Response to Comments from Referee #2

- The paper "The influence of hyporheic fluxes on regional groundwater discharge zones" submitted to HESS by Mojarrad et al. investigates different scale flow systems by means of topographically induced groundwater circulation and the role of hyporheic flow on groundwater circulation in the river valleys. The flow systems are discussed in relation to possible accumulation of radioactive waste originating from deeper aquifer regions within the Quaternary deposits; by differentiating between re- and discharge zones.

We thank the referee for providing a thoughtful review of our paper. Our detailed reply to the comments (both major and minor) is provided below. The paper will be revised after the online discussion, and changes are presented in *underline text in italic.*

- I think that the approach, of the influence of topography on the distribution of hydraulic potential in different scales is interesting. The extent to which the link of deep groundwater circulation with the potential field of the hyporheic interstitial can be easily connected would have to be discussed in more depth, especially by delving into the processes that can also influence the potential fields at different scales.
  The concept underlying the work is not new and it is surprising that the authors do not mention the fundamental work of J. Toth.

Thanks for the comment. We will include a new section at the beginning of section 2.6 of the revised paper to describe the extent of the linkage between deep groundwater and hyporheic flow, 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.*

We completely agree that full credit should be given to the previous research conducted by Tóth. However, the main differences between our study and previous research (including Tóth (1963)) should also be better addressed. Therefore, a new section will be added in the Discussion (i.e., section 4.1) to address the hierarchal structure of the subsurface flow systems, as below:

> *Nested groundwater flow systems comprise subsurface flows across a wide range of spatial scales, all with different flow properties. The applied multiscale approach of this study addresses regional, intermediate and hyporheic flow systems, which is consistent with the hierarchically nested groundwater flow cells first described by Tóth (1963). In addition to basin geometry and the surface topography, as described by Tóth (1963), the geological heterogeneity of the subsurface hydraulic conductivity (as dependent on stratification and soil type) significantly impacts the local, intermediate and regional groundwater flow discharge zones (Jiang et al., 2010, 2011). Further, this study also separates the treatment of discharge and recharge zones by applying different top boundary conditions, and the local-scale investigation focuses on the boundary conditions that arise in surface water systems and impact hyporheic flow. These interactions are not considered in the previous literature incorporating the subsurface flow nested perspective.*

- The authors cite the work of W. Zijl, who, through a Fourier analysis and consideration of the anisotropy of the geologic sequences, or important boundaries, such as the topography of the bedrock surface, or different structural properties of the bedrock, determine a series of flow cells. A reduction to two or three as proposed in this paper is probably too simplified. Thus, I would find it justified for the authors to emphasize the conceptual aspect of the work and to discuss the role of influence of topography of the river bed (i.e., the river corridor concept of Stanford and Ward), the influence of heterogeneity of the geological sequence, the role of the relative water flux contributions etc.).
  Based on the work (concept) of Toth, it is not surprising that the drainage system can correspond to the exfiltration zones.

> However, there are other aspects to be considered:
> The River corridor concept of Stanford and Ward, shows that the topography of the riverbed and the topography of an impounding layer (can be e.g. glacial deposits, bedrock surface or discontinuities of the gradient of the riverbed along a river course) produce infiltration and exfiltration zones within the hyporheic interstitial, which can be very dominant with respect to water fluxes.
> I do not know the glacial sediments of the area, but I suspect that because of the diversity of processes, heterogeneities in these deposits also lead to vertical hydraulic gradients that could significantly affect the simple potential distribution.

This study divided the flow analysis into two scale ranges, the "regional-scale" and the "streambed induced flow"; however, the representation of the top boundary condition included a range of scales covering these two arbitrarily (but justifiably) separated aspects of the flow problem. Since this study considers a wide range of scales for the head boundary condition, we think that it describes a similar flow phenomenon to the river corridor concept of Stanford and Ward (1993). The following section will be added in section 4.1 to address the referee's comment:

> *Only decreasing the DEM resolution over the recharge zones, while maintaining the high DEM resolution (i.e., 2 m × 2 m) in discharge zones (i.e., stream network, lakes, etc.), allows us to evaluate in- and exfiltration zones via discontinuities in topographical gradient throughout the river network in the catchment-scale model (Stanford and Ward, 1993).*

