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Revision of the paper "Subsurface flow mixing in coarse, braided river deposits"

Dear Mauro Giudici

We appreciated the critical comments of the reviewer and we thank you for giving this manuscript a chance to be published. The suggestions of the two reviewers were in most cases implemented and a manuscript based on the revised version with all changes marked is attached.

The most important changes are listed below.

- The manuscript is better focused on advective mixing that is now defined, discussed and related to the existing literature.
- New computations were performed, the model boundary are now enlarged and quantitative measures of advective mixing are now proposed. We followed your recommendation concerning the clarity of the figures by removing the less interesting particles.
- The intertwining as well as the interplay between hydraulic conductivity and hydraulic heads are investigated and discussed

You suggested to make use of our whole data set to improve the hydrostatic set up. As explained in the submitted manuscript, the GPR data set consists of too widely-spaced GPR profiles such that only three of them image the trough fills.

Below are our specific comments to each reviewer. We hope that the submitted revised manuscript now meets the standards of the journal.

Best regards,

Emanuel Huber (on behalf of P. Huggenberger)

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Referee #1

Major comment 1.

"Mixing" is now replaced by "advective mixing" to avoid any confusion, and advective mixing is defined (l. 31-33) as the permanent deformation of streamlines resulting in streamline intertwining (Janković et al., 2009). The term advective mixing is introduced in the abstract and the introduction presents the influence of the advective mixing on solute transport.

Following the recommendation of referee \#1 we use particle tracking/streamlines to visualize and quantify advective mixing (MODPATH, Pollock, 2012). We quantify particle deviation, particle divergence, and particle intertwining.

Major comment 2.

As we are now using particle tracking, this comment is no more relevant.

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.

The introduction shortly discuss the difference between two-dimensional and three-dimensional flow in terms of advective mixing. Due to this difference, we do not cite study on two-dimensional flow because it is not straightforward of results from two-dimensional flow studies apply to three-dimensional flows. We now show that the overlapping trough fills do not act like a normal high-conductivity structure. A strong partilce mixing is induced by the overlapping trough fills. The interplay between hydraulic conductivity and hydraulic heads is now more deeply investigated.

Major comment 5.

As suggested by referee #1, we use particle tracking instead of advective solute transport simulation to discuss the advective mixing. Furthermore, we illustrate the interplay between the hydraulic head field and hydraulic conductivity field.

Major comment 6.

We do not adress the suggested question about the upscaling of the trough fill structure. This is an interesting question but answering this question 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).

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 (see l. 259-261).

Major comment 8.

With particle tracking, this study allows clear statement about possible advective mixing in natural environment. We discuss the impact of the sedimentary structures on advective mixing.

Detailed comment

1. "transverse mixing/solute mixing"

> Done as suggested by referee #1.

2. "i.e. is encapsulated by comma before and afters"

> Done as suggested by referee #1.

3. "Abstract".

> Good point. Few lines were added in the abstract on advective mixing.

4. page 9296, line 24 & page 9297, line 2.

> This sentence is removed from the submitted manuscript.

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.

> Done as suggested by referee #1.

19. page 9301, lines 15-16.

> Because we now use particle tracking instead of solute transport simulation, this sentence is removed (see Major comment 1).

20. End of section 2.

> Transport simulation is steady state and the transport scheme within MT3DMS was the third-order TVD. This information is however no more relevant.

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.

22. Rest of the results and discussion section.

In order to reduce the influence of the boundary conditions on the flow field, the the model domain is enlarged. The discussion about flow dipping was about focusing/defocusing, which is now mentioned in the Result section. 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, see Discussion section, l. 292-297. We add some measures of advective mixing.

23. Conclusions.

The conclusion is now reshaped and provide clear "lessons learned" as well as limitations of the study.

Referee #2

Major comment 1.

"Mixing" is replaced by "advective mixing" and defined in the introduction.

Major comment 2.

We agree with referee #2 that the modeled trough fill is rather an idealized than a simplified representation of the local sedimentary structure of the Tagliamento deposits. The model is now described as a synthetic model and the conclusion clearly states that the study findings are only valid for this synthetic model.

Major comment 3.

Fourteen widely spaced GPR profiles were recorded on the active floodplain of the Tagliamento River (spacing between lines is about 20 m, survey area is about 100 m x 200m). The objective of the survey was to record many lines over a large area in order to estimate statistical trends and to quantify the proportion of trough fills in the subsurface. Therefore, we do not have a "traditional grid of closely-spaced GPR profile" from which the subsurface structure would be better inferred. This is explained in the Method section (l. 89-96). Furthermore, the discussion is more tightly related to the specific set-up of this study.

Major comment 4

The question if it is "really necessary to resolve the alternating layers of open-framework [...] and bimodal gravel" is interesting but is not directly related to the objective of the study, that is to characterize the impact of a geologically realistic three-dimensional representation of coarse, braided deposits on the advective mixing. Therefore, we do not adress this question.

Referee #2 states that our representation mixes two level of hierarchic heterogeneity. We disagree. The same "level of hierarchy" is used to model the coarse, braided deposits, namely the sedimentary textures as described by Huggenberger and Regli (2006). Furthermore, the difference in terms of advective mixing between a layered representation and an anisotropic homogeneous representation corrupted by an uncorrelated noise is negligible (l. 259-261). The study set-up is not unrealistic even if thin finite sub-horizontal layers of open-framework can also be found in layers of poorly-sorted gravel (Huggenberger and Regli, 2006). However, we expect that such thin finite layers of open-framework gravel have a negligible contribution to the advective mixing (particularly for vertical advective mixing), because they focus and defocus the streamlines. The degree of details of the different modelled structures reflects our (conceptual) knowledge on the spatial arrangement of the textures. See the Discussion section (l.284-292).

Specific remarks

1. Abstract.

      We added a few lines to describe the impact of the modeled trough fill on advective mixing.

2. Line 7: "drawn (instead of draw)?"

      We will do as suggested by referee #2.

3. Page 9297, lines 3-5.

The following references are added in the Introduction: Anderson et al. (1989) and Lunt et al. (2004).

Page 9297, lines 7-9

The sentence line 6-9 (page 9297) does not exclude other depositional elements. Nevertheless, we modified this sentence (now l. 47-49) as follows to make it clear that Fig. 1 illustrates the two main depositional elements and not the heterogeneity of coarse, braided river deposits:

Coarse, braided river deposits are characterised by two main depositional elements (Fig. 1), namely horizontal to sub-horizontal layers of poorly-sorted gravel and trough fills characterised by clear-cut erosional lower-bounding surfaces.

And to clearly not exclude other forms of heterogeneity we added the following sentence (l. 55-56):

Additional sedimentary structures as well as depositional elements are described in the references above.

We agree that the open-framework texture is also observed in the layers of poorly sorted gravel and we remark that is the submitted manuscript (l. 289-290).

4. Page 9298, line 24.

The profiles are not very close to each other because we were surveying a large area within a limited period of time. We agree that a denser sampling of the area of interest would have significantly reduced the conceptual bias in the representation of the sedimentary heterogeneity.

5. Page 9299, lines 14-16.

We did not add the velocity data/profiles as they do not really contribute to the study (there was not enough place to add them in Fig. 2 of the manuscript).

6. Page 9300, lines 8-20

We now clearly stress that the flow and transport model is run on a synthetic model derived from GPR data.

7. Page 9300, lines 26 and following

We better explain that the hydraulic properties in this study are taken from hydraulic measurement made on disturbed and undisturbed samples in Quaternary coarse gravel deposits in northeast Switzerland (Jussel et al., 1994), see l. 143-148.

7. Page 9301, lines 4 and 5.

> Unclear what referee #2 means. Is it unnecessary to draw uncorrelated hydraulic conductivity values? It simply add more noise. See also our response to referee #1, Major comment 7.

8. Page 9303, Lines 10-13

> We completely agree with referee #2 that "this observation holds for the synthetic conceptual model that is under investigation". That is exactly why we used the phrase modelled trough fills to clearly state that the conclusion only holds for the modelled trough fills. This point is clarified in the conclusion (l. 324-319).

9. Page 9303, line 11.

> Done as suggested by referee #2.

