April 3, 2026

*Hydrology and Earth System Sciences*

**Re: Revised Manuscript Preprint egusphere-2025-5651 (Quantification of Delayed Recharge by Soil Surface and Riverbed Infiltration in a Deep Groundwater Depression Zone in the North China Plain)**

## Replies to Reviewer Dr. Nima Zafarmomen:

### General Comments

*The paper addresses an important and very topical problem: delayed recharge in deep vadose zones within a major groundwater depression cone in the North China Plain, comparing precipitation-fed vs riverbed recharge using HYDRUS-1D plus borehole lithology. The regional perspective and explicit focus on lag times and percolation velocities are valuable and fit well within hydrology / groundwater journals. I recommend it for publication after considering below comments.*

**Response**: We sincerely thank the reviewer for the positive evaluation and the encouraging summary of our work. We appreciate your recognition of the importance of this study regarding delayed recharge in the deep vadose zones of the North China Plain. We have carefully considered all the specific comments provided below and have incorporated the necessary revisions into the manuscript to further improve its quality. Below is an itemized list of all comments (in italics) and our responses. Revisions within the (marked) manuscript are indicated in track-changed mode.

### Specific Comments

*1. You currently equate "recharge efficiency" mostly with higher percolation velocity and shorter lag time, but sometimes imply it means larger recharge volume. Please give a clear, formal definition early in the paper and stick to it. When you say riverbed recharge is ~4.1× higher "per unit area", clarify this is based on velocity, not on simulated recharge flux volume, or explicitly compute and show fluxes.*

**Response 1**: We sincerely thanks for pointing out the ambiguity regarding the term "recharge efficiency". We agree that a formal definition is necessary to distinguish between the velocity of the process and the total recharge volume. Thus, we have made the following revisions to address this comment:

1) We have added a clear definition of "recharge efficiency" in the Introduction section. We have explicitly defined it as the average percolation velocity (which corresponds to a shorter lag time), to strictly distinguish it from the total recharge volume or flux.

2) In the Discussion section, we have clarified that the statement “4.1 times higher” refers to the recharge rate based on average percolation velocities, not the total simulated flux volume.

Therefore, in the revised manuscript, we have made it clear in the Abstract that:

> “Riverbed recharge was markedly faster, averaging 91 days, indicating higher infiltration efficiency than precipitation under equivalent lithological conditions.”

We have also made it clear on Page 27, Section 4.2 of the revised manuscript:

> “Based on these percolation velocities, the per-unit-area recharge efficiency from riverbed is approximately 4.1 times higher. Thus, despite its limited areal coverage, riverbed infiltration serves as a more efficient recharge approach in terms of vertical percolation velocities.”

*2. Key modeling choices—uniform initial head (–50 cm), 1D vertical flow only, and no root uptake for riverbed cases—are reasonable but need clearer justification. Explain that the long spin-up minimizes sensitivity to the initial profile and that omitting ET in riverbeds makes the riverbed scenario optimistic. Also acknowledge that lateral flow, preferential flow, and riverbed clogging are not represented and discuss qualitatively how this may bias lag times.*

**Response 2:** Thank you for highlighting the need to better justify our modeling assumptions and discuss their implications. We agree that while these simplifications are standard for regional-scale vadose zone modeling, their potential biases should be explicitly addressed. We have revised the manuscript in the “Methods” and “Discussion” sections to address these points and these additions provide a balanced and transparent interpretation of the model’s capabilities and limitations.

1) Regarding the justification for using a uniform initial head (-50 cm), we have clarified that the 6-year spin-up period (2016-2022) was specifically implemented to minimize the sensitivity of the simulation results to this uniform initial pressure head. We have added a new figure (Figure B in the Appendix B.) that displays the temporal evolution of soil water content at deep layers (20-80 m) for all boreholes during the spin-up period. As shown in the Figure B, the soil water content at these depths exhibited initial fluctuations during the first 1-2 years and subsequently reached a dynamic equilibrium state driven by the surface boundary conditions, rather than the initial settings. On page 13, Section 2.3.5 of the revised manuscript, we made it clear that:

“An initial pressure head of *h* = -50 cm was uniformly assigned to the unsaturated zone as a predefined condition. To ensure that the subsequent groundwater recharge analysis was not affected by this arbitrary starting value, it was necessary to include a sufficiently long model spin-up period (Jie et al., 2022). Accordingly, the model spin-up spanned from July 1, 2016 to July 31, 2022, enabling the soil water distribution to reach a dynamic equilibrium with the meteorological boundaries and hydrogeological conditions. To verify this equilibrium state, we analyzed the time series of deep soil water content (observation depths from 20 m to 80 m) calculated during the spin-up period. As shown in Figure B, the soil water content at these depths exhibited initial fluctuations during the first 1-2 years and subsequently reached a stable dynamic equilibrium driven by the surface boundary conditions, completely independent of the initial settings. Following this spin-up period, the actual groundwater recharge analysis commenced on August 1, 2022.”

**“Appendix B. Model Spin-up Process and Initial Condition Calibration.**

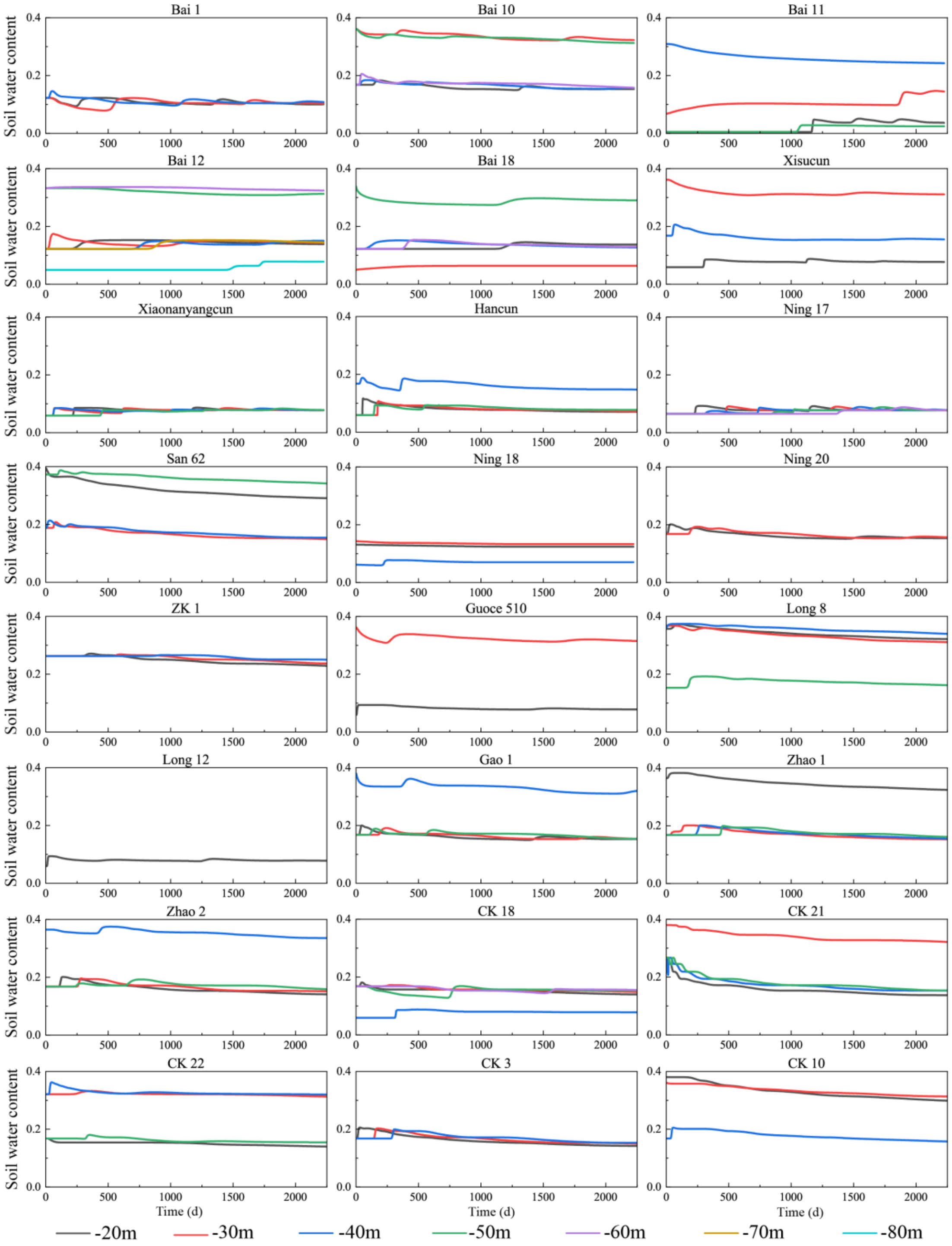

**Figure B: Temporal variation of deep vadose zone soil water content during model spin-up period.”**

2) Regarding your comment that omitting root water uptake makes the riverbed scenario optimistic, we completely agree. In the revised manuscript, we have explicitly acknowledged this assumption and have added an explanation that neglecting this process in the riverbed scenario provides an upper bound estimate of recharge efficiency. On Page 12, Section 2.3.4 of the revised manuscript, we have made it clear that:

“By omitting root water uptake, the model maximizes the water available for downward percolation, which contributes to an upper-bound estimation of infiltration volumes and percolation velocities for riverbed recharge.”

