General assessment: The manuscript investigates the contrasting effects of sediment and microbial heterogeneity on hyporheic nitrate removal using coupled flow, reactive-transport, and biofilm-growth models. The topic is highly relevant, and the modelling framework is potentially valuable. The manuscript is generally well organized, but several points should be clarified before publication.

Response to the general comments: We sincerely thank the reviewer for the positive assessment of the relevance and potential value of this study, as well as for the constructive comments. In response, we will clarify the definition of microbial heterogeneity and its coupling with biomass evolution and bioclogging, and better explain why surface bioclogging weakens the influence of deeper sediment heterogeneity under the modeled conditions. We will also define the applicability and limitations of these findings, particularly with respect to fixed streambed conditions, biofilm detachment, and hydrodynamic forcing. In addition, we will improve the descriptions of model calibration and validation, the constant-biomass scenario, and the selection of the flow and nutrient conditions. The Abstract and entire manuscript will be carefully revised for scientific style, language, notation, and clarity. Finally, we will moderate the novelty statement and update the Data and Code Availability section in accordance with the HESS policy. Detailed responses are provided below.

1. The comparison between the heterogeneous-growth and constant-biomass scenarios changes not only the spatial distribution of biomass but also microbial growth, biomass evolution, and bioclogging feedback. Therefore, the large differences in nitrate removal cannot be attributed exclusively to microbial heterogeneity. The authors should clarify this limitation and moderate statements such as "microbial heterogeneity plays a decisive role."

Response to comment #1: Thank you for this important comment. In this study, "microbial heterogeneity" refers not only to the spatial distribution of biomass, but also to its temporal evolution and the associated feedbacks on reaction rates and bioclogging. The heterogeneous biomass develops dynamically near the sediment–water interface, concentrates biogeochemical reactions in the surface layer, and progressively restricts hyporheic exchange through bioclogging. Therefore, these processes are integral components of the microbial heterogeneity considered in our modeling framework, rather than independent effects.

We agree, however, that the comparison with the constant-biomass scenario does not isolate the effect of spatial biomass heterogeneity alone. We will clarify this definition and limitation throughout the manuscript. Accordingly, the conclusion will be revised to state that, the spatiotemporally evolving microbial heterogeneity and its associated bioclogging feedback play a decisive role in controlling hyporheic nitrate removal.

2. The conclusion that sediment heterogeneity has a negligible effect is based on two selected small-scale sediment structures and the tested parameter ranges. This finding should not be generalized to all hyporheic zones. Please consistently qualify the conclusion as applying to the model configurations, heterogeneity scales, and environmental conditions considered here.

Response to comment #2: Thank you for this important comment. We agree that our conclusion should be restricted to the sediment structures and environmental conditions considered in this study. Within the modeled scenarios, microbial biomass and the associated bioclogging progressively concentrate solute transport and biogeochemical reactions near the sediment–water interface. As a result, deeper sediment structures become increasingly disconnected from active hyporheic exchange, substantially weakening the influence of small-scale variations in permeability and organic matter content on nitrate removal.

We will also clarify that the simulated long-term bioclogging represents an upper-bound effect under a fixed streambed configuration. In natural systems, strong hydrodynamic forcing, sediment mobility, bedform migration, and biofilm detachment may disrupt the clogged surface layer and reopen flow paths into deeper sediments. Under these conditions, bioclogging would be weaker and the influence of sediment heterogeneity on nitrate removal could become more pronounced. We will revise the Abstract, Discussion, and Conclusions to define this applicability more clearly and avoid generalizing the finding to all hyporheic zones.

3. Please provide some additional information on model calibration and validation, particularly the parameters that were calibrated and the experimental observations used for comparison. Quantitative goodness-of-fit measures may also be included if available. A brief discussion of the limitations of applying the calibrated parameters to the present simulation scenarios would further improve the manuscript.

Response to comment #3: Thank you for this helpful suggestion. In fact, Table 1 has distinguished parameters obtained from calibration, experimental observations, and the literatures. We will revise its notes to make these sources clearer. The model was calibrated and validated against the residence-time distribution and the observed DO and NO_3^- concentrations reported by Quick et al. (2016). We will also provide the corresponding R^2 values in Sect. 3.1 to quantify the goodness of fit. Moreover, we will clarify that transferring the calibrated parameters from the laboratory flume to the present synthetic simulation scenarios introduces uncertainty; therefore, the results are intended primarily for comparisons among scenarios rather than site-specific predictions.

