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March 25, 2026

Memorandum

To: Xavier Sanchez-Vila, Ph.D. Editor, *Hydrology and Earth System Sciences*

Subject: Final response of **EGUSPHERE-2025-6295**

Dear Editor:

Thank you for handling our manuscript entitled "Eddy-Driven effects on solute transport in turbulent channel flows in porous media" (Manuscript ID: EGUSPHERE-2025-6295). We also wish to express our sincere gratitude to the two anonymous reviewers for their time, effort, and highly constructive feedback during the open discussion phase.

We deeply appreciate the reviewers' insightful comments, which have been invaluable in helping us identify areas for improvement and enhancing the overall quality, rigor, and clarity of our work. We fully agree with their assessments and have carefully considered each point raised.

In the detailed point-by-point responses below, we have addressed all the referees' comments (RCs). We have provided our explanations and explicitly outlined the specific revisions we plan to incorporate into the revised manuscript, pending your approval to proceed to the next stage.

Response to Reviewer #1:

The authors present a novel 3D quantitative method for characterizing eddy zones and successfully link these physical characteristics to the Mobile-Immobile Model (MIM) parameters. The methodology is sound, and the results are clearly presented. Here are a few questions and suggestions, particularly the simplification and deepening of the introduction section, to help further refine the manuscript:

1. Terminology Consistency (Turbulence vs. Laminar Flow): The title of the manuscript uses the phrase "turbulent channel flows". However, in Section 3.2, the authors note that the Reynolds numbers range from 113 to 1697 and explicitly clarify that the observed eddy formation is a result of "inertial effects within the laminar flow regime, rather than full turbulence". The authors should clarify this terminology choice, which would be helpful to either adjust the title or add a brief explanation in the introduction to ensure consistency with the described flow regime.

Reply: We sincerely thank the reviewer for pointing out this important inconsistency. We completely agree with your assessment. The use of the word "turbulent" in the original title is inaccurate and contradicts the actual flow regime investigated in our study. As you rightly noted, the Reynolds numbers (Re = 113 to 1697) in our experiments and simulations represent a flow regime dominated by inertial effects within the non-linear laminar to transitional regime, rather than fully developed turbulence.

Proposed Revision: To ensure strict scientific precision and consistency throughout the manuscript, we will adjust the title to remove the inaccurate term. The revised, more concise title will be: Eddy-driven effects on solute transport in porous media. Furthermore, we will carefully revise the introduction section to explicitly state that our research focuses on the non-Fickian transport behavior driven by eddy formation under non-linear laminar and inertial flow conditions, ensuring the term "turbulence" is not misused.

2. Optical Measurement Uncertainty: The authors accurately acknowledge the "increased uncertainty in low-concentration estimation" which is an inherent limitation of the optical calibration method. Given that late-time tailing (e.g., t98) relies heavily on these low-concentration readings to quantify eddy-driven retention, the authors should briefly discuss in the text how this specific limitation might affect the precision of the fitted MIM parameters, particularly the immobile zone ratio (1-β)?

Reply: We greatly appreciate this insightful comment. The reviewer raises a highly valid point regarding the inherent limitations of optical measurement methods at low concentrations and their potential impact on accurately capturing late-time tailing behaviors.

First, we would like to clarify a critical methodological detail that we realize was not emphasized sufficiently in the original manuscript: The parameter inversion for the Mobile-Immobile Model (MIM), including the immobile zone ratio (1-β), was conducted using the high-resolution breakthrough curves (BTCs) generated from our numerical simulations, NOT the experimental optical data.

As stated in lines 692-700, the inverse modeling was performed directly within the COMSOL Multiphysics® environment by minimizing the difference between the "simulated breakthrough curves (BTCs) and the concentrations predicted by the MIM." Because the numerical simulations provide highly accurate and continuous concentration data down to t_{98} and beyond, the precision of the fitted MIM parameters remains robust and is not compromised by the optical limitations mentioned in lines 181-182.