- The structural heterogeneity of the bedrock and the character of the hydraulically relevant structures of the subsurface (shear zones, fracture patterns, etc.) can also significantly affect the anisotropy of the hydraulic conductivities, so that over long geologic times the pattern of the exfiltration zones is also not necessarily uniformly distributed along the drainage system.
- The concept depth decaying hydraulic conductivity has to be approved by regional specific data. Other, more complex heterogeneity development with depth could have a strong influence on the Potential distribution.
- A much more important point influencing the regional flow systems over longer times periods (transport of radionuclides from certain depths of the bedrock) is the dynamics of the development of the topography. Please discuss, how topography was shaped during the last 15'000 years. Over long time periods, topography cannot be assumed to constant.
- **I think the paper could benefit from a more in-depth discussion. In its current form, the argumentation is a bit too simplistic.**

Thanks for the comment. The heterogeneity of the bedrock domain was determined by applying depth decaying hydraulic conductivity functions. In addition, previous studies showed the controlling effects of topography variation compared to heterogeneity in the fracture network within the bedrock domain, as regards the travel time of deep groundwater in different subsurface strata as well as their discharge zones at the topographical surface (Selroos et al., 2002; Marklund et al., 2008; Welch et al., 2012). The following discussion is added to the revised paper to address the referee's comment:

> *Previous studies have indicated that the deep groundwater discharge location at the topographical surface is primarily controlled by topographical variation, and the distribution of the fracture network only slightly affects the discharge locations (Selroos et al., 2002; Marklund et al., 2008; Welch et al., 2012). In the absence of detailed data for the study region, the bedrock was assumed to be a continuum subsurface stratum with average hydraulic conductivity, and the horizontally constant hydraulic conductivity was assumed to decay with depth (Figure 1). In the present study, the applied depth-decaying hydraulic conductivity function was based on regional hydraulic conductivity field measurements conducted by Swedish Nuclear Fuel and Waste Management, SKB (Ericsson et al., 2006). Horizontal variability in the hydraulic conductivity was assumed, but only for the overlying soil strata (Quaternary deposits and possible aquatic sediments). These uppermost layers have a dominating effect on the discharge of groundwater, and thus, we believe that this simplified model represents the most important patterns in hydraulic conductivity.*

We agree with the referee that the topography is not constant over a long time period, and that this needs to be discussed as regards groundwater discharge as well as solute/contamination transport over long distances. This region is primarily affected by retreating glaciation, which has led to initial glacial processes followed by sea sedimentation and substantial landrise, with a change in ambient groundwater flow. Therefore, we expanded the discussion of the implications of the dynamic behavior of the topographical and subsurface geological properties over a long time period in our results. However, for the assessment of the flow in discharge zones, which is the main focus of the paper, non-stationarity is of less importance, and a quasi-steady condition might be more relevant. This is because of the quick adaptation of the groundwater flow to specific changes in the boundary condition—non-stationarity is primarily reflected in the continuity equation and the associated change in groundwater storage over long time. The following will be added into section 4.1 to address the referee's comment:

> *In this study, the bedrock domain was assumed to be an equivalent continuum subsurface stratum, where average hydraulic conductivity with an exponential decay function (Figure 1) was assumed to represent both the intact bedrock and fractures. Depth-decaying hydraulic conductivity has previously been suggested for the Krycklan catchment (e.g., Ameli et al., 2016b). Moreover, in the present study, the applied depth-decaying hydraulic conductivity function was based on regional hydraulic conductivity field measurements conducted by Swedish Nuclear Fuel and Waste Management, SKB (Ericsson et al., 2006). Topography and bedrock evolution occurred from 3000 Mega-annum ago (Mega-annum abbreviated as Ma, where 1 Ma is equal to 1 million years) (formation of basement rock) to less than 1 Ma ago (glacial erosion, slope formation, as well as frost process) (Lidmar-Bergström, 1996); in this time, glacial erosion could have changed the bedrock formation and surface topography by up to 600 m in northern Sweden (Lidmar-Bergström, 1997). About 10,000 years ago, retreating glaciation initially led to a glacial process followed by substantial landrise, with successive changes in regional groundwater flow. These factors may hold significance as regards the transport along regional flow paths. However, the locations of discharge zones at the topographical surface adapt relatively quickly to changes in boundary conditions, and the location of discharge follows the valleys in the low lands, which could slightly vary within less than 3 Ma in northern Sweden (Lidmar-Bergström, 1996). Since our results for groundwater transport time (Figure 5) are in the range of hundreds-thousands years, they are representative of stationary/quasi-stationary conditions, but not necessarily of a specific historic or future period's transport scenario.*

General Comments

- Although the character of the model is mostly conceptual the authors state that results from intense field investigations exist. Nevertheless, nearly none of these existing data are specified or used for calibration and/or validation of the model (i.e. character of the hyporheic zone, heterogeneity character of the glacial deposits.