4. Please revise the Abstract into a more concise scientific style. Expressions such as “helpful microbes,” “sticky substances,” and “cleaning streams” are overly informal for a research article.

Response to comment #4: We agree and will rewrite the Abstract in a concise scientific style. Informal expressions will be removed and terminology will be aligned with the model formulation. The proposed revised Abstract emphasizes the coupled flow–reactive-transport–biofilm framework, the two sediment structures, the three microbial/sediment representations, and the scope-qualified findings. In particular, ‘helpful microbes,’ ‘sticky substances,’ and ‘cleaning streams’ will be replaced by ‘functional microbial biomass,’ ‘extracellular polymeric substances and biomass accumulation,’ and ‘hyporheic nitrate attenuation,’ respectively.

5. The manuscript requires careful language editing. Please correct grammatical and typographical issues, including duplicated brackets, subject–verb agreement, inconsistent abbreviations, and expressions such as "are called as" and "momentously enhances."

Response to comment #5: We agree. The entire manuscript will be carefully edited for grammar, spelling, punctuation, and scientific style. We will correct the duplicated parenthesis in the study aim; revise subject–verb agreement (e.g., 'High concentrations … pose'); standardize HZ/HZs, OM/POC, NO_3^-, DO, DOC, and biomass notation; replace 'are called as' with 'are referred to as'; replace 'momentously enhances' with a quantitative, qualified description; and correct additional typographical errors in the text, captions, equations, tables, and references.

6. Please clarify how the spatially uniform microbial biomass value was determined in the "Hetero. Sed. & Const. Bio." scenario, including whether the averaging was performed over space, time, or both. This information is important for interpreting the comparison between the microbial scenarios.

Response to comment #6: We will clarify this point in Sect. 2.2 and Table 2. For each corresponding 'Hetero. Sed. & Bio. Growth' simulation, the biomass field X(x,z,t) was averaged arithmetically over all elements of the two-dimensional sediment domain and over the full 730-day analysis period. The resulting single scalar $\overline{X}$ was assigned uniformly throughout the sediment and held constant in time in the 'Hetero. Sed. & Const. Bio.' scenario. The 180-day initialization used to establish the starting state was not included in this 730-day averaging interval. We will also state explicitly that this construction preserves the space–time mean biomass concentration, but not its instantaneous total biomass, spatial localization, growth dynamics, or bioclogging feedback.

7. Please briefly explain the rationale for selecting the two stream velocities and nutrient conditions. It would be helpful to indicate whether these values represent typical or contrasting conditions reported for natural streams.

Response to comment #7: Thank you. We will add the rationale in Sect. 2.2. The velocities (0.2 and 0.8 m s^{-1}) were selected as contrasting low- and high-velocity cases within the range commonly encountered over permeable bedforms, thereby varying the pressure forcing and hyporheic exchange. The nutrient pairs (DOC/NO_3^- = 5/2 and 20/10 mg L^{-1}) were chosen to contrast relatively low-nutrient and enriched conditions and to test whether the inferred controls persist across differences in electron-donor and nitrate supply. We will emphasize that these are synthetic bounding scenarios rather than a statistical representation of all natural streams, and we cite the relevant stream and hyporheic studies already used to support the selected ranges.

8. Please moderate the statement "This study is the first to reveal..." unless this claim can be fully demonstrated. A more appropriate formulation would be "This study provides new insights into the contrasting roles of sediment and microbial heterogeneity in hyporheic nitrate removal."

Response to comment #8: We agree and will adopt the reviewer's suggested formulation. The priority claim will be removed from the Conclusions. The proposed revised sentence reads: 'This study provides new insights into the contrasting roles of sediment representation and spatially and temporally evolving microbial biomass in modeled hyporheic nitrate removal.' This wording also reflects the limitation identified in Comment 1.

9. The current statement that all raw data are available upon request does not fully follow the HESS data policy. The model inputs, key simulation outputs, and data underlying the figures should be deposited in a reliable public repository with a persistent identifier. The authors are also encouraged to share the relevant model files or configuration information where possible. If any material cannot be made publicly available, the reason should be clearly explained in the Data and Code Availability section.

Response to comment #9: We agree and will replace the 'available upon request' statement. The proposed revised Data and Code Availability section will identify a public repository containing the processed sediment-property fields, model input tables, boundary-condition data, key simulation outputs underlying all figures and tables, and model configuration information sufficient to reproduce the scenarios. The final manuscript will provide the persistent identifier in the following form: 'The data and model materials supporting this study are available at HydroShare'. We will activate and verify the DOI before resubmission.