Response to Comments from Referee #1

General Comments

- This paper investigates how hyporheic flow redistributes regional discharge at the scale of riverbeds in a case study and discusses the implications for the fate and transport of radionuclides from deep nuclear waste depositories. The study involves a multiscale flow and transport modelling framework and a rather sophisticated analysis of model outputs.
  The main result (fragmentation of the regional discharge by hyporheic flow) is rather intuitive and could already be anticipated by looking at Tóth (1963) flow fields. This takes nothing away from the merit of the study, which achieved a proper demonstration and quantification of this phenomenon in a realistic example. Therefore, I recommend publication without any doubt.
  The main issue I found is that the paper lacks a number of explanations (see below), but I am sure the authors can improve on this aspect.

We are grateful to the referee for the positive feedback on the paper. The paper is consistent with the hierarchically nested groundwater flow cells first described by Tóth (1963). However, as an expansion of the work of Tóth (1963), the geological heterogeneity of the subsurface (soil type and stratification) as well as the difference in boundary conditions in re- and discharge zones were taken into account. In particular, different boundary conditions representing flowing surface water, groundwater table topography and recharge-controlled boundary conditions were applied in discharge and recharge areas of the top surface of the catchment-scale numerical model. This required a consideration of the interaction between the nested groundwater flow systems across spatial scales and variation in boundary conditions. A detailed reply to the comments of the referee is provided below. The paper will be revised after the online discussion, in which the changes are indicated by *underline text in italic*.

Detailed Comments

- L51-56: I am not sure that velocity is the most relevant indicator for what you are trying to convey here. In fact, all the flow paths end up having similar velocities when approaching discharge (Cardenas and Jiang, 2010; Zijl, 1999; Zlotnik et al., 2011). Instead, I would think that the ratio of hyporheic flow (i.e., its total flow rate) to that of regional flow is more relevant in this discussion.

Thanks for the comment. The section will be revised as follows:

> *Values founds in the literature indicate that the ratio of regional groundwater flow to hyporheic exchange flow in the streambed sediment is in the range of 10^{-2}-10^{-4} (Bhaskar et al., 2012; Goderniaux et al., 2013; Gomez-Velez et al., 2014).*

- L59: I guess you mean "principal effects" and not "principle effects".

Thanks for the comment. That is correct. The term will be corrected in the revised paper.

- L62-64: The sentence is grammatically incorrect.

Thanks for the comment. The sentence will be revised as follows:

> *We hypothesize that hyporheic fluxes significantly influence the discharge of deep groundwater into streambeds, reflecting the fact that hyporheic fluxes, in combination with other factors (such as landscape topography, geology, and climate), control groundwater discharge at the scale of the watershed.*

- L110: This section should be better put before the description of the models.

Following the referee's suggestion, the section will be placed at the beginning of the "Methodology" section (before the description of the models) in the revised version of the paper.

- L111-114: A situation map would be useful (I would suggest including Figure S1 here).

A map of the study's catchment (Figure S1 from previously submitted supporting information) will be added to this section.

- L129: This sentence is unclear. I guess you mean: the mean annual runoff estimated from the stream discharge measurements was set as the infiltration (please correct if needed).

Thanks for the comment. The sentence will be revised as the referee suggested.

- L129: Is it reasonable to neglect overland flow in your study area (you may be overestimating infiltration)?

Thanks for the comment. Basically, overland flow occurs when the rainfall intensity exceeds the hydraulic conductivity of the saturated soil. The mean annual runoff (i.e., 400 mm/year), estimated from the precipitation data of the Krycklan catchment, is 1.27×10^{-8} (m/s), which is significantly lower than any plausible value of the hydraulic conductivity of the land surface in the boreal forested catchment. The following text will be added to the paper to address the referee's comment:

> *The infiltration rates in boreal forested catchments are generally higher than the precipitation rate, especially when the yearly average precipitation is used (Diamond and Shanley, 2003; Laudon et al., 2007). Hence, the mean annual runoff estimated from precipitation data was set as the infiltration rate (i.e., 400 mm/y was used as the estimated runoff value, provided by ©Swedish Meteorological and Hydrological Institute, SMHI; whereas the remaining precipitation, 214 mm/y, was used as the evapotranspiration rate (Karlsen et al., 2016)).*

- L129: Can you indicate the calculated infiltration rate?

