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Discussions

Interactive comment on "Subsurface flow mixing in coarse, braided river deposits" *by* E. Huber and P. Huggenberger

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We thank referee #1 for his critical review of our manuscript.

Major comments

Major comment 1. There has been considerable confusion regarding the term "mixing" because mixing was not defined. This study solely addresses the impact of a complex heterogeneous structure on the advective subsurface flow field and does not consider any solute mixing possibly resulting from (transverse) dispersion. Therefore, "mixing" was used as a synonym for subsurface flow distortion. We propose (i) to re-

place "mixing" by "advective mixing" to avoid any confusion, and (ii) to define advective mixing as the subsurface flow distortions resulting in flow deviation, stream-tube intertwining and stream-tube folding (e.g., Janković et al., 2009). In the revised manuscript, the term advective mixing will be introduced in the abstract and the consequences of the observed advective mixing for solute transport will be added in the discussion as it is a current field of interest (Janković et al., 2009; Chiogna et al., 2014; Chiogna et al., 2015; Cirpka et al., 2015; Ye et al., 2015). Note that advective mixing tends to enhance transverse dispersion mixing (e.g., Cirpka et al., 2015) but concentration measurements on the field would not allow to distinguish between advective mixing and dispersion/diffusion mixing (e.g., Janković et al., 2009). Following the recommendation of referee #1 we suggest to consider particle tracking/streamlines instead of solute transport to better visualize and quantify advective mixing. Furthermore, the use of particle tracking/streamline reduces the risk of confusion between solute mixing and advective mixing. We tested the particle tracking scheme MODPATH (Pollock, 2012). One particle per cell was set on the inflow face of the model and the position of the particles traveling trough the model was recorded (a subset of the streamlines is shown in Fig. 1). The vertical and horizontal mixing can be visualized by comparing the positions of the particles on the inflow and outflow face (Fig. 2). We propose the following quantitative measures to characterize advective mixing:

- *vertical and horizontal particle deviation*, Fig. 3 (for each particle compute the vertical and horizontal distance between its position on the outflow face and its position on the inflow face; average the distance for all the particles belonging to the same cell on the outflow face; Stauffer, 2007).
- *particle divergence*, Fig. 4 (for each particle compute (i) the distance between the particle and its eight neighbors on the inflow face and (ii) the distance between the particle and its eight inflow-neighbours on the outflow. Take the difference of this two distances as a measure of divergence and display this value on the cells of the inflow face).

- *particle intertwining*, Fig. 5 (for each particle estimate how many of its 4 inflow-neighbours are still its neighbours on the output flow face. The neighbours on the output face are estimated with the Delaunay triangulation by taking as first and second order neighbours to really include all the particles around the considered particle. The first order neighbours are the particles connected to the considered particle through an edge of the "Delaunay triangles", the second order neighbors are the particles connected through two edges).

Major comment 2. As stated by referee #1, there is no solute mixing in advective transport . The only reason why a solute transport simulation was performed was to better visualize the advective flow at three different depths. Unfortunately, this justification was only stated in the abstract. The chosen transport scheme in MT3DMS was the third-order total-variation-diminishing method (TVD) method (based on the ULTIMATE algorithm). Compared with standard finite-difference method, this mass-conservative scheme minimizes both numerical dispersion and artificial oscillation. However, the third-order TVD scheme is not exempt of numerical dispersion (Lagrangian or mixed Euler-Lagrangian scheme can be more effective at a higher computational cost for highly-heterogeneous model). The numerical dispersion of the transport scheme raises two question: (i) Is the numerical dispersion significant with regard to the objective of the study? (ii) If yes, does it influence the study conclusions? The comparison of the results of the particle tracking with that of the solute transport simulation shows that the numerical dispersion was not as significant to alter the analysis of the advective mixing. However, we admit that the use of particle tracking allows a much better characterization of the advective mixing.

Major comment 3. We thanks referee #1 for suggesting some free-numerical dispersion schemes/codes to simulate transverse dispersion. Because our study does not address solute transverse mixing caused by dispersion or diffusion we see no need to apply these schemes.