However, to directly answer the reviewer's theoretical question: If we had relied on the optical experimental data for MIM inversion, the increased uncertainty at low concentrations (typically causing signal noise or baseline drift near zero) would indeed blur the exact shape of the long tail. Because the immobile zone ratio (1-β) fundamentally governs the mass of the solute trapped in the eddies, a high-variance or prematurely truncated low-concentration tail would likely lead to an underestimation of 1-β and increase the uncertainty bounds for the mass transfer coefficient (α).

Proposed Revision: To avoid any future confusion for readers and to strengthen the justification for our methodology, we will add a brief discussion clarifying this point in Section 4. We propose adding the following sentences after line 700: "It should be emphasized that the MIM parameter inversion was performed exclusively on the numerical simulation BTCs rather than the experimental data. This strategy was specifically chosen to bypass the inherent optical measurement uncertainties at low concentrations (as discussed in Section 2.1), ensuring that the quantification of the late-time tailing and the derived immobile zone ratio (1-β) are robust and unaffected by experimental detection limits."

3. Inert Tracer Assumption: The numerical simulation and the governing equations of the MIM model assume that Brilliant Blue acts as a perfectly inert solute without adsorption or degradation. While this is a reasonable assumption for the experimental setup, is there any possibility of very slight physical sorption onto the artificial spheres? A brief comment on whether minor sorption could have any compounding effect on the observed non-Fickian tailing would strengthen the discussion.

Reply: We deeply appreciate the reviewer's rigorous perspective. The reviewer is absolutely correct that distinguishing between physically-driven tailing (e.g., eddy retention) and chemically-driven tailing (e.g., sorption/desorption) is a critical issue in solute transport studies.

While Brilliant Blue is widely accepted and utilized as a conservative, inert tracer in hydrological laboratory experiments due to its highly stable chemical properties and low affinity for most solid surfaces. Theoretically, if even minor, reversible physical sorption occurred on the surface of the artificial spheres, it would induce an additional retardation effect, which would indeed compound the late-time non-Fickian tailing observed in experimental breakthrough curves (BTCs).

However, we would like to highlight a key advantage of our methodology that addresses this exact concern. Our quantitative analysis, specifically the mapping of the hydrodynamic eddy proportion to the MIM immobile zone ratio (1-β), is primarily driven by our numerical simulations. In COMSOL model, the solute is explicitly mathematically defined as perfectly non-reactive (governed strictly by the advection-diffusion equation, with zero sorption/desorption sink or source terms). The fact that our pure-physics numerical simulations successfully capture the pronounced tailing behavior, and the physical eddy proportion aligns so well with the MIM conceptual parameters, which strongly demonstrates that the non-Fickian tailing quantified in this study is overwhelmingly governed by physical retention within the eddy zones. This numerical approach effectively isolates the physical eddy-driven tailing from any potential sorption-induced artifacts in the physical experiments.

Proposed Revision: We completely agree that explicitly discussing this theoretical compounding effect and how our numerical setup addresses it will significantly strengthen the rigor of our manuscript. We will add a brief discussion in Section 4 (Solute transport model), immediately following the introduction of the MIM governing equations (around line 639).

We propose adding the following paragraph: "While Brilliant Blue is practically treated as an inert tracer in our physical experiments, it is theoretically possible that very slight, reversible physical sorption onto the artificial spheres could occur. If present, this minor sorption would induce additional solute retardation, potentially compounding the observed non-Fickian tailing. However, a major advantage of incorporating numerical simulations in this study is the ability to perfectly isolate physical heterogeneity. Because our numerical model explicitly defines the solute as strictly non-reactive (controlled solely by advection-diffusion mechanics without sorption terms) and still accurately reproduces the pronounced tailing behavior, we can confidently conclude that the tailing quantified herein is dominantly driven by physical hydrodynamic retention within the eddy zones, rather than chemical sorption."

4. Robustness of the v_c Threshold Method: The determination of the critical velocity threshold (vc) using the PDF/CDF inflection point is an elegant approach for quantifying the 3D eddy volume in these specific structural packings. How robust do the authors expect this threshold identification method to be if applied to more natural, highly heterogeneous porous media with a wide particle size distribution (unlike the uniform spheres used here)? Adding a short perspective on this in the discussion would highlight the broader applicability of your method.

