

Reply to Referee #1:

As I was not involved in the first round of revisions, my evaluation focused primarily on the clarity, coherence, and readability of the manuscript, as well as how well the scientific content is conveyed to the reader. While the overall structure is sound and the topic of interest, there are several aspects that should be addressed to improve the manuscript. I found two major points:

Dear Referee, We greatly appreciate your detailed review regarding the manuscript's clarity, coherence, and readability, as well as your valuable suggestions. We have revised the manuscript based on your recommendations.

1) Lines 108–114 mention turbulence and RANS modeling, but this is not addressed further in the manuscript. If turbulence is not part of the model, this should be clarified; if it is, further explanation is needed. The paragraph is loosely connected with the paragraphs above and below. If turbulence is not further considered in the model, I suggest to reformulate this paragraph, placing it elsewhere or improve the text flow by connecting it better to previous and following paragraphs.

Thank you for pointing out the issue with this paragraph's connection to the surrounding text. To avoid confusion and ensure textual fluency, we have removed this paragraph in the revised manuscript.

2) The conclusions, while summarizing model development and mechanisms well, still lack a clear statement on the implications for groundwater management in karst systems, which was a key point raised by reviewers in the previous round.

Thank you for your comment. We have significantly revised the conclusion section, adding a dedicated paragraph to discuss the practical implications of our model and research findings for understanding karst groundwater flow paths, future assessment of water resource vulnerability, and developing more effective groundwater management strategies.

Lines 919-949:

“This study employed the Darcy-Brinkman-Stokes (DBS) method and the Volume of Fluid (VOF) technique to develop a unified model capable of coupling seepage and free flow, and meticulously characterizing two-phase (water-air) dynamics in a karst aquifer-stream system. The research confirms that, compared to conventional models like MODFLOW-CFPv2, this unified, multi-physics approach is essential for capturing the complex, dynamic processes inherent to karst systems.

High Non-linearity and Threshold Effects: The interaction between the karst aquifer and the stream is a highly non-linear process. Precipitation intensity acts as the primary driver,

fundamentally altering flow paths and the contribution ratios of different media by triggering dynamic saturation, overflow, and synergistic recharge.

Necessity of Multi-Medium Coupling: The system's hydrological response is not governed by any single medium, but is co-determined by the rapid drainage capacity of conduits, the storage capacity of the matrix, and the permeability of the epikarst. For instance, while conduit geometry primarily controls peak discharge and recession efficiency, matrix porosity and epikarst permeability dictate the system's buffer capacity and the overall hydrograph morphology.

Importance of Unsaturated Zone Physics: The simulation results underscore the necessity of accurately describing unsaturated zone physics. The choice of Water Retention Models significantly impacts the stream hydrograph by altering the water storage and release dynamics of the matrix.

In summary, this study provides a robust framework for karst hydrological simulation. It demonstrates that a unified model capable of resolving coupled multi-medium and multi-phase flow is imperative for accurately predicting the complex hydrological responses of karst systems under varying precipitation scenarios. This enhanced predictive capability is fundamental for moving beyond oversimplified single-continuum models and developing more effective strategies for flood risk assessment, sustainable water resource allocation, and contamination vulnerability planning in these sensitive environments.

In future work, this research framework can provide critical tools for karst groundwater management:

By capturing non-linear thresholds, the model can more accurately predict how specific rainfall events trigger disproportionate flood peaks, thereby improving flood warning systems.

Aquifer Vulnerability Assessment: By coupling with a solute transport model, the framework can differentiate between acute/rapid contamination risks in conduits and chronic/slow risks in the matrix, providing a scientific basis for developing targeted source water protection strategies.”

Minor changes necessary:

** There is a repetition of sentences between lines 78–82 that should be removed for conciseness.*

Thank you for your comment. The repeated sentences have been deleted in the revised manuscript to make the language more concise.

** Minor spelling and typesetting mistakes are present at lines 89, 104, and 395 (and probably elsewhere) and should be corrected.*

Thank you for your comment. The indicated spelling and typesetting errors, as well as others, have been corrected in the revised manuscript.

** The capitalization of section headers is inconsistent (e.g., "3.1" vs. "3.1.1") and should be standardized.*

Thank you for your comment. The capitalization of all section headers has been standardized according to the journal's format in the revised manuscript.

** Line 835 should be reformulated for readability.*

Thank you for your comment. The conclusion section has been rewritten in the revised manuscript, and the problematic sentences from the old version have been deleted.

** The figure naming convention (e.g., "3.a1", "Fig. 8c (2)") is somewhat confusing. I suggest introducing defined scenarios (e.g., "Scenario I", "Scenario II") based on b-value combinations to streamline presentation.*

Thank you for your comment. Your suggestion is excellent. We have introduced scenario definitions based on b-value combinations (e.g., "Scenario I", "Scenario II") and have updated the figures and related descriptions in the text to make the presentation clearer and more intuitive.

Lines 1308-1320:

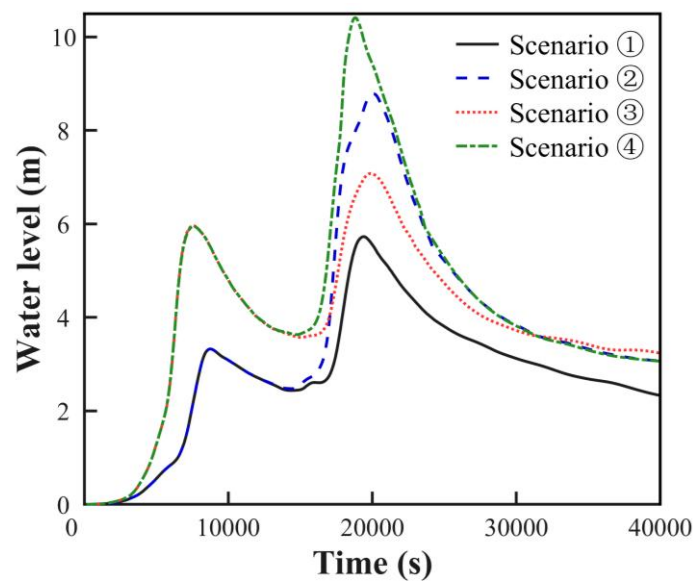


Figure 7. Water levels in stream for two consecutive precipitation events with first and second precipitation intensities: Scenario ① $b_1 = 3$ and $b_2 = 3$; Scenario ② $b_1 = 3$ and $b_2 = 5$; Scenario ③ $b_1 = 5$ and $b_2 = 3$; and Scenario ④ $b_1 = 5$ and $b_2 = 5$, respectively.