10. Page 9304, lines 13-15

> In this context, the whole geological fabric means the whole hydraulic conductivity field *of the model*. The phrase geological fabric refers to the model (all the voxel), not to the true geological units.

11. Figure.

> The coordinates of the survey field are provided. A simple map showing the survey location would not add any useful information.

12. Fig. 2.

> Good idea. Some arrows are now added on Fig. 2, 3 and 4 to show the strike of the GPR profiles.

13. Fig. 4.

> A scale is added to the photos.

14. Fig. 5.

> This figure does no longer exist as we use particle tracking instead of advective solute transport to investigate the effect of through fills on the advective mixing.

15. Fig. 5, 6 and 7.

> The x, y and z coordinates/axes are now shown on these figures.

16. Fig.7.

> Done as suggested by referee #2.

References

Anderson, M.P., J.S. Aiken, E.K. Webb, D.M. Mickelson (1999), Sedimentology and hydrogeology of two braided stream deposits. Sediment. Geol., 129: 187-199. doi:10.1016/S0037-0738(99)00015-9

Lunt, I.A., J.S. Bridge, R.S. Tye (2004), A quantitative, three-dimensional depositional model of gravelly braided rivers. Sedimentology, 51(3): 377-414. doi:10.1111/j.1365-3091.2004.00627.x

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Subsurface flow mixing in coarse, braided river deposits

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Abstract. Coarse, braided river deposits show a large hydraulic heterogeneity at the metre scale. One of the main depositional elements found in such deposits is a trough structure filled with ~~open-framework–bimodal gravel couplet cross-beds. Several studies investigated the impact of the highly permeable~~ alternating layers of bimodal gravel and open-framework gravel~~texture mainly in terms of concentration breakthrough curves. However, although the trough fills are expected to be significant mixing agents for the subsurface flow, their impact on the three-dimensional flow field has not draw~~, the latter being highly permeable. The impact of such trough fills on the subsurface flow and advective mixing has not drawn much attention. ~~This study aims to evaluate the subsurface flow mixing caused by overlapping trough fills embedded in a poorly-sorted gravel matrix. Below~~ A geologically realistic model of trough fills is proposed and fitted to a limited number of ground-penetrating radar records surveyed on the river bed of the Tagliamento River (northeast Italy)~~, trough fills were identified with ground-penetrating radar (GPR) probing. Based on field observations of coarse, braided river deposits, a simple three-dimensional geometrical model with associated hydraulic properties was fitted to the interpreted GPR reflectors. Then,~~. A steady-state~~subsurface flow and advective transport simulations were~~, saturated subsurface flow simulation is performed on the small-scale, high-resolution, synthetic model (size: ~~45m×50m×10.26m~~~~The impact of trough fills on the flow field is visualised by the injection of a conservative tracer at three different depths.~~ $75\,\text{m} \times 80\,\text{m} \times 9\,\text{m}$). Advective mixing (i.e., streamline intertwining) is visualised and quantified based on particle tracking. The results indicate a strong advective mixing as well as a large flow deviation induced by the asymmetry of the trough fills with regard to the main flow direction that results in a partial, large-scale rotational effect. These findings depict possible advective mixing found in natural environment and can guide the interpretation of ecological processes such as in the hyporheic zone.

1 Introduction

The subsurface heterogeneity at the ~~10~~ 1 to 100 m scale can induce significant subsurface flow mixing ~~processes that are~~ that is relevant for aquifer remediation or drinking wa-

ter extraction near a river or a contaminated area ~~(e.g. Kitanidis, 1994; ?; ?; ?)~~. ~~However, the~~ (e.g., Kitanidis, 1994; Mattle et al., 2001; Mays and Neupauer, 2012; Cirpka et al., 2015). Subsurface flow mixing is generally decomposed into an advective transport process combined with diffusion/dispersion (e.g., Mays and Neupauer, 2012). The advective transport process is best visualised with streamlines or streamtubes. Two-dimensional and three-dimensional ~~aspect of the sedimentary structures is often ignored or oversimplified~~ flows exhibit a different streamline rearrangement when flowing through heterogeneities (Steward, 1998). Two-dimensional, divergence-free flows locally deform the streamline geometry whereas three-dimensional, non-axisymetric flows permanently rearrange their streamtubes by redistributing the fluid within the subsurface (Steward, 1998; Janković et al., 2009). Janković et al. (2009) illustrated this difference by comparing two-dimensional and three-dimensional flows through an isolated, high-permeable subsurface structure whose rotational axis was not aligned with the mean flow direction (i.e., non-axisymetric flows). For two-dimensional flows, the distance between the streamlines at a large distance upstream and downstream from the high-permeable structure remains the same. On the contrary, the streamlines of three-dimensional flows are permanently deformed downstream from the high-permeable subsurface structure resulting in a complex intertwining of streamlines. Janković et al. (2009) coined the phrase *advective mixing* to describe this phenomena. Cirpka et al. (2015) identified three advective mixing phenomena that enhance solute mixing: (1) streamline focusing/defocusing, (2) depth-dependent streamline meandering (i.e., streamline deviation), and (3) secondary motion consisting in persistent twisting, folding, and intertwining of streamlines. Chiogna et al. (2015) demonstrated the occurrence of macroscopic helical flow in subsurface flow simulations ~~(e.g. when borehole information is horizontally/sub-horizontally interpolated, the vertical subsurface flow mixing can be smaller tha~~ the hydraulic conductivity field was heterogeneous and locally isotropic. Advective mixing plays an important role in solute mixing processes by enhancing diffusion/dispersion (Hemker et al., 2004; Janković et al., 2009; Cirpka et al., 2015; Ye et al., 2015) but volumetric concentration measurements on the field do not allow to distinguish between advective mixing and dispersion/diffusion (Janković et al., 2009).

~~This study focuses on~~ This study is part of a research project on the heterogeneity characterisation of coarse, braided river deposits ~~that~~ at different scales. The focus is here on one important aspect of heterogeneity, namely its influence on advective mixing. Coarse, braided river deposits are highly heterogeneous in terms of hydraulic properties (e.g., Jussel et al., 1994a; Anderson et al., 1999; Lunt et al., 2004) and make up many of the groundwater reservoirs worldwide ~~(???)~~ (Huggenberger and Aigner, 1999; Klingbeil et al., 1999; Bayer et al., 2011) and more than two thirds of the aquifers in Switzerland (Huggenberger, 1993). As schematically represented on Fig. 1, coarse, braided river deposits are characterised by two

main depositional elements, namely horizontal to sub-horizontal layers of poorly-sorted

65 gravel and trough fills characterised by clear-cut erosional lower-bounding surfaces ~~(e.g. ??????????????)~~ (e.g., Siegenthaler and Huggenberger, 1993; Jussel et al., 1994a; Beres et al., 1995, 1999; Rauber et al., 199 The fills generally consist of alternating open-framework–bimodal gravel couplet cross-beds, but fills consisting of poorly-sorted cross-beds or of interfingering crossbeds of poorly-sorted gravel and sand are not uncommon ~~(e.g. ?)~~ (e.g., Siegenthaler and Huggenberger, 1993) . Other less frequent

70 sedimentary structures and depositional elements are described in the references above. Because the permeability contrast between the open-framework gravel texture and the other textures is up to 3 orders of magnitude ~~(e.g. ?, Table 1)~~ (e.g., Jussel et al., 1994a, Table 1) , the spatial distribution of the open-framework gravel texture is expected to strongly influence the subsurface flow field and therefore to enhance ~~the vertical subsurface flow~~ advective mixing (Stauffer, 2007).

75 ~~Based on the observation~~ Based on observations of hydrofacies or sedimentary structures, several studies developed hydrogeological models of coarse, braided river deposits to investigate ~~the subsurface flow~~ subsurface transport. Most of these studies assessed either macro dispersion processes ~~(e.g. ??)~~ (e.g., Jussel et al., 1994b; Stauffer and Rauber, 1998) , sorption processes ~~(e.g. ??)~~ (e.g., Rauber et al., 1998; Teutsch et al., 1998) or particle concentrations ~~(e.g. ??) using~~

80 ~~mainly~~ (e.g., Anderson et al., 1999; Heinz et al., 2003) , mainly analysing breakthrough curves.

