Feb 1, 2024

To: Editor of Hydrology and Earth System Sciences

Subject: Revision of HESS-2023-29

Dear Editor:

Thank you for giving us the opportunity to revise our manuscript. We are submitting the revised manuscript titled "Influence of bank slope on sinuosity-driven hyporheic exchange flow and residence time distribution during a dynamic flood event" (HESS-2023-29). All the comments and suggestions from the reviewer and editor have been carefully addressed in the revised version of the manuscript.

We have explained the definition of mean residence time distribution, and revised Section 2 to further discuss the biogeochemical implications of our results. We have also revised minor issues throughout the manuscript as suggested.

Below you can find an itemized response to the review comments. The original comments are included verbatim in blue text, and our response to each comment follows in black text while the revised texts as they appear in the revised version of manuscript follow in underlined black text.

We would like to express our heartfelt appreciation to the associate editor and the reviewer for their constructive comments that undoubtedly increased the scientific value of this manuscript. We hope the revised manuscript will meet your expectations. Should you have any further queries, please feel free to contact me.

Again, we thank you very much for your consideration and look forward to your favorable response.

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Point to point response of the comments.

Comments from Reviewer

Comment 1 Definition of residence or travel time

In this manuscript the term residence time is not defined. There are various definitions of residence time. The common definition of residence time, travel time, or transit time is the time that a parcel or particle spends in a system, subsystem, control volume. Residence time is also often defined as the average time that water spends in a system. The authors do also not explicitly define the system for which they quantify the residence time.

Interpretation of Figure 8 suggests that the authors define the residence time in the hyporheic zone as the travel time passed since the infiltration of river water into the riverbed or bank. However, this is commonly referred to as the age of the water. There is a major risk that the main messages and conclusions of the study are very confusing and hard to understand without a proper definition of these terms. For example, phrases such as 'the spatiotemporal distribution of the residence time distribution' (l. 386) are unintelligible if the reader uses the above traditional and common definition of residence time.

The authors should define the term residence time and the system with a proper reference to the literature.

Reply:

Thank you for your comment. We define residence or travel time as shown in Equation xxx implemented in COMSOL. We acknowledge that different authors have taken a slightly differing approach in previous work, but we base our definition on Gomez-Velez et al. (2017); Singh et al., 2019. The term "RTD" throughout this paper refers to the mean (average, or first moment of) RTD, In order to avoid any confusion, we have revised the "RTD" by using "mean RTD" throughout the paper. We have also added further information to the main text and SI:

Revision made:

Please see lines 143-145 in the revised manuscript: "The RTD represents the distribution of average pore water travel time since the infiltration of river water into the system for a given time (Gomez-Velez et al., 2012; Singh et al., 2019)."

Please see lines 123-130 in the revised SI: "The residence time (also terms as travel time or age) (RT) in the HZ describes the characteristic time scale over which water or solute molecule are exposed to the biogeochemical conditions within the hyporheic sediment. For HEF process, RT is controlled by the advective and dispersive characteristics of the system, thereby it is hard to calculate the RT of each molecule due extremely large computational demand. Thus, the residence time distribution equation was proposed (Ginn, 2000; Gomez-Velez et al., 2012,), and has been widely applied to calculate the mean residence time distribution (RTD) in HEF models (Gomez-Velez et al., 2017; Singh et al., 2019)."

Comment 2. Vague and sloppy formulations. The authors tend to use vague and, therefore, meaningless or, at least, incomprehensible phrases throughout the text. To refer to a few exampl-es: Line 95: 'By comparing RTD with the timescale of nitrification /denitrification reactions, a meander can be classified as a source or sink of nitrate.'

Reply: We have rewritten that sentence.

Revision made: Please see lines 94-96: "The authors analyzed the RTD for various aquifer conditions to study when a meander can play a role as both source or sink of nitrate."

Comment 3. Line 595: 'Bank slope could result in longer (near the point bar) or shorter (near the cut bank) pore water travel time s throughout the flood event.'

Reply: We have rewritten that sentence.

