Anonymous Referee #2

The manuscript addresses the transport of nitrogen in river networks, and proposes an extension of the SWAT model that includes water exchange and biogeochemical reaction in the hyporheic zone. The model is applied to the watershed of the Columbia River. Proposing an extention of SWAT that includes the effect of hyporheic process is a valuable contribution to research in solute fate in catchments, as catchment-scale models usually do not encompass these processes. However, additional efforts are needed to clarify some methodological parts. The main issues are described below.

Response: We thank the reviewer for recognizing the value of our work and the constructive comments to improve our manuscript.

Main comments:

- ROLE OF GROUNDWATER: Vertical upwelling of groundwater through the hyporheic zone and to the stream seems not to be included (see detailed comments, line 205). The contribution of groundwater as lateral flow should be better explained (206). USE OF RESIDENCE TIME DISTRIBUTION: the authors explore the impact of using a distribution of residence time instead of an average value. This is a valuable attempt, but the way these distributions are chosen is unclear (251, 305).

Response: We apologize for the incomplete description of the boundary conditions and they will be added in the detailed comments below.

The details of how the residence times were chosen based on a given distribution is shown below:

we assume equal fraction for each sub-storage zone, i.e., a vertical or horizontal storage is evenly divided into N_s sub-storage zones.

To extract N_s residence times for the sub-storage zones in a given HZ with mean residence time τ_m, we use the exponential distribution ($P=1-e^{(-\tau s/\tau m)}$). We have one distribution for the vertical HZ and one for the lateral HZ, with means equal to the vertical and lateral residence time calculated from NEXSS. N_s discrete residence time values with their corresponding probability were then extracted from this distribution for both HZs. For example, if N_s = 10, the fraction of each sub-storage zone is 0.1. The average residence time of each sub-storage corresponds to a value with probability less than or equal to 0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, and 0.95, respectively. The minimum and maximum residence time are discrete values that are less than or equal to the given probability of 0.05 and 0.95, respectively. The maximum residence is interpolated from equation $1-e^{(-\tau s/\tau m)}= 0.95$. The other discrete residence times are similarly solved.

Detailed comments:

line 205 "the bottom boundary has a prescribed flux" -> how is it chosen? Is it equal to zero?

Response: The bottom boundary is defined as $q_u \approx 0.57K\, J_y$ (Boano et al., 2009), where J_y is the mean head gradient across the alluvial valley.

Boano, F., Revelli, R. & Ridolfi, L. Quantifying the impact of groundwater discharge on the surface–subsurface exchange. Hydrol. Process. 23, 2108–2116 (2009)

206 "flow is solved by the vertically integrated groundwater flow equation with the Dupuit–Forchheimer assumption" -> for consistence, I suggest to briefly state boundary conditions also for determining lateral flow.

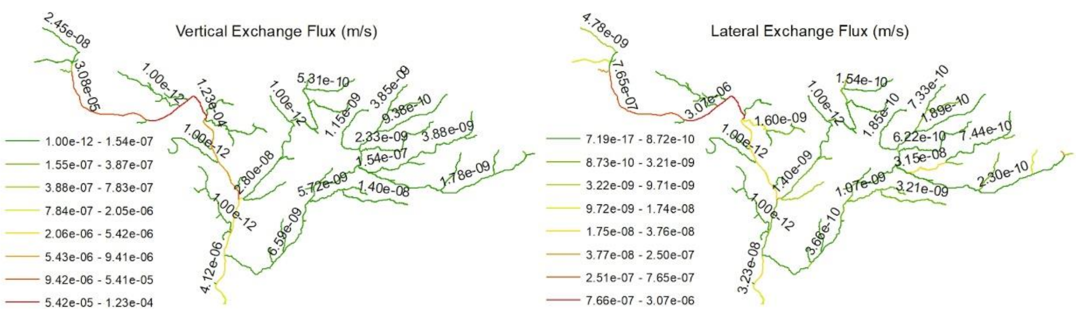
Response: The boundaries are stated below:

Following Gomez et al. (2012), the river is conceptualized as sinusoidal with wavelength λ [L] and amplitude α[L]. A prescribed hydraulic head $\psi_s(x) = \psi_0 + (J_x/\sigma)(s(x)$ is assigned along the river stretch, where ψ_0 [L] is the elevation of the free surface elevation at the downstream end of the river above the horizontal bottom, s(x) [L] is the arc length along the boundary, $\sigma = s(\lambda)/\lambda$ is sinuosity, J_x is the mean head gradient along the valley in the downstream direction. The boundary at a distance λ from the channel axis has a prescribed head $\psi(x,y = \lambda) = J_x x + J_y \lambda$, where Jy is the mean head gradient across the alluvial valley. The upgradient and downgradient boundaries of the domain along the reach are assumed periodic with a prescribed head drop $\psi(x = 0,y) = \psi(x = 2\lambda,y) - 2\lambda J_x$.

Gomez, J. D., J. L. Wilson, and M. B. Cardenas (2012), Residence time distributions in sinuosity-driven hyporheic 407 zones and their biogeochemical effects, Water Resources Research, 48, W09533, doi:10.1029/2012WR012180.

230 "Compared to other reaches in the watershed, the Columbia River is characterized by relatively larger exchange flow" -> Fig. 3 shows exchange flow values up to the order of 100 m3/s (vertical flow) and 1 m3/s (lateral flow). These values are extremely high and deserve some explanation on why they are considered realistic. It is possibly that they occur only on very long reaches, but I would check this and verify the values of flux per unit area that provide values whose magnitude can be more easily assessed.

Response: The relatively larger exchange flow is mainly due to the large size of a reach. We replotted Fig. 3 c,d as the values of flux per unit area for easy assessment as shown below.



247 "only one exchange rate [...] for each zone" -> I would state more clearly that two zones are used to represent vertical and lateral exchange, as it comes out later.

Response: Yes, two zones are used to represent vertical and lateral exchange. Thanks for the suggestion.

251 "1) replacing the residence time and exchange flux with those predicted by NEXSS using seasonal flow conditions; 2) replacing the single storage zone in vertical and lateral with sub-storage zones within a storage zone, assuming a distribution of residence time [...]" -> a few additional words would make easier to understand how these scenario have been built. Specifically, I recommend to specify 1) which "seasonal flow conditions" have been considered and 2) how the characteristics of the "distribution of residence time" have been determined. There is a mathematical explanation for it, but it is unclear how the specific values of tau_s,j have been chosen. At present, some of (but not all) these information are provide in sections 4.3 and 4.4 of the Results' section, but they would better located here rather than among the Results. Alternatively, is should be at least anticipated that they are reported later.

Response: For the seasonal flow conditions, NEXSS model was run 12 times using mean monthly streamflow conditions. The exchange fluxes and residence times now change monthly instead of being constants throughout the whole simulation

Please see the detailed description of how specific residence time have been determined in the response to the main comments above.

288 "It's not true [the fact that lateral HZ are in dynamic steady state] for RCH77 and RCH88 as their exchange flows are much smaller" -> why only these reaches? RCH67, 53, 93, 100 and 101 all exhibit the same behavior.

Response: Thanks for catching this. After careful checking, a bug was found and fixed in the code. The bug mainly affects the magnitude in the lateral HZ, not the overall observations in the original manuscript. We corrected the figure and the statement:

They are also in dynamic steady state with the lateral HZ for reaches RCH27, RCH24, RCH28, and RCH20, RCH77 and RCH88 suggesting that lateral exchange can be important too. It's not true for RCH77 and RCH88 RCH53, RCH67, RCH93, RCH100, RCH101 as their residence times are much longer.

Line plots in Figures 4, 5C,D, 6, 8 are corrected. Please find the updates at the end of the response.

Fig. 5, caption: it should specified that this is the MRMT scenario. Same for other figures.

Response: Specified as:

Figure 5. Nitrate concentration in the stream and HZs along the Columbia River using MRMT.

