Response to Comments from Referee #2

The authors present an extensive modelling study on the interplay between diurnal temperature effects and groundwater gradients on the dynamic evolution of the hyporheic zone in a river with a defined bedform topography. The hyporheic zone is a highly relevant transition zone controlling biogeochemical processes such as denitrification in streams (e.g., Gomez et al. (2015)). Therefore, the topic of the manuscript fits well with the scope of HESS.

The processes affecting the exchange between river water, the hyporheic zone and groundwater are highly non-linear and can lead to seemingly counter-intuitive effects. The authors build on previous work (e.g., Wu et al., (2020, 2018)) and a model to investigate the questions specific to this manuscript. In particular, they study how daily temperature fluctuations in a stream impact the hyporheic exchange and how it interfers with effects caused by dial fluctuations of groundwater fluxes caused by evapotranspiration or pumping.

The authors provide a broad range of data and results on the hyporheic water fluxes, temperature gradients and potential impacts on biochemical process rates such as denitrification.

The manuscript is interesting. But before it can be published I suggest major revisions for clarifying open issues and for improving the structure to enhance readability.

> **Response:** Thank you for providing such a comprehensive and thoughtful review on the manuscript. The authors appreciate the detailed comments and suggestions. Below please find the point-by-point reply to the comments. Changes that will be made in the manuscript after the online discussion are indicated by *underlined text in italic*. Line numbers in this response refer to the numbers in the original manuscript. Based on the comments and suggestions presented by the reviewer, we modified the structure of the manuscript, both for single paragraphs and entire section; additional explanations and figures were added to clarify ambiguities and uncertainties.

Major issues:

Improve readability The structure of the text is not always very reader-friendly. This means that it is not always easy to immediately understand and follow the logic of the arguments and results. This observation holds true for single paragraphs as well as for entire sections (e.g., the Result section). Often the starting point of an argument is not what is directly evident to the non-specialists but the necessary explanations follow only afterwards.

The text on L. 55 - 58 may serve as an illustrative example: The starting point is that there are diel fluctuations of hyporheic exchange and that they may interact with diurnal changes of groundwater fluxes. However, for the non-specialist regarding the hyporheic zone, the diel fluctions may not be evident. Hence, upon reading one stops and reflects why this should be the case. In the current manuscript, the explanation comes only afterwards. I suggest a different structure:

1. Daily temperature fluctuations in stream (every reader will know and agree)
2. This affects viscosity and hence hydraulic conductivity (the readers will follow)
3. This induces diurnal changes in hyporheic exchange as demonstrated in Wu et al. (2020) (the reader will believe this)
4. There are also diel fluctuations in groundwater fluxes for several reasons (readers will know and agree)
5. Therefore, there are two dynamic processes affecting the hyporheic zone and they may potentially interact in rather non-linear ways.

This is just an example but I suggest to pay due attention to this aspect because the authors claim (with good reasons) that hyporheic processes have wider implications. This means their paper should also be read by a wider audience in the hydrology and water resources management community. Accordingly, they should write the paper for such an audience and consider what to expect from such readers as starting points for presenting the arguments and results.

> **Response:** Thank you for suggesting a very clear outline for modifying the text. Indeed the ideas can be conveyed much more clearly with the suggested structure. We modified L.55-58 following the suggested outline as below:
>
> *River temperature often fluctuates with a clear daily cycle in response to the diurnal change in solar radiation (Caissie, 2006). This daily change in river temperature directly affects water viscosity and density, and subsequently the hydraulic conductivity of the sediment. As a consequence, hyporheic exchange*

rates often exhibit a diel fluctuation pattern due to the temperature-dependent hydraulic conductivity that governs the flow transport in the sediment. Wu et al. (2020) observe that hyporheic exchange fluxes inherit the daily-scale spectral signatures from river temperature fluctuations, and noticeably, however, these signatures are absent in river discharge of the studied site. This observation evidently indicates a strong control of the diel river temperature fluctuation on hyporheic exchange processes. However, the temperature-dependent diel rhythm of hyporheic exchange rates can be interfered by the daily groundwater table fluctuations due to evapotranspiration and anthropogenic pumping activities. Therefore, understanding the two players, namely daily groundwater hydraulic gradient change (as a result of daily groundwater table fluctuations) and diel hydraulic conductivity change (as a result of diel river temperature fluctuation), is important to characterize dynamic hyporheic exchange processes.

Model description There are several aspects of the model and its set-up that are not fully satisfactory:

1. *Model dimensions.* Given that the authors have used a 2-D model (L. 81), the model domain has to have dimensions along the x- and z-axes. Please provide this information (e.g., in terms of λ). Please demonstrate as well that this model set-up is a meaningful representation for the case study that represents a given real situation.