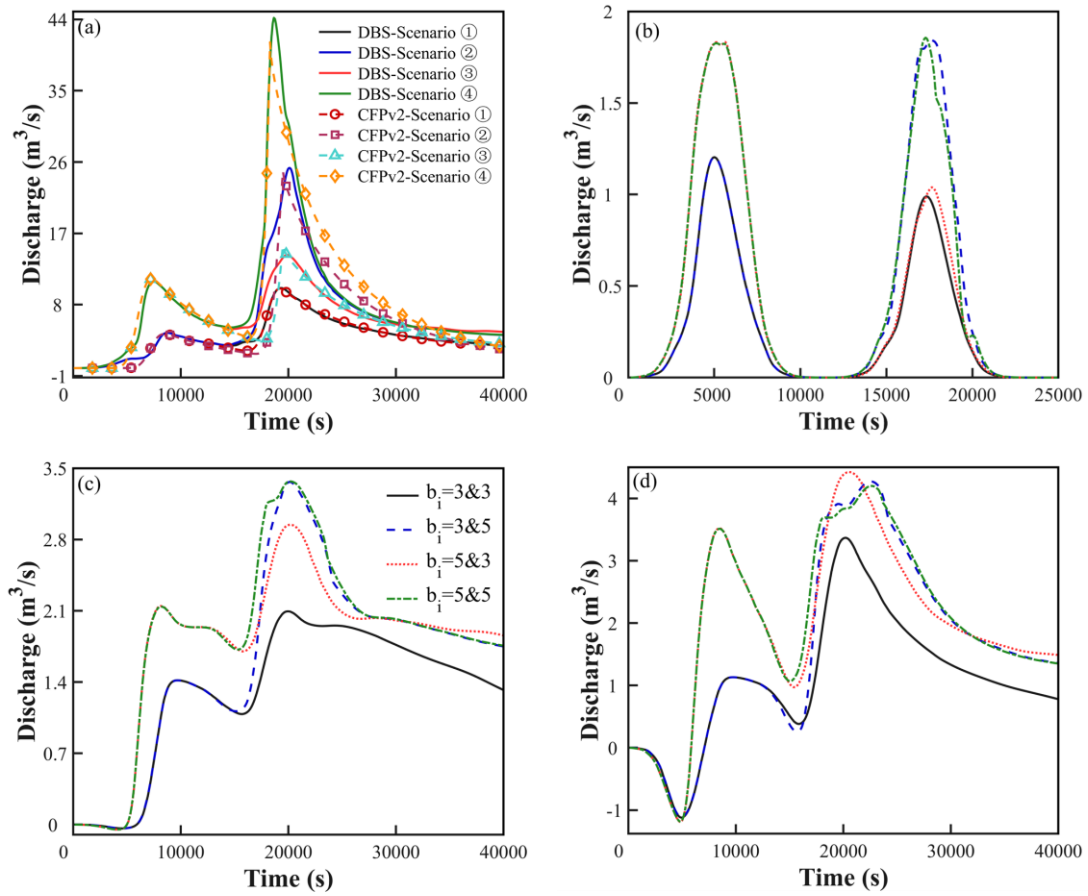


Figure 8. (a) Hydrological process curves of the stream; (b) Discharge process of groundwater through the epikarst to the stream; (c) Discharge process of groundwater through the karst conduit to the stream; (d) Discharge process of porous media (PM II) to the stream, for two consecutive precipitation events with first and second precipitation intensities: Scenario ① $b_1 = 3$ and $b_2 = 3$; Scenario ② $b_1 = 3$ and $b_2 = 5$; Scenario ③ $b_1 = 5$ and $b_2 = 3$; and Scenario ④ $b_1 = 5$ and $b_2 = 5$, respectively.

Addressing these points would substantially improve the clarity and impact of the manuscript.

Thank you once again for your valuable comments. These revisions have significantly improved the quality of the manuscript.

Reply to Referee #2:

The study is in the scope of the journal. The manuscript is overall well-written.

Dear Referee, thank you for your comprehensive review of the manuscript and for your specific, constructive comments. We have addressed your suggestions point by point.

P4 L89: missing space and capital letter. P4 L99: missing space. P4 L104: Remove space before end dot. P9 L248: missing space. P16 L395: missing space. P26 L675: Missing space.

Thank you for your comment. We have corrected all indicated missing/extra spaces and capitalization issues in the revised manuscript.

P6 L141: The impact of the different water retention models is too vague. Consider developing what “unsaturated flow processes” means.

Thank you for your comment. We have expanded and rewritten this section, detailing how dynamic saturation processes affect water exchange between the matrix and conduits, and specifically elaborating on the precise meaning of “unsaturated flow processes” in this study.

Lines 158-173:

“The DBS method was employed to couple seepage and free flow, enabling the quantitative characterization of groundwater flow through various media and the interaction processes between the karst aquifer system and adjacent streams.

Unsaturated flow processes within the karst matrix and epikarst zone fundamentally govern the water storage and exchange dynamics. For instance, the shape of the water retention curve determines the amount of water 'held' in the matrix at a given suction, thereby controlling the specific moisture capacity and the system's buffer capacity. Meanwhile, the relative permeability function dictates the rate at which hydraulic conductivity decreases as the matrix desaturates. Consequently, these variably saturated processes directly influence the predicted rates of matrix infiltration (during recharge events) and matrix drainage/exfiltration to the conduits (sustaining baseflow), thereby altering the overall storage characteristics and hydrograph response of the karst system.”

P8 L206: Section 2.2.2 on the governing equations is somewhat repetitive, and the description of the equations is somewhat shallow.

Thank you for your comment. We have rewritten Section 2.2.2, consolidated repetitive content, and provided a more in-depth description of the physical meaning of each equation and its role in the model. We have also elaborated on the conduit and matrix partitioning strategy to better connect with Section 2.2.3.

Lines 237-276:

2.2.2 Governing Equations

To precisely describe groundwater flow through porous media in the karst aquifer system and the free-surface flow processes between conduits and the adjacent stream, this study adopts the DBS equations to characterize immiscible and incompressible two-phase flow in porous media (Nillama et al., 2022; Carrillo et al., 2020; Lu et al., 2023; Huang et al., 2024; Soullaine, 2024). This model provides a unified mathematical framework capable of seamlessly coupling flow phenomena across different scales. This renders it particularly suitable for simulating karst aquifer systems, which are essentially dual-medium systems constituted by both conduits and porous media.

$$\nabla \cdot \bar{v} = 0 \quad (1)$$

$$\frac{\partial \phi \alpha_l}{\partial t} + \nabla \cdot (\alpha_l \bar{v}) + \nabla \cdot (\phi \alpha_l \alpha_g \bar{v}_r) = 0 \quad (2)$$

$$\frac{1}{\phi} \left(\frac{\partial \rho \bar{v}}{\partial t} + \nabla \cdot \left(\frac{\rho}{\phi} \bar{v} \bar{v} \right) \right) = -\nabla \bar{p} + \rho g + \nabla \cdot \left(\frac{\mu}{\phi} (\nabla \bar{v} + \nabla \bar{v}^T) \right) + F_c + S_f. \quad (3)$$

Here, t represents the computational time $[T]$, $\bar{v}$ is the velocity $[L/T]$, $\bar{v}_r$ is the relative flow rate of the gas phase to the liquid phase $[L/T]$, ρ is the average density of the gas and liquid phases $[M/L^3]$, $\bar{p}$ is the pressure $[pa]$, g is the acceleration due to gravity (9.81 m/s^2), μ is the viscosity $[L^2/T]$, F_c is the surface tension, and S_f is the resistance source term.

Specifically, within a single set of governing equations, the DBS model is capable of simultaneously describing:

- The high-velocity, free-surface flow within karst conduits;
- The low-velocity seepage flow within the surrounding matrix.

This unification is achieved by strategically incorporating a **porosity** (ϕ) and a **resistance source term** (S_f) into the single momentum conservation equation.

P9 L217: remove the comma. P14 L353: wrong sign for the comma.

Thank you for your comment. We have corrected the comma usage issues in the revised manuscript.

P14 L355: what is parameter b?

Thank you for your comment. We have further clarified the meaning and role of parameter b in the revised manuscript.

Lines 399-403:

“Variations in rainfall intensity during the infiltration recharge process, along with the total amount and peak intensity of the event, are controlled by adjusting the dimensionless scaling parameter b .”