Revision made: Please see lines 616-618: "Smaller bank slope angles could extend (near the point bar) or reduce (near the cut bank) pore water travel times throughout the flood event, compared to the non-sloping (vertical) riverbank condition."

Comment 4. Line 450-451: '… and residence (travel) times of river water in the aquifer would be overestimated or underestimated'.

Reply: We have rewritten the caption sentences of Fig. 9-12.

Revision made: Please see lines 417-421: "The colored areas indicate where the bank slopes have significant impact on RT (difference in RT between sloping and vertical model larger than 12.2%) and residence (travel) times of river water in the aquifer would be overestimated (cold color area) or underestimated (warm color area) if the effect of the bank slope was ignored."

Comment 5. Line 468: '…. show that bank slope can lead to both overestimated and underestimated RT area.'

Reply: We have rewritten this sentence.

Revision made: Please see lines 470-472: "At the time of peak flood ($t^* = 0.25$), the river still infiltrates into the aquifer. For $\Gamma_d = 0.1$, results of μ_r^* in Fig. 9 show that bank slope can lead to both overestimated and underestimated RT areas."

Comment 6. Line 816: 'Bank slope could result in longer (near the point bar) or shorter (near the cut bank) pore water travel times at various times of a throughout the flood event.'

These and similar phrases should be rephrased and clarified, so that is clear under what conditions which process or effect occurs.

Furthermore, the authors often use phrases in which they compare situations without referring explicitly to the situation with which they compare. For example, L. 33-35: 'The impact of bank slope on residence time was more pronounced during a flood event for high transmissivity aquifer conditions', or L. 450-451 and L. 468 (see phrases mentioned above): Overestimated or underestimated compared with what? (Line 25 have said that the rest have been modified)

Reply: We have rewritten these sentences and the revised the manuscript according to the comment.

Revision made: Please see lines 614-618: "For lower aquifer transmissivity conditions, bank slope seems more relevant for mean RTD after the flood event and its impact is more long-lasting. Smaller bank slope angles could extend (near the point bar) or reduce (near the cut bank) pore water travel times throughout the flood event, compared to the non-sloping (vertical) riverbank condition."

Please see lines 31-34: "The impact of bank slope on residence time was more pronounced during a flood event for high transmissivity aquifer conditions, while it had a long-lasting influence after the flood event in lower transmissivity aquifers."

Comment 7. New discussion section 4.2 on the implications for biogeochemical reactions

This section 4.2 is new in the revised version of the manuscript in response to a comment 1.50 by reviewer #1. This new paragraph is weak and it is often hard to understand the logic of the reasoning. This becomes particularly manifest in lines 569-570 in which the authors state that a small residence time to biogeochemical time scale ratio indicate a high reaction potential for that chemical species. This counterintuitive statement should be clarified or should be supported by literature references.

Reply: Agree. We have improved Section 4.2 and provide more references on and explanation about the relation between biogeochemical reaction potential and residence time.

Revision made: Please see lines 566-575 in the revised manuscript: "Under rather stable flow conditions, hyporheic exchange rate and river sinuosity control the biogeochemical zonation (RTD) in the HZ. A higher hyporheic exchange rate (caused e.g., by a larger hydraulic conductivity in the aquifer or a more sinuous meander) will reduce the mean RTD promoting biogeochemical reactions (Boano et al., 2010; Gomez-Velez et al., 2012). However, for a transient flood event, the mean RTD could be both extended and reduced depending on the location with respect to the meander, due to variations in the complex flow paths (Gomez-Velez et al., 2017). Our results indicate that smaller bank slope angles could not only increase HEF and thus lead to increased transport of oxygen and nutrient rich stream water into the aquifer, but also alter the location and the residence time of this water within the aquifer system."

Comment 8. Furthermore, in lines 596-599, the authors state 'that point bars with bank slopes are more favorable for removing dissolved organic carbon and for nitrification, while cut banks with bank slope may have adverse effects on the groundwater quality near rivers.' This statement suggests that the authors think that DOC removal and nitrification (nitrate production) has a positive effect on groundwater quality. Given the fact that increasing hyporheic exchange rates result in decreasing travel times in the aquifer, the assumption that long travel times (which occur, amongst others, in sloping point bars) promote the DOC removal and nitrification, would then imply that hyporheic exchange has an adverse effect on groundwater quality. This would be n contradiction with the common paradigm that hyporheic exchange controls water quality in a positive manner.