Major comment 4. Two-dimensional and three-dimensional flow exhibit a different character: compared with a two-dimensional flow (without source or withdrawal) a three-dimensional flow rearranges persistently the streamlines (e.g., Steward, 1998; Steward and Janković, 2001; Cirpka et al., 2015). Therefore, the way how results from two-dimensional studies (such as that proposed by referee #1) can improve our understanding of three-dimensional advective mixing is far from being trivial. In our manuscript it was not clearly shown that the two overlapping trough fills do not completely act like a normal high-conductivity structure that only focuses/defocuses the streamlines and thereby permanently deforms the stream tubes. On the one hand, the observed hydraulic head field seems similar to that resulting from a high-conductive structure. On the other hand, the preliminary results from the streamlines/particle tracking analysis show a complex vertical and horizontal intertwining/mixing of the streamlines (Figure 1-5). About 45% of the particles on the outflow face are no more surrounded by their neighbors from the inflow face (not that this number is slightly biased as the vertical density of particles set on the inflow boundary is not constant due to the increasing thickness of the lower 8 layers; Figure 5). Particularly, the particles close to the upstream end of the trough fills are strongly deviated from their vertical and horizontal position on the inflow face. Furthermore, we propose to discuss in the revised manuscript some recent studies on the flow topology (e.g., Janković et al., 2009; Chiogna et al., 2014; Chiogna et al., 2015; Cirpka et al., 2015; Ye et al., 2015) as they illustrate and provide theoretical basis for the processes resulting in advective mixing (focusing, depth-dependent meandering and secondary motion).

Major comment 5. As suggested by referee #1, we propose to use particle tracking instead of advective solute transport simulation to discuss the advective mixing. Furthermore, we will discuss more deeply the interplay between the hydraulic-head field and hydraulic-conductivity field.

Major comment 6. As described two paragraph above (Major comment 4), the two overlapping trough fill do not behave like an homogeneous high-conductive inclusion.

We agree that it would be interesting to compare the current setting with an approximation of the internal structure of the trough fills trough (i) an homogeneous anisotropic hydraulic conductivity (bulk anisotropic hydraulic conductivity tensor) and (ii) a spatially varying anisotropic hydraulic conductivity (using the method proposed by Borghi et al., (2015) and an other groundwater flow model than MODFLOW, because MODFLOW doest not consider the terms off the diagonal of the hydraulic conductivity tensor leading to an erroneous flow field, e.g., Li et al., 2010). However such an exercise would much increase the length of the manuscript and, most importantly, would deviate from the main objective of the manuscript (i.e., how does a geologically realistic structure impacts advective mixing). See also our response to review #2, Major comment 4.

Major comment 7. An heterogeneous hydraulic conductivity field (spatially correlated or not) produce variation of the flow field that better reflect the field behavior. However, this effect when compared with the advective mixing resulting from the trough fills is negligible.

Major comment 8. With the above clarification and the preliminary results of the suggested particle tracking, we believe that this study allows clear statement about possible advective mixing in natural environment. Nevertheless, we will sharpen our analysis on the interplay between hydraulic head field and hydraulic conductivity field and its impact on advective mixing and better discuss the consequences of the simulated advective mixing.

Detailed comments

1. "transverse mixing/solute mixing". We will do as suggested by referee #1.

2. "i.e. is encapsulated by commas (before and after)". We will do as suggested by referee #1.

3. "Abstract". Good point. We will add few lines in the abstract on advective mixing.

4. page 9296, line 24 & page 9297, line 2. This sentence will be modified as follows: *However, the three-dimensional geometry of the sedimentary structures is often ignored or oversimplified in subsurface flow simulations leading to a possible reduced vertical subsurface flow mixing.*

5. page 9297, lines 7ff. Following the hierarchy proposed by Huggenberger and Regli (2006), we distinguish between the sedimentary textures (e.g., poorly-sorted gravel, bimodal gravel, open-framework gravel), the sedimentary structure (i.e., the spatial arrangement of one or two alternating sedimentary textures) and the depositional elements that are related to specific depositional processes (e.g., trough fills, horizontally bedded gravel structures, overbank deposits). Therefore, we cannot apply the suggestion of referee #1 that confuses sedimentary structure (open-framework – bimodal gravel couplets) with depositional element (trough fills). Furthermore, the trough fills can consist of different (alternating) sedimentary textures (open-framework/bimodal gravel couplets, poorly-sorted gravel cross-beds, interfingering of poorly-sorted gravel and sand). Because the trough fills are much more complex than the layers of poorly sorted gravel, they need more explanation/description.