P17 L441 and P19 L474: the titles of the sections are identical

Thank you for your comment. We have modified one of the titles in the revised manuscript to accurately reflect its content and avoid repetition.

Line 523:

3.1.3 Dynamic interaction processes between various media within a karst aquifer system

P21 L544: DBS is used both for the Dual Domain Brinkman Stokes and the Darcy Brinkman Stokes model. Consider using only one.

Thank you for your comment. To avoid confusion, we have standardized the definition of DBS throughout the revised manuscript and explicitly stated that it stands for the "Darcy-Brinkman-Stokes" model.

P24 L616: The datasets are old (1979 and 1996) and contain a few points only. The choice could be discussed.

Thank you for your comment. We have added a discussion in the methods section regarding the dataset selection, explaining the reasons for choosing these classic datasets, acknowledging their limitation of having few data points, and noting that this does not affect the study's core objective of validating the model's mechanisms.

Lines 675-679:

This study selected the experiments by Warrick et al. (1985) and Vauclin et al. (1979) because, although these physical experiments have fewer data points (compared to modern numerical simulations), they clearly demonstrate the transient evolution of pressure head or water table position. This is both necessary and sufficient to validate the DBS model's capability in handling variably saturated flow.

P26 L672: It is not clear to me what the multi-level conduit configuration is.

Thank you for your comment. We have added an explanation for “multi-level conduit configuration” in the text.

Lines 728-730:

In this study, the ‘multi-level conduit configuration is our model’s conceptualization of the ‘nested hydraulic discontinuities’ (Halihan et al., 1999) inherent to karst, representing the spectrum of heterogeneity created by the co-existing matrix, fracture, and conduit flow components.

P30 L795: The conclusions are too descriptive about the paper. The summary could be brief using bullet points. Perspectives of this work could be added.

Accepting your suggestion, we have restructured the Conclusion and Abstract sections. We used bullet points to briefly summarize the main findings and added a new paragraph on the future perspectives of this research.

Lines 15-34:

Abstract. The interaction mechanism between karst aquifers and streams remains unclear, particularly regarding the impact of dynamic groundwater saturation processes under variable precipitation. This challenge hinders the accurate modeling of karst hydrology. This study developed a Darcy-Brinkman-Stokes model to analyze these complex interactions. The model integrates water-air two-phase flow and employs multiple water retention models to characterize variably saturated flow in porous media. We validated the DBS approach by comparing its numerical results against the MODFLOW-Conduit Flow Process v2 for generalized karst models. The key conclusions are as follows:

- Rainfall intensity is the dominant driver of the interaction. Higher intensities lead to more complex processes, involving multi-media collaborative recharge and shifting discharge contribution ratios from different media.
- During consecutive rainfall events, groundwater stored in porous media (matrix) significantly influences subsequent stream levels, whereas conduit storage shows negligible carry-over impact due to rapid drainage.
- Uncertainty analysis demonstrated that conduit geometry, epikarst permeability, and matrix porosity differentially influence system hydrology, controlling the magnitude, timing, and distribution of peak discharges.

The validated DBS model is a robust tool that accurately depicts the complex two-phase interactive flows (including infiltration, overflow, and recession) controlled by dynamic saturation. It successfully reveals the dynamic interactions between the epikarst, conduits, matrix, and stream, which is essential for understanding and managing karst water resources.

Lines 918-948:

This study employed the Darcy-Brinkman-Stokes (DBS) method and the Volume of Fluid (VOF) technique to develop a unified model capable of coupling seepage and free flow, and meticulously characterizing two-phase (water-air) dynamics in a karst aquifer-stream system. The research confirms that, compared to conventional models like MODFLOW-CFPv2, this unified, multi-physics approach is essential for capturing the complex, dynamic processes inherent to karst systems.

High Non-linearity and Threshold Effects: The interaction between the karst aquifer and the stream is a highly non-linear process. Precipitation intensity acts as the primary driver, fundamentally altering flow paths and the contribution ratios of different media by triggering dynamic saturation, overflow, and synergistic recharge.

Necessity of Multi-Medium Coupling: The system's hydrological response is not governed by any single medium, but is co-determined by the rapid drainage capacity of conduits, the storage capacity of the matrix, and the permeability of the epikarst. For instance, while conduit geometry primarily controls peak discharge and recession efficiency, matrix porosity and epikarst permeability dictate the system's buffer capacity and the overall hydrograph morphology.

Importance of Unsaturated Zone Physics: The simulation results underscore the necessity of accurately describing unsaturated zone physics. The choice of Water Retention Models significantly impacts the stream hydrograph by altering the water storage and release dynamics of the matrix.

In summary, this study provides a robust framework for karst hydrological simulation. It demonstrates that a unified model capable of resolving coupled multi-medium and multi-phase flow is imperative for accurately predicting the complex hydrological responses of karst systems under varying precipitation scenarios. This enhanced predictive capability is fundamental for moving beyond oversimplified single-continuum models and developing more effective strategies for flood risk assessment, sustainable water resource allocation, and contamination vulnerability planning in these sensitive environments.

In future work, this research framework can provide critical tools for karst groundwater management:

By capturing non-linear thresholds, the model can more accurately predict how specific rainfall events trigger disproportionate flood peaks, thereby improving flood warning systems.

Aquifer Vulnerability Assessment: By coupling with a solute transport model, the framework can differentiate between acute/rapid contamination risks in conduits and chronic/slow risks in the matrix, providing a scientific basis for developing targeted source water protection strategies.

Fig. 1: Consider adding labels for the stream and karst spring to the sketch, and clarify the PM i, ii, and iii in the caption for better understanding.

Thank you for your comment. In the latest revised manuscript, we have added labels for the stream and karst spring in the figure and explained the meaning of PM i, ii, and iii.

Lines 1276-1283:

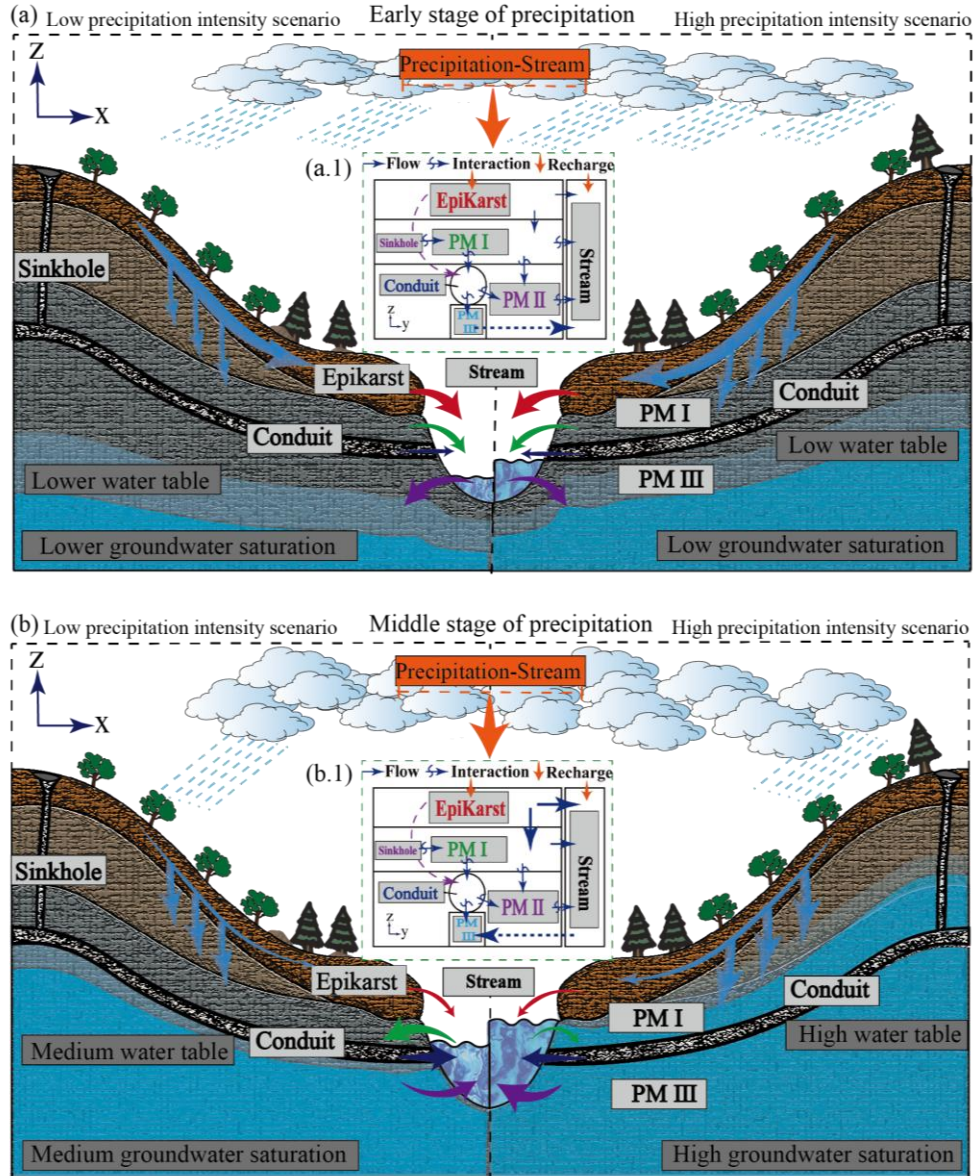


Figure 1. Schematic diagrams of the modelling of the interaction between the karst aquifer (epikarst, sinkhole, karst conduit, PM I (Porous Medium I), PM II (Porous Medium II), and PM III (Porous Medium III)) and stream under dimensionless precipitation intensities ($b = 3$ and $b = 5$). (a) and (a.1) Schematic diagram of the interaction flow between each medium and stream in the early stage of a precipitation event; (b) and (b.1) Schematic diagram of the interaction flow between each medium and stream in the middle stage of a precipitation event. The size of the arrows represents the magnitude of the flow rate, and the direction of the arrows represents the direction of interaction between the two.

Fig. 5: Consider using the same Y-axis scale for comparison between the different cases.

Thank you for your comment. In the revised manuscript, we have adjusted the Y-axis of all subplots to the same scale for direct comparison.

Lines 1301-1303:

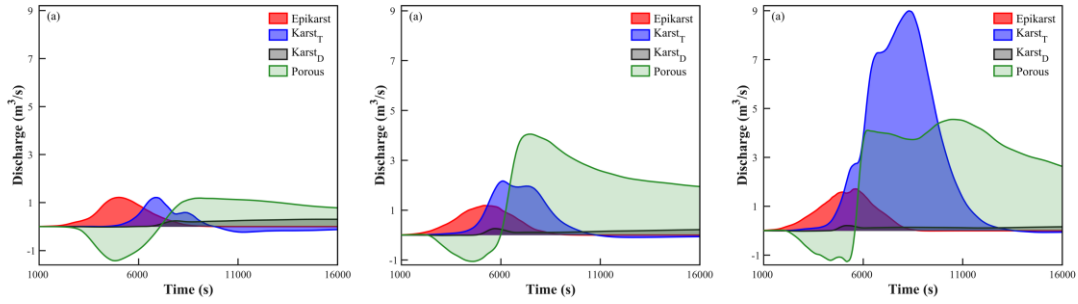


Figure 5. Interaction process of epikarst, porous media, and stream for different precipitation intensities: (a) $b = 3$, (b) $b = 5$, (c) $b = 7$.

Fig. 6a: Consider checking the colors to match color blind requirements.

Thank you for your comment. We have redrawn this figure in the revised manuscript to be color-blind friendly.

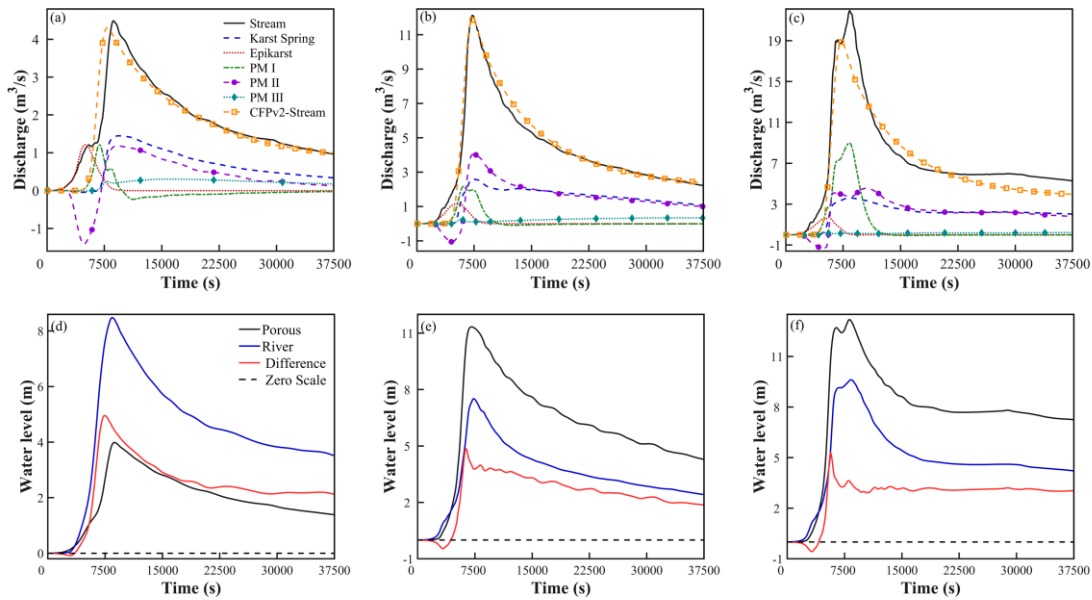


Figure 4. Hydrological process curves of each medium in the karst aquifer and stream for different precipitation intensities: (a) $b = 3$, (b) $b = 5$, (c) $b = 7$. Water level changes and differences in water levels in the karst aquifer and stream for different precipitation intensities: (d) $b = 3$, (e) $b = 5$, (f) $b = 7$.