The existing data for independent parameters were used in the development of the numerical model, such as hydraulic conductivities, channel properties, topography and bedrock surfaces, etc. However, very few data on the dependent flow field exist. The interaction between deep groundwater flow and hyporheic fluxes was investigated using the independently developed model over a wide range of spatial scales of regional groundwater flow. However, the limited data necessitated the use of Monte Carlo simulation as a sensitivity analysis to cover the uncertainty of the hyporheic flow evaluation. Hence, the study's aim was to provide a more comprehensive picture of the investigated phenomenon, rather than being a case-specific investigation.

- For seven different soil types in the Krycklan catchment hydraulic conductivity was obtained. A sensitivity analysis for hydraulic conductivity of streambed sediment would be interesting.

Thanks for the comment. Previous studies have reported streambed sediment hydraulic conductivity in the range of 10^{-3}-10^{-5} (m/s) (Wörman et al., 2002; Salehin et al., 2004; Ryan and Boufadel, 2006; Song et al., 2007), regardless of the dominant soil type of the adjacent area. Therefore, in this study we used the results of a field investigation conducted by Morén et al. (2017) on a 1500-meter stretch for estimating the hydraulic conductivity of the streambed sediment. However, it would be great if a sensitivity analysis could be performed using other field experimental results in the future.

- Provide a more quantitative of visualization of discharge locations (Fig. 1), e.g. by means of point densities. Likewise, an illustration with the "pinholes" of groundwater discharge and/or "nested" flow cells (maybe for a zoom) would also help to understand the different flow processes.

Figure 1 shows only the hydraulic conductivity and the porosity of the different subsurface domains. If the referee meant to refer to Figure 2 (which shows the nested flow system), this figure does not present results of the analysis, but instead tries to illustrate the applied method. However, the paper will be revised after the online discussion, and Figure 1 and Figure 2 will be combined. It should also be mentioned that the result concerning nested flow cells (containing groundwater and hyporheic flow fields) within the streambed sediment had already been illustrated in Figure 8. In addition, Figure 7 shows the quantitative results of the impact of hyporheic fluxes on deep and intermediate upwelling groundwater at the deep groundwater discharge points in a nest flow system within the streambed sediment.

- How was the catchment area delineated (surface?). And is this approach appropriate when evaluating the deep aquifer, when the shape of the topography changed over the last 15’000 years? A 3D visualization would help to better understand the geological settings in relation to the topography.

The catchment area was derived from a basin that had already been delineated in previous research (Laudon et al., 2013), which used the topography DEM file to identify the upstream area that contributes to a common outlet draining the region. The following text will be added to describe the extension of the model in the revised version of the paper:

> *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).*

Comparing the depth of the subsurface layers (the depth of Quaternary deposits was almost 40 m, and the deep groundwater was traced from 500 m depth) with the extent of the domain (11.6 × 10.3 km^2) shows that the catchment area is relatively far from the lateral boundaries. In addition, in our study, a constant hydraulic head was assumed for the lateral surfaces of the catchment-scale model in order to incorporate the effect of the sides of the numerical model on groundwater flow circulation. Therefore, part of the deep groundwater flow (represented by the particles in the catchment-scale particle tracing) showing upward flow at 500 m left the domain via the side walls (particle tracing statistics already presented in Figure S4, supporting information). As was mentioned earlier in response to the referee’s main comments, a new section of text will be added into the revised version of the paper, where the dynamic behavior of the topography will be discussed.

- Some repetitions could be avoided, like e.g. Software use.

Thanks for the comment. The comment of the referee will be addressed by removing the repetitions.

Detailed Comments

- L29: Definition of "long-term"

Thanks for the comment. The definition of “long-term” in this paper will be added in the revised version, as follows:

> *Long-term radionuclide safety assessment regards the maximum consequences of radionuclide compounds for human health and the environment over a time span up to 1 million years after the radionuclide waste repository has been closed (Kautsky et al., 2013).*

- L54: This strongly depends on the geology which means that without a regional geological model a detailed statement due to deep groundwater discharge zones remain fragmentary

Thanks for the comment. The sentence will be revised and supported by other studies, 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).This suggests that local hyporheic flows can have significant effects on deep groundwater discharge zones, and thus on the solutes and heat transport associated with the flow of deep groundwater into streams.*

- L66: please add References of S. Todd

The referee did not provide information for the suggested references, and we could not find the appropriate references.