~~However, the impact of the trough fills on the subsurface flow mixing has not drawn too much attention. Stauffer (2007) simulated the subsurface flow through~~ Stauffer (2007) modelled a trough fill of alternating open-framework–bimodal gravel couplets ~~that was modelled~~ by a ~~highly permeable rectangular cuboid~~ highly-permeable rectangular cuboid with an anisotropic hydraulic conductivity

85 tensor. He quantified the subsurface flow disturbance downstream from the cuboid embedded in a homogeneous background matrix ~~. More particularly, he investigated the impact of diverse anisotropies of the three-dimensional hydraulic tensor of the cuboid on the flow field. "The maximum effect was observed for a horizontal angle of about 52and a inclination of 126. The~~ as a function of the angle of anisotropy of the hydraulic conductivity tensor. He noticed that "the disturbance manifests itself by

90 a ~~~~distinct distortion of the streamtubes. Laterally, the influenced width is about 2.5 times the width of the [cuboid] for the considered case. Vertically, this influenced width makes up about 10 times the thickness of the [cuboid]" (Stauffer, 2007).

~~This study aims to assess the impact of high-permeable~~ To the best of our knowledge the influence of trough fills on ~~the subsurface flow mixing processes. The sedimentary structure of two overlapping~~

95 ~~trough fills was imaged with~~ advective mixing has not been investigated with the exception of the work of Stauffer (2007) in which the complex trough fill structure was reduced to a simple cuboid with an homogeneous anisotropic conductivity.

The aim of the present work is to assess the influence of a *geologically realistic* representation of high-permeable trough fills on advective mixing.

100   The flow simulation is performed on a synthetic, conceptual model derived from ground-penetrating radar (GPR) data recorded over a small area (about $100\,\text{m} \times 50\,\text{m}$) on the river bed of the coarse, braided Tagliamento river (northeast Italy). ~~GPR is high-resolution geophysical imaging method that was proven to be particularly effective in outlining the main sedimentary structures (e.g. Huggenberger, 1993; ?; ?; ?) . The GPR profileswere then interpreted and simple geometric~~

105   ~~objects with associated hydraulic properties were~~ First, the sedimentary structure of two overlapping trough fills is inferred from three GPR profiles, one 53 m long approximatively parallel to the main flow direction and two 7.5 and 10 m long approximatively perpendicular to the main flow direction. Simple geometric objects corresponding to each sedimentary structure are manually fitted to the ~~interpretation. This study focuses on trough fills with alternating open-framework and bimodal~~

110   ~~gravel couplets because of their high permeability contrast (?) . A~~ interpretated GPR records. Then, a high-resolution, steady-state, three-dimensional ~~subsurface flow simulation was performed on this high-resolution hydraulic model and the advective transport of a conservative tracers placed at three different depths at the upstream model boundary was assessed~~groundwater model is set up based on hydraulic properties borrowed from the literature. Finally, advective mixing is investigated with

115   particle tracking.

2   Methods

2.1   Ground-penetrating radar data acquisition

~~Several common-offset GPR data (Fig. 2) were acquired~~ The project includes a collection of fourteen widely spaced GPR lines (about 25 m line spacing on average) recorded in a $100\,\text{m} \times 200\,\text{m}$ large

120   area on the river bed of the coarse, braided Tagliamento River downstream from the Cimano bridge ($46°12'37.945''$ N, $13°0'50.165''$ E; WGS1984)~~using~~. The objective of the project was to quantify the proportion of depositional elements in the sedimentary deposits. The interpretation of the GPR data showed that the reflectors corresponding to the erosional lower bounding surfaces of trough shaped depositional elements can be followed over large distances (> 25 m). Therefore, the chosen

125   spatial survey density was sufficient to accomplish the project task. The GPR data were recorded with a a PulseEkko Pro GPR system (Sensors & Software Inc., Mississauga, Canada) with $100\,\text{MHz}$ antennae. The nominal spatial resolution length of the $100\,\text{MHz}$ antennae is of the order of $0.3\,\text{m}$ (Bridge, 2009). The topography of the GPR profiles was surveyed with a Total Station.

The GPR data were processed as follows:

130   – Time-zero adjustment.

– Direct current-offset (DC-offset) removal based on samples before time-zero.

– Dewowing of each ~~traces~~ trace by removal of the trend estimated with a Hampel filter (Pearson, 2002).

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- A spherical and exponential gain was applied to compensate for geometric spreading and attenuation ~~(??)~~ (Kruse and Jol, 2003; Grimm et al., 2006) . This gain preserves the relative amplitudes.

- Low-pass filtering to remove the high (noisy) frequencies (corner frequencies at 150–200 MHz).

- Time-to-depth conversion with a constant velocity of 0.1 m ns^{-1} that leads to results that are sufficiently accurate for the purpose of this study. The velocity was estimated from previous common-mid point surveys recorded ~~on~~ in the same area.

~~Ground-penetrating radar data interpretation~~

2.2 Ground-penetrating radar data interpretation

The interpretation of the GPR profiles is based on (i) the continuity of the dominant reflectors within and between the profiles, (ii) the differences of reflection patterns, and (iii) the angular unconformity between the reflectors that ~~may~~ can indicate an erosion surface or the superposition of two sedimentary structures with different sedimentary textures (Beres et al., 1995, 1999) .
~~The GPR profiles that imaged a~~ Three GPR profiles image three relatively well-preserved~~trough fill structure were selected and interpreted (~~, overlapping trough fill structures that are identified by their erosional lower-bounding surfaces. Fig. 2 ~~). Two main erosional lower-bounding surfaces and therefore two main overlapping trough fill structures were identified~~shows the three GPR profiles as well as their interpretation. The GPR data ~~show~~ indicate that the trough fills are elongated in the main flow direction (i.e., the valley orientation) with cross-tangential reflector. The GPR profile "xline1" (perpendicular to the mean flow direction; Fig. 4A) displays asymmetrical circular-arced reflectors that are almost symmetrical on the profile "xline2". Most of the older trough (~~in blue on~~ represented in green in Fig. 2) is eroded by the younger ~~trough (in red~~troughs (represented in blue and red in Fig. 2).

2.3 Subsurface structural modelling

~~A~~The observed reflections are consistent with the results of many studies on coarse deposits that compared GPR reflections with sedimentological structures of outcrop exposures (e.g., Huggenberger, 1993; Bayer et al., 2011) . Because only three GPR records image the trough fills, a conceptual representation of the sedimentary structure is needed to ~~model~~ infer the three-dimensional structure of the imaged trough fills ~~from a few two-dimensional GPR data~~at a high resolution. The approach proposed by ~~?~~ Siegenthaler and Huggenberger (1993) is adopted. ~~? hypothesised that the~~ Siegenthaler and Huggenberger (1993) hypothesised that trough fills originate from confluence scours that can migrate. Therefore, they suggested to simulate the internal structure of the trough fills through geometric considerations, i.e., by several shifted half-ellipsoids

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representing the trough migration ~~(see also ?)~~ (see also Best and Rhoads, 2008) . In this study, the trough fills are represented by truncated ellipsoids. The position and the size of several truncated ellipsoids was ~~adjusted by hand~~ manually adjusted to match the GPR reflectors of the ~~two identified trough fill deposits~~ three identified trough fills. A top view of the resulting subsurface structural model is shown in Fig. 3. The GPR profiles are compared to vertical sections of the structural model as well as to vertical gravel pit exposures of coarse, braided river deposits located in northeast Switzerland (Fig. 4).

