Hydrol. Earth Syst. Sci. Discuss., 12, C3958–C3966, 2015
www.hydrol-earth-syst-sci-discuss.net/12/C3958/2015/
© Author(s) 2015. This work is distributed under
the Creative Commons Attribute 3.0 License.

Hydrology and Earth System Sciences
Open Access
Discussions

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

Anonymous Referee #1

Received and published: 30 September 2015

The paper of Huber and Huggenberger touches an important aspect of groundwater hydraulics, namely how real sedimentary structure affect flow and transport in aquifers. They focus on the effects of two intersecting inclusions of trough fills in otherwise poorly sorted sediments. Within the troughs, layers of open-framework gravel and biomodal gravel alternate. The authors use real GPR data of the Tagliamento valley to construct the model.

1 Major Comments

The key question according to the title of the manuscript is how the internal architecture of coarse, braided-river deposits affect subsurface mixing. This question is very relevant. However, I don't believe that the study is really able to answer it. It is striking that mixing is not mentioned at all in the abstract, whereas in the main body of the text "mixing" is discussed a lot, but clear definitions are missing:

- What do the authors really mean by mixing?
  This is not clarified.
- In which direction?
  Obviously in transvese directions, but this is not specified.
- Which metrics do they apply to quantify mixing?
  I have not seen any.
- What do they believe are the mechanisms of mixing enhancement by trough fills?
  The explanations are quite vague, and I doubt that they are correct.

There are a couple of fundamental problems with the transport simulations. First of all, if transport is really advective, there is no solute mixing whatsoever. The authors of course discuss observations of the model results that indicate mixing, but the way the model is set up, these observations are numerical artifacts. The authors use MT3DMS to simulate transport (without specifying the transport scheme they have chosen within MT3DMS), but all schemes within MT3DMS are prone to numerical dispersion. In the transverse direction, numerical dispersion is particularly big when the flow field is not alligned with the grid direction, many changes of the flow direction occur, and the grid is coarse. Realistic local transverse dispersivity-values are in the order of a few percent of the mean grain diameter. Being genereous, 1cm may be OK. With a grid resolution of 50cm x 50cm x 10cm, the numerical effects are considerably bigger. The scheme is simply not suitable to analyze transverse mixing in the given domain. The straight-forward to fix this problem would be to use a grid resolution in the order of the transverse dispesivity, unfortunately this would lead to a grid containing 23 billion cells, so this would not work without a massively parallel computer (and not with MT3DMS to begin with). There are very specialized codes in which advection is simulated along streamlines and transverse exchange either by smoothed-partcle hydromechanics (Herrera et al., 2010) or by a Finite Volume method using Voronoi polygons (Cirpka et al., 2015). These codes would most likely be available from the developers upon request, but they are not set up as user-freindly end product. The easiest approach would be to use particle-tracking random-walk methods, which are free of numerical dispersion and have frequently been applied to MODFLOW-derived velocity fields. As the paper stands, the authors largely discuss numerical artifacts, without addressing them.

I find the explanations by the authors quite cumbersome. The main effect that they show is that the two overlapping trough fills act like a normal high-conductivity inclusion. This is not surprising because the conductivity of the open-framework gravel is considerably larger than the conductivity of the surrounding poorly sorted matrix, so that even in the alternating sequence of open-framework and bimodal gravel, the effective hydraulic conductivity within the inclusion is much larger than in the matrix. Effects of high-conductivity inclusions on transverse mixing in 2-D have intensively been studied by Werth et al. (2006), Rolle (2009), and many follow-up studies by the same authors. In 3-D, Ye et al. (2015) have recently shown that the enhancement of transverse mixing by flow focussing is smaller in 3-D than in 2-D, whereas absolute dilution by transverse dispersion is larger because of the higher dimensionality. I strongly recommend that the authors of the present study carefully read these papers as they quite clearly explain the mechanisms by which flow focussing in high-conductivity inclusions enhance transverse mixing. It is a matter of transverse diffusion lengths versus diffu-

sion times. Statements by the authors that the hydraulic-head field is controlling mixing are misleading (even though travel paths are of course determined by the interplay of the hydraulic-head field and the hydraulic-conductivity field).