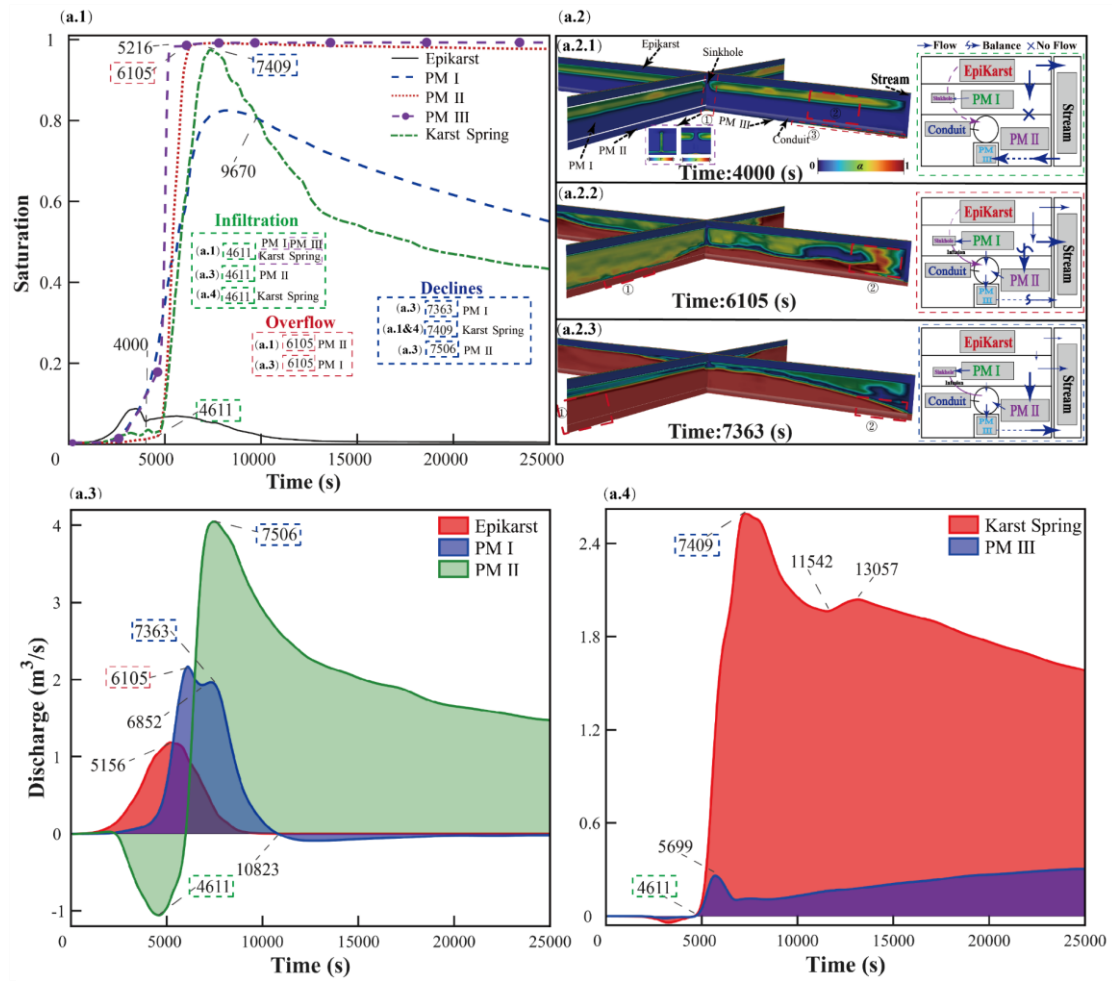


Figure 6. For the Darcy-Brinkman-Stokes model: (a.1) Variations in the saturation levels of epikarst, various porous media, and the karst spring. (a.2) Saturation fields and the interaction among different media at 4000 s, 6105 s, and 7363 s. (a.3) Interaction volumes between epikarst, porous media I, II, and the stream. (a.4) Interaction volumes among the karst spring, porous media III, and the stream.

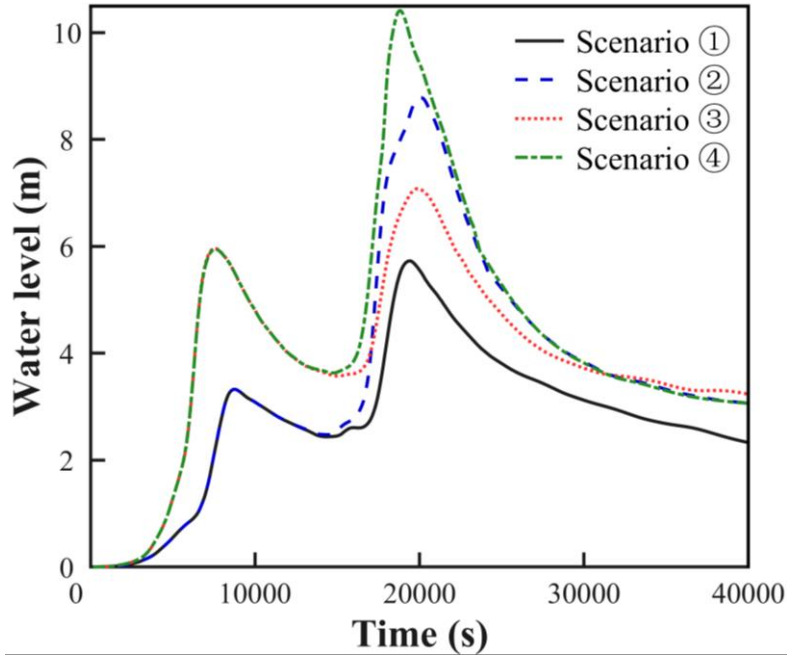


Figure 7. Water levels in stream for two consecutive precipitation events with first and second precipitation intensities: Scenario ① $b_1 = 3$ and $b_2 = 3$; Scenario ② $b_1 = 3$ and $b_2 = 5$; Scenario ③ $b_1 = 5$ and $b_2 = 3$; and Scenario ④ $b_1 = 5$ and $b_2 = 5$, respectively.