3) Regarding your recommendation to discuss potential biases from unrepresented processes (lateral flow, preferential flow, and riverbed clogging), we have added a new paragraph in the Discussion section (Section 4.3) to qualitatively analyse the biases introduced by 1-D flow, preferential flow, and riverbed clogging. We explicitly acknowledge that our 1-D model assumes uniform matrix flow and static riverbed conditions, which might introduce specific biases to the simulated lag times. Specifically, omitting preferential flow (e.g., through macropores or fractures) likely leads to an overestimation of lag times, as preferential pathways would allow water to bypass the soil matrix and reach the aquifer much faster. Conversely, omitting riverbed clogging likely leads to an underestimation of lag times. Finally, ignoring lateral flow might also result in an underestimation of true travel times, as lateral dispersion extends the actual flow paths. Therefore, we have incorporated detailed explanations into the revised manuscript. On Page 28, Section 4.3 of the revised manuscript, we have made it clear that:

“Thirdly, certain simplifications in the model structure may introduce biases into the calculated lag times. Specifically, our model does not account for three complex processes, i.e., preferential flow, dynamic riverbed clogging, and lateral flow. For instance, the assumption of homogeneous matrix flow omits preferential flow paths (e.g., macropores or fractures). Since these pathways allow water to rapidly bypass the soil matrix, neglecting them means our simulated lag times are likely overestimated (i.e., actual recharge is faster) (Li et al., 2025). Additionally, the model assumes static soil hydraulic properties, neglecting dynamic riverbed clogging (such as physical sedimentation). Because clogging typically reduces surface permeability over time, omitting this process likely leads to an underestimation of the true lag times for riverbed recharge. Furthermore, the HYDRUS-1D model is restricted to strictly vertical flow, neglecting lateral fluxes. As highlighted by recent comprehensive studies, the limitations of strictly 1D conceptualizations become significantly more pronounced in highly heterogeneous domains (Fan et al., 2019; Chen et al., 2022). Particularly in our study area, when infiltrating water encounters low-permeability stratigraphic interfaces at depth (e.g., clay layers), temporary perched conditions can induce localized lateral redistribution (Vereecken et al., 2019). In reality, this lateral flow extends the travel path of infiltrating water, suggesting that our strictly 1D simulation may underestimate the actual lag times (Isch et al., 2022). However,

> implementing a multi-dimensional (2D/3D) model requires detailed data on horizontal stratigraphic continuity, which is rarely available at the regional scale and could introduce substantial uncertainty. Besides, the flat topography and deep water tables across the North China Plain result in a vertical hydraulic gradient that far exceeds horizontal gradients. Previous modeling and field studies have successfully demonstrated that 1D vertical flow effectively captures the dominant mechanisms controlling groundwater recharge through the thick vadose zone in this region (Huo et al., 2014; Min et al., 2015; Cao et al., 2016). Consequently, despite potential biases, we ultimately chose the HYDRUS-1D model as the robust and practical approach for simulating regional recharge dynamics in this study."

*3. IDW interpolation of 24 points over ~2,000 km² is appropriate for a first-order picture but provides no uncertainty and may be weak where points are sparse. Clarify that maps of infiltration time and velocity should be interpreted qualitatively, especially in poorly constrained regions. Briefly justify the choice of IDW over kriging (e.g., limited data for robust variogram fitting) and mention this as a limitation.*

**Response 3:** We appreciate the reviewer's insightful comment regarding the spatial interpolation method. We acknowledge that with a limited dataset (num = 24), the resulting maps serve primarily as a regional trend. Specifically, on Page 14, Section 2.4 of the revised manuscript, we have made it clear that:

> "Given the limited number of observation points (num = 24) distributed over the 2,092 km$^2$ study area, robust variogram fitting required for Kriging interpolation was not feasible (Oliver and Webster, 2014)."

On Page 20, Section 3.2.2 of the revised manuscript, we have added a clarification stating that:

> "It is important to note that due to the sparse density of observation points, these interpolated maps should be interpreted qualitatively as indicators of general regional gradients rather than precise local predictions, particularly in areas poorly constrained by borehole data."

On Page 29, Section 4.3 of the revised manuscript, we have clarified that:

> "For the same reason, while IDW interpolation provided a useful spatial representation of recharge patterns, it did not quantify estimation errors. Consequently, the prediction accuracy may be lower in regions where sampling points are sparse."

*4. The constant-head lower boundary at the long-term average groundwater level is a strong simplification in a declining groundwater system and likely underestimates true lag times.*

*Justify this assumption more clearly and discuss its effect on results; a short sensitivity discussion would help. Similarly, using a single rainfall station and a single river stage series for the whole area needs explicit justification and acknowledgement of added uncertainty.*

**Response 4:** We thank the reviewer for identifying these critical simplifications regarding the boundary conditions and forcing data. We agree that these assumptions require explicit justification and a discussion of their implications. We have revised the manuscript to address these concerns as follows:

Considering that the actual groundwater level in the North China Plain is constantly changing, we agree that assuming a constant groundwater level is a simplification. We therefore have made it clear on Page 11, Section 2.3.3 of the revised manuscript:

> "Since the groundwater levels fluctuate over time and depend on the volume of infiltration recharge from surface water, incorporating a time-variable lower boundary would indeed provide a more realistic representation of the simulations. However, due to the inherent uncertainties in future precipitation conditions and the primary focus of this study on the impact of vadose zone characteristics on the infiltration process, a constant lower boundary was assumed for model simplification (Šimůnek et al., 2016). Consequently, a constant pressure head condition was applied to the lower boundary in both scenarios, using the average groundwater level from January 1, 2018 to December 31, 2023 as a fixed reference depth for calculating groundwater infiltration times and velocity."

Regarding the comment "using a single rainfall station and a single river stage series for the whole area", we have added text to explicitly justify the use of single-station data on Page 11, Section 2.3.3 of the revised manuscript:

> "Within the study area, precipitation data were exclusively obtained from the Baixiang Rain Gauge Station. Given the relatively small spatial extent of the study area and the availability of continuous, long-term historical records at this station, the precipitation data from this station were utilized as the upper boundary input for all boreholes across the study area, covering the period from July 1, 2016 to July31, 2023. The river water level data were obtained from the hydrological stations near the Bai 11, Hancun, and Guoce 510 boreholes during the flood season from July to August 2016, and then applied the same average water level data from these stations to simulate the riverbed infiltration to all the boreholes that are not close to the river.
>
> Data from the single rain gauge station and the averaged river stage time series were utilized as consistent inputs for the regional simulations due to the high continuity of their observational records. Furthermore, applying these uniform upper boundary conditions

> across the entire region effectively controlled for meteorological variations, thereby isolating and highlighting the primary influence of vadose zone characteristics on infiltration recharge.”

*5. I strongly recommend to discuss the paper and deepen your discussion “Assimilation of sentinel‐based leaf area index for modeling surface‐ground water interactions in irrigation districts”.*

**Response 5:** Thank you for the comments. We have carefully reviewed the recommended paper and agree that it offers critical insights into improving the representation of vegetation dynamics in hydrological modeling. We have integrated a discussion of this work into the Discussion section of the revised manuscript.

