Reply to Referee 1:

The article focuses on studying the interactions between hydrological processes involving karst aquifers, conduits, and streams, varying with precipitation and other factors that are later described in detail. The work is well-structured, the figures are of good quality, and the reading is fairly smooth.

Dear Reviewer: Thank you very much for your comments and suggestions. Our replies are listed as follow:

(1) *The topic is, in my opinion, significant but somewhat self-contained when the discussion remains limited to numerical results without extending them to a broader analysis—namely, how this study could be useful in managing water resources in these complex aquifers or how it could be applied at a regional scale.*

Thank you for pointing out the need to strengthen the practical application relevance in the Discussion section. In response to this suggestion, we have added implications of modeling parameters for karst water resources management in the revised version, as follows:

- Lines 847-855: Discusses the effect of conduit geometry (e.g., square cross-section) on aquifer-stream interaction fluxes, emphasizing its critical role in enhancing simulation accuracy.
- Lines 886-894: Analyzes the regulatory mechanism of epikarst permeability on groundwater flow paths, illustrating the importance of parameter calibration for water resources prediction.
- Lines 917-930: Adds an analysis of the impact of porosity parameters on karst water resources allocation and geological stability, clarifying the model's potential application in flood warning.

Lines 847-855:

"Conduit geometry (radius and shape) constitutes a critical factor in karst aquifer hydrological modeling. Larger circular conduits accelerate peak discharge arrival and amplify stream-connected flow peaks and karst spring discharge. Square-section conduits outperform circular equivalents in peak discharge capacity under identical nominal radii due to cross-sectional area advantages. Enlarged conduits intensify porous medium-stream interactions and amplify PM III recharge through gravitational effects. Comprehensive consideration of conduit geometry impacts on hydrological elements is essential for improving model accuracy and reliability in simulating karst aquifer-stream interaction processes."

Lines 886-894:

"Epikarst permeability constitutes a critical factor in hydrological modeling of karst aquifer systems. Highly permeable epikarst produces rapid streamflow peaks followed by sharp declines, reflecting efficient groundwater leakage to the stream. Conversely, low permeability yields diminished peaks and broader discharge curves. While karst spring discharge remains relatively stable when epikarst permeability differs from porous media, proper characterization of epikarst permeability is essential for accurately simulating hydraulic interactions between media, regulating groundwater flow pathways and velocities. This enhances model reliability in capturing complex flow dynamics within karst conduit-stream systems."

Lines 917-930:

"In hydrological modeling, porosity parameters must be calibrated to accurately simulate groundwater flow paths and storage-release dynamics. For low-porosity regions, models should emphasize rapid drainage capacity of conduit systems and transient flow variations. In high-porosity areas, considerations should include fluid retention risks, stream-porous media interactions, and their long-term impacts on geological stability and water resource allocation. Proper porosity parameterization enhances simulation accuracy for diverse hydrological processes, enabling improved prediction and management of karst water resources.

Karst hydrological vulnerability manifests prominently through rapid infiltration, epikarst runoff, groundwater table fluctuations, and abrupt spring discharge variations. The DBS model effectively simulates multi-media interactions during extreme recharge events, enabling temporal analysis of media-stream exchanges, identification of peak interaction values, and applications in coupled conduit flow-seepage processes for two-phase flow systems."

(2) *The analytical and numerical approach is based on a representative sample of an aquifer, with the conduit size set by the authors (which I also find quite large) and a variation in rainfall intensity that I do not understand, as it is measured in meters according to Table 1. In hydrology, rainfall intensity is measured in mm/h, representing the amount of rainfall per unit of time. I kindly ask the authors to better define this aspect and, if necessary, correct it.*

Thank you for your corrections regarding the units for conduit dimensions and precipitation intensity:

- Rationality of conduit dimensions: We have added a parameter sensitivity analysis (Lines 816-855), which quantifies the impact of different conduit diameters (0.2–0.5 m) and cross-sectional shapes (circular/square) on fluxes between media components using Fig. 12. This validates the physical basis for the parameter settings.
- Correction of precipitation intensity unit: The entry "Precipitation intensity (m)" in Table 1 was a typographical error; we have deleted this column. Furthermore, detailed definitions of the precipitation function have been added in the "2.5 Rainfall Infiltration Recharge

Boundary" subsection (Lines 712-735): The precipitation function is defined as a time-dependent variable I(t), with its intensity modulated by the dimensionless parameter b, consistent with conventional expressions in the hydrology field.

