Authors' Responses to Comments from Reviewer #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 heavily appreciate your recognition of the study's structure, the appropriateness of the HYDRUS-1D modeling approach, and the novelty of comparing recharge efficiencies between precipitation-fed and riverbed infiltration.

We also value your constructive suggestion to further extend the analysis regarding the flexibility and applicability range of our method. We have carefully considered your specific concerns below and will incorporate 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 will add a dedicated 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 acknowledged that neglecting lateral flow likely leads to an underestimation of lag times compared to reality, as lateral flow extends the travel path (Isch et al., 2022). We incorporated findings from Chen et al. (2022) to provide a quantitative reference for the potential error. Their simulations in heterogeneous domains suggested that neglecting lateral connectivity could lead to peak flow deviations of approximately 8.0% and timing shifts of 4 to 17 minutes.

We clarified that while 2-D models are superior for specific conditions (e.g., furrow irrigation as noted by Crevoisier et al., 2008), they strictly require detailed data on horizontal stratigraphic continuity, which is unavailable at our regional scale. Forcing a 2D model without such data would introduce greater uncertainty. On the other hand, previous studies in the North China Plain (Huo et al., 2014) have demonstrated that vertical flow remains the dominant mechanism for groundwater recharge in this thick vadose zone.

We believe this expanded discussion will provide a balanced view of the model's limitations and justifies the applicability of HYDRUS-1D for the study's objectives.

2. Equations (2) – (6) describe the van Genuchten–Mualem constitutive relationships. However, the formulation appears inconsistent in places, and some parameters (e.g., θ_s and θ_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 checking 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 will revise Section 2.3.2 to present the complete set of equations for these modified equations (Equations 2-7 in the revised manuscript). Furthermore, as requested, we will explicitly define all parameters (including θ_r, θ_s, θ_m, h_s, et al.) immediately following their introduction to ensure clarity and reproducibility.

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. We will describe these definitions in Section 2.4 (Spatial Interpolation), and we will standardize the terminology throughout the manuscript. We now consistently use the term "infiltration time" to refer to the lag time, replacing the previous mix of "recharge time" and "infiltration time."