On Page 28, Section 4.3 of the revised manuscript, a more detailed explanation has been included as follows:

> “In addition to soil hydraulic parameters, the representation of vegetation dynamics plays a critical role in partitioning precipitation into infiltration and evapotranspiration. In this study, root water uptake was simulated using the default parameters and literature-based LAI values. However, recent advancements have demonstrated that the assimilation of high-resolution remote sensing data, such as Sentinel-based LAI, can significantly enhance the modelling of surface water-groundwater interactions, particularly in agricultural irrigation districts (Zafarmomen et al., 2024). These studies highlight that incorporating dynamic, spatially distributed vegetation data by relying on data assimilation frameworks can effectively reduce uncertainties in evapotranspiration estimation and, consequently, improve the accuracy of deep percolation and recharge fluxes. Future investigations could benefit from integrating field experiments for parameter calibration and adopting remote sensing assimilation techniques to refine upper boundary conditions, collectively enhancing the robustness of vadose zone modelling in similar hydrogeological settings.”

*6. The phrase “two infiltration modes were considered: precipitation-fed and riverbed infiltration” could be tightened to “precipitation-fed soil infiltration and riverbed infiltration”.*

**Response 6:** Thank you for the comments. We have modified the phrase in the Abstract exactly as suggested.

On Page 1, in the Abstract of the revised manuscript, we make it clear that:

> “Two infiltration modes, precipitation-fed soil infiltration and riverbed infiltration, were considered.”

*7. When mentioning the regression equations, briefly state the key predictors (vadose zone thickness and particle fractions) to give the reader more context.*

**Response 7:** Thank you for the comments. We have revised the sentence to explicitly list the specific independent variables used in the regression analysis.

On Page 1, in the Abstract of the revised manuscript, we clarify that:

> “Regression equations were derived to predict percolation velocities using vadose zone thickness, sand fraction, and clay fraction as key predictors.”

*8. Some paragraphs are quite long and dense (e.g., lines 41–64, 85–110). Consider splitting into shorter paragraphs to improve readability.*

**Response 8:** Thank you for the comments, we have divided the relevant paragraphs into shorter ones to improve readability. On Page 2, Introduction of the revised manuscript, we have clarified that:

> “Extensive research has explored the principles of infiltration in the vadose zone based on the theory of unsaturated soil water movement. This theory governs how water infiltrates through partially saturated porous media under the influences of gravity and matric potential gradients (Assouline, 2013; Vereecken et al., 2019; Christine and Gerhard, 2022; Schübl et al., 2023; Gao et al., 2024). Consequently, these studies highlight the critical role that heterogeneities in soil lithology (soil texture), structure, and vadose zone depth can play in regulating infiltration rates, lag times, and overall recharge efficiency, particularly in overexploitation regions (Szabó et al., 2019; Turkeltaub et al., 2015).
>
> Among various surface inputs, precipitation-fed infiltration emerges as the primary driver of vadose zone and groundwater recharge, directly linking atmospheric inputs to subsurface hydrology through vertical percolation. For instance, Dafny and Šimůnek (2016) investigated layered loess deposits in Israel’s coastal plain. They calibrated van Genuchten parameters using a HYDRUS-2D/3D model informed by infiltration tests, confirming that saturated conductivities vary significantly across different soil lithologies. Employing HYDRUS-1D with 25-year meteorological data, they further demonstrated that vegetation reduces recharge through enhanced transpiration. Moreover, sediment layering caused lag times of 2.5-20 years for wetting fronts to reach a 22 m depth, emphasizing lithological control on infiltration efficiency in arid areas. Jie et al. (2022)

> quantified vadose zone thickness impacts on delayed recharge in Jingdian Irrigation District in Northwest China using HYDRUS-1D. Their simulations revealed a linear lag increases (up to 5,000 days for depths >8 m). Consequently, overall recharge rates were significantly reduced as the vadose zone thickness increased.
>
> Extending this perspective to global scales, Moeck et al. (2024) assessed groundwater recharge responses to monthly-decadal infiltration variability using an analytical solution of the Richards equation. They found that vadose zones dampen short-term fluctuations globally, with lags exceeding years in arid regions and transient recharge driven by multi-annual cycles such as ENSO. As depth increases, the correlation between infiltration and recharge weakens. More recently, Yin et al. (2025) utilized GRACE data and wavelet transforms to analyze precipitation-fed recharge from Heilongjiang Basin in China. They identified dominant 1-2 year cycles with lags of 2-6 months in plain areas. These hydrological responses are heavily modulated by topography and soil type, highlighting an accelerated dynamic under climate change."

On Page 3, Introduction of the revised manuscript, we have clarified that:

> "In general, research on groundwater recharge has primarily focused on vertical infiltration into the vadose zone. Widely used methods for evaluating infiltration recharge volumes include physical methods (e.g., Racz et al., 2012; Ganot et al., 2017), tracer methods (e.g., Wang et al., 2024), and mathematical models (e.g., Vereecken et al. 2019; Šimůnek et al., 2012; Arnold et al., 2012). A comprehensive overview of mathematical models for infiltration processes was provided by Vereecken et al. (2019). These models range from empirical approaches, such as the Kostiakov equation (1932) and Horton equation (1941) to analytical solutions such as the Green-Ampt (1911) and Philip (1957) models. Importantly, they emphasized the Richards equation as the fundamental framework for unsaturated flow. This framework incorporates essential soil hydraulic properties such as the water retention curve $\theta(h)$ (e.g., Brooks and Corey, 1964; van Genuchten, 1980) and hydraulic conductivity $K(h)$. For complex, real-world infiltration problems (e.g., layered soil profiles, variable initial saturation, time-variable rainfall, and limited ponding), quantitative analysis is typically achieved through numerical solutions of the Richards equation.
>
> Leveraging computational advances over the past decades, several software codes have been developed to simulate vadose zone infiltration and groundwater recharge dynamics by numerically solving the Richards equation and related processes. Well-known methods include HYDRUS (Šimůnek et al., 2012, 2016, 2024), SWAP (Van Dam et al. 2008;

> Kroes and Supit 2011), and SWMS (Li et al., 2019). Among these, HYDRUS-1D is a one-dimensional soil water model that comprehensively accounts for precipitation, vegetation water uptake, evaporation, soil water movement, and groundwater table fluctuations (Assefa and Woodbury, 2013; Stafford et al., 2022; Dadgar et al., 2018).
>
> The practical utility of HYDRUS-1D has been demonstrated across various spatial scales and environmental conditions. For instance, Assefa and Woodbury (2013) integrated field observations with HYDRUS-1D to model transient, spatially varied groundwater recharge in North Okanagan, Canada. Coupled with ArcGIS, the model produced recharge maps for the Deep Creek watershed, estimating average recharge at 77.8 ± 50.8 mm year$^{-1}$ over 25 years, with significant spatiotemporal variability. More recently, Wolf et al. (2022) advanced the understanding of recharge mechanisms in thick vadose zones (14-38 m) under varying land use/land cover and climate conditions. By calibrating HYDRUS-1D models using monitoring data from the High Plains aquifer, they suggested that land use/land cover is a major controlling factor. In addition, they found that irrigated sites exhibited relatively short lag times of 20-24 months, contrasting sharply with extended lags of 5-31 years at rangeland sites. Combined these studies show that HYDRUS-1D is a valuable tool for quantifying recharge rates and time-delay of deep-vadose zone groundwater under a wide spectrum of environmental conditions."

*9. When you review past work (HYDRUS applications, global lag studies), explicitly state the remaining gap you are addressing (combined effect of deep vadose zones, complex lithology, and 'comparison of two recharge sources under identical profiles)'. You do this, but it could be more sharply framed at the end of the Introduction.*

**Response 9:** Thank you for the comments. We have rephased the paragraph at the end of the Introduction to explicitly state the gap regarding the combined effects of lithology and depth, and the lack of comparisons under identical profiles.

On Page 5, in the Introduction of the revised manuscript, we have made it clear that:

> "Despite the fact that there have been substantial advances in the quantification of precipitation-fed groundwater recharge, few efforts have addressed the challenges in areas with deepening groundwater levels and complex vadose zone lithology. In such areas, groundwater recharge takes much longer due to delayed water percolation through thick variable unsaturated zones, yet few studies have explicitly quantified the resulting lag times and percolation velocities. More importantly, existing studies have analysed precipitation infiltration and riverbed infiltration independently. Consequently, systematic

> comparison of their recharge efficiencies under identical vadose zone conditions remain scarce, particularly in terms of infiltration times and rates across heterogeneous vadose zones."