2.4 Hydrogeological model

The three-dimensional model grid has a size of ~~$45\,\mathrm{m} \times 50\,\mathrm{m} \times 10.26\,\mathrm{m}$ and a horizontal resolution of $0.5\,\mathrm{m} \times 0.5\,\mathrm{m}$. The first 62 layers are 0.1thick whereas the thickness of the last 8 layers increases geometrically by 1.3.~~ $75\,\mathrm{m} \times 80\,\mathrm{m} \times 9\,\mathrm{m}$ and a resolution of $0.5\,\mathrm{m} \times 0.5\,\mathrm{m} \times 0.1\,\mathrm{m}$. The truncated ellipsoids are discretised into the model grid between the 7 and the 31 layers (i.e.~~,~~ between 0.6 and 3.1 m below the surface). Because of the close correspondence of the GPR reflection patterns and of the sorting process with the observations made by Siegenthaler and Huggenberger (1993); Huggenberger (1993); Beres et al. (1995, 1999); Heinz et al. (2003) , we assume the hydraulic properties of the different types of gravel texture to be in the same order of magnitude as those estimated from measurements on disturbed and undisturbed samples in Quaternary coarse gravel deposits in northeast Switzerland (Jussel et al., 1994a) . The hydraulic properties of the poorly-sorted gravel (see Table 1) are attributed to the background matrix while the hydraulic properties of the bimodal and open-framework gravel (Table 1) are alternatively assigned to the voxels located between two consecutive truncated ellipsoids, following the conceptual model shown ~~on~~ in Fig. 1. For each voxel the hydraulic conductivities are drawn from ~~a~~ log-normal ~~distribution without taking into account any spatial dependence~~ distributions neglecting any spatial correlation (they are identically and independently distributed). The resulting conductivity field is displayed in ~~Figs~~ Fig. 5~~and 6. Note that the hydraulic~~ . The hydraulic conductivity tensors of the bimodal and open-framework gravel are ~~isotropic as the~~ both isotropic. A vertical anisotropy of the ~~open-framework–bimodal gravel couplets (e.g. ?) is already given by their three-dimensional spatial arrangement.~~

~~Hydraulic boundary conditions are~~ hydraulic conductivity $(K_h/K_v = 6)$ is assigned to the ~~three-dimensional grid as follows.~~ poorly-sorted gravel texture to reflect the layered structure that hinders vertical flow.

All the model boundaries are set as no-flow boundary with the exception of the ~~upstream and downstream~~ inflow $(x = 0\,\mathrm{m})$ and outflow $(x = 75\,\mathrm{m})$ model faces where constant head boundary conditions are specified (Fig. 5). The gradient between the ~~upstream and the downstream boundaries is 0.03~~ inflow and the outflow model faces is 0.03 and corresponds to a locally large hydraulic gradient as found in situations where a groundwater–surface water interaction occurs. The ~~concentration~~

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~~of three conservative tracers A, B and C is set constant at three different depths at the upstream~~
~~model boundary (i.e. 0.7–1.0, 1.9–2.2, 5.1–5.4; Fig. 5).~~

~~The~~ saturated, steady subsurface flow simulation is performed with MODFLOW (Harbaugh, 2005)~~and the advective transport simulation with MT3DMS (?) , both within the GMS software (Aquaveo)~~.

2.5 Advective mixing quantification

The advective flow is simulated with the particle-tracking scheme MODPATH (Pollock, 2012) . One particle per cell is set on the model inflow face and the position of the particles travelling through the model is recorded. The resulting streamlines combined with a judicious color scheme allow for visualisation of the advective mixing. Furthermore, we quantify the advective mixing by evaluating between the inflow face and the outflow face (i) particle deviation, (ii) particle divergence, and (iii) particle intertwining.

Particle deviation (Δ) is equal to the transverse distance between the particle position on the inflow face (y_i, z_i) and on the outflow face (y_o, z_o):

$$\Delta = \sqrt{(y_i - y_o)^2 + (z_i - z_o)^2} \tag{1}$$

For each cells of the outflow face we compute the median particle deviation from all the particle within the cell.

The particle divergence indicates how far a particle flowed away from its eights particle neighbours. For each particle we compute the absolute difference between (i) the median distance between the particle and its eight neighbours on the inflow face and (ii) the median distance between the particle and its eight neighbours from the inflow face on the outflow face.

The particle intertwining is estimated by the proportion of the four inflow neighbour a particle still has as neighbours on the outflow face. In order to really include all the neighbour particles, the neighbours on the outflow face are defined as the first and second order neighbours of the Delaunay triangles, i.e., the particles that are connected to the considered particles through an edge or two edges of the Delaunay triangles.

3 Results and discussion

~~The~~

3.1 Hydraulic heads

Similarly to a high-permeable homogeneous structure, the overlapping trough fills significantly influence the hydraulic head distribution – vertically (Fig. 5b) and horizontally (Fig. 6) – ~~and therefore the subsurface flow. They act as an attractor for the subsurface flow because the highly permeable~~

~~layers of open-framework gravel increase the hydraulic gradient close to the interface between the background matrix and the trough fills. However, the hydraulic gradient within the trough fills is much smaller (about 0.002). Figure~~inducing an asymmetric flow focusing and defocusing (compare with Fig. 7). Fig. 6 shows on longitudinal cross sections how the vertical distribution of the hydraulic heads is ~~clearly~~ significantly influenced by the trough fills: the hydraulic gradient is oriented upward, toward the trough fills at their upstream end and downward, outward the trough fills at their downstream end. However, this pattern is never symmetric even in the middle of the model (Fig. 6b) because of (i) the asymmetry of the internal structure of the trough fills and (ii) the non-alignment of the trough fills with the mean flow direction. The asymmetry of the vertical hydraulic head distribution becomes more asymmetric close to the lateral model boundaries. The upward gradient upstream from the trough fills slowly disappears toward the right model boundary (looking downstream; Fig. 6a), while the downward gradient downstream from the trough fills slowly disappears toward the left model boundary (Fig. 6c). The hydraulic gradient within the trough fills is very small (about 0.002).

~~We expected~~that the considered type of trough fills would enhance the vertical subsurface flow mixing by leading the upper subsurface flow downward through the highly permeable layers of open-framework gravel. However, the simulation results indicate a complex vertical mixing that is similar for all three tracers (Fig~~The asymmetry of the three-dimensional hydraulic head distribution causes a permanent rearrangement of the streamlines. Therefore, in addition to a flow focusing and defocusing effect, persistent streamline deformations and rearrangements are expected. ~~??).~~ ~~At the upstream end, the tracers (particularly B and C) are vertically attracted by the trough fills and therefore they flow upward. This effect that starts about 10~~

3.2 Particle tracking

Fig. 8 shows the position of the particles on the model outflow face coloured by their initial y- and z-coordinates on the inflow face. The convex hull of the particles on the outflow face that flowed through the trough fills as well as the shape of the trough fills projected on the outflow face are also represented. The size of the projected trough fill shape and of the convex hull are about 38.5 m~~away from the right model side is more pronounced toward the left model side. Then, a strong vertical and horizontal mixing associated with a dilution of the tracer concentrations occurs where the tracers meet~~ $\times 2.2$ m and 52.0 m $\times 6.7$ m, respectively. On the inflow face, the shape of the convex hull of the particles that flow through the ~~trough fills, within and downstream from the troughs. The tracer component that do not meet the through fills flow according to the hydraulic head distribution (~~trough fills (not shown) is up to a lateral shift of 8 m nearly identical to the convex hull shown in Fig. 8. This could indicate a similar flow focusing and defocusing effect combined with a lateral flow deviation. However, a notable particle deviation is clearly visible inside and outside the convex hull (see also

Fig. 6), namely horizontally on the left model side and downward on the right model side and do not significantly mix.

At the downstream model boundary, the maximal thickness of the mixing zones reaches 59). The median particle deviation is 4.0 m for all the tracers (i.e. twice the thickness of the trough fills).The maximal width is 42whereas the maximum is 28.1 mfor tracer A and B (i.e. the width of the projection of . The particle deviation outside the convex hull is very small at the exception of some particles below the convex hull (up to 12 m). Even if small, the particle deviation outside the convex hull is smoothly varying because these particles flowed through the low heterogeneous poorly-sorted gravel. The largest particle deviations are observed in the convex hull. There, the particle deviations are irregular in amplitude and direction but still show an horizontal trend as expected from the orientation of the trough fills. Note that the asymmetry of the trough fills on the downstream model side) and 29causes a partial, large-scale rotation of the particles.

The largest median distances between each particle and its eight inflow neighbours on the outflow face are found within the convex hull (Fig. 10a), where most of the particles lay at least four times farther away from their inflow neighbours as on the inflow face. The median distance between a particle and its eight neighbours is 0.1 for tracer C. Note that even if the specified concentration of tracer C is set m on the inflow face and less than 2% of the particles are more than 10 m below away from their neighbours. The largest distance are found in the central part of the convex hull that is associated to the two younger trough fills (trough fills 2 and 3 in Figs. 2 and 3. More than the half of the particles outside the convex hull lay closer to their inflow neighbours on the outflow face. The analysis of the remaining neighbours (Fig. 10b) attests a strong particle intertwining as indicated by Fig. 10a. Indeed, about 70% of the particles in the convex hull on the outflow face are no more surrounded by their four initial neighbours from the inflow face.