Figure 8. Nitrate concentration in the stream and vertical HZ at RCH27 (a),(b) and at the outlet (c),(d) with and without HZ perturbation using MRMT+BGC

305 "Using exponential residence time distribution and 20 sub-storage zones, we had multiple rates based on the mean residence time from NEXSS. Assuming the exchange flux from the NEXSS estimation is equally distributed in each sub-storage zone, the residence time for each sub-sotrage zone is calculated using Eq. 12." -> this explanation is unclear. How has each residence time estimated with NEXSS (denoted here as T) transformed into multiple (20) residence times? From this description I imagine that for each zone an expontial distribution with mean equal to T was defined, and then 20 values with their corresponding probability were extracted from this distribution. Anyway, this is not fully clear from the text, and in any case many details are missing (e.g., how was the maximum residence time chosen?). I strongly recommend to provide more details about this part as it is fundamental to obtain a representative distribution of residence times. As a further notice, the choice of equally distributed fluxes is simple but debatable, as it is known from the classic theory of Elliott and Brooks (1997) that exchange flowpaths with higher fluxes penetrate deeper in the streambed and are hence characterized by longer times. I am unsure if this would entail a significant difference, but if it is feasible I recommend verifying the impact of this assumption.

Response: Thanks for the suggestion and the reference. Please see the response to the main comment on how to choose residence times.

We ran another simulation assuming higher exchange fluxes are associated with longer residence times and compared the impact of flux distribution based on different assumptions. Nitrate removal due to denitrification in the HZs can be significantly reduced if larger flux associated with longer residence time is assumed compared to that with the assumption of equally distributed fluxes.

307 "sotrage" -> "storage"

Response: Thanks for the correction!

307 "Simulation with multiple exchange rates within each storage zone showed less removal of nitrate in the stream through microbial respiration in the HZs compared to the single-rate simulation (Fig. 7)." -> as far as I can see by eye, the difference is rather small. If so, I would mention it.

Response: Agreed.

Fig. 6: because all these scenarios include biogeochemical reactions, I recommend labeling them coherently, i.e., MRMT+BGC, SEASONAL MRMT+BGC.

Response: Thanks for the suggestion.

318 "high stream nitrate concentration than those shown in the bASE case can occur" -> is this a regular feature or has it only been observed occasionally?

Response: It seems to be a regular feature based on limited samples at a location close to the outlet.

319 "bASE" -> "BASE"

Response: Thanks for the correction.

325 "nitrate coming from these wasteways will exchange in the HZs in a short time and will not be expected to have a big impact on surface water quality" -> the link between residence time and impact on water quality is not so evident. What is clear from fig.10 is that in this reach HZ and river concentrations exhibit syncronous variations, as already expected from the previously shown results. I understand that if the residence time in the HZ is large enough then the increase in NO3 concentration due to the point source can be buffered and possibly attenuated, but the comments here do not clarify this well enough.

Response: Shorter residence time results in faster nitrate exchange rate (which is the inverse of residence time) between the stream and HZ. Faster exchange rate drives more stream nitrate into the HZ if stream nitrate concentration is high and increases the nitrate concentration in the HZ, which then increases the denitrification rate or nitrate consumption rate in the HZ. It can be better explained by the total nitrate consumption in the HZ.

341 "our simulations show that HZs can attenuate the peak nitrate concentrations in the stream" -> it would be useful to report a quantative assessment (e.g., concentration reduction between xxx and yyy %) instead of just sending back the reader to fig.4.

Response: There was a 11.6% of concentration reduction on average compared to the base case without MRMT.

375 "limations" -> "limitations"

Response: Thanks for the correction!

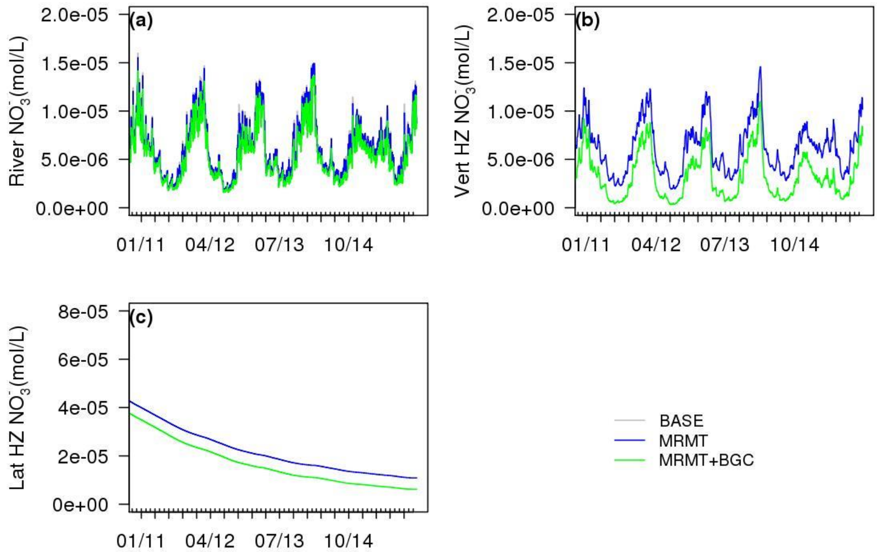


Figure 4.

