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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 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 much attention. This study aims to evaluate the subsurface flow mixing caused by overlapping trough fills embedded in a poorly-sorted gravel matrix. Below 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, steady-state subsurface flow and advective transport simulations were performed on the small-scale, high-resolution model (size: 45 m × 50 m × 10.26 m). The impact of trough fills on the flow field is visualised by the injection of a conservative tracer at three different depths.

1 Introduction

The subsurface heterogeneity at the 10 to 100 m scale can induce significant subsurface flow mixing processes that are relevant for aquifer remediation or drinking water extraction near a river or a contaminated area (e.g. Kitanidis, 1994; Mattle et al., 2001; Mays and Neupauer, 2012; Cirpka et al., 2015). However, the three-dimensional aspect of the sedimentary structures is often ignored or oversimplified in subsurface flow simulations (e.g. when borehole information is horizontally/sub-horizontally interpolated, the vertical subsurface flow mixing can be smaller than the horizontal subsurface flow mixing because of the influence of low hydraulic conductivities values in the sequence of sediments; Whittaker and Teutsch, 1999).

This study focuses on coarse, braided river deposits that 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 gravel and trough fills characterised by clear-cut erosional lower-bounding surfaces (e.g. Siegenthaler and Huggenberger, 1993; Jussel et al., 1994a; Beres et al., 1995, 1999; Rauber et al., 1998; Stauffer and Rauber, 1998; Teutsch et al., 1998; Anderson et al., 1999; Klingbeil et al., 1999; Whittaker and Teutsch, 1999; Heinz and Aigner, 2003; Heinz et al., 2003; Huggenberger and Regli, 2006; Bayer et al., 2011). 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. Siegenthaler and Huggenberger, 1993). Because the permeability contrast between the open-framework gravel texture and the other textures is up to 3 orders of magnitude (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 mixing (Stauffer, 2007).

Based on the observation of hydrofacies or sedimentary structures, several studies developed hydrogeological models of coarse, braided river deposits to investigate the subsurface flow transport. Most of these studies assessed either macro dispersion processes (e.g. Jussel et al., 1994b; Stauffer and Rauber, 1998), sorption processes (e.g. Rauber et al., 1998; Teutsch et al., 1998) or particle concentrations (e.g. Anderson et al., 1999; Heinz et al., 2003) using mainly 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 a trough fill of alternating open-framework–bimodal gravel couplets that was modelled by a highly permeable rectangular 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 52° and a inclination of 126°. The disturbance manifests itself by 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 trough fills on the subsurface flow mixing processes. The sedimentary structure of two overlapping trough fills was imaged with ground-penetrating radar (GPR) over a small area (about 100 m × 50 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; Beres et al., 1999; Heinz and Aigner, 2003; Bayer et al., 2011). The GPR profiles were then interpreted and simple geometric objects with associated hydraulic properties were manually fitted to the interpretation. This study focuses on trough fills with alternating open-framework and bimodal gravel couplets because of their high permeability contrast (Siegenthaler and Huggenberger, 1993). A 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.

2 Methods

2.1 Ground-penetrating radar data acquisition

Several common-offset GPR data (Fig. 2) were acquired 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 a PulseEkko Pro GPR system (Sensors & Software

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Inc., Mississauga, Canada) with 100 MHz antennae. The nominal spatial resolution length of the 100 MHz antennae is of the order of 0.3 m (Bridge, 2009). The topography of the GPR profiles was surveyed with a Total Station.

The GPR data were processed as follows:

- Time-zero adjustment.
- Direct current-offset (DC-offset) removal based on samples before time-zero.
- Dewowing of each traces by removal of the trend estimated with a Hampel filter (Pearson, 2002).
- 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 the same area.

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 indicate an erosion surface or the superposition of two sedimentary structures with different sedimentary textures.

The GPR profiles that imaged a well-preserved trough fill structure were selected and interpreted (Fig. 2). Two main erosional lower-bounding surfaces and therefore

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two main overlapping trough fill structures were identified. The GPR data show 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 Fig. 2) is eroded by the younger trough (in red).

2.2 Subsurface structural modelling

A conceptual representation of the sedimentary structure is needed to model the three-dimensional structure of the imaged trough fills from a few two-dimensional GPR data. The approach proposed by Siegenthaler and Huggenberger (1993) is adopted. Siegenthaler and Huggenberger (1993) hypothesised that the 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 representing the trough migration (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 to match the GPR reflectors of the two identified trough fill deposits. 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).