Reply: Thanks for the reviewer's scientific comment. For a simple hyporheic exchange system like an aquifer between the two rivers (Fig. R1), increasing HEF will increase the hyporheic area and promote the biogeochemical processes like DOC removal and nitrification, therefore plays a positive role with regards to groundwater quality.

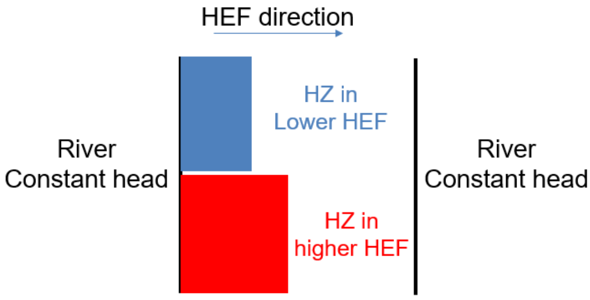

Figure R1, hyporheic exchange system between the rivers plot

However, for more complex aquifer systems when river stage fluctuations or river sinuosity are also present, the hyporheic exchange path could be extremely complex (see Fig. 4 of this study). The role of increased HEF would have both positive and negative effect on groundwater quality, depending on the time with respect to the river stage fluctuation (Derx et al., 2017; Gome-Velez et al., 2017) and location with respect to the river geometry (Gome-Velez et al., 2017; and this study).

According to the that comment, we have made more explanations about the effect of banks slope on groundwater quality.

Revision made: Please also see lines 566-575, and lines 621-626: "The vertical profile modelling study of Derx et al. (2014) suggested for riverbank restoration projects, increasing HEF by reducing the slope angle may have a negative effect on restoration. The mean RTD results of this study also suggest that the impact of bank slope on groundwater quality is determined by the location with respect to the meander (near point bar or cut bank)."

Comment 9. The authors should rewrite this entire section 4.2 with a sound logical reasoning and consider/discuss the following aspects in their argument:

- The effects of hyporheic exchange rate in addition to the associated effects of residence time on biogeochemical reactions.

- The effects of hyporheic exchange and residence time on denitrification rates, and possibly other important biochemical reactions controlling water quality.

- The effects on river water quality in addition to the effect on groundwater quality.

Reply: We have rewritten the Section 4.2.

Revision made: Please see the revised Section 4.2.

Comment 10. Line 34: 'This decreases': To what does "this" refer? Please rephrase and clarify.

Reply: We have rewritten this sentence.

Revision made: Please see lines 34-35: "Consequently, the impact of bank slope decreases the travel time of water discharging into the river relative to base flow conditions."

Comment 11. L. 36: 'More complex' : more complex than what? (see also my comment about comparisons under my major comment 2)

Reply: We have rewritten this sentence.

Revision made: Please see lines 35-39: "These findings highlight the need for (re)consideration of the importance of complex riverbank morphology conceptualization in numerical models when account for the HEF and RTD. The results have potential implications for river management and restoration and the management of river and groundwater pollution."

"

Comment 12. L. 104: 'will likely result in' = show? (use present tense) (with regards to the entire sentence, see also my comment about comparisons under my major comment 2)

Reply: We have rewritten this sentence.

Revision made: Please see lines 101-104: "Their results indicate that during a flood event the dynamic forcing greatly influences net HEF, the area of the HZ as well as mean RTD across different settings, whereby the aquifer transmissivity is one of the key parameters."

Comment 13. L. 115-116: What are 'globally spreading processes'? It is hard to imagine that riverbank erosion has global consequences. Please clarify.

Reply: We have rewritten this sentence.