*10. It might be helpful to explicitly mention average annual precipitation and reference ET, if available, to characterize the climate quantitatively.*

**Response 10:** Thank you for the comments. We have added the long-term average precipitation and evaporation data to Section 2.1 Study Area.

On Page 6, Section 2.1 of the revised manuscript, we have made it clear that:

> "The region lies at the junction of the Taihang Mountains and the North China Plain, characterized by a temperate semi-humid to semi-arid continental monsoon climate, with an annual average precipitation of 540 mm and an annual average potential evaporation of 1,600 mm."

*11. The description of boundaries (Taihang Mountains, Shijiazhuang, Hengshui) is good, but consider adding one sentence stating dominant land use (e.g., double cropping, wheat–maize rotation) to connect with the root uptake assumptions.*

**Response 11:** Thank you for the comments. We have added a description of the dominant cropping system to Section 2.1 (Study Area), on Page 5, Section 2.1 of the revised manuscript, we have made it clear that:

> "The Ningbailong shallow groundwater depression zone is located in Xingtai City, Hebei Province, China, as shown in Figure 1, within one of the main grain-producing regions in the NCP, where a double-cropping rotation of winter wheat and summer maize is the dominant cropping system."

*12. "Depth (cm)" is given for boreholes, but values like 8,080 cm (= 80.8 m) etc. Make clear that these are vadose zone thicknesses down to shallow groundwater table or borehole depth; the phrase "Depth (cm)" is ambiguous.*

**Response 12:** Thank you for the comments. We clarify that the values listed in Table 1 represent the thickness of the vadose zone rather than the total depth of the borehole and added an explanatory note to the caption of Table 1.

On Page 7, Section 2.2 of the revised manuscript, we have made it clear that:

> "In Table 1, the "Infiltration Mode" column uses "P" or "R" to respectively indicate that the well is currently receiving precipitation-fed or riverbed infiltration, and "Depth" represents the vadose zone thickness."

*13. You might add a column indicating vadose zone thickness vs. total borehole depth if they differ.*

**Response 13:** Thank you for the comments. Since the focus of this study is on vadose zone infiltration and recharge, the "Vadose Zone Thickness" is the critical parameter. As detailed in our response to the previous comment, we have explicitly clarified in the caption of Table 1 that the listed "Depth" refers specifically to the vadose zone thickness. We believe this clarification effectively removes the ambiguity regarding the vertical dimension used in our models.

**References:**

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Zafarmomen, N., Alizadeh, H., Bayat, M., Ehtiat, M., and Moradkhani, H.: Assimilation of Sentinel-based leaf area index for modeling surface–ground water interactions in irrigation districts, *Water Resour. Res.*, 60, e2023WR036080, https://doi.org/10.1029/2023WR036080, 2024.

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*Hydrology and Earth System Sciences*

**Re: Revised Manuscript Preprint egusphere-2025-5651 (Quantification of Delayed Recharge by Soil Surface and Riverbed Infiltration in a Deep Groundwater Depression Zone in the North China Plain)**

## Replies to Reviewer Anonymous Referee #1:

### General Comments

*In this paper, the authors present a solid and well-structured study addressing an important issue in groundwater sustainability in the North China Plain. The use of HYDRUS-1D to analyze recharge delays in thick vadose zones is appropriate and well justified. In addition, the comparison of recharge efficiency and time lag under identical vadose zone conditions for two distinct recharge modes is novel and provides clear practical relevance for managed aquifer recharge (MAR) planning in groundwater depression zones. The results, as currently presented, also seem reasonable. I encourage the authors to further extend their analysis to address several concerns and questions that other readers may also raise regarding the flexibility of the approach and the range of conditions under which the method can be reliably applied. My main concerns are summarized as follows.*

**Response**: We sincerely thank the reviewer for the encouraging evaluation of our work. We appreciate your constructive suggestion to further extend the analysis regarding the flexibility and applicability range of our method. We have carefully considered the concerns below and have incorporated additional analyses and discussions into the revised manuscript to address the robustness of our approach under varying conditions. Please see our point-by-point responses below.

### Specific Comments

*1. The authors clearly highlight heterogeneity in horizontal boundary conditions across the North China Plain (Table 1), where some locations are characterized by precipitation–evaporation–infiltration processes, while others are governed by constant-head riverbed infiltration. At the same time, strong vertical heterogeneity in soil types is emphasized (Figure 2). Given these heterogeneities, it is not fully clear whether a purely one-dimensional modeling framework can adequately resolve the dominant flow processes. For example, when infiltrating water encounters low-permeability layers at depth, lateral flow along stratigraphic interfaces may occur. Such lateral redistribution could potentially influence infiltration times and recharge efficiency. Under these heterogeneous horizontal boundary conditions, lateral soil water flow may not be negligible, unlike in traditional large-scale studies where lateral flow is* *often assumed to be insignificant. The manuscript would therefore benefit from a discussion of the potential magnitude of lateral flow and its implications, as neglecting horizontal flow may limit the applicability of a one-dimensional approach in settings with heterogeneous boundary conditions.*

**Response 1:** We sincerely thank the reviewer for this insightful comment regarding the dimensionality of our modelling approach. We fully agree that lateral redistribution, particularly in heterogeneous domains, is a critical process that is simplified in our 1D framework. To address this, we have added a paragraph in the Discussion section to explicitly analyse the implications and potential magnitude of this simplification, supported by comparative literature between 1D and 2D models. We believe this expanded discussion provides a balanced view of the model's limitations and justifies the applicability of HYDRUS-1D for the study's objectives.

On Page 28, Section 4.3 of the revised manuscript, we have added a clarification stating that:

> "Thirdly, certain simplifications in the model structure may introduce biases into the calculated lag times. Specifically, our model does not account for three complex processes i.e., preferential flow, dynamic riverbed clogging, and lateral flow.
>
> …
>
> Furthermore, the HYDRUS-1D model is restricted to strictly vertical flow, neglecting lateral fluxes. As highlighted by recent comprehensive studies, the limitations of strictly 1D conceptualizations become significantly more pronounced in highly heterogeneous domains (Fan et al., 2019; Chen et al., 2022). Particularly in our study area, when infiltrating water encounters low-permeability stratigraphic interfaces at depth (e.g., clay layers), temporary perched conditions can induce localized lateral redistribution (Vereecken et al., 2019). In reality, this lateral flow extends the travel path of infiltrating water, suggesting that our strictly 1D simulation may underestimate the actual lag times (Isch et al., 2022). However, implementing a multi-dimensional (2D/3D) model requires detailed data on horizontal stratigraphic continuity, which is rarely available at the regional scale and could introduce substantial uncertainty. Besides, the flat topography and deep water tables across the North China Plain result in a vertical hydraulic gradient that far exceeds horizontal gradients. Previous modeling and field studies have successfully demonstrated that 1D vertical flow effectively captures the dominant mechanisms controlling groundwater recharge through the thick vadose zone in this region (Huo et al., 2014; Min et al., 2015; Cao et al., 2016). Consequently, despite potential biases, we

> ultimately chose the HYDRUS-1D model as the robust and practical approach for simulating regional recharge dynamics in this study.”

*2. Equations (2) – (6) describe the van Genuchten–Mualem constitutive relationships. However, the formulation appears inconsistent in places, and some parameters (e.g., $\theta_s$ and $\theta_r$) are not clearly defined when first introduced. Clarifying the parameter definitions and ensuring consistency with standard van Genuchten notation would improve transparency and reproducibility.*

**Response 2:** Thank you for your careful review of the mathematical formulation. We utilized the modified van Genuchten-Mualem model as proposed by Vogel et al. (2000), which is implemented in HYDRUS-1D to improve numerical convergence near saturation by introducing a small air-entry pressure head ($h_s$). We have revised Section 2.3.2 to present the complete set of equations for these modified equations (Equations 2-7 in the revised manuscript) and explicitly defined all parameters immediately following their introduction to ensure clarity and reproducibility.