2.3 Hydrogeological model

The three-dimensional model grid has a size of 45 m × 50 m × 10.26 m and a horizontal resolution of 0.5 m × 0.5 m. The first 62 layers are 0.1 m thick whereas the thickness of the last 8 layers increases geometrically by 1.3. 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). 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 Fig. 1. For each voxel the hydraulic conductivities are drawn from a log-normal distribution without taking into account any spatial dependence (they are identically and independently distributed). The resulting conductivity field is displayed in Figs. 5 and 6. Note that the hydraulic tensors of the bimodal and open-framework gravel are isotropic as the anisotropy of the open-framework–bimodal gravel couplets (e.g. Jussel et al., 1994a) is already given by their three-dimensional spatial arrangement.

Hydraulic boundary conditions are assigned to the three-dimensional grid as follows. All the model boundaries are set as no-flow boundary with the exception of the upstream and downstream model faces where constant head boundary conditions are specified (Fig. 5). The gradient between the upstream and the downstream boundaries is 0.03 and corresponds to a locally large hydraulic gradient as found in situations where a groundwater–surface water interaction occurs. The concentration 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 m; Fig. 5).

The saturated, steady subsurface flow simulation is performed with MODFLOW (Harbaugh, 2005) and the advective transport simulation with MT3DMS (Zheng and Wang, 1999), both within the GMS software (Aquaveo).

3 Results and discussion

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 6 shows on longitudinal cross sec-

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tions how the vertical distribution of the hydraulic heads is clearly 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). 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), while the downward gradient downstream from the trough fills slowly disappears toward the left model boundary (Fig. 6).

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. 7). 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 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 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 (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 5 m for all the tracers (i.e. twice the thickness of the trough fills). The maximal width is 42 m for tracer A and B (i.e. the width of the projection of the trough fills on the downstream model side) and 29 m for tracer C. Note that even if the specified concentration of tracer C is set 2 m below the trough fills, tracer C partially reach the bottom of the scour fills and mixes vertically and laterally. Tracers A, B and C are vertically deviated up to 3.1, 2.8, and 1.5 m from their input elevation.

To summarize, the modelled trough fills act as (i) an upward attractor for the groundwater upstream the trough fill centre, (ii) a vertical and horizontal mixing agent for the flow that enters the trough fills, and (iii) a downward/upward repeller for the groundwater flow downstream from the trough fill center.

When the tracers enter the downward-dipping layers of the 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 the trough fills, the tracers are not significantly influenced by the dipping-upward layers of the open-framework gravel, thus the mixing of the tracers continues. Flow direction and mixing seems to be dominated by the hydraulic head distribution and to a less extend by the anisotropy due to the open-framework–bimodal gravel distribution in 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). (i) The larger and wider the trough fills are, the larger the zone vertical mixing and dilution. (ii) The deeper the trough fills are, the deeper is the groundwater that is attracted by the trough fills.

Note that trough fills consisting of cross-bedded poorly-sorted gravel or of interfingering cross-beds are likely to lead to different flow structures 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 mixing and dilution observed in this study). Furthermore, a large proportion of trough fills in the subsurface would interfere the mixing and diverging properties of each single trough fill, and therefore, result in a more complex subsurface flow pattern. 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 in coarse fluvial aquifers at the 10 to 100 m scale.

4 Conclusions

A simplified three-dimensional hydrogeological model of two overlapping trough fills was built from interpreted GPR data following the concepts introduced by Siegenthaler and Huggenberger (1993). Isolated trough fills that consist of alternating open-framework–bimodal gravel couplets strongly impact the flow field by acting (i) an upward attractor for the groundwater upstream the trough fill centre, (ii) a vertical and horizontal mixing agent for the flow that enters the trough fills, 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. Sophocleous, 2002; Kollet and Zlotnik, 2005; Fleckenstein et al., 2006), this study puts the hydraulic heterogeneity of coarse, braided river deposits in concrete terms. Whereas the emphasis is often put on the fast flow pathways and their connectivity, this study shows how the hydraulic head field, which 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 determinant to subsurface flow mixing processes but also to stream water–groundwater exchange as well as biological exchange in the hyporheic zone (e.g. Fleckenstein et al., 2006; Boulton et al., 2010; Boano et al., 2014).