   Response: Thank you for this suggestion. *The streamwise length and the depth of the modeling domain are $L = 3\lambda$ and $d_{gw} = 5\lambda$, respectively.(added in Line 83)*

   To demonstrate if the model set-up is a meaningful representation, the following paragraph is added in section 4.5 “Study Limitation”:

   The morphological setting of the model is dune with aspect ratio of 0.1 under subcritical flow conditions with a Froude number around 0.39 (Bridge, 2009; Dingman, 2009). The geological setting has been simplified *as homogeneous and isotropic porous media. Even though the sediment in nature can rarely be homogeneous and isotropic, this simplification is necessary for improving computational efficiency without defeating the objective of identifying the interactions among river discahrge, temperature and groundwater dynamics.*

2. *Fig. 2.* At that point, the panels b and c are rather confusing. Panel a is very generic, but on the lower panels real dates are given and it is not clear to the reader what these values on the x-axes mean and why the are chosen. It is also obscure what the temperature represents. It takes a lot of reading until one can make the link to the case study and the respective observations.

   Response: Thank you for pointing out this issue. The dates in x-axes were chosen randomly with the objective of presenting the difference between the in-phase and out-of-phase scenarios. Because the groundwater flux was conceptualized as uniform sinusoidal curve, plotting it for a long period would make these two scenarios hard to distinguish. After plot experimenting, 10-day time window is appropriate to preserve the difference between the two scenarios. To clarify the meaning of the x-axes, the following sentences are added in the figure caption:

   Temperature time series are obtained from the U.S. Geological Survey (USGS, Site ID: 06893970). Groundwater flux is conceptualized as sinusoidal curves with varying amplitudes representing the strength of the groundwater upwelling or downwelling, and varying phases representing in-phase and out-out-phase scenarios. For figure clarity, a 10-day time window is selected arbitrarily from Jun 21 to Jun 30, 2017.

3. *Mass balance.* From Fig. 2 (a), it follows that the water balance for the model domain is given by $Q_{river-out}(t) = Q_{river-in}(t) + q_b(t)$. Based on how the boundary conditions are defined however, the water flow in the river is independent on the groundwater fluxes imposed (the flow simply follows from the prescribed $H_s(t)$ (Eq. 2, 3). Also the head distribution at the water-sediment interface is flux-

independent. However, this distribution was derived from empirical observations Elliott & Brooks (1997) without considering gaining or losing situations. This seems to be adequate as long as $U_s\ (t)\ H_s\ (t) >> q_b\ (t)\ L_{domain}$ with L_{domain} being the length of model domain. Please i) provide the evidence that this holds true for the case study and the dimension of the model domain, and ii) make these aspect also clear in the discussion. Actually, this aspect seems to emphasis the importance of the findings: even small groundwater fluxes may have a pronounced influence on the hyporheic zone. This may be evident to the authors, but I missed that point in the context of the entire paper.

> **Response:** This is a good point. We calculated the river discharge and groundwater discharge/recharge as the reviewer suggested. The results indicate that the river discharge is 4 orders of magnitude higher than the groundwater discharge/recharge (Figure R1), suggesting that ignoring the impact of groundwater flow on the head distribution at the sediment-water interface is a reasonable simplification. To address this issue in the manuscript, the following sentences are added in the Discussion 4.5 "Study Limitation":
>
> *In the present study, surface water flow is an independent system that is not affected by groundwater flows. However, in nature groundwater discharges into surface water under gaining conditions, and surface water recharges into groundwater under losing conditions. This simplification can only be used when groundwater discharge or recharge is significantly smaller than the river discharge. In our case, the groundwater discharge or recharge is at least 4 orders of magnitude lower than the river discharge. Therefore, this simplification has limited impact on the results. The notable difference in the magnitude between groundwater discharge/recharge and river discharge also emphasizes the finding that even small groundwater fluxes may have a pronounced influence on the hyporheic zone.*