The estimated infiltration rate provided by ©Swedish Meteorological and Hydrological Institute (SMHI) will be added to the following sentence:

> *The mean annual runoff estimated from the precipitation data was set as the infiltration (i.e., 400 mm/y, as provided by ©Swedish Meteorological and Hydrological Institute, SMHI; the remaining precipitation, 214 mm/y, was used as the evapotranspiration rate (Karlsen et al., 2016)).*

- L161-162: I suggest referring to Haitjema and Mitchell-Bruker (2005) in support of this sentence.

Thanks for the suggestion. The suggested reference will be added to this sentence.

- L162-164: I suggest referring to Bresciani et al. (2016a, 2016b) in support of this sentence.

Thanks for the suggestion. The suggested references will be added to this sentence.

- L166-173: This only makes sense if hydraulic head is specified and equal to the topography along the top boundary, but you just said above that you are using a recharge condition, so I am lost here.

Mojarrad et al. (2019) indicated that the topography-controlled boundary condition is predominant in the Krycklan catchment. Therefore, topography was used as the main constraint of the top boundary condition in this study. However, the boundary condition should not result in a higher infiltration rate than the excess precipitation and, thus, the infiltration rate must be considered as an additional constraint in recharge areas. One way of achieving this goal (satisfying the infiltration rate) is to only smooth the topography DEM resolution over the groundwater recharge zones to represent the recharge-controlled boundary condition (Marklund and Wörman, 2011; Wang et al., 2018), while maintaining the high resolution of the DEM file over the discharge areas to represent the topography controlled case. As a consequence, both the recharge- and topography-controlled boundary conditions were used in our groundwater model.

We have clarified the sentence,

"The applied method helps to satisfy both the Dirichlet and Neumann boundary conditions through a practical way of recognizing an unknown and spatially variable infiltration."

as follows in the manuscript:

"*The applied method implies that the numerical solution is formally derived using a constant head (Dirichlet boundary condition) at the groundwater table, but the smoothed boundary also satisfies the limited infiltration (Neumann boundary condition).*"

- L134-185: What are the horizontal limits of the domain?

The horizontal limits of the domain will be presented in the paper as follows:

The bounding rectangle of the Krycklan catchment (i.e., 11.6 × 10.3 km^2) was set as the horizontal limit of the numerical model's domain (64°11.8´N-64°17.6´N, 19°39.5´E-19°54.3´E).

- L194: I do not understand the meaning of "$C_{damp}(\lambda_i)$". Is C_{damp} a function of λ_i (I would think not since C_{damp} seems to be treated as a constant)? And if it is, shouldn't it be λ_{ij}?...

Thanks for the insightful comment. The results of previous studies (Morén et al., 2017; Mojarrad et al., 2019) show that the hydrostatic damping factor (C_{damp}) of the stream's surface, resulting from the independent spectral analysis conducted in 1D, is a function of wavelength (λ). In particular, the results of a field investigation conducted by Morén et al. (2017) indicate that the damping factor is close to 1 for topographic wavelengths greater than 300 m, and that it decreases to 0.3 for wavelengths of around 5 m. Therefore, the damping factor should have been written as $C_{damp}(\lambda_{i,j})$, but it only varies with index i, and considered as constant with index j. Equation 5 and the notation for the damping factor will be corrected throughout the paper. The following text will also be added to the revised version of the paper to address the referee's comment:

$C_{damp}(\lambda)$ is the hydrostatic damping factor representing the smoothness of the water's surface in comparison to the streambed surface, which has been shown to be a function of wavelength (Morén et al., 2017). In the present study, $\lambda_{i,j}$ was used as the wavelength in the x and y directions, but it should be noted that the damping factor only varied with an index i, and was treated as a constant with index j.