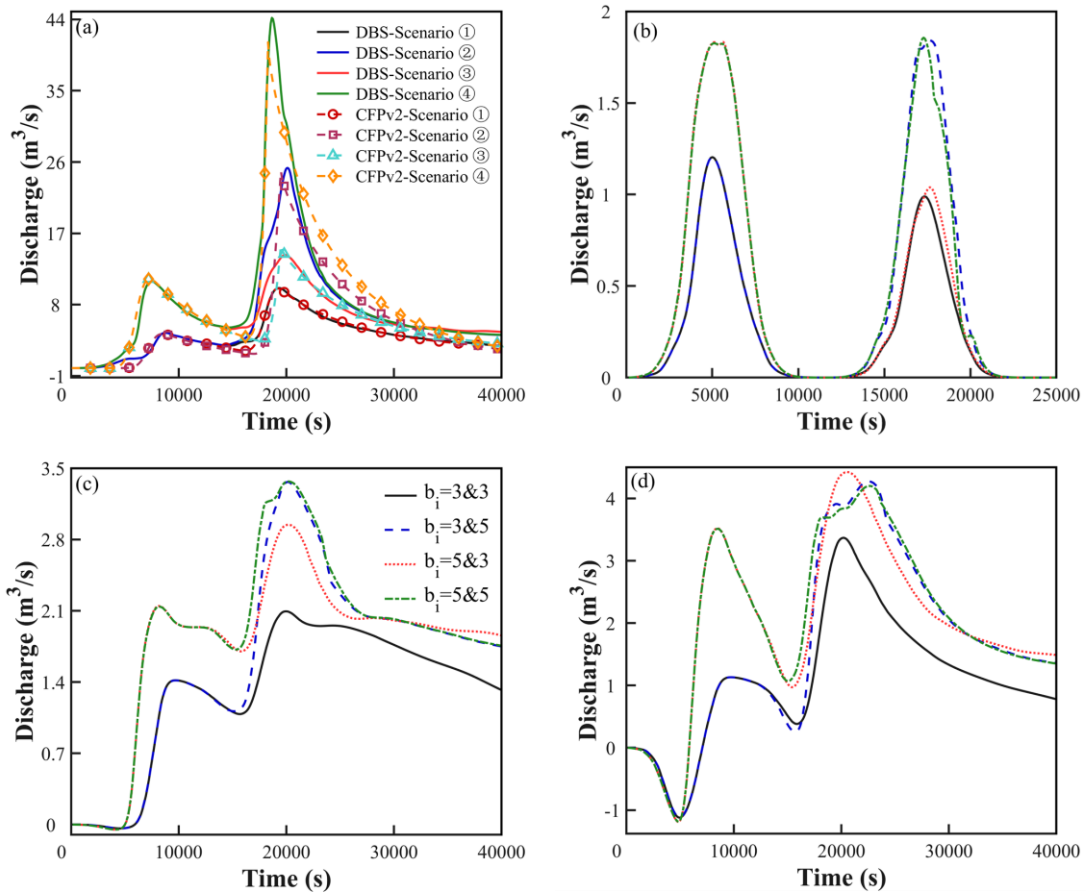


Figure 8. (a) Hydrological process curves of the stream; (b) Discharge process of groundwater through the epikarst to the stream; (c) Discharge process of groundwater through the karst conduit to the stream; (d) Discharge process of porous media (PM II) to the stream, for two consecutive precipitation events with first and second precipitation intensities: Scenario ① $b_1 = 3$ and $b_2 = 3$; Scenario ② $b_1 = 3$ and $b_2 = 5$; Scenario ③ $b_1 = 5$ and $b_2 = 3$; and Scenario ④ $b_1 = 5$ and $b_2 = 5$, respectively.

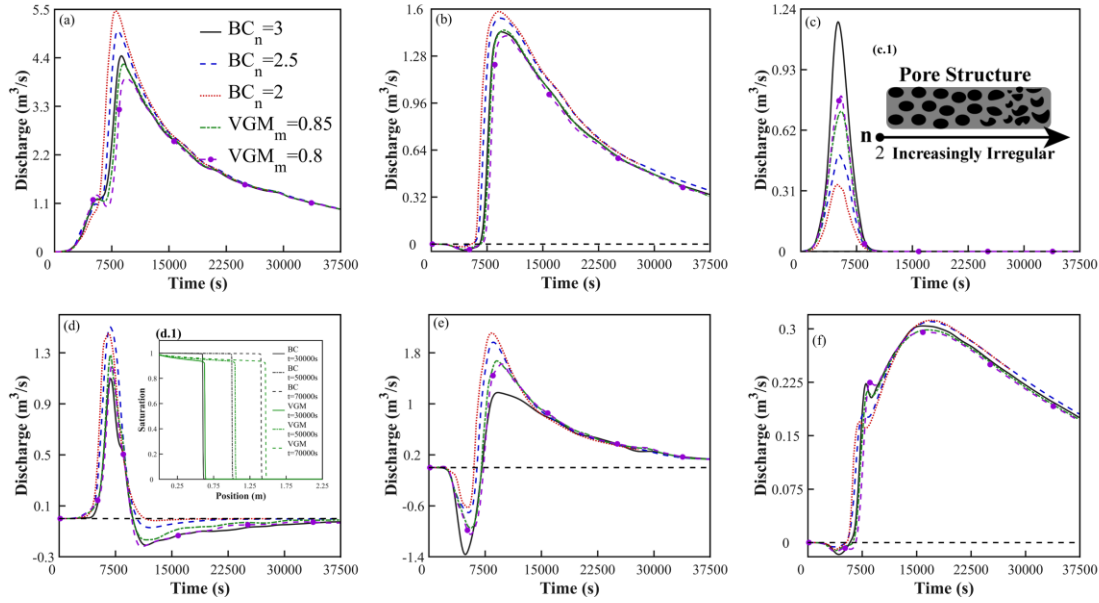


Figure 10. Hydrological process curves under different water retention model parameters ($BC_n = 3, 2.5, 2$ and $VGM_m = 0.85, 0.8$) for (a) stream, (b) karst spring, (c) epikarst, (d) PM I, (e) PM II, and (f) PM III. Subplots (c.1) and (d.1) show the schematic diagram of parameter effects on porous media morphology and the water retention curves of the BC and VGM models, respectively.

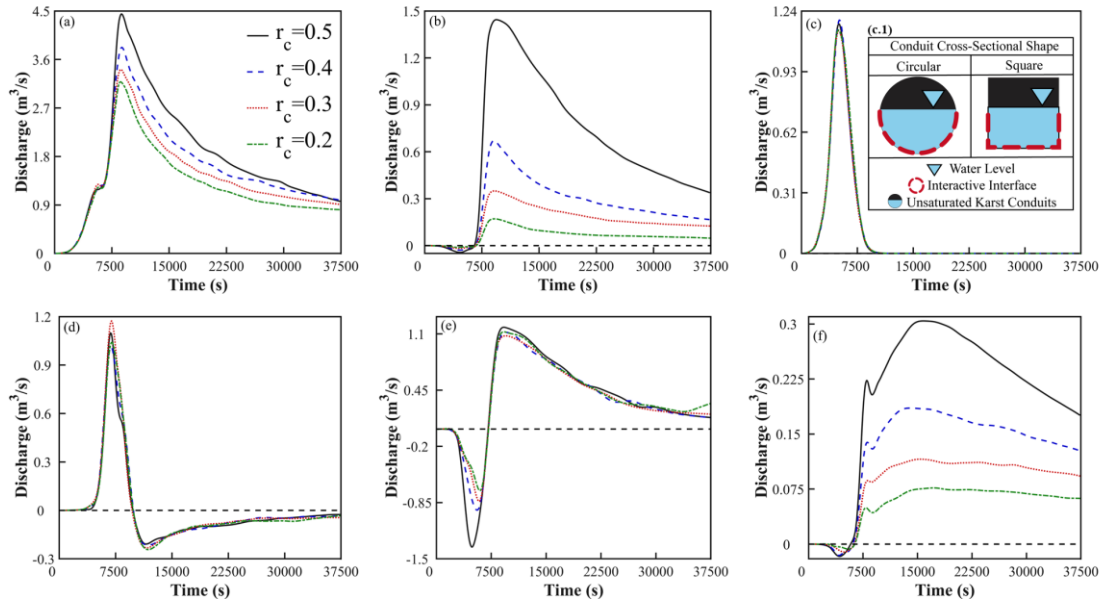


Figure 12. Hydrological process curves for (a) stream, (b) karst spring, (c) epikarst, (d) PM I, (e) PM II, and (f) PM III under conditions of circular conduits with radii $r_c = 0.2, 0.3, 0.4, 0.5$, and square cross-section conduits with $S-r_c = 0.5$. Subplot (c.1) shows a schematic diagram of different conduit cross-sectional shapes.