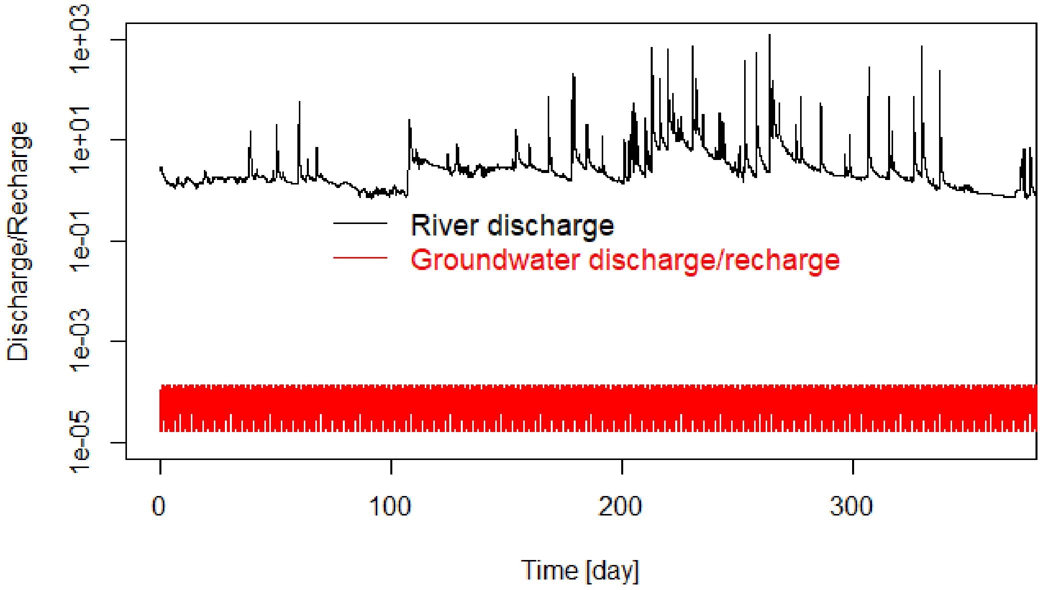

Figure R1: River discharge and groundwater discharge/recharge in logarithmic scale (log$_{10}$*[m*^{3}*/s]). River discharge time series are obtained from the U.S. Geological Survey (USGS) with the site no. 06893970 and observations in the year of 2015. Groundwater flux is conceptualized as sinusoidal curves with varying amplitude and phases. The groundwater flux presented here is with the highest amplitude among the three scenarios explored. The groundwater discharge or recharge is at least 4 orders of magnitude lower than the river discharge. Therefore, ignoring the impact of groundwater discharge on the surface water flow will not affect the results. Note that this figure is only used for review purpose.*

4. *Eq. 6a*. I could not find an explanation for a_0. It is tedious to go to previous publications and guess that $a_0 = 1$.

Response: Thank you for pointing out this problem. The following sentence is added in Line 125:

"the initial condition for the moments $a_0 = 1$*,…"*

5. *Model implementation.* Please provide some information on the model implementation (grid set-up, model version, run time etc.).

   Response: Thank you for this suggestion. The following information is added at the end of Method section:

   The flow and transport models described are solved with the finite element method implemented in COMSOL Multiphysics (version: 5.4) using a mesh with telescopic refinement near the boundaries and approximately 54,000 elements. The computation time for each scenario is around 60 hours.

6. *Defining the hyporheic zone.* It is unclear how the procedure described on L. 130 - 136 is actually implemented. First, because the hyporheic zone changes over time, the proposed procedure needs to be repeated, I assume. Can you comment on that? Second, for neutral and losing conditions, it seems that the threshold $C \geqslant 0.9C_s$ will eventually exceeded across the entire domain. Can you clarify?

   Response: Thank you for this question. *A no-reactive solute transport model is solved simultaneously as the flow transport model. The boundary of the hyporheic zone is renewed at every time point with the threshold $C \geqslant 0.9C_s$. Therefore, the boundary of the hyporheic zone is changing over time under varying flow conditions.(added in line 136)*

   For neutral condition, we think that the threshold may not be exceeded eventually because of the underflow (or baseflow) driven by the horizontal pressure gradient induced by the channel slope. This horizontal pressure can limit the hyporheic zone expansion under rising hydraulic gradient at the streambed. For losing conditions, it is true that the threshold will be eventually exceeded across the entire domain. Therefore, it is quite common to use reversed Darcy flow to define the hyporheic zone under losing conditions in order to track the subsurface regions that are really flushed by surface water. The results presented in the manuscript were not based on flow-reversed losing condition simulations. To find out the difference, we have re-run all the losing scenarios with flow-reverse. The results of exfiltrating hyporheic fluxes, temperature of exfiltrating hyporheic fluxes, and mean residence time distributions show nearly no differences compared with the results simulated without flow-reverse. Only the infiltrating hyporheic fluxes show higher fluctuation amplitudes. The figure below is the same as figure 5 in the manuscript but with simulated hyporheic fluxes using flow reverse (Figure R2).