Revision made: Please see lines 112-119: "However, riverbanks are usually sloping (inclined) rather than vertical (Liang et al., 2018) as they undergo erosion (by surface and subsurface water) and gravity collapse (Osma and Thorne, 1988; Fox and Wilson, 2010). Previous research has proven that bank erosion and bank collapse are controlled by various factors, such as initial bank slope angle (Zingg, 1940; Lindow et al., 2009), surface flow forces (Hagerty et al., 1995; Fox and Wilson, 2010), vegetation cover (Mayor et al., 2008; Gao et al., 2009; Puttock et al., 2013) and sediment properties (Millar and Quich, 1993)."

Comment 14. L. 130: analytical and numerical model solutions of what? Please clarify.

L. 130: 'therefore': The claim that Neglecting bank slope may have a significant influence on the prediction accuracy of HEF and RTD does not logically follow from the previous sentence. Please rephrase.

Reply: We have rewritten this sentence.

Revision made: Please see lines 119-122: "Previous studies have demonstrated that neglecting bank slope when modelling riverbank hyporheic exchange may have significant impact on model prediction accuracy (Doble et al. 2012a, 2012b; Liang et al. 2020) and RTD (Derx et al., 2014; Siergieiev et al., 2015) in an unconfined floodplain aquifer."

Comment 15. L. 141: 'evolution': I would avoid the term 'evolution' as a synonym for 'temporal change', since its formal definition is strictly biological. Here, but also elsewhere in the manuscript, the term is used incorrectly, as it does not even refer to a change in time. In this particular sentence, it refers to a change in in RTD in response to a change in aquifer transmissivity. Such changes only occur in model simulations and not in reality. Please use a different word for evolution in the entire manuscript.

Reply: Thank you for your suggestion. Although we would argue that the term "evolution" nowadays is being widely used to discuss temporal change/variability in research unrelated to biological aspects and used in similar studies in the past (e.g., Gomez-Velez et al., 2017; Singh et al., 2019; Botter et al., 2011; Nechita et al., 2023). We have replaced the "evolution" by "progression" throughout the paper according to the comment and have rewritten this sentence and replaced the word "varying" by "different" to avoid misleading.

Additionally, we would like to point out that evolution in our text had referred in many cases to the change in spatio-temporal progression of the infiltration front/flow field. Transmissivity is used here as one parameter to study the change of this flow field in space and time. This was done by conducting **different** simulations with the same model setup where the only parameter changed was the transmissivity. **However, within one model simulation transmissivity stays constant**! This way of using different model scenarios is a common way to study riverine settings with very different parameterization.

Botter, G., Bertuzzo, E., & Rinaldo, A. (2011). Catchment residence and travel time distributions: The master equation. Geophysical Research Letters, 38(11).

Nechita, M. T., Suditu, G. D., Puiţel, A. C., & Drăgoi, E. N. (2023). Residence Time Distribution: Literature Survey, Functions, Mathematical Modeling, and Case Study—Diagnosis for a Photochemical Reactor. Processes, 11(12), 3420.

Revision made: Please see the lines 139-143: "<u>In this study, we therefore quantify the effect of bank slope on the spatial extent (area) of the HZ in sinuosity-driven river meanders in response to a flood event and how it impacts the progression of HEF and RTD under varying aquifer transmissivity conditions to better understand lateral HEF through the alluvial plain.</u>"

<u>Comment 16.</u> L. 156: parameterization metrics = parameterization? (i.e. omit 'metrics').

Reply: We have deleted "metrics".

Revision made: Please see line 156.

<u>Comment 17.</u> L. 159: I would recommend writing out the abbreviation DGM (deformed geometry method) when used for the first time in the methods section.

Reply: We have defined DMG when used for the first time.

Revision made: Please see line 160-164: "<u>However, where their previous research assumed a vertical river bank for sinuosity-driven HEF, we consider a sloping riverbank and use the Deformed Geometry Method (DGM) approach to capture the dynamic progression of the surface water interface (SWI) along the river course.</u>"

Comment 18. L. 174 (Equation (1)): please explain M(t) directly underneath the equation (following the explanation of Y0(x)).

Reply: We have done the revision accordingly.