Reply: We thank the reviewer for this insightful comment regarding the scalability and robustness of the v_c threshold method. While this study utilized structured and random packings of uniform spheres to isolate fundamental mechanisms, the v_c identification via the PDF/CDF inflection point is fundamentally a statistical approach grounded in the physical separation of flow regimes.

In natural, highly heterogeneous porous media with a wide particle size distribution, we expect the velocity PDF to be broader and potentially multi-modal. However, the physical distinction between the high-velocity "advective backbone" and the low-velocity "stagnant or recirculating zones" (eddies) remains a universal feature of inertial flows in porous media. Although the inflection region in the CDF might become "smoother" or less pronounced than in uniform packings, the transition point still represents the statistical threshold where the flow effectively becomes "trapped" or significantly delayed relative to the main stream. We believe the method is inherently robust because it relies on the internal distribution of the velocity field itself rather than an arbitrary global constant.

Proposed Revision: As suggested, we have added a short perspective on the broader applicability of this method to heterogeneous media in the Section 3.1 (around Lines 319-320).

We propose adding the following paragraph: "Furthermore, while the v_c threshold identification via the PDF/CDF inflection point was established here for relatively uniform packings, its statistical nature suggests potential robustness for heterogeneous natural media. Although a wider particle size distribution would broaden the velocity PDF, the physical transition between advective channels and recirculating zones (eddies) should still manifest as a characteristic inflection in the CDF. This provides a physically-grounded and consistent basis for eddy quantification across diverse and complex porous structures, even where pore-scale geometry is highly irregular."

5. The first paragraph of the introduction contains a significant amount of textbook knowledge or general background information, such as the current state of contamination and classification of aquifer media. While such content is necessary, it has not yet established a strong connection with the core keyword "Eddy effects" and therefore requires substantial condensation. Similarly, lines 73–83 are overly verbose in setting the stage for introducing "Eddy."

Reply: We agree with the reviewer that the initial background was too broad and lacked a direct bridge to the study's core focus on "eddy effects." In response, we have substantially condensed the first paragraph of the Introduction (Lines 43–61) by removing general descriptions of groundwater importance and aquifer classifications. Instead, we now lead directly from the challenges of groundwater pollution to the limitations of the macro-scale "seepage assumption" in capturing pore-scale flow complexities, specifically eddies.

Furthermore, we have streamlined the description of Fickian versus non-Fickian transport in Lines

73–83. The revised text now more concisely establishes the link between observed solute tailing and the underlying pore-scale stagnant zones (eddies), providing a more efficient transition to our research objectives.

Proposed Revision:

Regarding the first paragraph (Lines 43–61), the original text has been replaced with the following condensed version (starting at Line 43):

"Effective prevention and control of groundwater pollution is a global priority, yet remediation remains challenging due to the inherent complexity of aquifer systems. Most quantitative assessments of groundwater transport rely on the macro-scale 'seepage assumption', which simplifies actual pore-space movement into a linear velocity field through solid particles. However, this simplification often overlooks the complex curved motion and boundary-driven eddies that occur at the pore scale, which significantly govern flow resistance and solute distribution."

Regarding the verbosity in Lines 73–83, the text in Lines 73–83 has been condensed and replaced as follows:

"While traditional advection-diffusion models assume Fickian behavior, a growing body of evidence shows that breakthrough curves (BTCs) in porous media frequently exhibit non-Fickian characteristics, such as early arrival and significant tailing. This behavior is largely attributed to the heterogeneous distribution of flow velocities and the trapping of solute in stagnant or recirculating zones, known as eddies, which dramatically increase residence times and complicate remediation efforts."