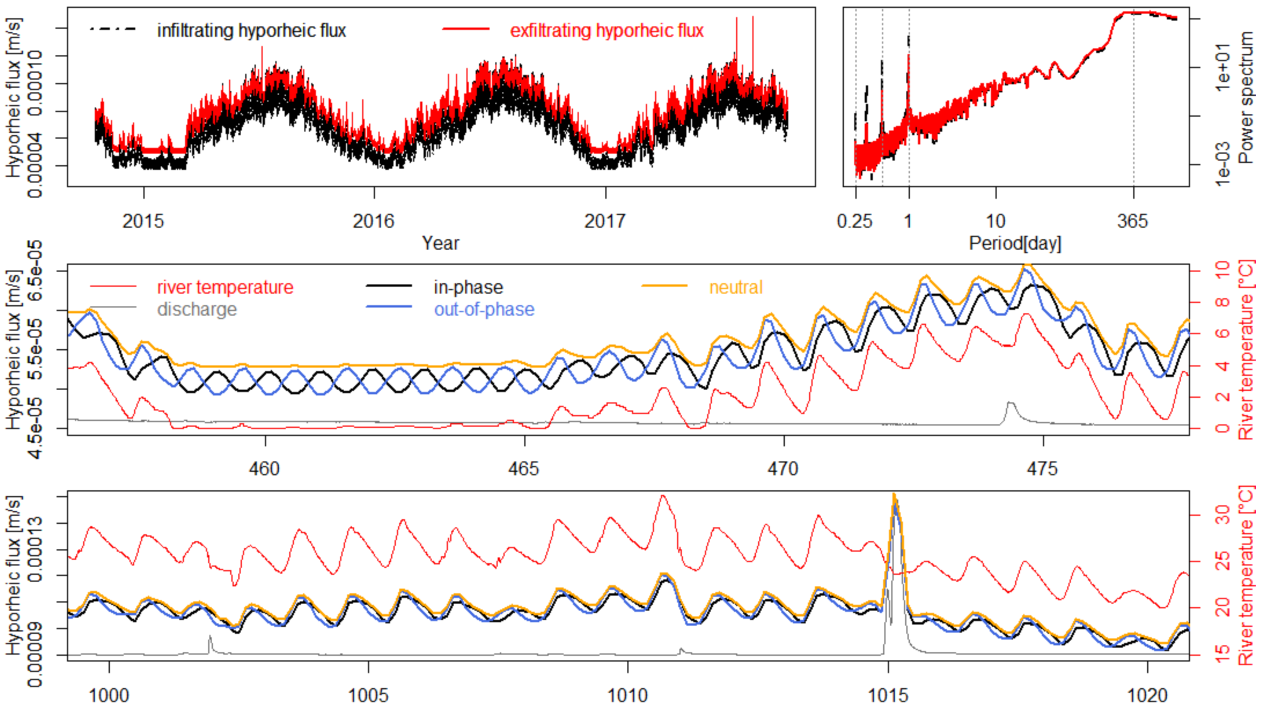

Figure R2: This is the same figure as Figure 5 in the manuscript but with simulations using flow reverse.

If strictly following the definitions from Triska et al. (1989) and Gooseff (2010), tracking HZs with flow reverse is not necessary for losing conditions. However, after some discussions we think that tracking HZs under losing conditions using flow reverse is more appropriate to identify the areas with the largest influence from the surface water. Therefore, we added more details for tracking HZ under losing conditions in the method section (Line 136):

With this condition, the threshold $C \geqslant 0.9C_S$ will be eventually exceeded across the entire domain under losing conditions. Therefore, hyporheic *zone is tracked using reversed Darcy flow in order to identify the areas with the largest influence from the surface water under losing conditions.*

Additionally, the Figure 5 will be replaced with the simulations results using reversed flow field as shown here in Figure R2.

Description of the case study This description is very superficial and has to be improved substantially.

1. *Site identification and description* Please provide more information on the site including the location and name. It is not necessary that every interested reader has to check the USGS website. Describe some key characteristics of the climate and hydrology of the catchment and the measuring site (altitude, mean discharge etc.). This is important to put the findings in a proper context.
   It is also essential to know which observation period was used for the simulations. One learns only at a later stage (e.g., from Fig. 3a) that three hydrological years seem to have been used.

   Response: Thank you for this suggestion. The following site description is added in Line 139:

   We use the observed river discharge and temperature measurements from USGS gauging station in Spring Branch Creek at Holke Road in Independence, Missouri (ID: 06893970, Lat 39°05’18”, Long 94°20’36” referenced to North American Datum of 1927). The station is on upstream left bank Missouri Highway 78 about 2.4 km above the confluence with the Little Blue River with a drainage area of 22 km^2. The observation period is from 2014-10-16 to 2017-10-16.

On L. 160, the amplitude of groundwater flux changes are linked to a range of the groundwater table fluctuations. Although a reference is provided, this is not sufficient. Boano et al. (2008) presents a general framework for linking stream-groundwater interactions and the influence on the hyporheic zone, but not any site-specific information for this case study. Describe the approach including the equations used and the model assumptions. In this context, it would be also useful to provide evidence that this assumed water table fluctuation is also reasonable for a hypothetical groundwater pumping operation.