- L84: the history of the hydrology at different time scales will also influence the contribution of water from different flow systems in the exfiltration zones.

Thanks for the comment, which we agree with. An explanation will be added in the Discussion section of the revised version, as below:

> *In this study, the topography-controlled boundary condition was considered at the discharge location in a stationary model. Therefore, the role of hydrological variation over different time scales, which could potentially affect the contribution of water from various spatial scales in subsurface discharge regions, was not investigated (Dam et al., 2012). However, due to the quick adaptability of groundwater flow to variations in boundary conditions, the non-stationary condition is less important to instantaneous groundwater discharge in the case of groundwater flow with a travel time in the range of hundreds to thousands of years.*

- L82: I cannot find information on geological heterogeneity

The geological heterogeneity is addressed in section 2.2 (i.e., empirical and observational data), where the seven different soil types are used to describe the spatial heterogeneity of Quaternary deposits. In addition, the depth-decaying hydraulic conductivities were considered in all the modeling domains (i.e., streambed sediment, QD, and bedrock).

- L86: Darcy's law should be known to the readership?

The definition of Darcy's law will be added to the paper, as follows:

> *The momentum equation for subsurface flow in saturated porous media at a sufficiently low Reynolds number is generally derived by neglecting inertia terms, while maintaining the potential energy and adopting a linear friction-loss relationship. This leads to the well-known Darcy's law:* $\boldsymbol{q} = [U, V, W] = -K\boldsymbol{\nabla}H$*. Here,* K *(m/s) is the hydraulic conductivity,* $\boldsymbol{\nabla}$ *is the nabla operator,* H *(m) is the total hydraulic head,* q *(m/s) is the Darcy velocity vector, and* U *(m/s),* V *(m/s) and* W *(m/s) are the Darcy's velocities in the x, y, and z directions, respectively, while bold symbols denote vector quantities (Whitaker, 1986).*

- L103: Missing specific information on the time scale and the rates of considered processes

We do not fully understand this comment. Line 103 of the paper refers to a description of the seepage velocity concept that was applied in the paper. We assume that "time scale and the rates of considered processes" refers to lines 105-107, where the retardation of the solutes due to adsorption and diffusion processes is described. In this section, the objective is to use the concept of the retardation of solute transport due to sorption to highlight the fact that the solute transport velocity is lower than the water seepage velocity, and, consequently, the transport time of the solutes in porous media is generally greater than that of seepage water through pores and fractures.

- L118: There should be drillings for geological information's. A corresponding map and a stratigraphic-lithologic overview, allowing to evaluate the degree of vertical variability of hydraulic properties is missing.

Unfortunately, we could not find quantitative geological information (i.e., borehole drilling information) for the Krycklan catchment. However, Sterte et al. (2018) and others provided an overview of the soil stratification in the Krycklan catchment. We will add the following to address the comment of the referee:

> *The Krycklan landscape was formed during the last glaciation (Lidman et al., 2016); the northern part primarily consists of a 15-20 m thick glacial till. The glacial till intertwines with regions containing peat and/or lake sediment towards the east. The glacial till mainly contains basal till in the deep soil, which is replaced with ablation till in the shallow soil (Jutebring Strete et al., 2021). The southern side of the Krycklan catchment has a lower elevation compared to other regions, where the soil is a mixture of fluvial and glaciofluvial deposits. Those regions mainly consist of sandy and silty sediments with significant soil thickness (i.e., approximately 40 m deep), where the soil has been compacted by its own weight (Lyon et al., 2011). Generally, the aggregates of till soil shrink with depth, and in the sandy silty sediment, sand is replaced with silty clay as the depth increases. In addition, peat is replaced with clay within a few meters of the surface (Sterte et al., 2018).*

- L122: a sedimentological decription of the glacial sediments would allow a better info on heterogeneity, till compris a lot of different glacial sediment types

As was stated in a previous response, a brief description of the different glacial sediment types in the Krycklan catchment will be added to the revised version of the paper, as follows:

> *The Krycklan landscape was formed during the last glaciation (Lidman et al., 2016); the northern part primarily consists of a 15-20 m thick glacial till. The glacial till intertwines with regions containing peat and/or lake sediment towards the east. The glacial till mainly contains basal till in the deep soil, which is replaced with ablation till in the shallow soil (Jutebring Strete et al., 2021). The southern side of the Krycklan catchment has a lower elevation compared to other regions, where the soil is a mixture of fluvial and glaciofluvial deposits. Those regions mainly consist of sandy and silty sediments with significant soil thickness (i.e., approximately 40 m deep), where the soil has been compacted by its own weight (Lyon et al., 2011). Generally, the aggregates of till soil shrink with depth, and in the sandy silty sediment, sand is replaced with silty clay as the depth increases. In addition, peat is replaced with clay within a few meters of the surface (Sterte et al., 2018).*

- L134: There is no information about the geometric extension of the model and why was Comsol chosen for such a simple model of the geological setting and not modflow, feflow or any groundwater affine software?

In general, other software could have been used, but based on our previous experience, we used COMSOL. Specifically, this software offers several key functionalities, such as the ability to apply different boundary conditions (such as the topography and recharge boundary conditions) within a single model, the ability to use mathematical functions as input for the hydraulic conductivity decay in different subsurface layers, improved nonrectangular mesh types, the ability to export results into MATLAB (for superimposing the hyporheic and regional-scale models), etc. In addition, COMSOL is a fully 3D software, whereas Modflow is only semi-3D. Hence, COMSOL was used as the numerical modeling software for our research, the focus of which is the upward flow in the discharge zones.

The geometric horizontal limits of the model will be added in the revised version of the paper, as below:

> *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 domain (64°11.8´ N -64°17.6´N, 19°39.5´E-19°54.3´E).*

- L137: The presented material does not allow this simplification, which project data support the statements of the cited publications?

The choice of depth-decaying hydraulic conductivity can be supported by the semi-analytical solution applied by Ameli et al., (2016b), which used the Krycklan catchment as its study domain. Moreover, although not specific to our study area, Ericsson et al. (2006) investigated the deep groundwater flow circulation in eastern småland, Sweden (using regional groundwater flow modeling). They measured the hydraulic conductivity of the bedrock domain at several depths, and fitted a depth-decaying exponential function representing the hydraulic conductivity within the bedrock. In addition, the observational data of hydraulic conductivity derived by Swedish Nuclear Fuel confirm the depth-decaying hydraulic conductivity in the bedrock domain (Swedish, N. F., 2008). Ingebritsen and Manning (1999) investigated the permeability of the continental crust using geothermal data, and identified a depth-decaying behavior in the permeability of the soil. We support our assumption regarding the depth-decaying hydraulic conductivity of the streambed sediment with a number of field investigation (e.g., Ryan and Boufadel, 2006; Song et al., 2007).

A new section of text will be added to the revised version of the paper to address the referee's comment, as follows:

> *Previous studies have shown that hydraulic conductivity decays with depth for most geological features (Ingebritsen and Manning, 1999; Saar and Manga, 2004; Jiang et al., 2009; Grant et al., 2014; Ameli et al., 2016a; Ryan and Boufadel, 2006). In particular, Ameli et al. (2016b) used a semi-analytical approach to determine the depth-decaying hydraulic conductivity in the Kryclan catchment.*

- L158: The information of the mesh sizes should be expanded with the number and delaunay quality of elements

The details pertaining to the mesh size and the quality of the mesh elements will be updated in the revised version of the paper, as follows:

A nonuniform mesh was used for the flow calculation of each layer. The mesh sizes varied within the ranges of 0.1-2 m, 2-17 m and 17-403 m for the streambed sediment, Quaternary deposit and bedrock layers, respectively. In addition, the maximum element growth rate and the curvature factor for the streambed sediment are 1.15 and 0.1, while these change to 1.2 and 0.2 for Quaternary deposits and 1.35 and 0.3 for streambed sediment, respectively.

- L175: DT has not been introduced

D_T is the total depth of the domain, as already defined: "the total depth of the domain, D_T, varied spatially within the catchment….".

- L178: give a reference to the particle tracing routine used

A reference to Genel et al. (2013) will be added to the revised paper.

- L181: One of the described aims in the introduction is the influence of radionuclide spreading for humans and biota. With a residence time of 320 million years it would be hard to make any predictions at all? A cumulative curve from particles reaching the surface over time could be more detailed.
  At the long time scale the topography has changed and as a result the flow field also would have changed.

The study was performed to investigate the effects of the hyporheic zone on groundwater discharge, and to show how it can affect the transport of radionuclides in shallow sediments below the surface of the water. The influence on humans and biota is beyond the scope of this study, but a potential connection was highlighted.