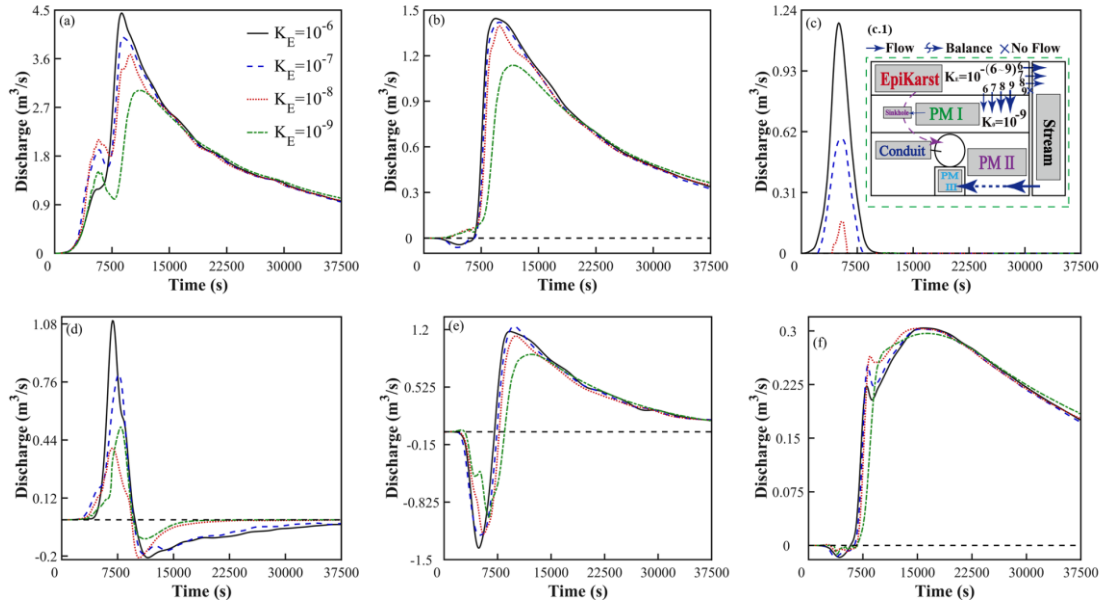


Figure 13. Hydrographs under different epikarst permeability conditions ($K_E = 10^{-6}$, $K_E = 10^{-7}$, $K_E = 10^{-8}$, $K_E = 10^{-9}$) for: (a) stream, (b) karst spring, (c) epikarst, (d) PM I, (e) PM II, (f) PM III. Subfigure (c.1) shows a schematic diagram of media interactions under varying epikarst permeability conditions.

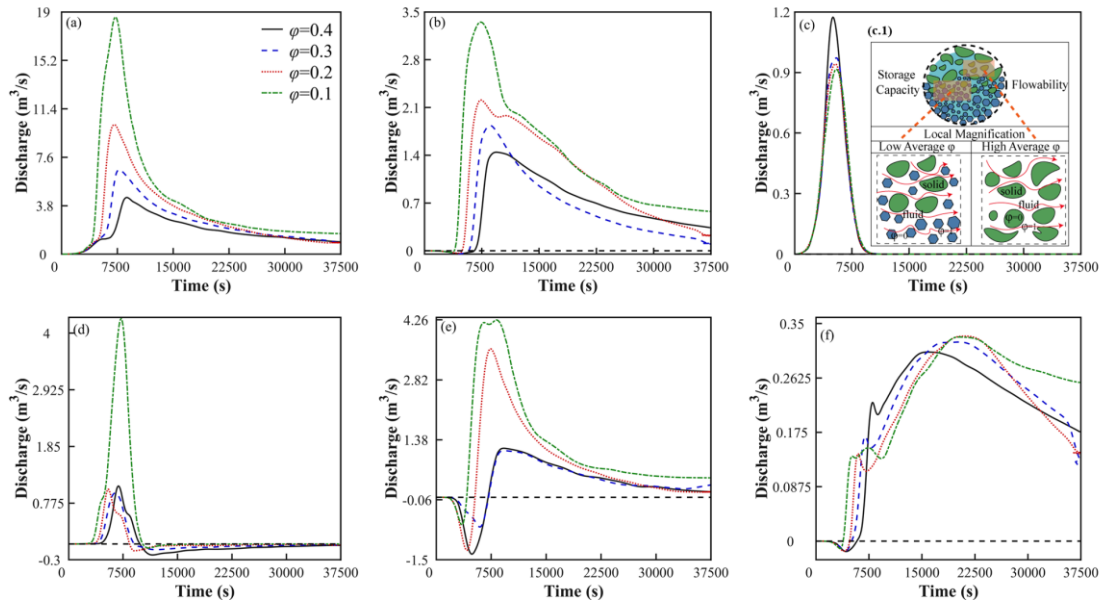


Figure 14. hydrograph curves under different porosity conditions ($\phi = 0.4$, $\phi = 0.3$, $\phi = 0.2$, $\phi = 0.1$) for (a) stream, (b) karst spring, (c) epikarst, (d) PM I, (e) PM II, and (f) PM III. Among these, (c.1) illustrates a schematic diagram of the medium's water storage capacity and flow capacity under varying porosity conditions.

Fig. 11a: blue is for M-Stream

Thank you for the correction. We have clarified in the figure caption that the blue curve represents M-Stream.

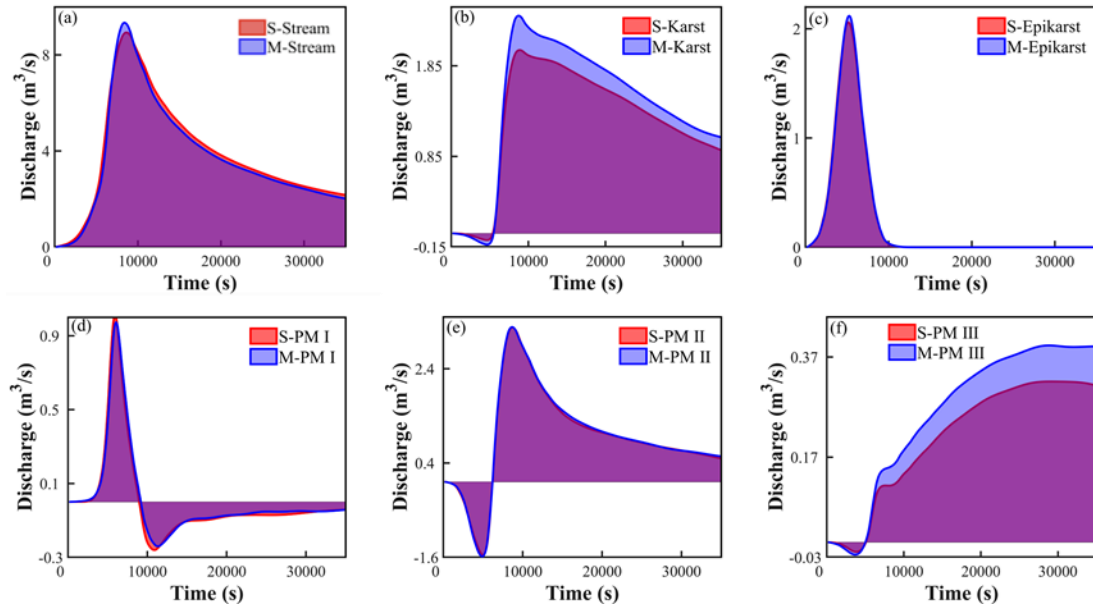


Figure 11. Impacts of single-stage and multi-stage conduit hydrological process changes in various media of the karst aquifer for a precipitation intensity $b = 5$.

Thank you very much for your detailed work. The quality of manuscript improved significantly after these revisions.

Reply to Referee #3:

Overall opinions

The manuscript propose a complete modeling exercise to investigate how precipitation signal affects recharge processes in karst system. The methodology appears well designed and the results are of interest for publication in HESS journal.

Before the manuscript being ready for publication, I found number of inconstancy in the text that might be addressed.

Dear Referee, Thank you for your in-depth analysis of the manuscript and your valuable suggestions. We have carefully considered all your recommendations and made corresponding revisions to the manuscript.

Specific comments

Line 26 : “CPRv2 and DBS” – acronyms might be detailed in the abstract.

Thank you for your comment. We have provided the full names for CPRv2 and DBS upon their first appearance in the abstract.

Line 63 : citation (Duran et al., 2020; Bittner et al., 2020) are not consistent with the text. Please provide more relevant references here.