On Page 10, Section 2.3.2 of the revised manuscript, we have made it clear that

> “The soil hydraulic properties were described by the modified van Genuchten model (van Genuchten, 1980; Vogel et al., 2001). The soil water retention characteristic $\theta(h)$ and hydraulic conductivity $K(\theta)$ are given by:
>
> $$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_m-\theta_r}{\left[1+(\alpha h)^n\right]^m}, & h<h_s\\ \theta_s, & h\geq h_s\end{cases} \tag{2}$$
>
> $$K(h)=\begin{cases}K_sK_r(h), & h<h_s\\ K_s, & h\geq h_s\end{cases} \tag{3}$$
>
> $$K_r(S_e)=S_e^l\left[\frac{1-F(S_e)}{1-F(1)}\right]^2 \tag{4}$$
>
> $$F(S_e)=\left[1-(S_e^*)^{1/m}\right]^m \tag{5}$$
>
> $$S_e(h)=\frac{\theta(h)-\theta_r}{\theta_s-\theta_r} \tag{6}$$
>
> $$S_e^*=\frac{\theta_s-\theta_r}{\theta_m-\theta_r}S_e \tag{7}$$
>
> where $\theta_r$ represents the residual soil water content (cm$^3$ cm$^{-3}$), $\theta_s$ indicates the saturated water content (cm$^3$ cm$^{-3}$), $\alpha$, $n$, and $m$ are empirical parameters, whereby $m$ can be related to $n$ by $m$=1-1/$n$, $\theta_m$ represents the fictitious saturated water content slightly larger than $\theta_s$,

> acting purely as a mathematical artifact to maintain the smooth analytical shape of the retention curve, $h_s$ is the air-entry pressure head (cm) used to improve numerical stability near saturation, $K_s$ is the saturated hydraulic conductivity (cm $d^{-1}$), $K(h)$ represents the unsaturated hydraulic conductivity (cm $d^{-1}$) at the pressure head $h$, $K_r$ represents the relative hydraulic conductivity (-), $l$ is the pore connectivity parameter usually assumed to be 0.5, $S_e$ is the effective saturation (-), and $Se^*$ is the fictitious effective saturation (or scaled effective saturation), normalized by the fictitious saturated water content ($\theta_m$)."

*3. The terms "infiltration time" or "recharge time" are used throughout the manuscript. I recommend explicitly defining these quantities early in the Methods section, preferably in mathematical form, and using the terminology consistently thereafter to avoid ambiguity.*

**Response 3:** Thank you for the comments. To avoid any ambiguity, we have explicitly defined this quantity in mathematical form in the Methods section (Section 2.4). Furthermore, we have standardized the terminology throughout the revised manuscript. We now consistently use the term "infiltration time" ($T_{inf}$) and "average percolation velocity" ($V_{perc}$). Specifically, the following definitions have been added to Section 2.4 of the revised manuscript

> "In the simulations, the infiltration process was deemed to have reached the groundwater table when initial outflow occurred at the bottom boundary of the soil profile. This duration is formally defined as the infiltration time ($T_{inf}$), expressed as $T_{inf} = t_{\text{outflow}} - t_{start}$, where $t_{start}$ is the timestamp when the initial surface recharge event starts, and $t_{\text{outflow}}$ is the timestamp when outflow is first recorded at the profile base.
>
> Furthermore, to allow for a fair comparison between different vadose zone thicknesses ($L$), we calculated the average percolation velocity ($V_{perc}$) as the ratio of the vadose zone thickness to the infiltration time, i.e., $V_{perc} = L/T_{inf}$."

Additionally, to ensure strict consistency, we have conducted a global replacement throughout the revised manuscript.

On Page 5, in the Introduction of the revised manuscript:

> "More importantly, existing studies have analysed precipitation infiltration and riverbed infiltration independently. Consequently, systematic comparison of their recharge efficiencies under identical vadose zone conditions remain scarce, particularly in terms of infiltration times and rates across heterogeneous vadose zones."

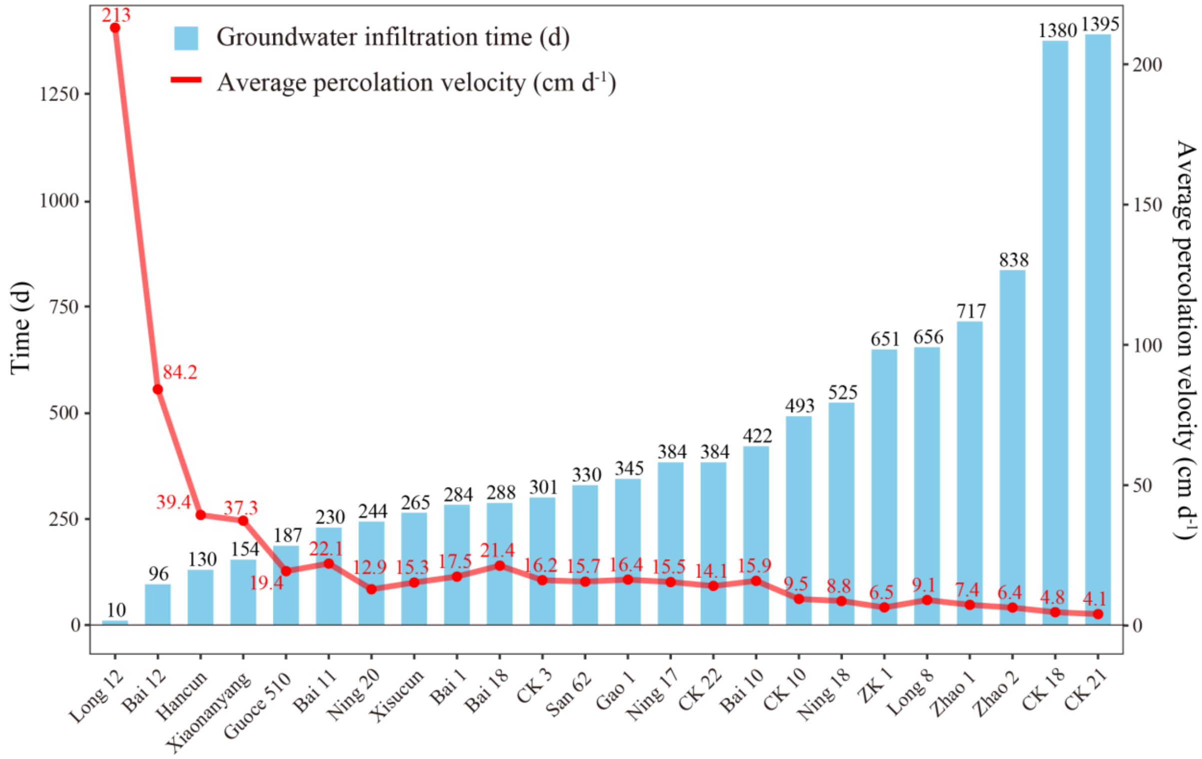
On Page 5, in the Introduction of the revised manuscript:

> “The main objectives of this paper are to: (1) quantitatively assess the groundwater infiltration times and percolation velocities under two recharge regimes (i.e., precipitation-fed infiltration and riverbed infiltration), using measured borehole lithological data and hydrometeorological observations from the Ningbailong groundwater depression zone;”

We have also made it clear on Page 16, Section 3.2.1 of the revised manuscript:

> “Simulations of the infiltration process under precipitation recharge conditions using the HYDRUS-1D model yielded estimates of groundwater infiltration times and average percolation velocities at borehole locations across the study area (Figure 5).”

On Page 18, Section 3.2.1 of the revised manuscript:

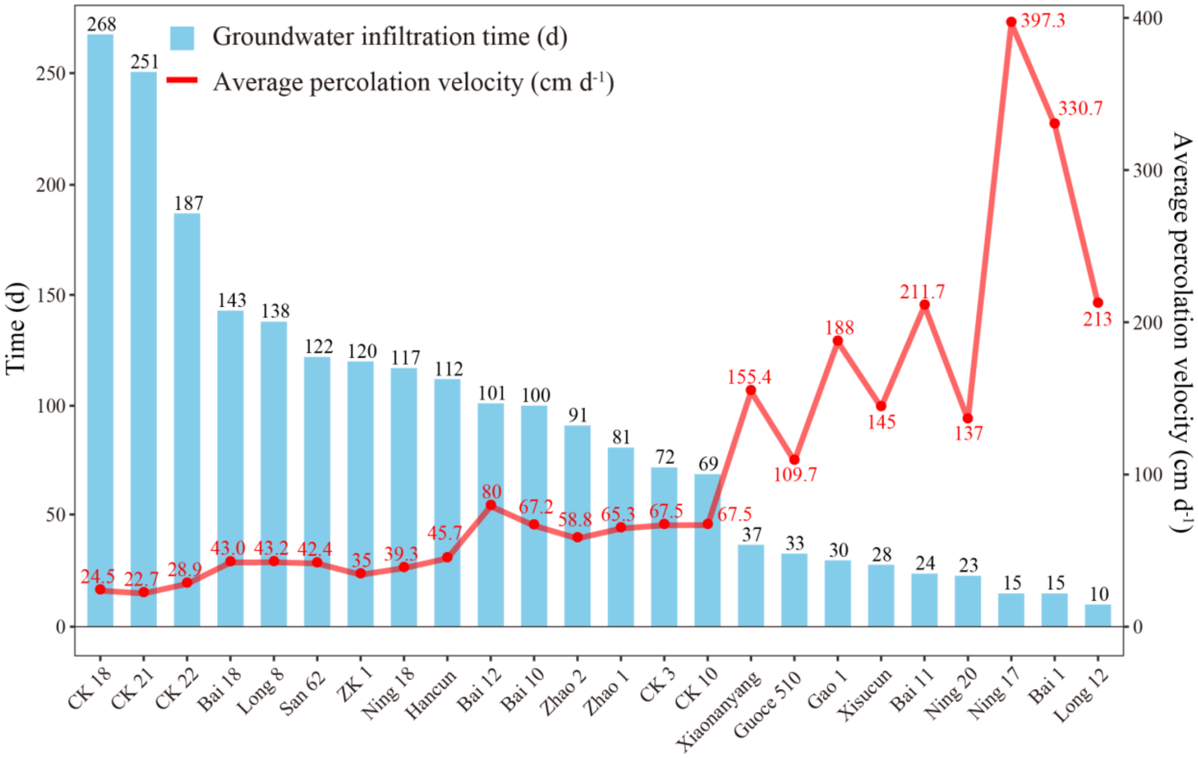


> “Figure 5: Groundwater infiltration time (d) and average percolation velocity (cm $d^{-1}$) for locations under precipitation infiltration recharge scenarios.”

On Page 22, Section 3.3 of the revised manuscript:

> “Figure 8 illustrates the groundwater infiltration time and average percolation velocity at borehole locations across the study area under riverbed recharge conditions.”

On Page 24, Section 3.3 of the revised manuscript:



> "Figure 8: Groundwater infiltration time (d) and average percolation velocity (cm $d^{-1}$) for locations under riverbed infiltration recharge scenarios."

On Page 25, Section 3.3 of the revised manuscript:

> "These comparisons enabled to assess the recharge efficiency and highlight the differences in infiltration time and spatial scope between the two conditions."

On Page 30, in the Conclusions of the revised manuscript:

> "In contrast, riverbed infiltration is markedly faster and more concentrated, with average infiltration times of 91 days and percolation velocity of 109.1 cm $d^{-1}$ under equivalent lithological conditions, highlighting its superior efficacy for rapid groundwater recovery."

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Chen, L., Šimůnek, J., Bradford, S. A., Ajami, H., and Meles, M. B.: A computationally efficient hydrologic modeling framework to simulate surface–subsurface hydrological processes at the hillslope scale, *J. Hydrol.*, 614, 128539, https://doi.org/10.1016/j.jhydrol.2022.128539, 2022.

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Zafarmomen, N., Alizadeh, H., Bayat, M., Ehtiat, M., and Moradkhani, H.: Assimilation of Sentinel-based leaf area index for modeling surface–ground water interactions in irrigation districts, *Water Resour. Res.*, 60, e2023WR036080, https://doi.org/10.1029/2023WR036080, 2024.

April 3, 2026

*Hydrology and Earth System Sciences*

**Re: Revised Manuscript Preprint egusphere-2025-5651 (Quantification of Delayed Recharge by Soil Surface and Riverbed Infiltration in a Deep Groundwater Depression Zone in the North China Plain)**

## Replies to Reviewer Anonymous Referee #2:

### General Comments

*This manuscript investigates the mechanisms of soil water movement and groundwater recharge in the North China Plain, a region facing significant water scarcity issues. The authors employ numerical simulations combined with multiple regression analysis to quantify the influence of vadose zone thickness, soil texture (clay and sand fractions), and lithology on percolation velocities and recharge rates. The study compares different infiltration modes (such as precipitation vs. managed aquifer recharge/riverbed infiltration) and aims to provide theoretical support for sustainable groundwater extraction and crop production. The topic is highly relevant to regional water resources management and addresses a pressing global concern regarding aquifer depletion. But there are significant methodological concerns that must be addressed to ensure the validity of the results.*

**Response**: We sincerely thank the reviewer for recognizing the value and relevance of our study to regional and global groundwater management. To address the methodological concerns and ensure the validity of our results, we have strengthened the justification for our methodology and improved the statistical rigor of our regression analysis. Please see our point-by-point responses below.

*1. Since measured initial soil water content was unavailable, the reliability of the simulation results depends heavily on the sufficiency of the spin-up period. It is unclear from the current text whether the spin-up period has made the initial state reached a dynamic equilibrium state, especially for deep soil layers. The authors should provide justification or graphical evidence (e.g., time series of soil water content or pressure head deeper than a certain depth at the profile) to demonstrate that the model achieved a robust equilibrium prior to the main simulation period.*

**Response 1:** We thank the reviewer for this critical comment regarding the initial conditions and the model spin-up. We fully agree that in the absence of measured initial profiles for such deep vadose zones, ensuring a sufficient spin-up period is essential to eliminate the influence of the arbitrary initial setup (uniform pressure head of -50 cm). In the revised manuscript, we have provided additional evidence to justify the sufficiency of the 6-year spin-up period (July

2016 - July 2022). Specifically:

1) We have added a new figure (Figure B in the Appendix B.) that displays the temporal evolution of soil water content at deep layers (at intervals of 10 m from 20 m to 80m) for all boreholes during the spin-up period. As shown in Figure B, the pressure heads at these depths exhibited a rapid adjustment during the first 1-2 years and subsequently reached a dynamic equilibrium state driven by the surface boundary conditions, rather than the initial settings. On Page 13, Section 2.3.5 of the revised manuscript, we have made it clear that:

   "An initial pressure head of $h$ = -50 cm was uniformly assigned to the unsaturated zone as a predefined condition. To ensure that the subsequent groundwater recharge analysis was not affected by this arbitrary starting value, it was necessary to include a sufficiently long model spin-up period (Jie et al., 2022). Accordingly, the model spin-up spanned from July 1, 2016 to July 31, 2022, enabling the soil water distribution to reach a dynamic equilibrium with the meteorological boundaries and hydrogeological conditions. To verify this equilibrium state, we analyzed the time series of deep soil water content (observation depths from 20 m to 80 m) calculated during the spin-up period. As shown in Figure B, the soil water content at these depths exhibited initial fluctuations during the first 1-2 years and subsequently reached a stable dynamic equilibrium driven by the surface boundary conditions, completely independent of the initial settings. Following this spin-up period, the actual groundwater recharge analysis commenced on August 1, 2022."

2) On Page 35, we have added Appendix B. of the revised manuscript:

## **“Appendix B. Model Spin-up Process and Initial Condition Calibration.**

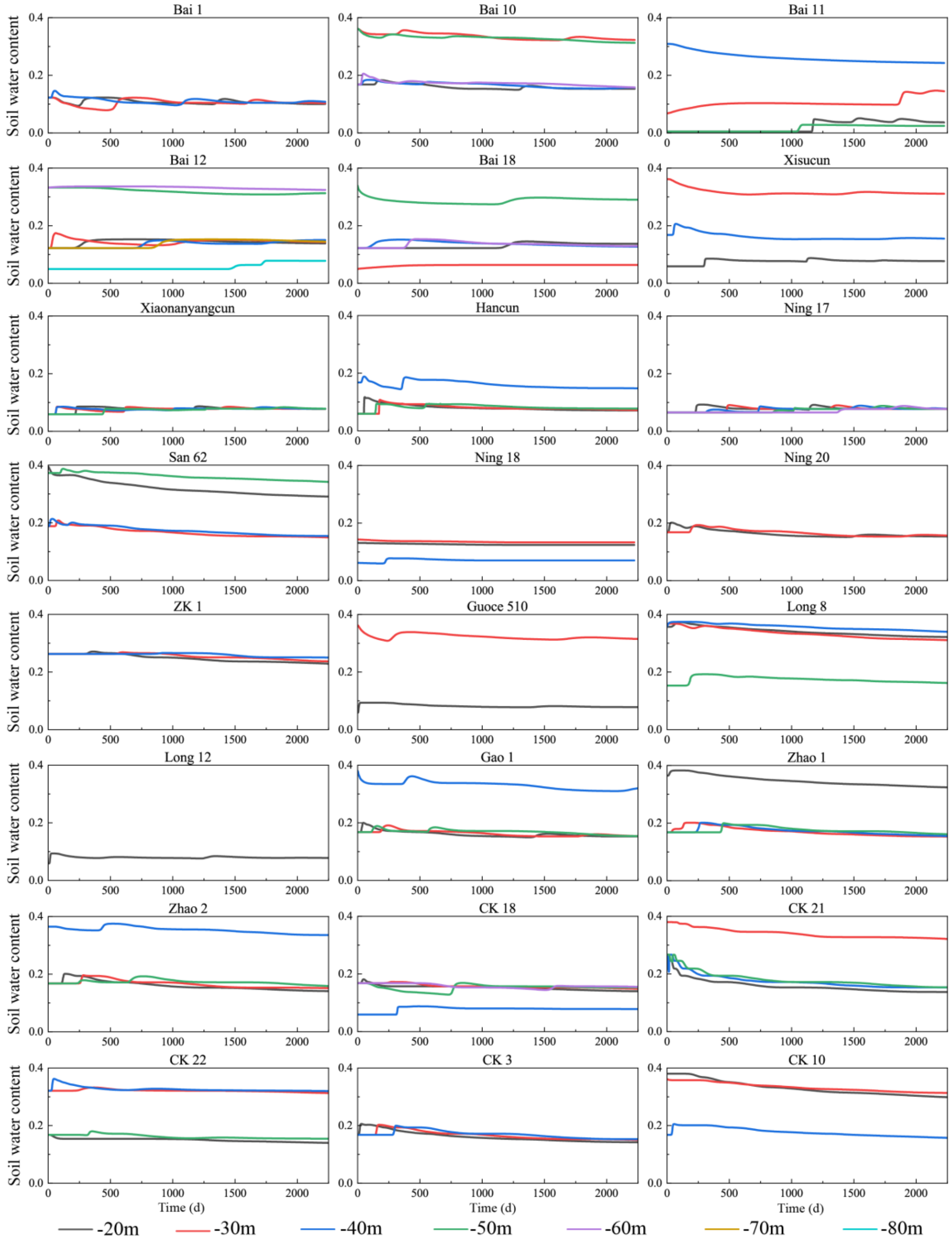

**Figure B: Temporal variation of deep vadose zone soil water content during model spin-up period.”**

*2.The multiple regression models employ clay, sand fractions, and depth as independent predictors. Since soil textural components are compositional data (summing to 100% with silt, clay and sand), there is an inherent negative correlation between these variables. To ensure the robustness of the regression coefficients presented in Tables A.1 and A.2, please check the independence of the input variables or calculate the Variance Inflation Factors for the* *predictors. If high multicollinearity is detected, the authors should discuss how this affects the physical interpretation of the coefficients.*

**Response 2:** We thank the reviewer for raising this important point. To verify the independence of the selected predictors (vadose zone thickness**,** clay fraction, and sand fraction), we have performed a multicollinearity test using the Variance Inflation Factor (VIF). We have added an introduction to the VIF method on Page 14, Section 2.5 Multiple regression analysis of the revised manuscript that:

> "To ensure the independence of the predictors and the robustness of the subsequent regression coefficients, Variance Inflation Factors (VIF) were calculated prior to model fitting (O'brien, 2007).
>
> $$VIF_i = \frac{1}{1-R_i^2} \tag{11}$$
>
> where, $R_i^2$ is the squared multiple correlation coefficient between the $i$th factor and all the other factors. In this study, a VIF value below 5 was adopted as the threshold indicating negligible multicollinearity."

On Page 19, Section 3.2.1 Infiltration times and average percolation velocities under precipitation recharge, the VIF values have been analysed to confirm the independence of the input variables:

> "Prior to evaluating the specific regression outcomes, the independence of the input variables was assessed to ensure the reliability of the model. The calculated VIFs for vadose zone thickness, clay fraction, and sand fraction were 1.018, 1.208, and 1.225, respectively. All values were well below the established threshold of 5, indicating that multicollinearity among the predictors is negligible. Consequently, the physical interpretation of the regression coefficients presented in the subsequent analyses is considered robust."

*3. The Conclusions suggest the construction of recharge basins; however, the implications for groundwater management could be further strengthened. Given the limited land resources in the North China Plain, does this recommendation adequately consider land-use constraints?*

**Response 3:** We appreciate the reviewer's valuable perspective on land-use constraints. We are fully aware that the North China Plain is a densely populated region and a critical agricultural base where land resources are limited. We have refined our recommendations in the Discussion and Conclusion sections to explicitly address the land scarcity. Specifically, we have revised the manuscript to address these points explicitly, including:

On Page 27, Section 4.2 of the revised manuscript:

> "However, given the North China Plain's intensive agriculture and severe land scarcity, constructing new large-scale infiltration basins is largely impractical. Instead, our percolation velocity data demonstrate that existing seasonal dry riverbeds can serve as highly efficient, natural infiltration zones. By prioritizing riverbed infiltration, particularly in foothill alluvial fan areas with coarse-grained sediments (e.g., near boreholes Long 12, Bai 1), this strategy can achieve rapid groundwater replenishment without sacrificing valuable arable land or requiring high land acquisition costs."

On Page 31, in the Conclusions of the revised manuscript, we have added one sentence to highlight this strategy:

> "Given the region's severe land-use constraints, we recommend prioritizing existing dry river channels for floodwater capture to achieve rapid groundwater recovery without occupying valuable agricultural land."

**Specific comments:**

*1.Line 18 "…sustainable groundwater extraction and crop-production," "Crop production" is typically not hyphenated unless used as a compound modifier before a noun.*

**Response 1:** We appreciate these suggestions. On Page 1, in the Abstract of the revised manuscript, clarifications have been made:

> "This has created a large groundwater depression zone up to 80 m deep, severely limiting sustainable groundwater extraction and crop production."

*2. Line 19, The word "however" is redundant following "few studies".*

**Response 2:** We appreciate these suggestions. On Page 1, in the Abstract of the revised manuscript, we have made it clear that:

> "Few studies have quantified recharge delays and efficiencies in deep vadose zones with complex lithology."

*3.Line 23 "…compared between these two infiltrations," the word "infiltrations" is a non-standard pluralization in this context. Please revise "compared between these two infiltrations" to "compared between these two infiltration modes".*

**Response 3:** Done.

*4. Line 33, there is a subject-verb agreement error. "…the depletion of aquifers have become…" should be corrected, as the subject "depletion" is singular.*

**Response 4:** We appreciate these suggestions. On Page 2, in the Introduction of the revised manuscript, we have rephased this sentence and make it clear that:

> "The depletion of aquifers, driven by groundwater over-exploitation, has become a pressing global concern …"

*5. Line 33, in the same sentence, "pressing global concerns" should be changed to "a pressing global concern" to match the singular subject.*

**Response 5:** We appreciate these suggestions. Done.

*6. Line 43, In soil science, the standard term is "matric potential." Please change "matrix potential gradient" to "matric potential gradients".*

**Response 6:** We appreciate these suggestions. On Page 2, in the Introduction of the revised manuscript, we have made it clear that:

> "… under the influences of gravity and matric potential gradients".

*7. Line 118, A preposition is missing in the phrase "holistic understanding soil water movement." Please change it to "holistic understanding of soil water movement".*

**Response 7:** We appreciate these suggestions. On Page 4, in the Introduction of the revised manuscript, we have made it clear that:

> "A holistic understanding of soil water movement …"

*8. Line 198, it should be corrected to "and t represents time".*

**Response 8:** We appreciate the reviewer's careful reading. You are correct that the original phrasing was grammatically awkward. We have fixed this error by removing the extraneous "is". On Page 9, Section 2.3 of the revised manuscript, the revised sentence is as follows:

> "where $\theta$ is the volumetric soil water content ($cm^3\ cm^{-3}$), $t$ represents time (d), $z$ represents the soil depth (cm)…"

*9. Line 202, "set up" should be written as two words when used as a verb.*

**Response 9:** We appreciate these suggestions. On Page 9, Section 2.3 of the revised manuscript, we have clarified that:

> "In this study, the borehole data from Table 1 were selected to set up the HYDRUS-1D model for the individual locations."