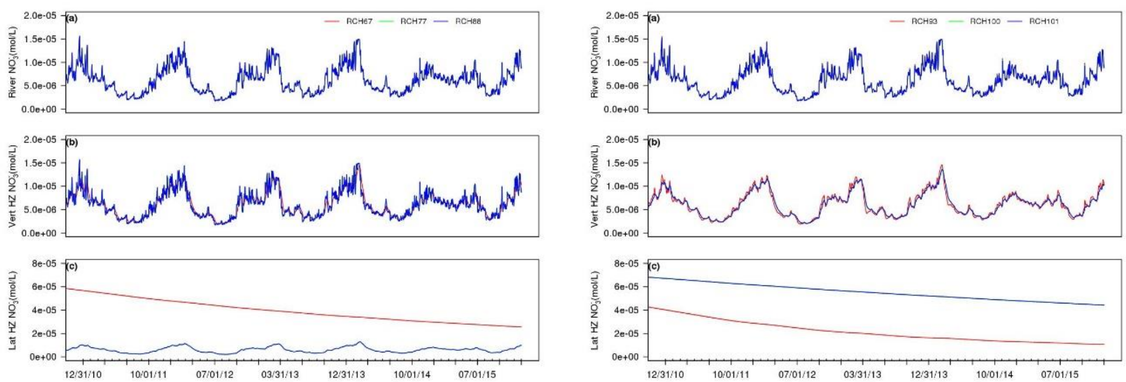


Figure 5C,D

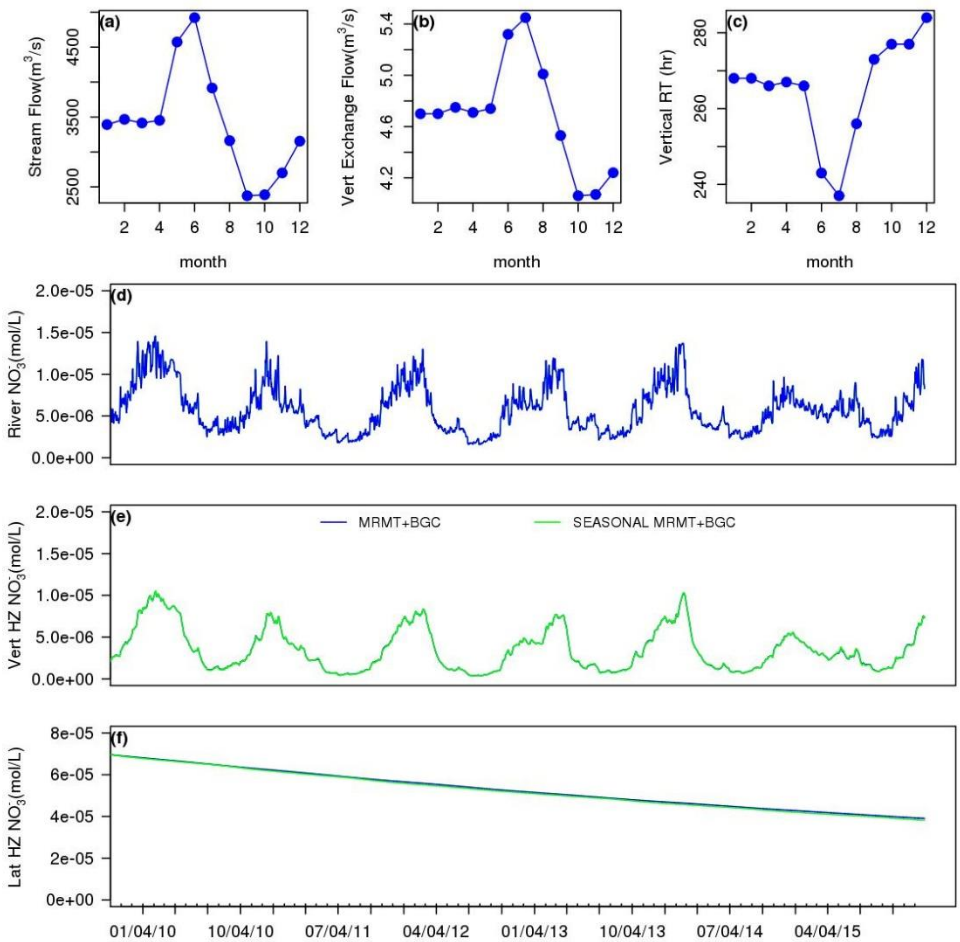
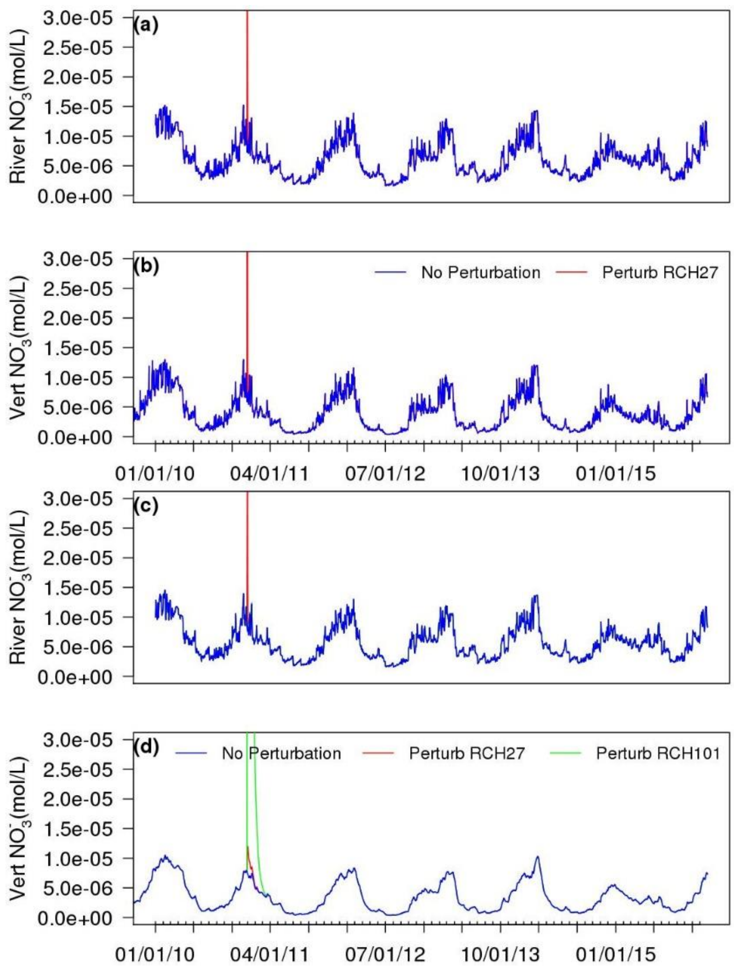

(a)
(b)
(c)
Stream Flow(m^3/s)
Vert Exchange Flow(m^3/s)
Vertical RT (hr)
month
month
month
(d)
River NO_3^-(mol/L)
(e)
MRMT+BGC
SEASONAL MRMT+BGC
Vert HZ NO_3^-(mol/L)
(f)
Lat HZ NO_3^-(mol/L)
01/04/10
10/04/10
07/04/11
04/04/12
01/04/13
10/04/13
07/04/14
04/04/15

Figure 6



(a)
River NO$_3^-$(mol/L)
(b)
No Perturbation
Perturb RCH27
Vert NO$_3^-$(mol/L)
(c)
River NO$_3^-$(mol/L)
(d)
No Perturbation
Perturb RCH27
Perturb RCH101
Vert NO$_3^-$(mol/L)
3.0e-05
2.5e-05
2.0e-05
1.5e-05
1.0e-05
5.0e-06
0.0e+00
01/01/10
04/01/11
07/01/12
10/01/13
01/01/15

Figure 8