6. The entire introduction section contains only lines 84–107 that offer an in-depth literature review of the core topic. While the latter part of this section talks about the advantages of the MIM model in characterization from a technical perspective, the first half still fails to clearly articulate the significance of this study. For example, line 93 mentions that current research rarely considers the impact of eddies on solute transport at the pore scale, even though the preceding text has already discussed their influence on pore-scale water flow. However, why bridging the understanding from water flow to solute transport presents such a major challenge or gap remains unclear to the reader. Thus, further elaboration is needed.

Reply: We sincerely appreciate the reviewer’s constructive feedback. We agree that the transition from hydrodynamics to solute transport lacked a clear articulation of the fundamental challenges that have historically prevented this connection.

Bridging the understanding from fluid flow to solute transport at the pore scale is inherently difficult because it requires transitioning from steady-state or macroscopic hydrodynamic observations to tracking dynamic, three-dimensional mass exchange processes across complex, microscopic fluid boundaries. Experimentally, capturing the real-time concentration gradients between an advective main channel and an adjacent micro-eddy requires exceedingly high spatiotemporal resolution, which traditional column effluent data (BTCs) cannot provide. Computationally, coupling non-linear fluid dynamics with the advection-diffusion equation at a resolution fine enough to resolve these local recirculating zones is highly resource-intensive.

To clarify this significant gap and better articulate the motivation for our study, we have substantially expanded the literature review and elaborated on these specific technical and theoretical challenges in the Introduction (Lines 93–97).

Proposed Revision: We have revised and expanded the text originally spanning Lines 93–97. The original sentences have been replaced with the following elaborated paragraph: "Although the impact of complex boundary morphology on pore-scale flow fields is well-documented, bridging this hydrodynamic understanding to predict solute transport presents a formidable scientific challenge. Tracking the dynamic, three-dimensional mass exchange between high-velocity advective channels and low-velocity recirculating eddies requires mapping localized concentration gradients across microscopic fluid boundaries. Experimentally capturing these real-time, micro-scale diffusion processes demands exceedingly high spatiotemporal resolution, rendering them largely invisible to traditional macroscopic column studies that only measure bulk effluent. Furthermore, computationally coupling non-linear fluid dynamics with solute transport at resolutions fine enough to resolve internal eddy mass-transfer is highly demanding. Consequently, the explicit mechanisms by which these transient hydrodynamic structures dictate macroscopic non-Fickian tailing have remained an unresolved gap in the literature. By employing high-fidelity, three-dimensional coupled models alongside physical experiments, this study aims to directly penetrate this 'black box' and quantify the eddy-driven solute exchange process."

7. Line 92 mentions that previous studies have not directly observed the eddy region. This raises the question: are there any potential experimental methods or techniques that could address this gap? Given that the authors subsequently conducted detailed laboratory experiments, it is recommended that they provide some background on the current state of research regarding such methods. This would help underscore the necessity and significance of the experimental work presented later.

Reply: We sincerely thank the reviewer for this excellent suggestion. We fully agree that outlining the current state of experimental visualization techniques significantly strengthens the rationale for our methodological design.

While advanced techniques exist for pore-scale observation, they each carry severe limitations when applied to large-scale, 3D physical models. For instance, micro-Particle Image Velocimetry (micro-PIV) is highly effective in 2D microfluidic chips but requires perfectly matched refractive indices and transparent media, making it unsuitable for standard 3D opaque packings. Furthermore, non-destructive 3D imaging methods like dynamic X-ray Micro-CT or Magnetic Resonance Velocimetry (MRV) excel at resolving static pore structures but generally lack the high temporal resolution required to capture fast, transient vortex flows in a large experimental column (such as our 150 cm setup).

Because of these experimental bottlenecks, it is practically impossible to obtain a complete 3D dynamic eddy field solely through physical observation. This directly necessitates our coupled approach: using a robust photographic tracer method to validate the macroscopic solute transport, while deploying strictly validated high-fidelity 3D numerical simulations to extract the "invisible" internal eddy volumes.

To underscore this significance, we have added a brief background on these experimental methods to the Introduction (Lines 92-96).