3.3 Advective mixing mechanism

For the sake of clarity, Fig. 11 shows only the paths of few particles that cross the trough fills, tracer C partially reach the bottom of the scour fillsand mixes vertically and laterally. Tracers A , B and C are vertically deviated up to 3.1, 2.8, and 1.5from their input elevation.

To summarize, the modelled trough fills act as (i) an upwardattractor for the groundwater upstream the trough fill centre, (ii) a vertical and horizontal mixing agent for . The particles upstream from the trough fills are attracted by the highly-permeable layers of the flow that enters open-framework gravel. Shortly before the particles enter the trough fills, and (iii) a downward/upward repeller for the groundwater flow downstream from the trough fill center. some of them show a strongly curved path toward the trough fills. The particles that enter the open-framework gravel layers flow rather horizontally within these layers until they dip upward. A closer look on Fig. 11 reveals series of sharp vertical zigzags of the particle paths, predominantly at the downstream end of the trough fills

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where the layers of open-framework gravel dip upward. These zigzags occur where the particles tightly jump vertically between two adjacent layers of open-framework gravel.

~~When the tracers enter the downward-dipping layers of the~~ Fig. 12 displays an enlarged view of a vertical section of the model along the main flow direction that shows the layers of open-framework ~~gravel, they are not pushed downward as the hydraulic gradient is there horizontal or slightly dipping upward. Within the trough fills the tracers mix in all direction. At the moment the tracers reach the other side of~~ gravels as well as the vertical hydraulic head distribution. The arrows represent the volumetric flux (Darcy's flux) vectors projected on the vertical section for each cells of the open-framework layers. Note that the hydraulic conductivity tensor within the trough fills ~~, the tracers are not significantly influenced by the dipping-upward layers of the~~ is isotropic. Therefore, the volumetric flux along each dimension of the Cartesian coordinate system is proportional the hydraulic conductivity at the cell interface times the hydraulic gradient along the same dimension. Fig. 12 reveals a complex spatial distribution of the volumetric flux that appears rather chaotic in the upward-dipping part. However, we observe that four of the upward-dipping layers of open-framework ~~gravel, thus the mixing of~~ present a similar pattern: although very small in amplitude, the volumetric flux of the lower cells of these layers tend to point downward whereas in the upper cells the flux tend to point upward. The vertical position of the particles within the open-framework gravel layers is therefore critical because two closely spaced particles can flow in opposite direction. As a consequence, the volumetric flux pointing downward lets some of the ascending particles exit the trough fill earlier (see Fig. 11). In a similar way, two closely-spaced particles do not enter the ~~tracers continues. Flow direction and mixing seems to be dominated by~~ trough fills at the same position and therefore follow different paths within the trough fills. Small spatial variations of the volumetric flux (not only vertically but also horizontally) can drive the particles far away from each others (Fig. 11). This advective mixing illustrates the importance of the interplay between the hydraulic head ~~distribution and to a less extend by the anisotropy due to the open-framework–bimodal gravel distribution in~~ field and the spatially distributed hydraulic conductivity that results in an heterogeneous volumetric flux distribution within the trough fills.

~~Some conclusions can be drawn for this specific trough fill configuration (i. e. two isolated, overlapping trough fills with open-framework–bimodal gravel couplets)~~ In consequence, the transport process through the trough fills can be viewed as a chaotic process where the particle positions on the outflow face sensitively depends on the initial particle positions on the inflow face (Neupauer et al., 2014) . Note that the same effect is obtained with homogeneous hydraulic conductivity for each sedimentary texture. Spatial random hydraulic conductivity values increase advective mixing at level that is negligible compared with the advective mixing resulting from the three-dimensional arrangement of the different textures.

A brief investigation of the influence on some parameters on advective mixing showed the following. (i) ~~The larger and wider the trough fills are, the larger the zone vertical mixing and~~

~~dilution~~The decrease of the hydraulic gradient significantly increases the lateral deviation of the particles. (ii) ~~The deeper the trough fills are, the deeper is the groundwater that is attracted by~~ The extend of the convex hull of the particles that crossed the trough fills~~.~~

~~Note that trough fills consisting of cross-bedded~~ , the particle deviation and mixing increase with increasing hydraulic conductivity of the open-framework gravel. (iii) The vertical extend of the convex hull zone downstream from the trough fills as well as the vertical particle deviation are inversely proportional to the vertical anisotropy (K_h/K_v) of the poorly-sorted gravel ~~or of interfingering cross-beds are likely to lead to different flowstructures and therefore mixing patterns. Furthermore, the spatial location of the tracer boundary condition may play a relevant role for understanding the subsurface flow mixing (e.g. a specified tracer concentration over the whole depth of the upstream model boundary would enhance the effects of the fast flow pathways at the expense of the subsurface flow~~ texture (matrix) because a large vertical anisotropy of the poorly-sorted gravel texture hampers vertical flow. The angle between the trough fills and the main flow direction plays an important role for the mixing ~~and dilution observed in this study). Furthermore, a large proportion~~ processes. The width and height of the mixing zones negatively correlate when the orientation of the trough fills changes impacting significantly advective mixing. Furthermore, when the trough fills are aligned with the main flow direction a partial, transverse rotation of the particles is observed within the convex hull. When the trough fills are perpendicular to the main flow direction, the advective mixing is the smallest. The largest convex hull, particle deviation and mixing are found when the trough fills form an 45deg angle with the main flow direction.

4 Discussion

Adjective mixing is enhanced by the spatial distribution of trough fills in the ~~subsurface would interfere the mixing and diverging properties of each single trough fill, and therefore, result~~ sedimentary records and by the unsteady flow magnitude and direction. The advective mixing zones of closely spaced trough fills can interfere resulting in a more complex subsurface flow pattern. Under unsteady boundary conditions the mean flow direction and therefore the angle between the trough fills and the main flow direction change with time. In such a situation, the advective mixing zone as well as the flow patterns are expected to vary spatially and temporally leading without doubt to an enhanced advective mixing. Because of this complexity, the present experiment is a starting point for further investigations on the influence of different proportions and types of trough fills on ~~the subsurface flow field and mixing processes~~ advective mixing in coarse fluvial aquifers at the ~~10~~ 1 to 100 m scale.

~~A simplified three-dimensional hydrogeological modelof two overlapping trough fills was built from interpreted GPR data following the concepts introduced by ? . Isolated trough fillsthat consist of alternating~~ In the presented synthetic model, the layers of poorly-sorted

gravel are not modelled by individual layers but by matrix because the interface between the layers of poorly-sorted gravel are barely identifiable on the GPR records. While the model set-up (isolated trough fills embedded in poorly-sorted gravel) was observed in gravel carries (e.g., Siegenthaler and Huggenberger, 1993) , thin, finite layers of open-framework gravel can also be found within the layers of poorly-sorted gravel (e.g., Huggenberger and Regli, 2006) . However, the contribution of these thin, high-permeable structures to advective mixing is expected to be negligible compared to that of the trough fills. The hydraulic conductivity tensors of the bimodal and open-framework gravel are both isotropic. But at a larger scale, when considered together, the open-framework–bimodal gravel couplets ~~strongly impact the flow field by acting (i) an upward~~ show an anisotropic hydraulic conductivity (e.g., Jussel et al., 1994a; Stauffer, 2007) because of their layered structures and of the hydraulic conductivity contrast between the open-framework gravel and the bimodal gravel. Therefore, at this scale, the flow direction may be not parallel to the hydraulic head gradient.

Note that the use of an interpolation scheme is superfluous if densely-sampled GPR data are available (e.g., pseudo three dimensional GPR survey), on condition that the different sedimentary textures are well-resolved by GPR.