*10. Line 244, in the sentence "...and then apply the same average water level data…" the verb "apply" should be in the past tense to match the preceding "were obtained".*

**Response 10:** We appreciate these suggestions. On Page 11, Section 2.3.3 of the revised manuscript, we have clarified that:

> "and then applied the same average water level data from these stations to simulate the riverbed infiltration to all the boreholes that are not close to the river."

*11. Line 328, for more formal academic tone, please change "interplay between these factors in controlling water movement" to "interaction between these factors in governing water movement."*

**Response 11:** We appreciate these suggestions. On Page 16, Section 3.2.1 of the revised manuscript, we have clarified that:

> "reflecting the interaction between these factors in governing water movement through the unsaturated zone."

*12. Line 335, to ensure grammatical parallelism with "thickness," please change the adjective "lithological" to the noun "lithology".*

**Response 12:** We appreciate these suggestions. On Page 17, Section 3.2.1 of the revised manuscript, clarifications have been made:

> "… highlighting how lithology and vadose zone thickness propagate to dictate recharge dynamics,"

*13. The fonts in Figures 5 and 8 are inconsistent with those in the manuscript. If there is no special meaning, it is recommended to make them consistent with the fonts of the other figures.*

**Response 13:** We thank the reviewer for pointing this out. The fonts in Figures 5 and 8 have been updated to be consistent with the rest of the manuscript. The updated Figures 5 and 8 are shown below.

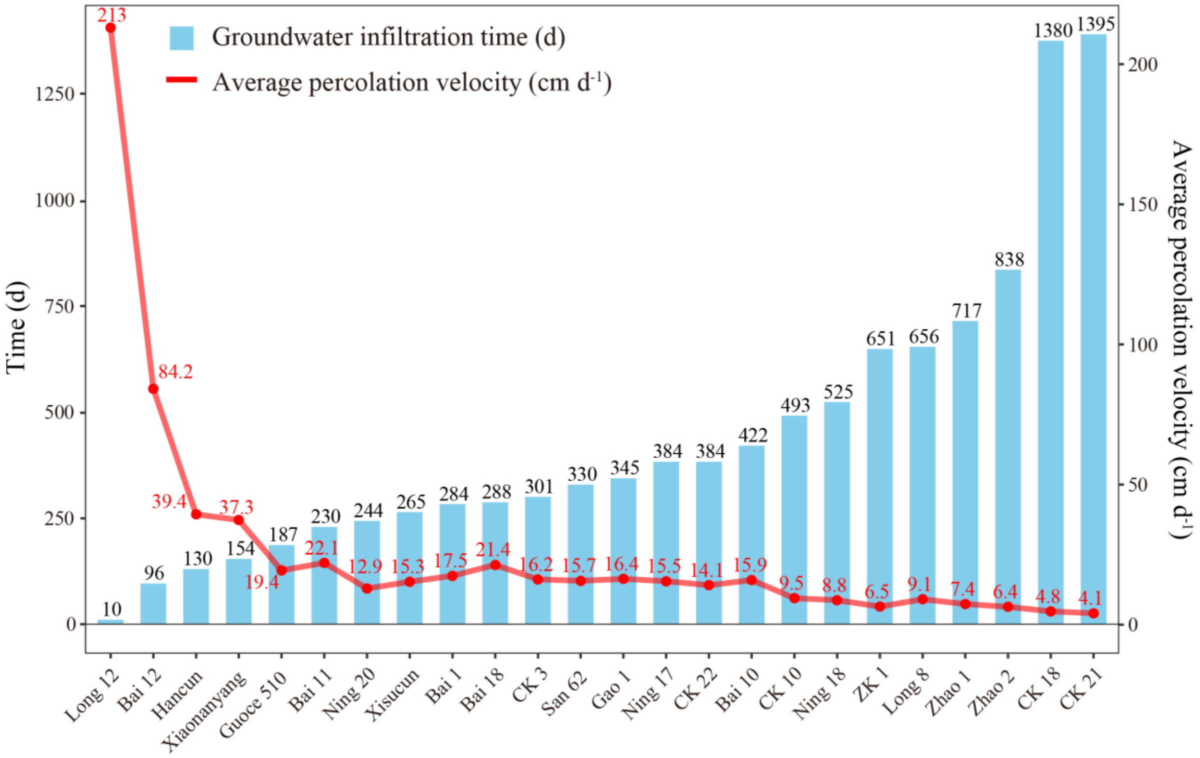

Figure 5: Groundwater infiltration time (d) and average percolation velocity (cm $d^{-1}$) for locations under precipitation infiltration recharge scenarios.

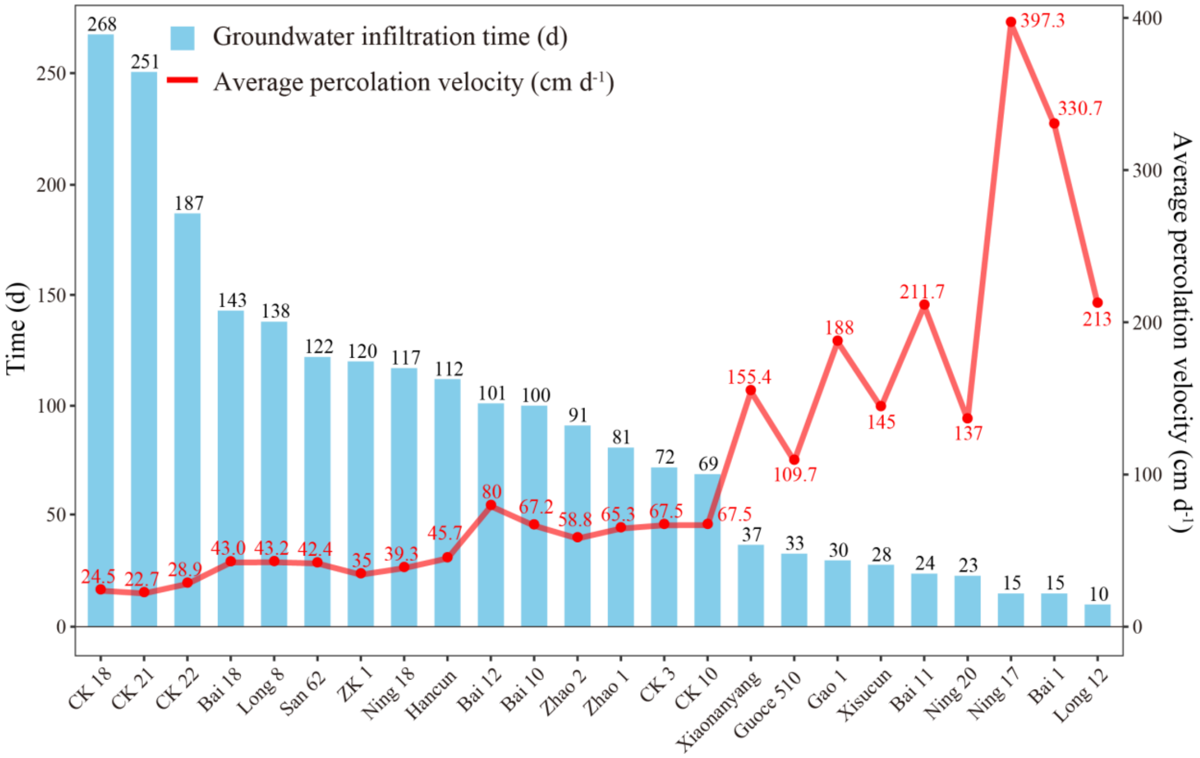

Figure 8: Groundwater infiltration time (d) and average percolation velocity (cm $d^{-1}$) for locations under riverbed infiltration recharge scenarios.

*14. In the titles of Figures 5 and 8, the unit of "Groundwater recharge time" should be marked as (d).*

**Response 14:** We appreciate these suggestions. Done.

## **References:**

Chen, L., Šimůnek, J., Bradford, S. A., Ajami, H., and Meles, M. B.: A computationally efficient hydrologic modeling framework to simulate surface–subsurface hydrological processes at the hillslope scale, *J. Hydrol.*, 614, 128539, https://doi.org/10.1016/j.jhydrol.2022.128539, 2022.

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