Thank you for your comment. We have re-checked the references in this part and rewritten the connecting sentences to ensure they are more relevant and appropriate to the text.

Line 80:

Together, they form a complex network for groundwater recharge and drainage.

Line 80 : There is a repetition.

Thank you for your comment. We have deleted the repeated sentence in the latest revised manuscript.

Line 89 : Missing capita at the beginning of the sentence.

Thank you for your comment. We have corrected the letter at the beginning of the sentence to uppercase in the latest revised manuscript.

Line 108 : “The karst aquifer are typically accompanied by turbulent flow.” It sounds unclear, please rephrase.

Thank you for your comment. This paragraph has been deleted in the latest revised manuscript to make the expression clearer and more accurate.

Line 125 : “This research elucidates how saturation ...” What coordinated recharge means ? Please rephrase.

Thank you for your comment. In the latest revised manuscript, “coordinated recharge” has been replaced with a clearer expression, and its specific meaning has been explained.

Lines 144-146:

This research elucidates how their saturation dynamics impact the flow exchange among different karst media during precipitation infiltration, and examines the evolving interaction between the karst aquifer and stream under such recharge conditions.

Line 131 : “The research results can further reveal the interaction” These two last sentence sounds useless here. It would be more appropriate in conclusion.

Thank you for your comment. We fully agree with you that placing these two sentences at the end of the introduction was inappropriate. This part has been deleted in the latest revised manuscript.

Line 138 : Acronyms for DBS and VOF are already given previously, at first appearance in the text. Line 188 : Acronym for VOF is already given previously in the text.

Thank you for your comment. The redundant definitions of VOF and DBS have been deleted.

Line 168 : “As a results, ...” Please give more justification to reach this statement, in particular regarding the multi-scale aspects.

Thank you for your comment. The logic of the original sentence was indeed problematic. “Rainfall causing water level fluctuations” is not a direct cause of “multi-scale characteristics.” The differences in scale and flow velocity between the slow flow in the media and the fast flow in conduits/streams are inherent properties of the system, not a result of rainfall fluctuations, which only exacerbate the process.

Therefore, we have changed the connecting sentence to:

Lines 152-154:

“This variability in water levels is therefore a key driver for the exchange mechanisms between the porous media and the stream.”

Line 195 : equation 2 and 3, index for the alpha seems to be missing, regarding the equation description in the text.

Thank you for pointing out this error. We have added the corresponding phase subscript to alpha.

$$\varphi = \begin{cases} 1 & \text{free regions} \\ 0 < \varphi < 1 & \text{porous regions} \\ 0 & \text{solid regions} \end{cases} \quad (4)$$

$$\alpha_l = \begin{cases} 1 & \text{water} \\ 0 < \alpha_l < 1 & \text{two-phase zone} \\ 0 & \text{air} \end{cases} \quad (5)$$

Line 208 : DBS was previously given for “Darcy-Brinkman-Stokes”. Please check acronym consistency along the manuscript,

Thank you for your comment! We have checked the entire manuscript to ensure the acronym DBS is consistent throughout.

Line 235: C_{μ} with value of 0.09. Where do this value come from ?

Thank you for your comment. In the latest manuscript, this part has been removed in response to other referees' suggestions. However, the value of 0.09 for C_{μ} and other parameters can be referenced from (Zhai et al., 2024; Shen et al., 2024; Hajivand and Mousavizadegan, 2015).

Zhai, Y., Fuhrman, D. R., & Christensen, E. D. (2024). Numerical simulations of flow inside a stone protection layer with a modified $k-\omega$ turbulence model. Coastal Engineering, 189, 104469. <https://doi.org/10.1016/j.coastaleng.2024.104469>

Shen, Z., Huang, D., Wang, G., & Jin, F. (2024). Numerical study of wave interaction with armor layers using the resolved CFD-DEM coupling method. Coastal Engineering, 187, 104421. <https://doi.org/10.1016/j.coastaleng.2023.104421>

Hajivand, A. and Mousavizadegan, S.H., 2015. Virtual maneuvering test in CFD media in presence of free surface. International Journal of Naval Architecture and Ocean Engineering, 7(3), pp.540-558. <https://doi.org/10.1515/ijnaoe-2015-0039>

Line 303 : It would be better to provide information about CPU and RAM capacity rather than a specific computer model.

Thank you for your comment! As per your suggestion, we have revised the latest manuscript to provide the CPU and RAM capacity of the computational resources used.

Lines 348-351:

To address this challenge, all simulations in this study were executed on a high-performance server equipped with 64 CPU cores (128 threads) and 256 GB of RAM, which provided the necessary computational power for handling complex 3D meshes.

Line 379 : extra space in the text after a coma

Thank you for your comment. We have deleted it in the latest manuscript.

Line 480 : It sounds confusing to get question in the results section. It would be more appropriate in the methodology or even in introduction.

Thank you for your comment. You are correct; it is inappropriate to ask a question in the results section. We have deleted the question.

Line 675 : Figure 11 : description for sub-figures are missing.

Thank you for your comment. Descriptions have been added for the sub-figures in Figure 11.

Lines 730-738:

In this study, the ‘multi-level conduit’ configuration is our model’s conceptualization of the ‘nested hydraulic discontinuities’ (Halihan et al., 1999) inherent to karst, representing the spectrum of heterogeneity created by the co-existing matrix, fracture, and conduit flow components. By comparing the multi-level and single-level conduit configurations, the results show that the configuration choice did not induce significant changes in the hydrological processes of the epikarst (Fig. 11c), PM I (Fig. 11d), and PM II (Fig. 11e). In these media, the ‘M’ and ‘S’ hydrographs are nearly identical. However, the impact of the multi-level configuration was significant for the main stream (Fig. 11a), the total karst system discharge (Fig. 11b), and PM III (Fig. 11f). In all these cases, the multi-level (M) configuration resulted in a visibly higher and earlier peak discharge compared to the single-level (S) configuration.

Line 704 : check for notation consistency along the manuscript PMI or porous medium I. Line 757 : check for notation consistency along the manuscript with PMIII or porous medium III

Thank you for your comment. We have checked and standardized the notation system throughout the manuscript to ensure consistency in expressions such as PMI/Porous Medium I.

Line 790 : Arriving here it is difficult to capture how the author moves from there results to vulnerability in karst. If vulnerability is still mentioned, more discussion might be given otherwise it might be pushed in conclusion as potential perspectives for future work.

Thank you for your comment. We recognize that the transition from results to the discussion of vulnerability was indeed insufficient. We have moved this to the conclusion as a perspective for future work.

Lines 944-950:

In future work, this research framework can provide critical tools for karst groundwater management:

By capturing non-linear thresholds, the model can more accurately predict how specific rainfall events trigger disproportionate flood peaks, thereby improving flood warning systems.

Aquifer Vulnerability Assessment: By coupling with a solute transport model, the framework can differentiate between acute/rapid contamination risks in conduits and chronic/slow risks in the matrix, providing a scientific basis for developing targeted source water protection strategies.

Line 837 : Diameter for a squared section sounds weird, please rephrase to make it coherent between shape and dimension of the conduit section.

Thank you for your comment. The expression was indeed inappropriate. It should be corrected to the more accurate term "side length".

Line 864 : The bibliography format is heterogeneous. Please check references and adopt a consistent reference format (check the journal's author guideline).

Thank you for your comment. We have checked and formatted all references according to the journal's author guidelines to ensure consistent formatting.

Thank you again for your comprehensive review and valuable suggestions.