Lines 816-855:

"4.1 Impacts of Conduit Diameter and Geometry on Interactions Between Karst Aquifer Systems and Streams

Fig. 12 presents hydrographs under conditions of circular conduits with varying radii (r=0.2, 0.3, 0.3, and 0.5 m) and square-section conduits (r=0.5 m) for (a) stream-connected flow, (b) karst spring discharge, (c) epikarst flow, (d) porous medium I (PM I), (e) PM II, and (f) PM III. Fig. 12(c.1) illustrates different conduit cross-sectional shapes to analyze their impacts on the interactive flow between karst aquifer systems and adjacent streams.

As shown in Fig. 12(a), larger conduit radii correspond to higher initial discharge peaks and shorter peak arrival times, indicating enhanced porous medium recharge and faster fluid transmission through larger conduits. Notably, the square-section conduit ($s\text{-}r_c$=0.5) exhibits higher peak discharge than its circular counterpart (rc=0.5) due to its surplus cross-sectional area accommodating greater fluid discharge under identical nominal radii.

Fig. 12(b) demonstrates that karst spring peak discharge increases with conduit radius. At r=0.5 m, the square-section conduit ($s\text{-}r_c$=0.5) achieves higher peak discharge than the circular conduit (r_c=0.5), but displays lower recession flow. This occurs because identical precipitation infiltration recharge leads to greater porous medium storage depletion during peak periods in square conduits, subsequently reducing porous medium-to-conduit recharge during baseflow recession.

Combined analysis of Figs. 12(c), (d), and (e) reveals that conduit radius variations do not significantly affect epikarst hydrographs or PM I/II hydrographs. However, square-section sinkholes modify flow patterns: epikarst hydrographs show lower values under square conduits, while PM I/II hydrographs exhibit higher values due to enhanced epikarst groundwater collection in square cross-sections, increasing recharge to PM I/II.

Fig. 12(e) indicates that larger conduit radii correspond to lower negative values. Combined with Fig. 12(a), this demonstrates that increased stream recharge through larger conduits elevates both stream peak discharge and water levels, thereby enhancing porous medium-stream interactions. Similarly, Fig. 12(f) shows that larger conduit radii increase karst spring discharge and PM III hydrograph elevation through enhanced gravity-driven groundwater recharge.

Conduit geometry (radius and shape) constitutes a critical factor in karst aquifer hydrological modeling. Larger circular conduits accelerate peak discharge arrival and amplify stream-connected flow peaks and karst spring discharge. Square-section conduits outperform circular equivalents in peak discharge capacity under identical nominal radii due to cross-sectional area advantages. Enlarged conduits intensify porous medium-stream interactions and amplify PM III recharge through gravitational effects. Comprehensive consideration of conduit geometry impacts on hydrological elements is essential for improving model accuracy and reliability in simulating karst aquifer-stream interaction processes."

Lines 1257-1263:

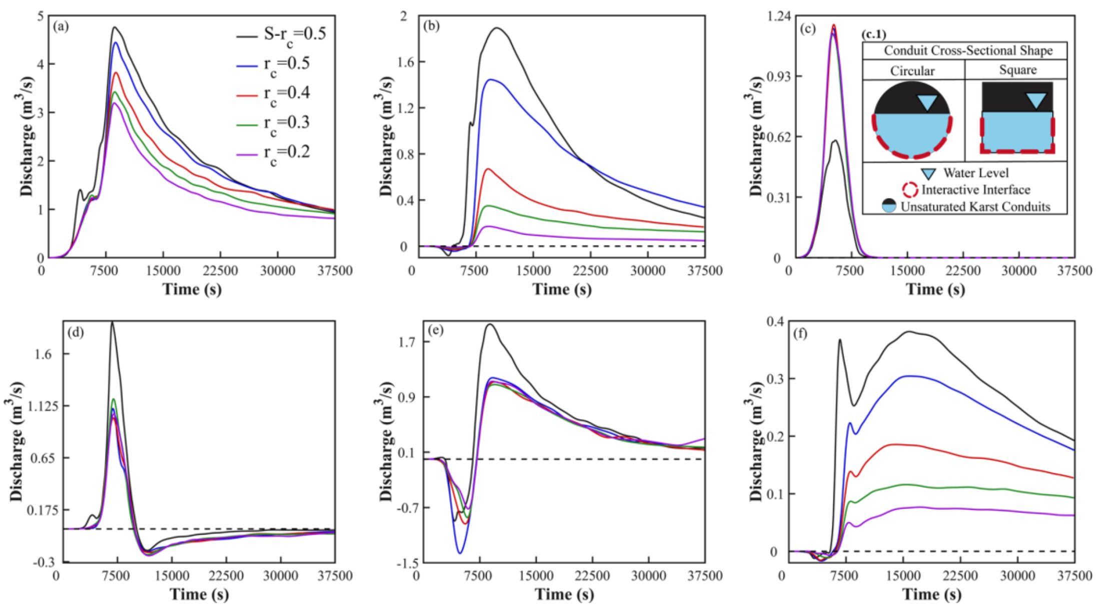

Figure 12. Hydrological process curves for (a) stream, (b) karst spring, (c) epikarst, (d) PM I, (e) PM II, and (f) PM III under conditions of circular conduits with radii r_c = 0.2, 0.3, 0.3, and 0.5, and square-cross-section conduits with S-r_c = 0.5. Subplot (c.1) shows a schematic diagram of different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

Lines 712-735:

"2.5 Rainfall Infiltration Recharge Boundary

The upper boundaries of both the DBS and CFPv2 models are defined as transient natural precipitation boundary conditions. In this study, the rainfall infiltration recharge boundary condition is formulated as follows (Huang et al., 2024; Chang et al., 2015):

$$I(t) = \frac{b}{\sqrt{2\pi\sigma^2}} \sum e^{-\frac{\left(\frac{t_i-\mu}{a}\right)^2}{2\sigma^2}} \tag{1}$$

Here, t_i denotes the time of the i-th rainfall event, and $I(t)$ represents the total rainfall amount at that time. According to Chang et al. (2015), the parameters μ、 σ^2, and a are set as constants (90, 1.5, and 20, respectively). Variations in rainfall intensity during the infiltration recharge process are controlled by adjusting the value of the dimensionless parameter b."

(3) *Another aspect concerns the discussion section. This should compare the obtained results with those in the literature, discuss the limitations and advantages of such an approach, perform a sensitivity analysis on the calibrated parameters, and assess the study's usefulness and general applicability. The current section focuses on comparing the results with those from the MODFLOW-CFP model, which the authors themselves implemented. In my opinion, this should still be described in the results section, and consequently, the methodological section should be expanded to include this additional approach.*

Thank you for your suggestions regarding results comparison and chapter organization:

• Literature comparison: Added quantitative validation against experimental data from Warrick et al. (1985) and Vauclin et al. (1979) (Lines 712-735), demonstrating the reliability of the DBS model in simulating variably saturated flow.

• Chapter restructuring: Relocated the MODFLOW-CFPv2 comparison section to the "Results" chapter (Lines 352-354) and expanded the explanation of CFPv2 principles in the "Methodology" section (Lines 328-340).

Lines 712-735:

"The external recharge of the system significantly influences the interaction processes among different media. This study further investigates how the inherent hydrogeological properties of karst systems affect these interactive processes. Variable saturated flow in the karst vadose zone plays a critical role (Dvory et al., 2018), where the water retention characteristics of porous media govern unsaturated flow dynamics. However, the CFPv2 model struggles to simulate variable saturation processes. This paper compares the DBS model results with two distinct experimental datasets to elucidate the advantages and limitations of the DBS approach in simulating variable saturated flow.

Case 1: A typical unsaturated-unsteady seepage problem in sandy clay loam (Warrick et al., 1985), where the soil hydraulic properties are provided by the international UNSODA database (Leij et al., 1996). Key parameters include: k = 1 × 10−6 m/s, α_s = 0.363, α_r = 0.186, and n = 1.53. The model consists of a vertical soil column (1 m thickness) with an initial pressure head of -8 m across the domain. The top boundary is set to a pressure head of 0 m to simulate free surface infiltration.

Case 2: A 2D laboratory infiltration experiment by Vauclin et al. (1979), widely used for evaluating saturated-unsaturated unsteady seepage models. The soil slab measures 2.00 m in height, 6.00 m in width, and 0.05 m in thickness, with an impermeable base and free drainage boundaries on both sides. Initially, the water table is set at 0.65 m. A central 1.00 m section of the top boundary receives uniform precipitation at 0.148 m/h for 8 hours, during which free surface evolution is monitored. Soil hydraulic properties are described using the van Genuchten-Mualem model with parameters: k = 0.35 m/h, α_s = 0.30, α_r = 0.01. Due to symmetry, the DBS model simulates the right half of the domain."