- L206-216: How does this relate to the previous paragraph?

The high-resolution streambed topography data required for hyporheic modeling were not available. However, the fractal pattern of the topography's fluctuation allows us to rescale the landscape topography to the smaller streambed scale. As such, the spectral solution to groundwater hydraulic head fluctuation was described in L195-205. Then, L206-216 describes the justification and the method for the rescaling of landscape topography (which was estimated in L195-206), in order to evaluate the streambed's hydraulic head at the hyporheic scale.

The following is the relevant section of the paper, where the added/revised parts are shown in italic and underlined font.

The topography of the landscape and the streambeds have been shown to follow fractal patterns, allowing a spectral representation of the head boundary condition, as well as solutions to topography-controlled groundwater circulation (Wörman et al., 2006, 2007b). The fractality reflects a constant power law correlation between the topographic amplitude and the wavelength across all scales in a real Fourier series representing the topographic elevation. This fractal power has been shown to prevail over a wide range of scales, from continents to bedforms in streams (Wörman et al., 2007a), suggesting the possibility of generalizing ground surface topography, such as streambed topography, over scales *for which the high-resolution streambed topography data required for hyporheic modeling are not available*.

- L187-216: What are the extent and boundary conditions of the hyporheic flow model? I guess the boundary conditions must be head = 0 everywhere but the top boundary so as to keep a continuous solution when doing the superposition...?

Thanks for the insightful comment. We have revised this sentence on line 187,

"The streambed hydraulic head was applied as a boundary condition for the hyporheic flow,…"

in the following way:

"In order to superimpose the results of the analyses of hyporheic flow onto the regional groundwater flow, at the top-boundary of the hyporheic flow domain, we only recognized the local fluctuations of the streambed hydraulic head from the regional hydraulic head. Hence, the fluctuations of the streambed hydraulic head were applied as a boundary condition for the hyporheic flow, i.e., the flow of surface water through streambed sediment inflow paths that re-emerges into surface water. The hyporheic flow model was analyzed at many points where discharge from deep groundwater was found (see section 2.5). These areas were used to determine the effect of the hyporheic flow on the discharge of groundwater."

In addition, the hyporheic scale model was represented with 5 × 5 × 5 m^3 cubes, wherein the hydraulic head estimated using the spectral exact solution (Equation 5 of the paper) was used as the top boundary condition. In addition, no flow boundary was assumed for the bottom and lateral surfaces of the hyporheic model. The hydraulic conductivity of the hyporheic-scale model was described according to Equation 4 (i.e., similarly to the streambed sediment layer of the regional-scale model). The following sentences will be added to the paper to address the referee's comment:

Finally, the hyporheic-scale mode was represented with 5 × 5 × 5 m^3 cubes, wherein the hydraulic head was estimated using the spectral exact solution (Equation 5) and was used as the top boundary condition. In addition, no flow boundary was assumed for the bottom and lateral surfaces of the hyporheic model. The hydraulic conductivity of the hyporheic-scale model was determined via to Equation 4 (i.e., similar to the streambed sediment layer of the regional-scale model).

- L219: The term "models" is confusing here. I guess you refer to the other parameters of the hyporheic flow model and all the parameters of the catchment-scale model.

Thanks for the comment. The sentence will be revised as follows:

This study recognized uncertainties in the hydrostatic and dynamic head boundary conditions by performing a sensitivity analysis on the parameters in Equation (5), while the uncertainty in the other parameters of the hyporheic flow model (such as hydraulic conductivity, etc.) and in those of the catchment-scale flow model was not formally analyzed.

L239: "Carlo", not "Carla".

Thanks for the comment. This will be corrected in the revised version of the paper.