5 Conclusions

This study puts the hydraulic heterogeneity of coarse, braided river deposits in a new term through a simple geometrical model. The modelled trough fills (1) act as an attractor for the groundwater upstream ~~the trough fill centre, (ii) a vertical and horizontal mixing agent for the flow that enters the trough fills~~ from the trough fills, (2) induce a significant intertwining of the streamlines that flow through resulting in a strong advective mixing, and (~~iii) a downward repeller for the groundwater flow downstream from the trough fill center.~~

~~While numerous authors identified the aquifer heterogeneity as one of the major controls on mixing and transport processes in groundwater and river-groundwater interaction (e.g. ???) , this study puts the hydraulic heterogeneity of coarse, braided river deposits in concrete terms~~3) cause a strong horizontal streamline deviation that results in a partial, large-scale flow rotation. Furthermore, the anisotropy of the hydraulic conductivity of the poorly-sorted gravel strongly influences vertical advective mixing whereas the orientation of the trough fills determine the flow patterns and therefore the degree of mixing. The advective mixing produced by the trough fills resembles a chaotic process that is very sensitive to the initial positions of the streamlines. Whereas the emphasis is often put on the fast flow pathways and their connectivity, this study ~~shows how~~ demonstrates the importance of the hydraulic head field ~~, which~~ in advective mixing. The hydraulic head field results from the boundary conditions and the *whole* geological fabrics ~~, plays an important role in the subsurface flow transport (see also Voss, 2011) . Furthermore, the high permeable connection patterns are not only~~

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determinant to subsurface flow mixing processes but also to stream water–groundwater exchange as well as biological exchange in the hyporheic zone (e.g. **???**) .

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Table 1. Hydraulic properties of the main sedimentary structures ~~(after ?)~~ (after Jussel et al., 1994a) .

	Poorly-sorted gravel	Bimodal gravel	Open-framework gravel
Porosity	0.2	0.25	0.35
K_h (m s^{-1})	1.5×10^{-3}	1.5×10^{-3}	1×10^{-1}
$\sigma_{\ln K}$ (m s^{-1})	0.5	0.1	0.1
K_h/K_v	6	1	1
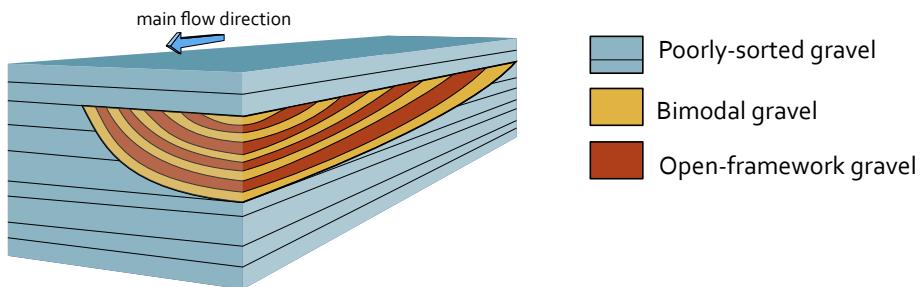
Figure 1. Simplified conceptual model of a single trough fill ~~deposit~~ (with alternating open-framework–bimodal gravel couplets) embedded into ~~a background matrix~~ layers of poorly-sorted gravel.
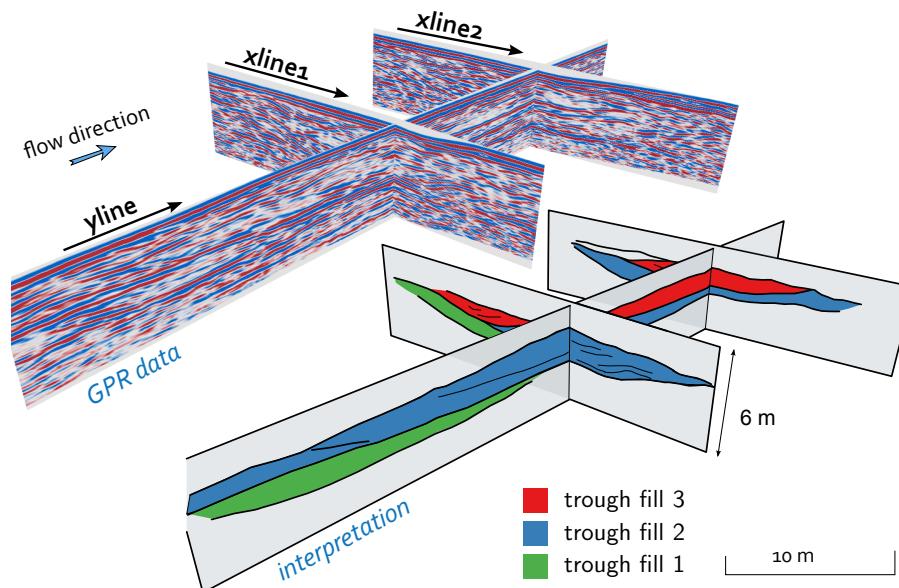
Figure 2. Fence diagram of the GPR data and their interpretation. The black arrows indicate the GPR survey direction.
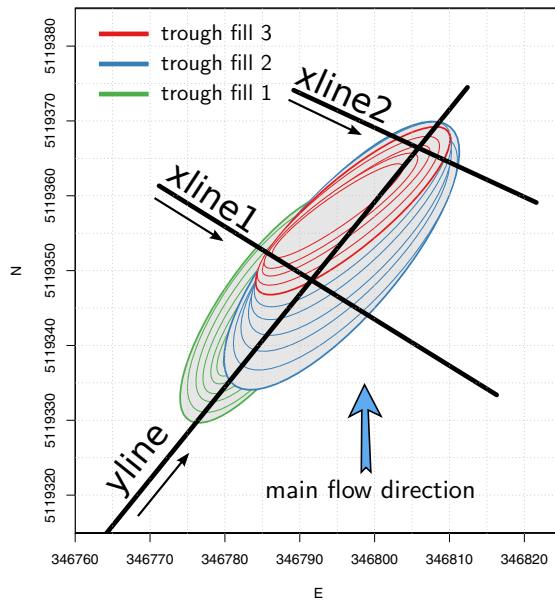
Figure 3. Top view of the geometrical trough fill model (Coordinate system: WGS 1984, UTM Zone 33N). The two trough fills are here represented by the green, blue and the grey red ellipses. The red black lines indicate the position of the ground-penetrating radar profiles and the black arrows the GPR survey direction.
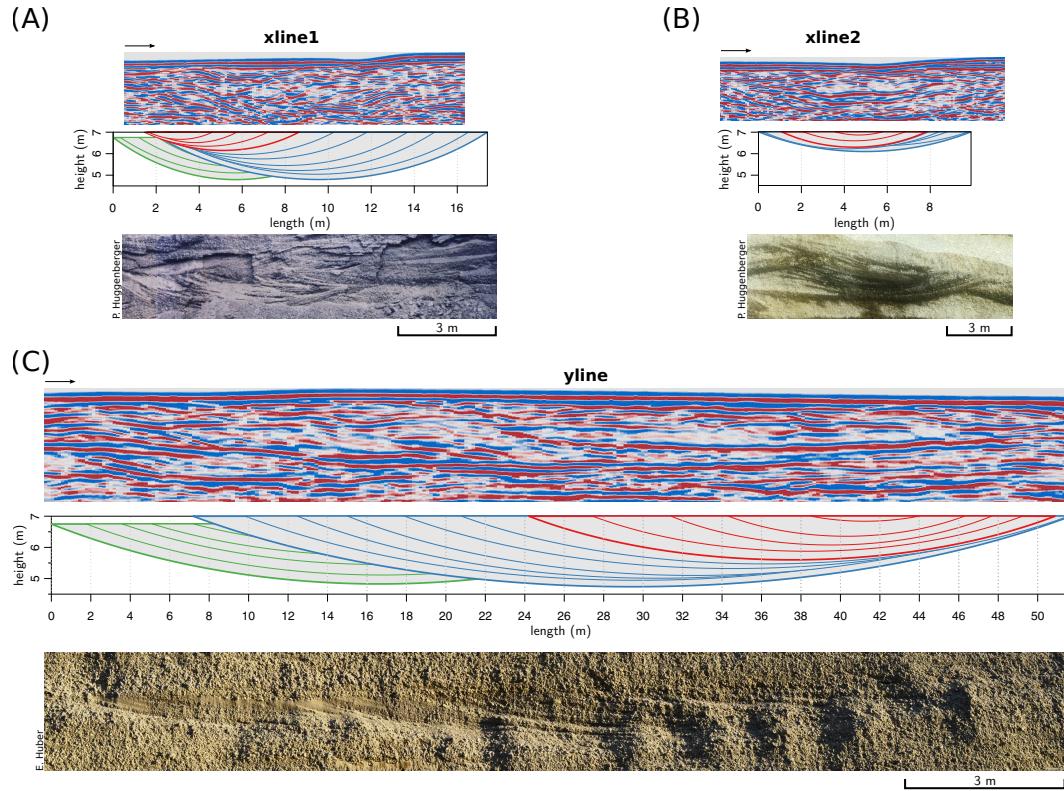
**Figure 4. (a)–(c)** Ground-penetrating radar data, sections of the geometric model and ~~, for comparison purposes,~~ vertical outcrop exposures (northeast Switzerland) <u>for comparison purposes</u>. The ~~two~~ trough fills are ~~here~~ represented by ~~the~~ <u>green,</u> blue and ~~the grey truncated~~ <u>red</u> ellipses. <u>The black arrows indicate the GPR survey direction</u>
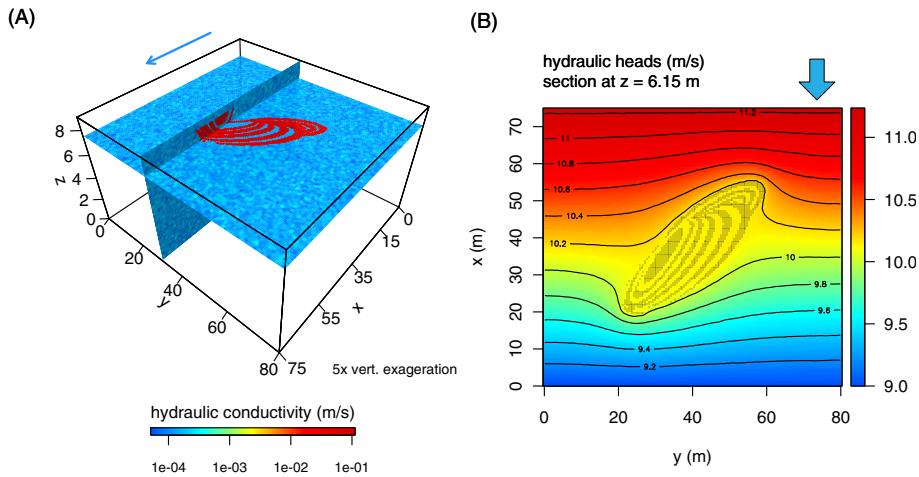