Response: Thank you for the suggestion. The following paragraphs are added at the end of the section "Study Scenarios":

Boano et al. (2008) performed a number of simulations for different stream aspect ratios (the ratio between river half-width and river stage) and average slopes of the groundwater table, and found out that the upwelling velocity has a linear correlation with the slope of the groundwater table:

$$\frac{q_b}{K} = 0.57\frac{dh}{L_w}$$

Where q_b *is the groundwater upwelling velocity,* K *is the hydraulic conductivity which is* 10^{-3} *m/s in this study,* dh *is the head difference between river stage and groundwater table elevation,* L_w *is the half-width of the river channel which is 2.5 m.*

In the present study, we made use of this linear relationship to evaluate how much the head difference dh would change due to the daily groundwater level fluctuations. To achieve this objective, we made additional assumptions that the distance between the river bank and the hypothetical groundwater level observation point is equal to the river half-width, L_w*; and the slope of the groundwater table is less than 0.1. The average river aspect ratio in the model setting is around 25, which falls within the range of the explored aspect ratios in Boano et al. (2008).*

With the highest groundwater level fluctuation amplitude, q_b *varies daily from* 1×10^{-6} *m/s to* 9×10^{-6} *m/s, resulting in a change in the head difference dh of 3.5 mm. With the medium groundwater level fluctuation amplitude, the change in the head difference dh is 1.7mm. With the lowest groundwater level fluctuation amplitude, the change in the head difference dh is 0.8mm.*

The paragraph on L. 144 - 155 describes the *in-phase* and *out-of-phase* conditions. It might enhance the intuitive understanding for a general reader if the authors indicate more explicitly that the *out-of-phase* conditions represent the natural state with high stream temperatures and lower water table in the aquifer due to transpiration by the vegetation.

Response: Thank you for the suggestion. The following text is added in Line 152:

Under gaining condition, out-of-phase conditions represent the natural state that highest river temperature occurs at the lowest water table (resulting to lowest groundwater flow rate) in the aquifer due to transpiration by the vegetation; under losing condition, in-phase condition represents the natural transportation condition because the lowered water table results in larger hydraulic head difference between river and aquifer which contributes to the higher losing groundwater fluxes.

Result section: This section contains a lot of material (which is positive) but the way of presenting needs improvement. The more so because not all of the necessary results seem to be shown so far.

1. *Structure* One of the key messages of the manuscript is that there is an intricate interplay between the temperature regime, the flow regime of the stream and the water table fluctuations in the aquifer that needs to be understood. To be able to understand this, one has to get an overview about the general conditions prevaling at the study site during the period of interest. Therefore, I suggest to start with a short description of the key features of the three hydrological years.

   Subsequently, it helps the reader if the complexity is increased in a stepwise fashion. Therefore, I would first describe the results for the neutral conditions, then the losing conditions and finally the gaining conditions. Furthermore, I suggest to use explanations such as on L. 277 - 279 to frame the result section in a way that is intuitive also to the non-specialist reader.

   Response: This is a good suggestion for describing and organizing results with increasing complexity. The results section is re-organized following the suggested order. Changes in the whole section can be found later in the track-change manuscript. Here below we present only the part of hyporheic fluxes as an example:

In the observation period, the river discharge is intermittent and characterized by short recession periods (approximately from 2 to 1500 m^3/s); the river temperature shows clear seasonal variations (approximately from 0 to 35°C) and daily fluctuation. Mean annual precipitation at the gauge location is 106 cm. Average annual air temperature at the gauge location is 12.6 °C. There is no dams in the watershed.

3.1 Hyporheic Fluxes

3.1.1 under Neutral Condition

Under neutral condition, exfiltrating hyporheic fluxes (the red solid line in Fig. 3a) present similar temporal variations as infiltrating hyporheic fluxes (the black dotdash line in Fig. 3a). The diel fluctuations of exfiltrating hyporheic fluxes (the orange solid line in Fig. 3e and 3f) follow the diel river temperature fluctuations (the red solid line in Fig. 3e and 3f). In winter, when the river temperature (the red solid line in Fig. 3e) is relatively stable (around Jan 20), the exfiltrating hyporheic fluxes also have negligible daily fluctuations; when temperature gets higher, the exfiltrating hyporheic fluxes start to fluctuate following the diel fluctuations of river temperature.