Revision made: Please see lines 178-183: "where $Y(x, t)$ [L] is the location of the SWI boundary while $Y_0(x)$ [L] is the initial location of the SWI. $M(t) = [h(t) - h(0)]/\tan(\delta)$ is the displacement of the SWI in *y*-direction due to river stage fluctuation and bank slope angle (see the horizontal distance between the vertical red and green solid line in Figure S2c). In contrast to the vertical riverbank models of Gomez-Velez et al. (2017), $M(t)$ is added in Eq. (1) to simulate sloping riverbank conditions.

"

Comment 19. L. 183: Provide a reference to COMSOL.

Reply: We have done the revision accordingly.

Revision made: Please see line 185.

Comment 20. Figure 1-3, 6-14: define t* in the main text as dimensionless time relative to the duration of the flood event. Use t* consistently without the formula in the figures.

Reply: We have done the revision accordingly.

Revision made: Please see the revised Fig. 1-3, 6-14 in the revised manuscript.

Comment 21. L 264: evaluate = evaluated (use past tense)

Reply: We have done the revision accordingly.

Revision made: Please see line 265.

Comment 22. Figure 3a: please use small letters when referring to the dimensionless times in figure 4

Reply: We have done the revision accordingly.

Revision made: Please see Fig. 3a in the revised version of manuscript at line 281.

Comment 23. Figure 4: In the figure caption, refer explicitly (i.e. in numbers) to the dimension times for figure a-e.

Reply: We have done the revision accordingly.

Revision made: Please see lines 292-295: "Plan view of the river channel and aquifer showing the temporal progression of the alluvial flow field and spatial extent of the HZ. (a)-(e) are snapshots of the flow field at different time steps (t^* = 0, 0.16, 0.39, 0.57, 1, 1.5) during the simulated event (pink dots in Fig. 3a)."

Comment 24. L. 385: Please rephrase the section title, since 'Spatiotemporal evolution of mean residence time distribution' is nonsense. It has multiple issues. First, it is totally unclear clear what is meant by both 'mean residence time' and 'distribution' (see also my major comment about the term residence time). Second, the term 'evoluation' should be avoided (see my above comment on L. 141).

Reply: Please see the reply for **Comment 8** and **Comment 15**.

Comment 25. Figure 8: In the figure caption, it should be mentioned that this is a plan view of the model area. With regards to 'mean residence time distribution', see my above comment about the section title.

Reply: We have done the revision accordingly.

Revision made: Please see lines 398-401: "Plan view of relative mean residence time distributions [-] for baseline flow conditions (no bank slope), which are represented by $\log_{10}\mu_\tau(\mathbf{x}, 0)/\log_{10}\mu_{\tau\text{-max}}(\mathbf{x}, 0)$ to show the distribution pattern. The value of the contour lines grows exponentially with the distance from the river meander.

"

Comment 26. L. 526-528: 526 'Furthermore, the stronger impact of smaller bank slope angles can both extend the time over which and increase the magnitude with which younger water was discharging along the downstream meander.' This sentence is incomprehensible. Please rephrase.

Reply: We have rewritten this sentence.

Revision made: Please see lines 527-529: "Furthermore, smaller bank slope angles can both extend the time that younger water is discharging along the downstream meander, and increase the difference in residence times of these younger waters between sloping and vertical conditions."

Comment 27. L. 570-572: The ranges of values of the first-order reaction rate constants reported by Hunter et al. (1998) refer to the different fractions of organic carbon with varying degrees of persistence and not on the spatial variation or site-specificness.

Comment 28. L. 572: ‘nitrite’: I assume that the authors mean nitrate here. If so, please correct.

Reply: Thanks for your suggestions. We have done the revision accordingly.

Revision made: Please see lines 581-584: “It has been documented that the BTS for dissolved organic matter (DOC) can vary over ten orders of magnitude (10^{-1} – 10^{9} d) (Hunter et al., 1998), while BTS for oxygen and nitrate have been found to vary over eight orders of magnitude (10^{-2} – 10^{6} d) (Gomez-Velez et al., 2012).”