Figure 5. (a) Hydrogeological model setup with spatial distribution of the hydraulic conductivity values. **(b)** Hydraulic head at the upper model boundary (top view, contour every 0.05 m). <u>The blue arrows indicate the main flow direction.</u>
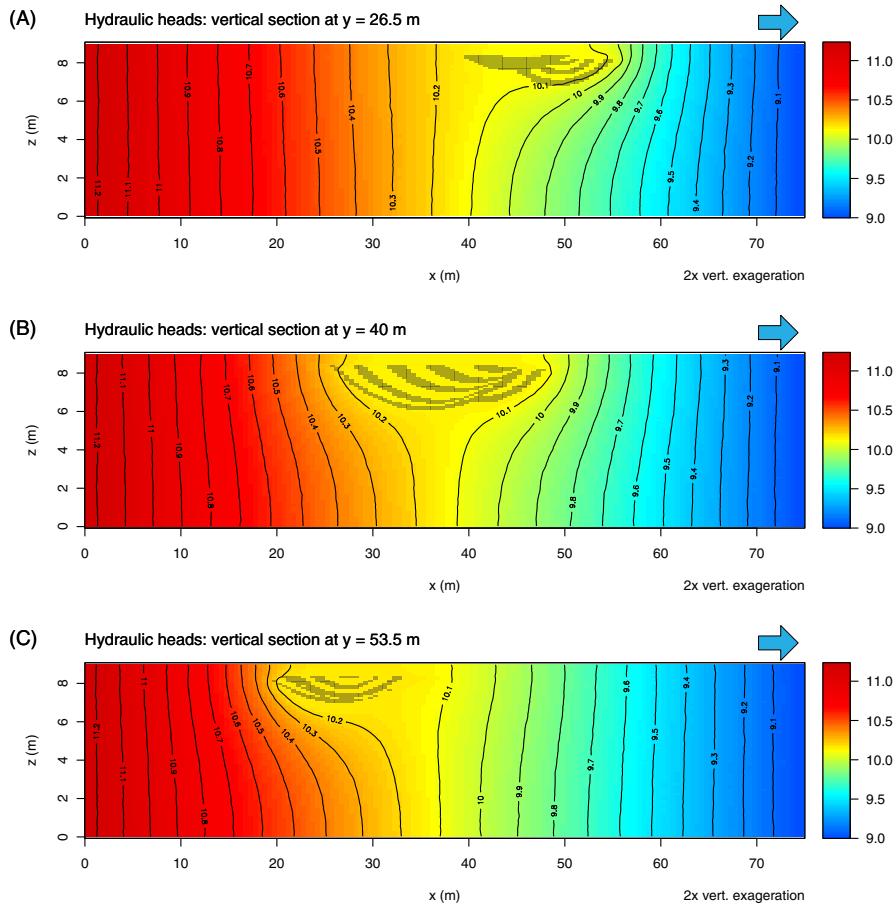
Figure 6. Cross sections of the hydrogeological model along the ~~y~~ x axis (see the coordinate system defined in Fig. ~~3~~5a) ~~. Hydraulic~~ with hydraulic head contours (every ~~0.1~~0.2 m) superimposed on the hydraulic ~~conductivity~~ head values. The blue arrows indicate the main flow direction. The grey pixels correspond to the highly-permeable layers of open-framework gravels.

(A) particles coloured by their inflow y-position (m)

(B) particles coloured by their inflow z-position (m)

inflow y-position (m)
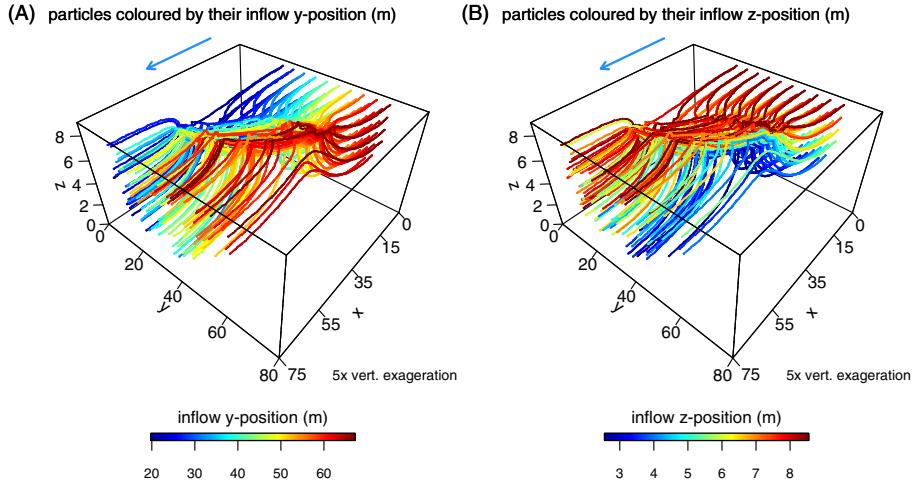
inflow z-position (m)

Figure 7. ~~Particles coloured by their~~ **(a)** ~~(c) spatial distribution of the tracer concentration for tracers A, B~~ y-coordinate position and ~~C~~**(b)** z-coordinate position on the inflow face. ~~They grey body represents~~ The blue arrows indicate the ~~overlapping trough fills~~ main flow direction.