I quite don't understand why the authors don't show any streamlines to highlight the velocity fields. That would be much easier to follow than arguments of hydraulic gradients (which tell only half of the story as the velocity is the hydraulic times the conductivity, which varies by orders of magnitude in the application).

A really relevant question arising from the set-up used has not been discussed by the authors altogether: Is is really necessary to resolve the alternating layers of open-framework gravel and bimodal gravel or would it be sufficient to simply assume a higher uniform hydraulic-conductivity value in the trough-fill inclusion, maybe accounting for anisotropy? If the authors had a numerical scheme that was not heaveliy affected by numerical transverse dispersion they could address this question quite easily. The chosen numerical method will not be suitable to do that. My personal guess would be the following: The layering may lead to a strong velocity component within the open-fremwork-gravel layers (this can actually be checked quite easily as the full velocity field has been computed and the geometry of the layers is known). Then, flow focussing within the layers would foster transverse mixing perpendicular to the layering. Also, the locally "stratified" sedimentary structure causes severe longitudinal spreading of solute plumes, which would not occur to the same extent if a uniform conductivity-tensor was assumed in the inclusions. Again, this could easily be addressed by particle-tracking random-walk methods comparing set-ups resolving the fine-scale structure versus those with effective conductivities of the trough fills.

I don't feel competent to comment on the construction of the sedimentary structure from the GPR surveys. As a non-specialist, this part appears reasonable to me. I doubt, however, that drawing uncorrelated hydraulic-conductivity values within the layers from a statistical distribution is necessary at all (it surely makes the transport scheme more prone to numerical dispersion).

In summary, I encourage the authors to continue their work, but I doubt that the transport simulations chosen allow statements about solute mixing. I also assess that the line of thought regarding how sedimentary structure affect transverse solute mixing needs to be sharpened.

2 Detailed Comments

1. Throughout the text: "subsurface flow mixing" is odd English. I would simply use "transverse mixing" or "solute mixing"
2. Throughout the text: "i.e." is encapsulated by commas (before and after)
3. Abstract: Nothing is said about solute solute mixing whatsoever.
4. page 9296, line 24 - page 9297, line 2: I am not quite sure what you want to say here. It would not hurt if you simply don't try to recall what Whittaker and Teutsch argued (it was a 2-D study anyay).
5. page 9297, lines 7ff.: The sentence start with saying that there are two main depositional elements, but then only one of it is really explained. I suggest something like: "...two main depositional elements, namely open-framework-bimodal gravel couplets and poorly sorted sediments. These are arranged ..."
6. page 9297, lines 22-23: "investigate subsurface transport" (delete "the" and "flow")
7. page 9297, line 26: order of "mainly" and "using" is wrong (I would also write "mainly analyzing" rather than "using")
8. page 9297, line 27-28: "However, the impact of trough fills on subsurface flow has not drawn too much attention. Stauffer (2007) simulated subsurface flow ..."

9. page 9298, lines 8-9: "This study aims to assess the impact of high-permeable trough fills on subsurface flow and mixing."
10. page 9298, line 11: "GPR is a ... method"
11. page 9298, lines 18-19: "Three-dimensional groundwater flow was simulated using this..."
12. page 9299, line 7: Either "each trace" or "all traces"
13. page 9299, line 16: "in the same area" rather than "on"
14. page 9300, line 16: "were manually adjusted"
15. page 9300, lines 22-24: As mentioned above, the model resolution is very coarse to simulate transverse mixing.
16. page 9301, line 4: "in Fig. 1"
17. page 9301, lines 4-9: As mentioned, I doubt that adding uncorrelated white noise to the log-conductivity values has any benefit. If so, write: "For each voxel the hydraulic conductivities are drawn from a log-normal distribution neglecting any spatial correlation".
18. page 9301, lines 14-15: "at locations where strong groundwater-surface water interactions occur."
19. page 9301, lines 15-16: "The concentrations of three conservative tracers A, B and C were set to uniform values at three different depths"
20. End of section 2: It seems that transport is simulated at steady state, but this is not mentioned. Also, the chosen transport scheme withn MT3DMS is not reported. As mentioned above, I don't think that this method is suitable to analyze transverse mixing in heterogeneous domains.