3.1.2 under Gaining Conditions

Compared to neutral condition, groundwater upwelling leads to an increased daily fluctuations of exfiltrating hyporheic fluxes. Under gaining condition, exfiltrating hyporheic fluxes (the red solid line in Fig. 3c) present larger daily amplitude variations than infiltrating hyporheic fluxes (the black dotdash line in Fig. 3c). These observations are reflected in the frequency domain using power spectrum. For neutral conditions, infiltrating and exfiltrating hyporheic fluxes show similar spectral power on both annual and daily scales (Fig. 3b); whereas for gaining conditions, *the spectral power of exfiltrating hyporheic fluxes (the red solid line in Fig. 3d) at daily scales are markedly higher than the spectral power of infiltrating hyporheic fluxes (the black dotdash line in Fig. 3d).*

With gaining groundwater fluxes, the fluctuation pattern of hyporheic fluxes changes substantially. Even with negligible diel fluctuations of river temperature (around Jan 20), the exfiltrating hyporheic fluxes still present clear daily fluctuations following the groundwater drawdown as indicated by the opposite fluctuating patterns between the exfiltrating hyporheic fluxes under in-phase (the black line in Fig. 3e and 3f) and out-of-phase (the blue line in Fig. 3e and 3f) groundwater scenarios. When temperature gets higher, the groundwater table-drawdown induced hyporheic fluctuations are maintained. The exfiltrating hyporheic fluxes under in-phase scenario have an opposite fluctuation pattern with the exfiltrating hyporheic fluxes under out-of-phase scenario, river temperature and the exfiltrating hyporheic fluxes under neutral condition; the exfiltrating hyporheic fluxes under the out-of-phase scenario fluctuate following river temperature. It's worth noticing that the peaks of exfiltrating hyporheic fluxes under out-of-phase scenario are slightly higher than the peaks of exfiltrating hyporheic fluxes under in-phase scenario at a warm temperature (Fig. 3f).

On Jul 27, under the same flood event, which causes a discharge increase from 2 to 1500 m3/s *(the gray solid line in Fig. 3f), exfiltrating hyporheic fluxes increase much more under in-phase scenario (the black solid line) than under out-of-phase scenario (the blue solid line). The increase of exfiltrating hyporheic fluxes under in-phase scenario is nearly two times as high as the increase of hyporheic fluxes under out-of-phase scenario.*

To explore the impact of groundwater table fluctuation amplitudes on dynamic hyporheic responses, groundwater table fluctuations with three different amplitudes are applied to simulate hyporheic exchange processes under in-phase scenarios (as the groundwater scenarios plotted in Fig. 2b). With the reduced groundwater upwelling amplitudes, the amplitudes of exfiltrating hyporheic flux fluctuations are also reduced (Fig. 4a). More *than the amplitude reduction of exfiltrating hyporheic fluxes, with decreasing groundwater upwelling amplitude, the peaks of exfiltrating hyporheic fluxes (the black dash line, blue solid line and red solid line in Fig. 4b) are shifted towards the patterns which are more coinciding with diel river temperature fluctuations (the dash line in Fig. 4b) and hyporheic fluxes under neutral conditions (gray solid line). In other words, with decreasing groundwater table fluctuation amplitude, river temperatures exhibit stronger controls on the phase of hyporheic flux diel fluctuations.*

Effects of groundwater table fluctuation amplitudes on dynamic hyporheic responses are only explored under in-phase scenarios, because under out-of-phase scenarios, fluctuations of exfiltrating hyporheic fluxes are almost always in the same phase with the diel river temperature fluctuations. Therefore, unlike in-phase scenarios, the phase shifts due to reduced amplitudes in groundwater table fluctuation are not observed. Reduced amplitudes in groundwater table fluctuation under out-of-phase scenarios only contribute to reduced amplitudes in exfiltrating hyporheic flux fluctuations. For simplicity, only results in in-phase scenarios are presented.

3.1.3 under Losing Conditions

Differing from the gaining conditions, under losing conditions, the fluctuation amplitudes of exfiltrating hyporheic fluxes have not substantially increased compared with infiltrating hyporheic fluxes (Fig. 5a). This is also revealed in the frequency domain where the spectral power is similar between infiltrating and exfiltrating hyporheic fluxes across all temporal scales (Fig. 5b).

The river temperature also demonstrates different impacts under losing conditions. In winter, when the river temperature (the red solid line in Fig. 5c) is relatively stable (around Jan 20), the exfiltrating hyporheic fluxes under in-phase and out-of-phase groundwater drawdown conditions exhibit an opposite fluctuation pattern resulting from the different timing of groundwater table drawdown (black and blue solid lines). This observation is the same with gaining conditions (Fig. 3e). However, when *the river temperature gradually increases, the phase differences between the diel fluctuations of exfiltrating hyporheic fluxes under in-phase and out-of-phase scenarios are diminishing. In summer, when river temperature is relatively high, exfiltrating hyporheic fluxes under in-phase and out-of-phase conditions are fluctuating with almost the same phase with the river temperature (Fig. 5d). This observation is in great contrast to the gaining condition where the opposite fluctuation patterns between exfiltrating hyporheic fluxes under in-phase and out-of-phase conditions are kept from winter to summer (Fig. 3f).*

Unlike gaining conditions, on Jul 27 under the same flood event (the gray solid line in Fig. 5d), the increases of exfiltrating hyporheic fluxes under in-phase and out-of-phase scenarios are similar. These distinctions indicate a vastly different coupled flow and heat transport pattern between gaining and losing systems.