- L247: What are "the" cubes? You have not talked about cubes before.

Thanks for the comment. A new section will be added to the revised version of the paper at the beginning of section 2.6 to describe the cubes.

- L252: What does "the 1552" refer to?

It refers to discharge points within the catchment boundaries. The text will be revised as follows:

The catchment-scale groundwater velocity field was superimposed on the corresponding streambed-scale velocity field (i.e., the corresponding deep groundwater discharge zone at each of the 1552 discharge points within the catchment boundaries; see section 3.1 and figure 4).

- L253-256: How did you distinguish between intermediate and deep groundwater flow paths from these particles (did you track them backward as well)? Furthermore, how can you be sure that some of these particles are not hyporheic flow?

Thanks for the comment. Particle tracking was used to identify streamlines that are considered to follow hyporheic, intermediate and deep groundwater flow. Backward particle tracking was conducted to distinguish the deep and intermediate groundwater flow paths, where deep groundwater was defined as flow that entered the bedrock and intermediate groundwater was determined as being only present in Quaternary deposits. Hyporheic flow involves streamlines starting and ending in the stream's bottom within the 5 m spatial scale. No flow boundary condition was assumed for the bottom surface of the hyporheic model (i.e., the 5×5×5 m^3 cubes), which allowed us to analyze the hyporheic flow without considering the ambient groundwater discharge. Therefore, none of the hyporheic flow paths originate from/touch the bottom surfaces of the superimposed models.

Particle tracing in the superimposed models was conducted by releasing particles at the bottom of the domain of each superimposed flow field (i.e., at a depth of 5 m). As such, the released particles reflected only the deep and intermediate flows in the superimposed models (Figure 2 illustrates the applied method).

A separate section will be added to the revised version of the paper to describe the method of particle tracking for different flow types, as follows:

> *Particle tracking was used to identify streamlines that follow hyporheic, intermediate and deep groundwater flows. Deep groundwater was defined as flow that entered the bedrock, and intermediate groundwater was determined to only be present in Quaternary deposits. Hyporheic flow contains streamlines starting and ending in the stream bottom within a 5 m spatial scale. Particle tracking was conducted at two different spatial scales: the regional scale (i.e., entire catchment) and the local scale (i.e., 5×5×5 m^3). The regional-scale particle tracking was conducted to evaluate deep groundwater discharge zones, as well as to distinguish the deep and intermediate groundwater flow fields (see section 2.6.1). In addition, particle tracking was conducted on a large number of 5×5×5 m^3 cubes containing a hyporheic flow field in deep groundwater discharge zones, in the absence and presence of upwelling groundwater (both deep and intermediate flows), in order to investigate the impact of hyporheic flow on deep groundwater discharge.*

As was mentioned in response to the referee's comment, a new description of the boundary conditions applied to hyporheic-scale flow will be added to the revised version of the paper (section 2.4) so as to facilitate the understanding of the nested flow system, as follows:

> *Finally, the hyporheic-scale model was represented by 5 × 5 × 5 m^3 cubes, wherein the hydraulic head was estimated using the spectral exact solution (equation 5) and was used as the top boundary condition. In addition, no flow boundary was assumed for the bottom and lateral surfaces of the hyporheic model. The hydraulic conductivity of the hyporheic-scale model was determined via Equation 4 (i.e., similar to the streambed sediment layer of the regional-scale model).*

- L264-272: This part could be clearer. Did you focus on the same 1552 areas as above (I guess so)? How did you determine the coherent catchment-scale discharge areas (I guess this would involve particle tracking and a certain grouping method)?

We agree with the referee that this part could be explained better. The coherent areas were evaluated in 5×5×5 m^3 cubes of the superimposed models, with and without the hyporheic flow field, in order to assess the impact of hyporheic flux on catchment-scale groundwater flow in these areas. In addition, the fragmentation analysis was conducted on catchment-scale model's top surface (for the whole catchment) to present the size distribution of the coherent groundwater upwelling zones throughout the whole catchment, regardless of groundwater penetration depth (i.e., no particle tracing was involved in the fragmentation of coherent upwelling zones across the catchment).