The particle tracing was conducted over a fictitious time period of 320 million years to allow all the particles to either leave the domain via the lateral sides or reach the top surface of the model. However, the maximum travel time of the groundwater flow was found to be approximately 40000 years (Figure 5). A cumulative curve reflecting the travel time of deep groundwater within each subsurface domain (from a depth of 500 m up to the topographical surface) has already been presented in Figure 5. Considering the range of travel times (100-40000 years in Figure 5), non-stationarity is of less importance, and a quasi-steady condition may be more relevant. This is because of the quick adaptability of the groundwater flow to a specific change in the boundary condition—non-stationarity is primarily reflected in the continuity equation and the associated change in groundwater storage over a long time. However, as was mentioned earlier in response to the comment of the referee, a separate discussion on the dynamic behavior of the geological formation will be added to the revised paper.

- L219-220: Specify "other models and statistical uncertainties"

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

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: Correct "Monte Carla"

The word will be corrected in the revised paper.

- L335: Can you better explain the role of the Froude number on the dynamic head component?

Thanks for the comment. The following text will be added to the revised paper:

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). The reason for this is that the amplitude of the hyporheic dynamic head depends on the ratio of the squared stream flow's velocity to its depth (Equation 6). The exact ratio varies with the relative penetration of bedforms (Z_{BM}/D_w), but generally, increasing the flow velocity and/or decreasing the flow depth leads to an increased contribution of the dynamic head component in the total hyporheic head.

- L348-350: Why you mention this? Is it not expected?

In this section, we show the difference between the travel times of intermediate and deep groundwater (in the absence of hyporheic flow fields) in streambed sediment, and ultimately quantitatively assess the impact of hyporheic fluxes (i.e., in the presence of hyporheic flow fields) on said travel times (Figure 7). Deep groundwater moves slower than shallow groundwater, which is expected; however, here, we quantitatively show how the hyporheic flow affects the groundwater flow's travel times in streambed sediments.

- L495: In the long time, changes of the Surface and streambed morphology is expected, therefore it is not clear how these changes interfere with the flow field in the deeper deposits (Quaternary and bedrock).

Thanks for the comment. As mentioned earlier in response to a comment of the referee, a separate discussion on the dynamic behavior of the geological formation and topographical changes will be added to the revised paper.

- L510 and following lines: Die you take into account structural aspects of the heterogeneity in the bedrock, such as heterogeneity due to shear zones , mylonites etc.

We agree that this is a point that could be discussed more thoroughly, which we have tried to do in the revised version of the paper. Our study accounts for the horizontal heterogeneity of soil hydraulic conductivity, as well as the vertical stratification and depth-decaying hydraulic conductivities, which we think represents the most essential heterogeneity pattern in the absence of more detailed data. The heterogeneity of the bedrock domain was characterized by applying a depth-decaying hydraulic conductivity function. In addition, previous studies showed the significant effects of topography variation, as opposed to heterogeneity, in the fracture network within the bedrock domain on deep groundwater travel time in different subsurface strata, as well as on their discharge zones at the topographical surface (Selroos et al., 2002; Marklund et al., 2008; Welch et al., 2012). The following discussion is added to the revised paper to address the referee's comment:

> *Previous studies have indicated that the deep groundwater discharge location at the topographical surface is primarily controlled by topographical variation, and the distribution of the fracture network only slightly affects the discharge locations (Selroos et al., 2002; Marklund et al., 2008; Welch et al., 2012). In the absence of detailed data for the study region, the bedrock was assumed to be a continuum subsurface stratum with average hydraulic conductivity, and the horizontally constant hydraulic conductivity was assumed to decay with depth (Figure 1). In the present study, the applied depth-decaying hydraulic conductivity function was based on regional hydraulic conductivity field measurements conducted by Swedish Nuclear Fuel and Waste Management, SKB (Ericsson et al., 2006). Horizontal variability in the hydraulic conductivity was assumed, but only for the overlying soil strata (Quaternary deposits and possible aquatic sediments). These uppermost layers have a dominating effect on the discharge of groundwater, and thus, we believe that this simplified model represents the most important patterns in hydraulic conductivity.*

- Integrate Figures 1 & 2

Figure 1 and Figure 2 will be combined in the revised paper.

- Figure 4: Up-date: Northing? Points instead of stars?

The symbol for north will be changed and the deep groundwater discharge locations will be presented by points in the revised paper.

- Figure 9: Correct catchemnt

The word "catchment" will be corrected in the revised paper.

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