-7/ Results: Figure 4: The regression plot between the observed and simulated streamflow makes it hard to visualize the patterns of the majority flow observations below 100m3/s, and appears to rely on a few of the larger flow metrics. I recommend a random thinning to effectively visualize the patterns in the majority of below 1000 m3/s.

R/ This is a very professional suggestion regarding the presentation. Following your advice, **flows below 1000 m3 s-1 were randomly thinned** to improve visual clarity. Furthermore, we have **added a scatter comparison in logarithmic space** in the Supplement, which clearly illustrates the simulated behavior

discussed in the manuscript, showing that the distributed parameterization improves high-flow simulation while exacerbating overestimation at low flows. The figure color scheme has also been adjusted to comply with journal requirements. The revised captions and figures are provided below for your review.

Line 398:

This behaviour is also evident in the scatter comparison on a logarithmic scale (Fig. S3).
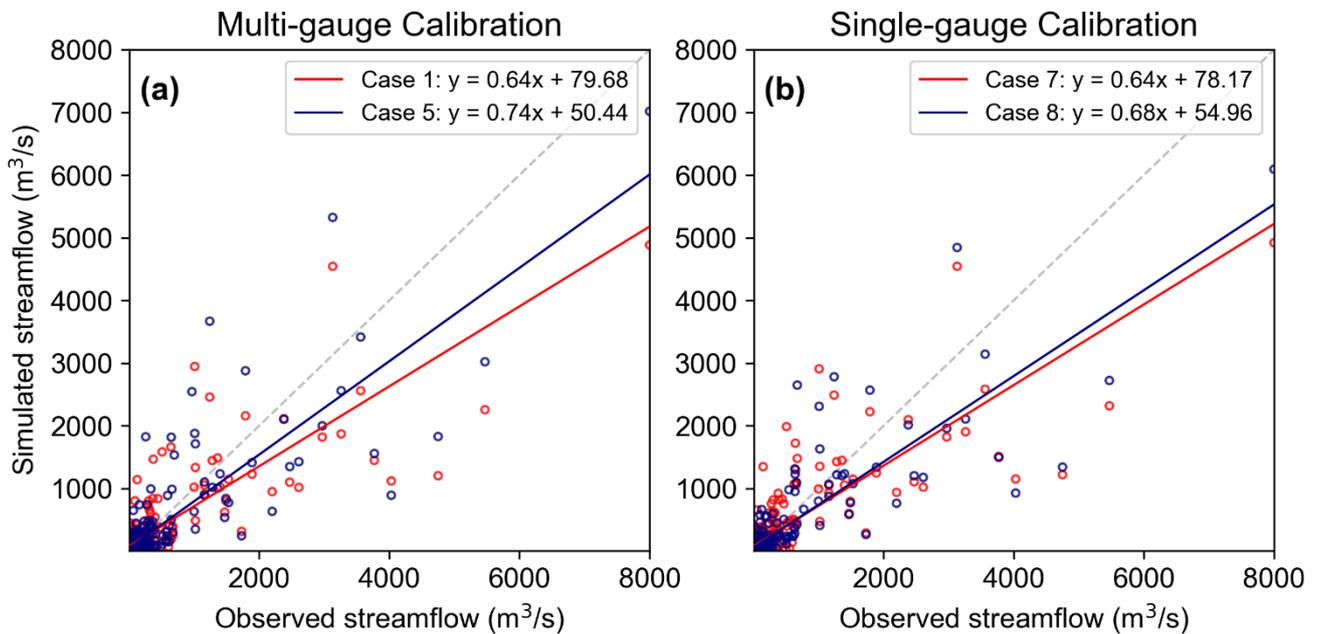
Line 409:

Figure 4. Scatterplots with least-squares regression lines comparing observed and simulated daily streamflow at the Shiquan station during the validation period, under different case configurations. The grey dashed line represents the 1:1 line. Flows below 1000 m^3 s^{-1} were randomly thinned for clarity.
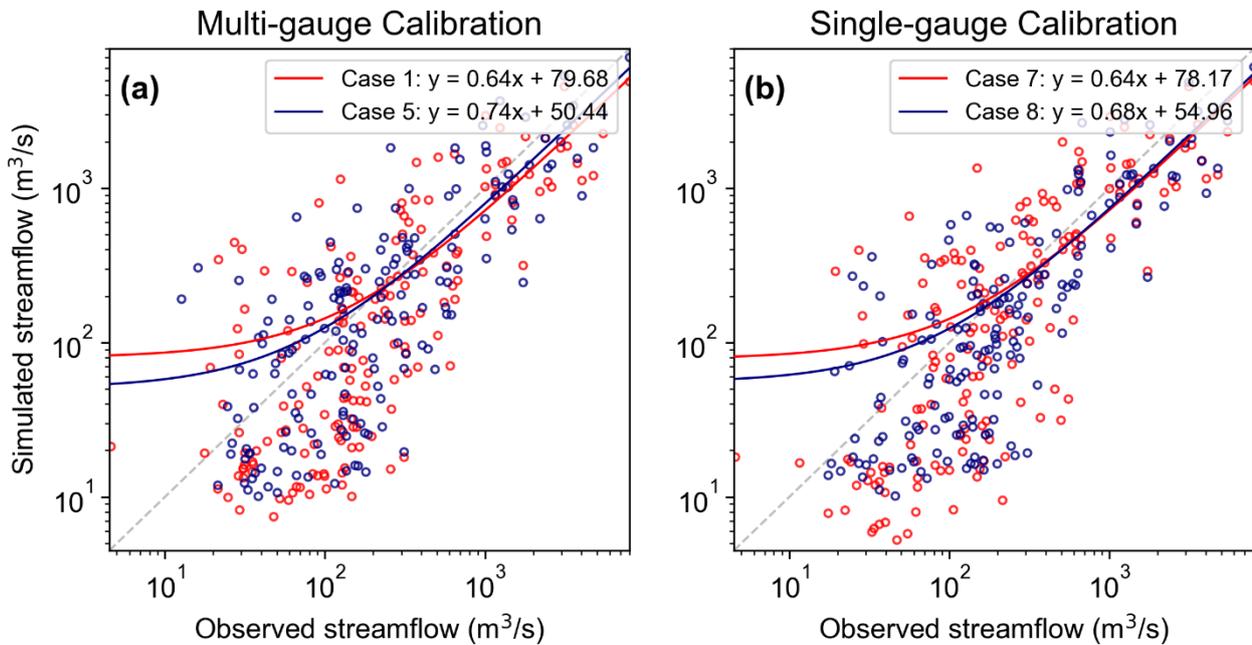
Figure S3. Scatterplots with least-squares regression lines comparing observed and simulated daily streamflow at the Shiquan station during the validation period, under different case configurations. The grey dashed line represents the 1:1 line. Flows below 1000 m^3 s^{-1} were randomly thinned for clarity, and both axes are shown on a logarithmic scale.

RC1-8/ Figure 6: I find the pie chart hard to visualize, and I would recommend converting to nested barcharts.

R/ Thank you for your suggestion. We have replaced the pie chart with a nested bar chart that provides a clearer comparison. The revised figure and corresponding modifications are provided below for your review.

Line 425:

This allows us to derive the relative contributions of each component, which are summarized as a nested barchart~~pie chart~~ in Fig. 6.
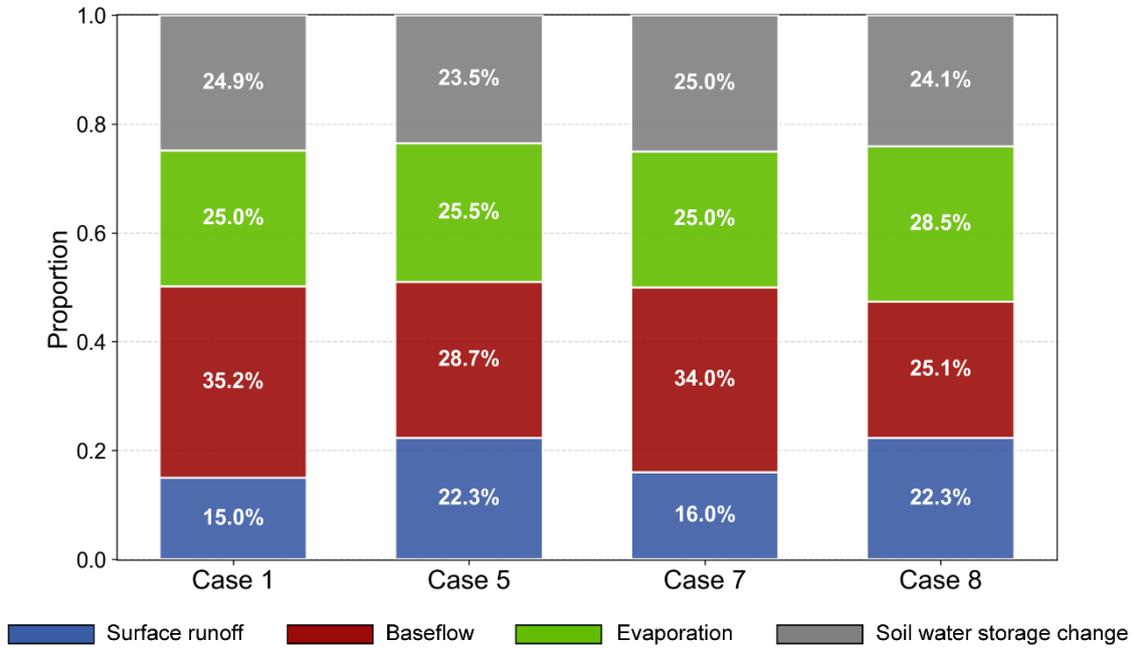
Figure 6. Relative contributions of four major water balance components for different case configurations during the validation period.