The following is the relevant section of the paper, in which the added parts are presented in italic and underlined font.

> In addition to the deep groundwater travel time in the superimposed models, the analyses also covered how the hyporheic flows affected the spatial distribution of various sizes of catchment-scale groundwater upwelling zones at streambed interfaces. *The fragmentation analysis was conducted on deep groundwater flow discharge zones (i.e., 1552 discharge zones within the catchment boundaries; refer to section 3.1 and Figure 4) using the particle tracing results for the 5×5×5 m^3 superimposed cubes.* These results were used to determine the fragmentation of catchment-scale groundwater flows arising at streambed interfaces, as defined from the change in the distributions of coherent areas that only experienced the upwelling of catchment-scale groundwater flow. The changes in coherent discharge areas were determined by superimposing and not superimposing the hyporheic flows on the catchment-scale groundwater flows. In this study, a coherent area was defined as an area in which the entire flow reflected only the catchment-scale upward groundwater flow. *In addition, fragmentation analysis was conducted on the catchment-scale model's top surface (with a resolution of 5×5 m^2 in different locations over the whole catchment) to determine the size distribution of coherent upwelling zones regardless of groundwater penetration depth.* Numerically, coherent upwelling areas were evaluated at the top surfaces of the streambed-scale and catchment-scale models using an orthogonal mesh with resolutions of 0.1×0.1 m^2 and 5×5 m^2, respectively, wherein the flow velocity values were considered only in the orthogonal directions.

- L308-310: I think the differences between the three layers are mostly independent of the hierarchical structure of flow cells (which was not evaluated in this study, by the way).

We agree with the referee that our paper evaluated differences in flow properties (i.e., travel time, velocity, etc.) between the three layers due to variations in the porosity, hydraulic conductivity, and thickness of those three subsurface layers. However, previous studies (Cardenas, 2007; Wang et al., 2016) have indicated that differences in the distribution of groundwater travel time are due to the hierarchical structures of groundwater flow cells. References will be added to this section of the paper to support the argument and to address the referee's comment (i.e., Cardenas, 2007; Wang et al., 2016).

- L331: Define the Froude number.

The Froude number will be defined in the revised version of the paper, as follows:

> *The results showed that the Froude number ($Fr = \frac{v_f}{\sqrt{gD_w}}$) plays a major role in the relative contribution of the dynamic head coefficient; the higher the Froude number, the larger the dynamic head contribution (Figure 6a).*

- L418-420: So is it a good news (less exposure time of aquatic sediments)?

Yes, the velocity of the groundwater flow (carrying, for example, radionuclide compounds from deep groundwater) is increased due to the presence of the hyporheic flow field; on the other hand, though, the groundwater discharge area at the sediment bed interface shrinks due to the impact of hyporheic flux. This reflects the shorter exposure time (due to the higher velocity) and the higher radionuclide activity (due to the smaller discharge area).

- L421: Why would it lead to higher exposure if the exposure time is shorter?

Thanks for the comment. As mentioned in the response to a previous comment, very narrow pinhole discharge areas of deep groundwater at the sediment bed interface result in higher radiologic activity (not higher exposure time). The sentence will be revised in the paper as follows:

> *Moreover, hyporheic flow causes the upwelling of deep groundwater to become more spatially focused, and also causes the accumulation of any radioactivity that may follow the flow in small areas, which potentially causes greater radiologic activity. The shorter residence time could result in reduced exposure time, but for most radionuclide compounds, these times would be much longer than the life-span of humans. Further, a lengthy duration of leakage (from a damaged radionuclide waste repository) might determine the actual period of contamination of aquatic sediments, thus reducing the importance of the residence time in those sediments.*

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