2. *Nomenclature* One of the confusing things is the terminology used for describing the hyporheic fluxes. Nowhere it is explained what actually meant by the infiltrating and exfiltrating hyporheic fluxes. For the neutral case, the two fluxes are identical, which makes sense. Under gaining conditions, the infiltrating flux is consistently larger than the exfiltrating flux. How is this explained and why is the same true for the losing conditions when there is a net flux from the river to the aquifer? Please clearly define the terms and explain the apparent contradictions mentioned.

Response: Thank you for asking this question. *With the dynamic hyporheic zone boundary defined at each time point, water flow into the hyporheic zone is defined as infiltrating hyporheic fluxes and water flow out of the hyporheic zone is defined as the exfiltrating hyporheic fluxes. (Added in Line 137)*

For the neutral case, even though the differences are trivial, we think the two fluxes are not identical due to the temperature-dependent fluid properties. If the geochemical definition of hyporheic zone is applied as in this case, these two fluxes might also be different due to the hyporheic zone boundary delineation. Under gaining conditions, the exfiltrating hyporheic fluxes show enhanced fluctuation amplitudes compared with the infiltrating hyporheic fluxes due to the additional fluctuations in the gaining groundwater fluxes that are mixed with the hyporheic fluxes that originated from the surface. Under losing conditions, since we reversed the flow directions when tracking hyporheic zone as discussed in the response to the comment "*6. Defining the hyporheic zone*", the results are difference than that presented in the manuscript. As indicated in the Figure R2, the infiltrating hyporheic fluxes have higher fluctuation amplitudes because there is no mixing exists in the exfiltrating hyporheic fluxes under losing condition as the mixing occurred under gaining conditions according to the geochemical definitions of hyporheic zones.

3. *Residence times* The method sections describe how to estimate time variable residence times in the hyporheic zone. Despite of using an average value for calculating the reaction significance factor RSF, no data on residence times are provided. This is essential if one would like to be able to evaluate the relevance of the results for any biological or bio(geo)chemical processes. Provide the results on the time-variant residence times and how they change upon the different boundary conditions.

   Response: Thank you for this suggestion. The calculation of RSF is explained in the response to the comment below. We will add the residence time data in the supplementary information.

4. *RSF* First of all, this approach has not been introduced so far. It should be mentioned in the Introduction when introducing the denitrification topic and described in the method section. Apart from that I am not sure whether the chosen form is an adequate implementation of the concept. I have three question marks:

   Response: Thank you for the comment. The equation of RSF was introduced in the results section 3.3. However, as the reviewer pointed out, it is better to introduce in the Method section. Therefore, we move line 253 to 260 to

Method where a new section is added “2.4 Reaction Significance Factor” and following sections are moved following the new section numbering.

(a) The first relates to q_{HZ} because I could not follow what this term actually represents (see above: how does it relate to infiltrating and exfiltrating fluxes?).

Response: Please refer to the response to the comment above.

(b) Why is the mean residence time used for calculating a time-variant quantity such as RSF when residence times were derived as a function of time? Depending on the temporal correlation functions between the relevant hyporheic flux q_{HZ} and the residence times τ_{HZ}, there might be substantial deviations from the current version.

Response: Thank you for asking this important question. To be more precise, it is the mean of the probability distribution of the residence time in any given time point. To clarify the meaning of τ_{HZ}, the following sentence is added in Line 258:

τ_{HZ} is the mean of the probability distribution of the residence time at any time point [T].

(c) The time scales of denitrification. First, the description of how τ_{HZ} was parameterised is insufficient. Which quantiles in Gomez et al. (2015) do you refer to? Second, denitrification depends very much on temperature (e.g., Boulêtreau et al. (2012)). This implies that τ_{dn} is not constant. Given that the manuscript deals with temperature as a key influencing factor, it would seem logic to consider such a temperature dependence also for τ_{dn}. At least one could test the sensitivity of RSF against the temperature dependence of denitrification.

Response: Thank you for these suggestions. Firstly, to better present the values of τ_{dn} we will add the following figure in the supplementary information to show the quantiles of the characteristic time scales for denitrification.