Comment 29. L. 573: Investigated range of biogeochemical time scales (BTS) is not the full range of previously reported BTS’s but the overlapping part of the BTS’s. Please rephrase.

Reply: Thanks, We have done the revision accordingly.

Revision made: Please see lines 584-588:“Here, we compare the mean RTD within the overlapping ranges of these two BTS for vertical and sloping riverbank conditions ($\delta = 10°$) at the peak time of the flood event ($t^* = 0.25$) for different aquifer transmissivity conditions, and show the zonation of residence times by using a BTS range of 10^{-1} – 10^{6} d (Fig. 15).”

Comment 30. 30 Figure 15: In the figure caption, it should be mentioned that this is a plan view of the model area. Furthermore, unlike the previous figures with a plan view, in this figure the spatial scale matters as the temporal scale not dimensionless but expressed in days.

Reply: We have done the revision accordingly.

Revision made: Please see new sentence at lines 595-597: “Unlike the previous mean RTD figures in which the relative mean RTD expressed in dimensionless form, the spatial scales of mean RTD in this figure are dimensional in days.
”

Comment 31. L. 585: ’will impact’: use present tense.

Reply: We have done the revision accordingly.

Revision made: Please see line 598.

Comment 32. L 587-588: 'For sloping bank conditions, the reaction hotspots (areas) expanded into the aquifer': What are 'reaction hotspots? Moreover, this formulation seems to refer to a temporal change in the position of 'hotspots' under the condition of sloping banks. However, I think the authors mean that the hotspots are at a position further away from the riverbank compared to a steep bank. 'identical' = similar? Please rephrase.

Reply: We have rewritten this sentence.

Revision made: Please see lines 600-604: "The reaction hot spots (areas indicated by the overlapping BTS ranges) for sloping riverbank conditions expanded further into the aquifer compared with the vertical bank conditions, similar to the overestimated areas in Fig. 9 to Fig. 12. Note that we did not aim to include specific reaction models in our study but instead used mean RTD as an indicator for various biogeochemical reactions in the aquifer."

Comment 33. Figure 15 scale bar of spatial scale. In contrast to the other figure, does scale matter because of the dimension of the biogeochemical time scale (in days)

Reply: We have added text to explain the impact of spatial scale.

Revision made: Please see new sentence at lines 605-611: "Furthermore, the wavelength of the river sinusoid in Fig. 15 was λ = 40 m to offer a representative riverbank-aquifer condition. The zonation of BTSs for larger and smaller river sinusoid wavelengths will be reduced towards the river boundary or further expanded into aquifer, respectively, for both sloping and vertical riverbank conditions. Although the dimensional BTS for various spatial scales are not shown here, similar patterns between Fig. 9-12 and Fig. 15 imply the usability of the mean RTD results (Fig. 9-12) to infer on potential biogeochemical reactions."

Comment 34. L. 592: sloppy formulation. I cannot think of a mechanism that increases aquifer transmissivity, at least not at the time scales considered in this study. An increase in aquifer transmissivity can only occur in model simulations. Please rephrase.

Reply: We have rephrased this sentence accordingly.

Revision made: Please see lines 612-616: "The impact of bank slope on RT is basically controlled by aquifer transmissivity. For higher aquifer transmissivity conditions, the impact of bank slope appears to be more pronounced when the river stage rises during a flood event. For lower aquifer transmissivity conditions, bank slope seems more relevant for mean RTD after the flood event and its impact is more long-lasting."

Comment 35. L. 599-604: These inferences are platitudes; see also my major comment 3 about this section.

Reply: Thanks for your suggestion, we have re-managed this section.

Comment 36. L. 648: bank slope angle

Reply: We have revised this word.

Revision made: Please see line 674.

Comment 37. L. 649: What is reasonable river water infiltration? Please clarify or rephrase.

Reply: We have rephrased the word "reasonable".

Revision made: Please see lines 671-675: "However, in mountainous settings, slope angles are often much steeper due to erosion (here rivers incising into the bedrock) and further simulations are required to better understand the feedback between bank slope angle, hydraulic gradient and maximum extent of the unconfined layer allowing for hyporheic exchange processes."