Proposed Revision: We have inserted the following background context into the Introduction, immediately following the sentence ending at Line 92 ("...it is difficult to directly observe the eddy region, resulting in insufficient quantitative identification of eddies."): "While advanced observational techniques have been developed to tackle pore-scale dynamics, they face significant constraints. Methods such as micro-Particle Image Velocimetry (micro-PIV) are highly effective in microfluidic applications but strictly require transparent media and refractive index matching, limiting their use in 3D opaque packings. Conversely, non-destructive 3D imaging techniques, including dynamic X-ray Micro-CT and Magnetic Resonance Velocimetry (MRV), provide excellent structural resolution but often struggle with the temporal resolution and field-of-view required to capture rapid, transient recirculating flows in larger macroscopic columns. Because directly quantifying the dynamic 3D eddy volume solely through physical experiments remains technologically prohibitive, there is a critical need for coupled approaches. This study bridges this gap by combining physical solute transport experiments with rigorously validated 3D numerical simulations, allowing for the precise extraction of internal eddy structures that physical sensors cannot capture."

8. Typos in this manuscript such as the figure caption in Fig. 4 ("comparison between") should be checked.

Reply: We apologize for these oversight errors. We have corrected the typo in the caption of Figure 4 (changing "comparison between" to the intended phrasing) and have conducted a thorough, line-by-line proofreading of the entire manuscript to identify and rectify any remaining spelling, grammatical, or formatting inconsistencies.

Proposed Revision: Figure 4 Caption (Line 232): The caption has been revised for clarity and accuracy.

Full Manuscript: A comprehensive linguistic and technical check has been performed, with minor typographical corrections made throughout the manuscript (e.g., ensuring consistent subscripting for chemical species and unit formatting).

9. Figure 4 is significant for the validation of this proposed method, there the authors should better try best to analyze why there are larger fitting errors in the case of "D=5mm"than those in other cases.

Reply: We agree with the reviewer that a deeper analysis of the fitting discrepancies in the D=5 mm case is essential for validating the limits of the proposed method. The larger fitting errors observed for the smaller particle size (D=5 mm) compared to larger diameters can be attributed to three primary factors:

1) Increased Wall Effects and Heterogeneity: As the particle diameter decreases relative to the column diameter, the ratio of the wall-affected region to the bulk flow region increases. In the D=5 mm packing, the local porosity fluctuations near the column wall are more sensitive, leading to more pronounced preferential flow paths that the idealized 3D numerical model may not fully capture, thus increasing the discrepancy between simulated and experimental BTCs.

2) Enhanced Dispersion at Lower Pore-Scale Reynolds Numbers: For smaller particles under the

same volumetric flow rate, the local velocity gradients are steeper and the characteristic length scales are shorter. This can lead to a more complex transition between transport regimes where the sensitivity of the MIM model parameters to small structural irregularities is magnified.

3) Experimental Observation Constraints: The photographic tracer method relies on capturing concentration changes through the pore spaces. With smaller particles (*D*=5 mm), the "optical paths" are more tortuous and the pore throats are narrower, which slightly reduces the signal-to-noise ratio of the image analysis compared to the *D*=10 mm or *D*=15 mm cases.

We have added a detailed discussion of these factors in the revised manuscript to provide a more transparent evaluation of the model's performance.

Proposed Revision: In Section 2.2 (Numerical simulation methods and model validation), following the description of Figure 4 at Line 236, we have inserted the following analysis:

"Notably, the fitting error for the *D*=5 mm case is slightly higher than that of the *D*=10 mm and *D*=15 mm cases. This is likely due to the increased influence of the column wall effect and local structural heterogeneity inherent in smaller particle packings. In these tighter configurations, the ratio of the wall-zone porosity to the bulk porosity creates more significant preferential flow, which poses a greater challenge for numerical alignment. Additionally, the reduced pore throat size in the *D*=5 mm media may introduce slight observational uncertainties in the photographic tracer capture, contributing to the observed deviation in the tailing part of the BTC."

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Sincerely Yours,

Zhongxia Li, Ph.D.
Haibo Feng, Ph.D.