6-18. We will do as suggested by referee #1.

19. page 9301, lines 15-16. Because we suggest to use particle tracking instead of solute transport simulation, this sentence will be removed (see Major comment 1).

20. End of section 2. Transport simulation is steady state. The transport scheme within MT3DMS is the third-order TVD.

First paragraph of section 3. We completely agree that many previous studies described the effected of high permeable structures on the flow field. However, the novelty of this study is the advective mixing resulting from a geologically realistic structure derived from field data. The resulting flow field is different from that produced by a high-conductive inclusion. See also our response to the major comments.

22. Rest of the results and discussion section. We agree that: (i) the model domain should be larger than bounding box of the overlapping trough fills in order to reduce the influence of the boundary conditions on the flow field, and (ii) the discussion about flow dipping is about focusing/defocusing. For the characterization of the advective mixing, see Major comment 1. We considered the single layers of open-framework and bimodal gravel as isotropic in terms of hydraulic conductivity following the results of fieldwork done by Jussel et al. (1994). But we completely disagree with referee #1 when he/she means that we made a "statement about the lacking importance of internal anisotropy". We have no field data to support an anisotropic representation of the open-framework and bimodal gravel. However, the macroscopic anisotropy of the trough fill is given by the alternating "layering" of open-framework and bimodal gravel: the streamlines within the trough fill do not flow perpendicularly to the hydraulic head gradient. The modeling of this macroscopic anisotropy would make sense if two alternating layers of open-framework and bimodal gravel would be considered as one single unit with a specific anisotropic hydraulic conductivity tensor. This aspect will be discussed in the revised manuscript.

23. Conclusions. We will reshape the conclusion to provide clear “lessons learned”.

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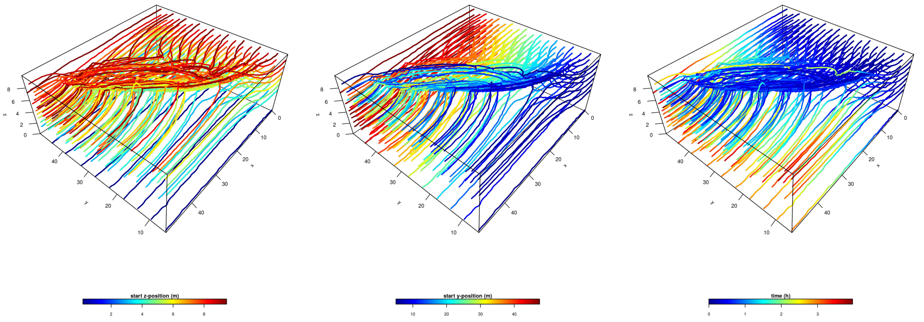

Fig. 1. From left to right: streamlines color as a function of (1) starting z-position, (2) starting y-position, (3) time (flow from top-right to bottom-left)

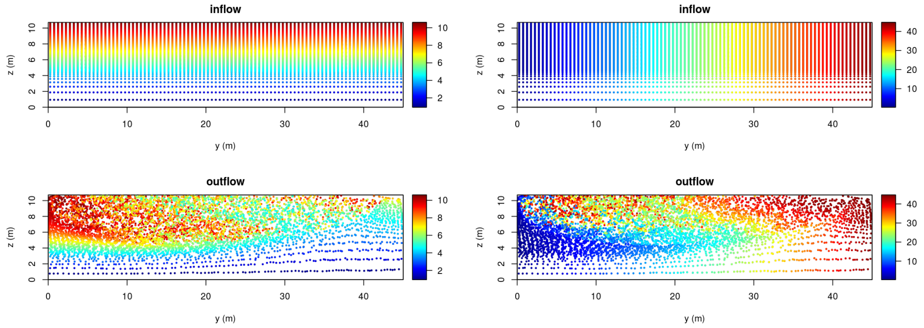

Fig. 2. Particle on the inflow and outflow model face (flow toward the reader) colored by the z-starting position (left) and their y-starting position (right).