(A) outflow: particles coloured by their inflow y-position (m)

(B) outflow: particles coloured by their inflow z-position (m)
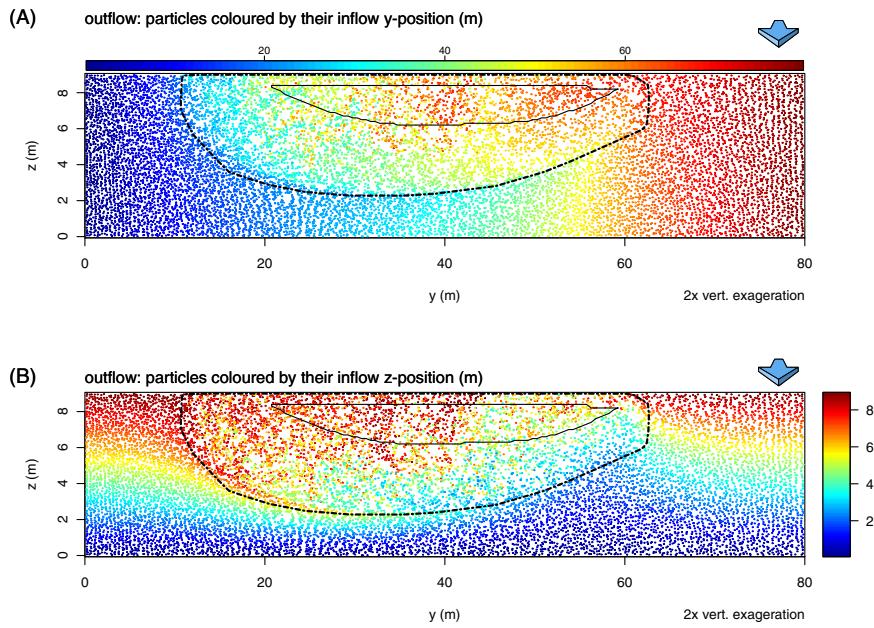
Figure 8. Particles on the model outflow face coloured by their **(a)** y-coordinate position and **(b)** z-coordinate position on the inflow face. The black line represents the shape of the trough fills projected on the outflow face and the dashed line represents the convex hull of the particles on the outflow face that flowed through the trough fills. The blue arrows indicate the main flow direction.
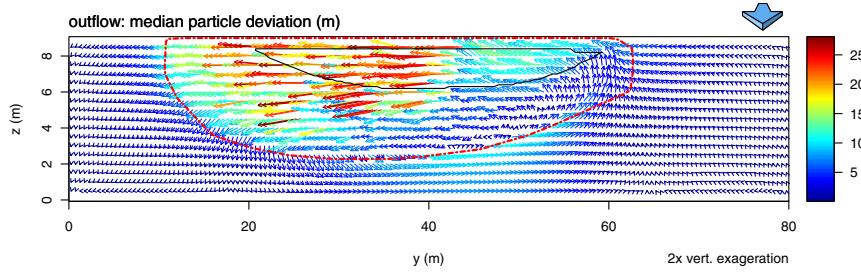
Figure 9. Median particle deviation between the inflow face and the outflow face (computed vertically for every five cells) represented by arrows. The arrow length and colour correspond to the deviation magnitude. The black line represents the shape of the trough fills projected on the outflow face and the dashed, red line represents convex hull of the particles on the outflow face that flowed through the trough fills. The blue arrow indicates the main flow direction.
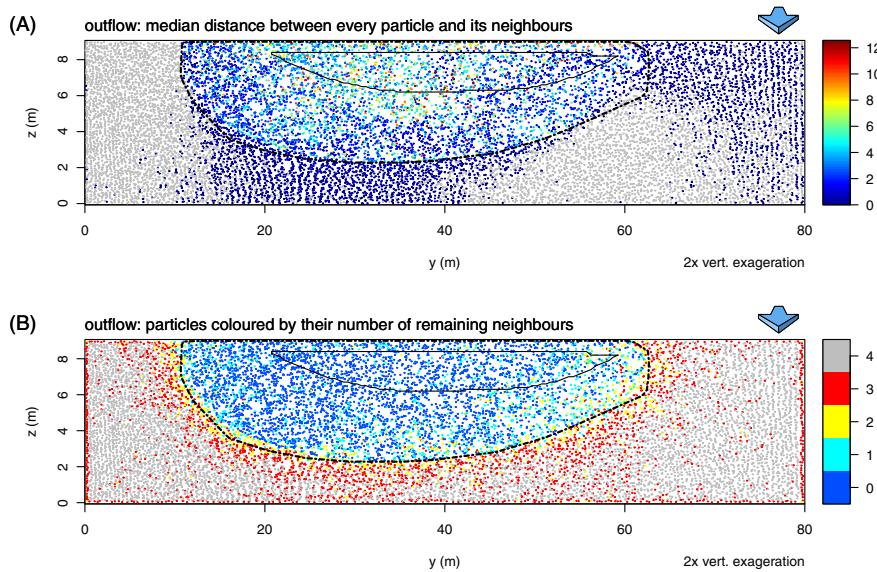

Figure 10. Particles on the model outflow face. **(a)** Median distance between each particle and its eight inflow-face neighbours computed on the outflow face. **(b)** For each particle on the outflow face, number of remaining neighbours from their four inflow-face neighbours. The black line represents the shape of the trough fills projected on the outflow face and the dashed line represents convex hull of the particles on the outflow face that flowed through the trough fills. The blue arrow indicates the main flow direction.

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(A) particles coloured by their inflow y-position (m)

(B) particles coloured by their inflow z-position (m)

inflow y-position (m)

20   30   40   50   60

inflow z-position (m)

4   5   6   7   8
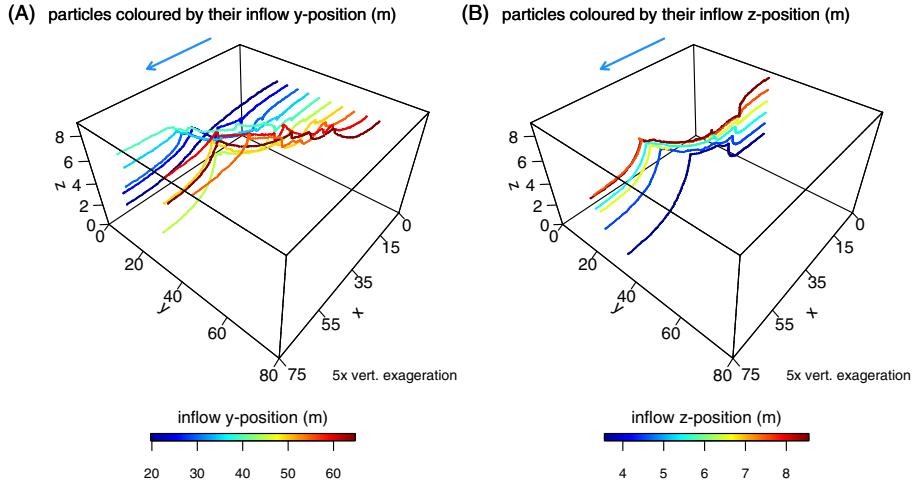
Figure 11. Selected particles coloured by their **(a)** y-coordinate position and **(b)** z-coordinate position on the inflow face. The blue arrow indicates the main flow direction.

Hydraulic heads (m) and volumetric flux (m/s): vertical section at y = 40 m
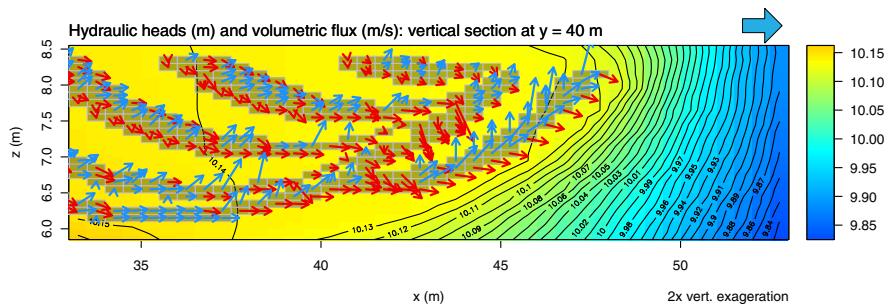
Figure 12. Enlarged view of the vertical section of the hydrogeological model along the x axis with the hydraulic head contours (every 0.01 m) superimposed on the hydraulic head values. The grey rectangles represent the open-framework cells. The arrows correspond to the volumetric flux vectors projected on the model section; red indicates that the flux flows downward, blue upward. The large blue arrow on top indicates the main flow direction