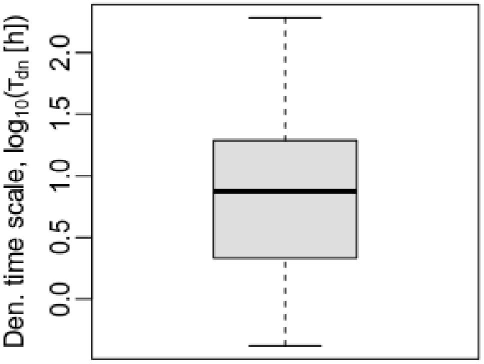

Figure S1: Box plot of the characteristic time scale for denitrification ($\log_{10}$[h]). The 25th quantile is 0.38, the 50th quantile is 0.87, and the 75th quantile is 1.28. (Taken from Gomez-Velez and Harvey (2014) and Gomez-Velez et al. (2015))

The second suggestion is also a good point. We add the following text to clarify in the manuscript in Line 371:

The temperature-dependence for τ_{dn} is not considered, however we use both the 25th and 75th quantiles as the lower and upper ranges for calculating RSF, which should include the variations caused by the changing temperature as indicated in Zheng et al. (2016) where a roughly five-fold increase was observed in denitrification rates when temperature increased from 5 °C to 35 °C.

What the reviewer suggested is definitely a better solution which we would like to test with a model including temperature-dependent denitrification process in a systematic way and to present the results in the future study.

5. *Plausibility check against empirical data* One of the values of such a model study is the possibility to study processes and their interactions under well defined conditions and to explore system behaviours that are otherwise impossible to obtain. This comes at the costs of the difficulty to relate the model findings and insights back to the real world. To improve on that the authors should provide more context on the case study (see above). On the other hand, they should also

add some comparisons of model results with empirical observations to provide some plausibility checks. Possibilities for doing so would for example be the extent of the hyporheic zone, residence times (both not even shown for the model results, see above) or RSF values as depicted in Fig. 8. Such values could for example be compared to estimates provided by Gomez et al. (2015).

> **Response:** We agree with the reviewer. The dimensionless RSF serves as a appropriate metric that can be used for comparisons with the other observations. Note that Gomez et al. (2015) only presented total RSF for denitrification (given by the sum of the vertical and lateral RSF), therefore we compared our results with Harvey et al. (2018) where RSF for riverbed induced hyporheic exchange was calculated. The following text is added in Line 367:
>
> *In Harvey et al. (2018), RSF was calculated with mean annual hyporheic flux and river discharge without considerations of the temporal variability of the flow conditions. To be able to compare with the results, we also calculated mean RSF using mean river discharge and mean hyporheic fluxes. The calculated mean RSF is approximately from -2.7 to -1.8 for gaining condition and -5.8 to -4.8 for losing condition, which falls within the range of the mean RSF observed in Harvey et al. (2018).*

Detailed comments:

L. 18 - 19: Why is this understanding *key to water resources management*? There are many aspects relevant for water management (land use management, hydropower generation schemes etc.). Please be more specific for aspects this understanding is key and why.

Response: Thank you for this question. This sentence is rephrased as below:

Understanding the spatiotemporal variability of hyporheic exchange processes is key to characterizing the nutrient cycling and river ecosystem functioning (Lewandowski et al., 2019)

L. 23, 26 and elsewhere: Articles or pronouns are missing sometimes. Please have a linguistic check.s

Response: Done as suggested.

Fig. 4: Explain the time axes and give a reason why only that part of the entire study period is displayed? It seems to be rather arbitrary. Are the results from the *in-phase* or *out-of-phase* simulations?

Response: The results are selected arbitrarily with the considerations of figure clarity. 10-day time window was selected, because longer time window makes the plots hard to distinguish. Effects of groundwater table fluctuation amplitudes on dynamic hyporheic responses are only explored under in-phase scenarios, because under out-of-phase scenarios, fluctuations of exfiltrating hyporheic fluxes are almost always in the same phase with the diel river temperature fluctuations. Therefore, unlike in-phase scenarios, the phase shifts due to reduced amplitudes in groundwater table fluctuation are not observed. Reduced amplitudes in groundwater table fluctuation under out-of-phase scenarios only contribute to reduced amplitudes in exfiltrating hyporheic flux fluctuations. For simplicity, only results in in-phase scenarios are presented (Line 210-215).

Fig. 6: Unfortunately, one can hardly see the differences between *a* and *b* or *c* and *d*, respectively. One option could be to show the respective difference plots and to add difference plots for the fluxes.

Response: Thank you for pointing out this issue. We will remove this figure and add a GIF figure in the supplementary information to better present the differences in the heat transport dynamics under different hydrologic conditions.

Fig. 8: Add the year to the time axes and explain why this specific period was selected.

Response: The year 2017 is added. The results are selected arbitrarily with the considerations of figure clarity. The full results time series will be added in the supplementary information.

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