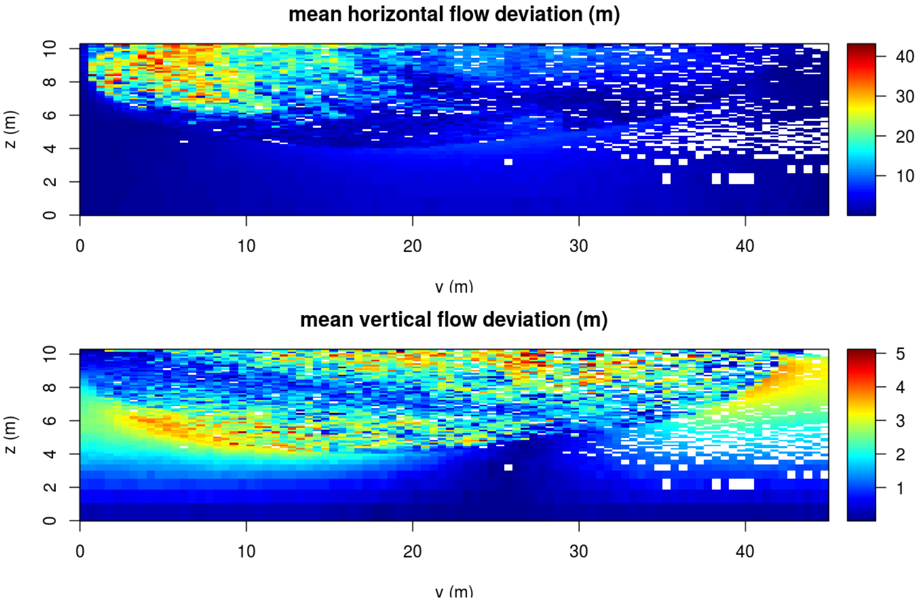

Fig. 3. Outflow: average horizontal (top) and vertical (bottom) particle deviation averaged for each cells of the outflow.

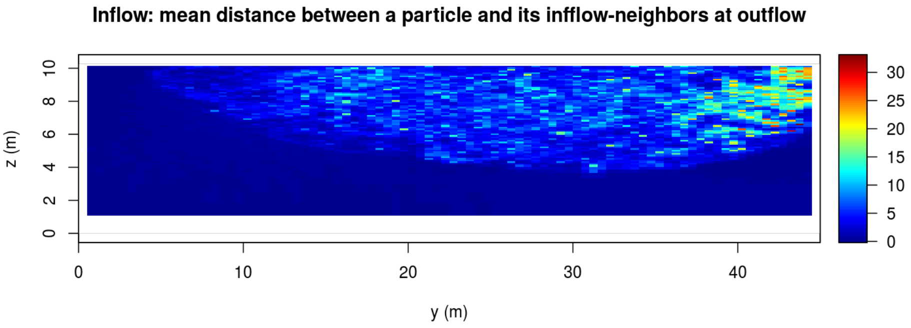

Fig. 4. Inflow: average distance between a particle and its-inflow neighbors at outflow, averaged for each cells at inflow.

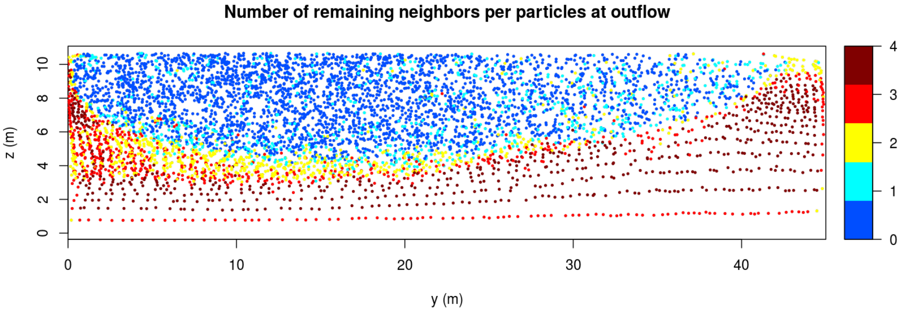

Fig. 5. Estimated number of remaining inflow particle neighbors for each particle at outflow.