RC1-9/ Figure 7: I recommend adding the explanation of Case 1, 5, 7, and 8 in the caption so readers don't have to refer to table 4 in order to interpret the results.

R/ Thank you for your valuable comment. Following your suggestion, we have added additional descriptions of each case below Fig. 7 to improve readability and facilitate interpretation.

The revised Fig. 7 is provided below for your review.

Line 452:

Case 1: Uniform, multi-gauge
Case 5: Distributed, multi-gauge

Case 7: Uniform, single-gauge
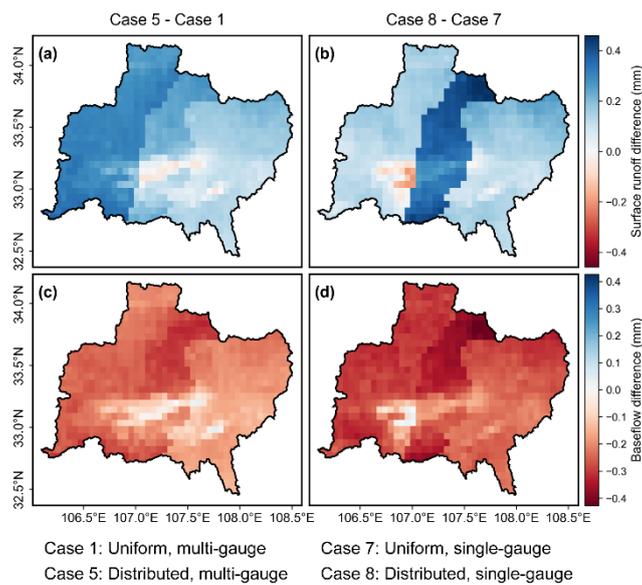Case 8: Distributed, single-gauge

Figure 7. Spatial distribution of differences in (a, b) surface runoff and (c, d) baseflow volumes between the two parameterization schemes over the validation period. Differences are calculated as spatially explicit minus uniform parameterization.

Reference

Lehner, B., Beames, P., Mulligan, M., Zarfl, C., De Felice, L., van Soesbergen, A., Thieme, M., Garcia de Leaniz, C., Anand, M., Belletti, B., Brauman, K. A., Januchowski-Hartley, S. R., Lyon, K., Mandle, L., Mazany-Wright, N., Messager, M. L., Pavelsky, T., Pekel, J.-F., Wang, J., Wen, Q., Wishart, M., Xing, T., Yang, X., and Higgins, J.: The Global Dam Watch database of river barrier and reservoir information for large-scale applications, Scientific Data, 11, 1069, 10.1038/s41597-024-03752-9, 2024.

Xu, X., Liu, J., Zhang, S., Li, R., Yan, C., and Wu, S.: China multi-period land use remote sensing monitoring dataset (CNLUCC), Resource and Environmental Science Data Registration and Publication System, https://doi.org/10.12078/2018070201, 2018.

Finally, we would like to once again thank the Editor and all the Reviewers for your thorough review and support of our paper. If you have any questions, suggestions, or discussions, please feel free to contact us.