Lines 328-340:

"2.3 CFPv2 model

The CFPv2 model, proposed by Reimann et al. (2014), is an advanced version of MODFLOW-CFP (Shoemaker et al., 2008). It extends functionalities such as flow interactions between conduits and porous media, as well as conduit boundary conditions. CFPv2 integrates with MODFLOW-2005 and employs the following approaches: **Laminar Flow in Conduits**: Described using the Hagen-Poiseuille equation for discrete conduits within conduit networks. **Turbulent Flow**: Calculated by combining the Darcy-Weisbach equation with the Colebrook-White equation. **Laminar Flow in Fractured Rock Matrix**: Simulated via a continuum approach. Detailed technical documentation for MODFLOW-CFP, including groundwater flow simulation methodologies, is provided by Shoemaker et al. (2008). Successful applications and evaluations of the model have been reported in studies such as Gallegos et al. (2013), Reimann et al. (2014), Chang et al. (2020), Gao et al. (2020), and Shirafkan et al. (2023)."

(4) *line 165: wrong unit of measure for permeability, gravitational acceleration*

Thank you for your comment. We have corrected the labeling errors in the revised manuscript.

(5) *line 205: delete ripetitive title*

Thank you for your comment. We have removed the duplicate headings in the revised manuscript.

(6) *Figure 1: insert letters a and b also in the figure for better readibility*

Thank you for the suggestion. We have clearly labeled subplots (a), (b), (a.1), and (b.1) in Fig. 1 and updated the captions (Lines 1200–1207) to enhance readability.

Lines 1200-1207:

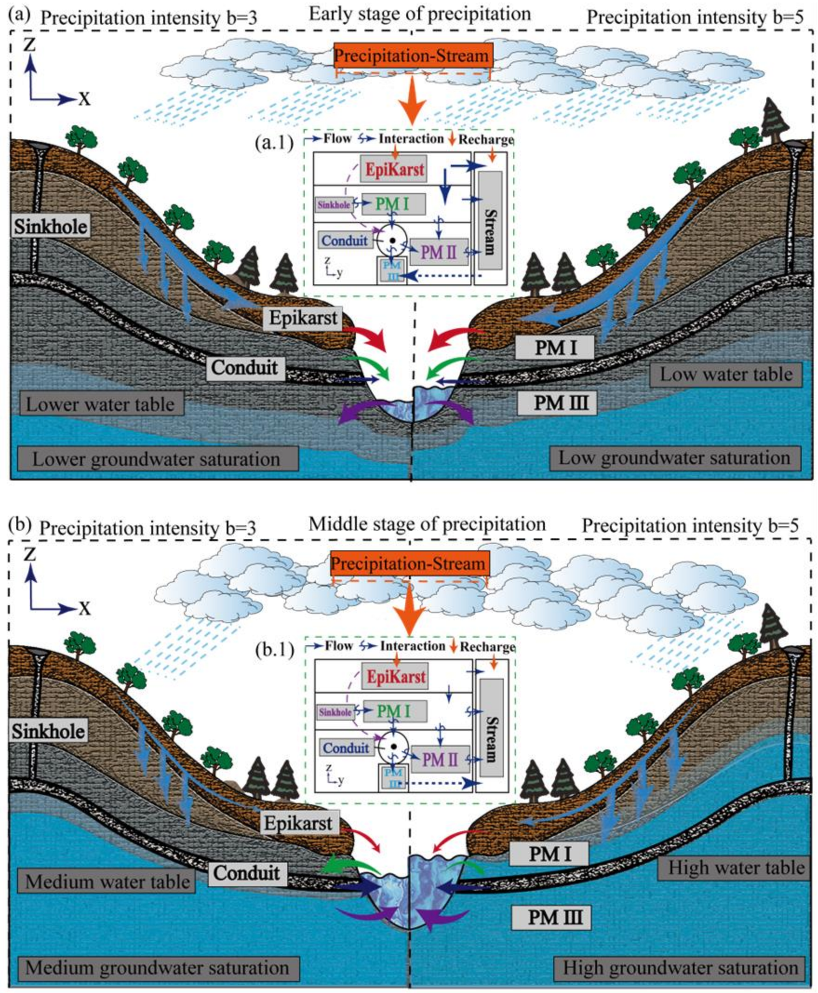

Figure 1. Schematic diagrams of the modelling of the interaction between the karst aquifer (epikarst, sinkhole, karst conduit, PM I, PM II, and PM III) and stream under dimensionless precipitation intensities (b = 3 and b = 5). (a) and (a.1) Schematic diagram of the interaction flow between each medium 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.”