21. First paragraph of section 3: Here you describe standard effects of flow focussing by high-hydraulic conductivity inclusions with some asymmetry resulting from the chose geometry. The general effects of high-K inclusions have been described in previous studies. It is not clear to me, what's really new in the present study with respect to mechanism of mixing enhancement. Also, discussing the flow field would be much easier if streamlines were shown.

22. Rest of the results and discussion section: With the current set-up, it's not so easy to say whether flow focussing is stronger in the horizontally transverse direction or in the vertical direction. To do that, you would need to outline bounding streamlines that barely touch the inclusion and see how these streamlines diverge in the far-distance limit. Unfortunately, the orientation of the inclusions is diagonal to the main direction of flow, and the width of the domain is hardly bigger than the width of the inclusion. With respect to flow focussing, you would have to compare the dimensions of the zone of influence in the far-distance limit to the projection of the trough-filling onto the y-z plane. The entire discussion about "flow dipping" is essentiallyabout focussing and defocussing of groundwater flow.

    I also want to highlight that mixing enhancement takes place only within the high-velocity inclusions. As outlined by Ye et al. (2015) , you may estimate a relative squeezing factor in the horizontal and vertical directions and approximate from that zero-order directional mixing-enhancement factors. The data shown do not allow to address additional effects like helical flow (Stauffer, 2007; Cirpka et al., 2015).

    As there are no real metrics of mixing applied in the study, discussing certain mechanisms of mixing enhancement is actually very difficult. The authors also make statement about the lacking importance of internal anisotropy but have not performed calculations that don't account for macroscopic anistropy within the trough fills. How can you then say that this feature is not important?

23. Conclusions: The conclusions are not conclusive enough. They mainly repeat what has been discussed in the results section (see my concerns about that above). But I miss clear "lessons learned" statements.

References

Cirpka, O. A., G. Chiogna, M. Rolle, and A. Bellin (2015), Transverse mixing in three-dimensional nonstationary anisotropic heterogeneous porous media, Water Resour. Res., 51, 241–260, doi:10.1002/2014WR015331.

Herrera, P. A., A. J. Valocchi, and R. D. Beckie (2010), A multidimensional streamline-based method to simulate reactive solute transport in heterogeneous porous media, Adv. Water Resour., 33(7), 711–727, doi:10.1016/j.advwatres.2010.03.001.

Rolle, M., C. Eberhardt, G. Chiogna, O. A. Cirpka, and P. Grathwohl (2009), Enhancement of dilution and transverse reactive mixing in porous media: Experiments and model-based interpretation, J. Contam. Hydrol., 110(3–4), 130–142, doi:10.1016/j.jconhyd.2009.10.003.

Stauffer, F. (2007), Impact of highly permeable sediment units with inclined bedding on solute transport in aquifers, Adv. Water Res., 30(11), 2194–2201.

Werth, C. J., O. A. Cirpka, and P. Grathwohl (2006), Enhanced mixing and reaction through flow focusing in heterogeneous porous media, Water Resour. Res., 42, W12414, doi:10.1029/2005WR004511.

Ye, Y., G. Chiogna, O. A. Cirpka, P. Grathwohl, and M. Rolle (2015), Enhancement of plume dilution in two-dimensional and three-dimensional porous media by flow focusing in high-permeability inclusions, Water Resour. Res., 51, 5582–5602, doi:10.1002/2015WR016962.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 12, 9295, 2015.