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

	Poorly-sorted gravel	Bimodal gravel	Open-framework gravel
Porosity	0.2	0.25	0.35
K_h ($\mathrm{m\,s^{-1}}$)	1.5×10^{-3}	1.5×10^{-3}	1×10^{-1}
$\sigma_{\ln K}$ ($\mathrm{m\,s^{-1}}$)	0.5	0.1	0.1
K_h/K_v	6	1	1

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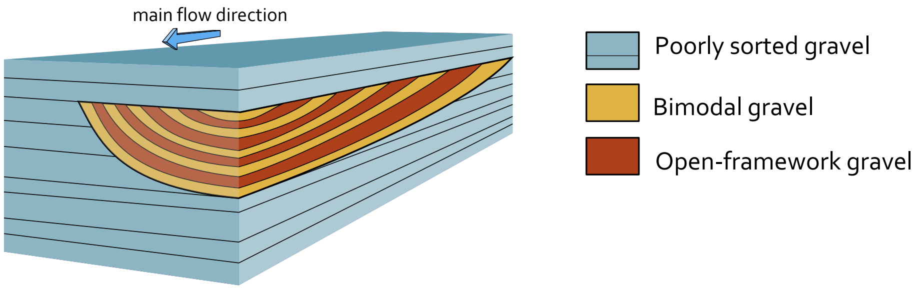

Figure 1. Simplified conceptual model of a single trough fill deposit (with alternating open-framework–bimodal gravel couplets) embedded into a background matrix of poorly-sorted gravel.

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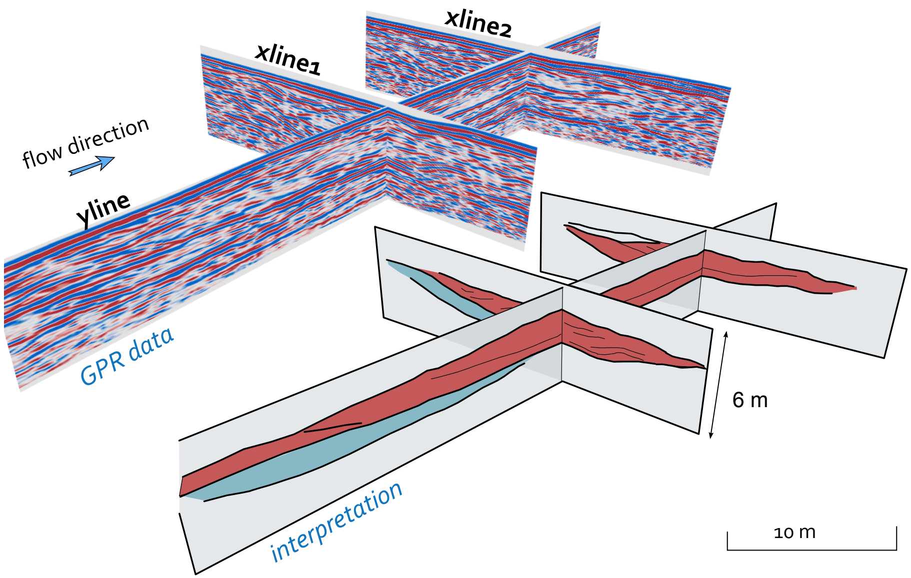

Figure 2. Fence diagram of the GPR data and their interpretation.

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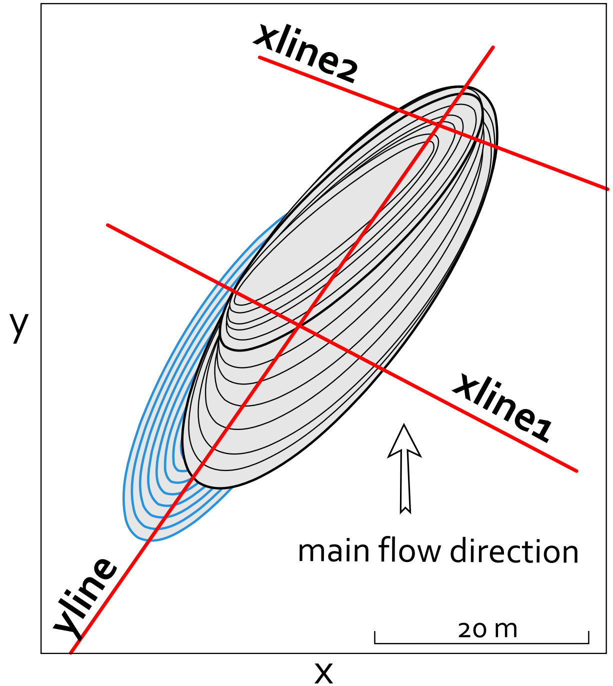

Figure 3. Top view of the geometrical trough fill model. The two trough fills are here represented by the blue and the grey ellipses. The red lines indicate the position of the ground-penetrating radar profiles.

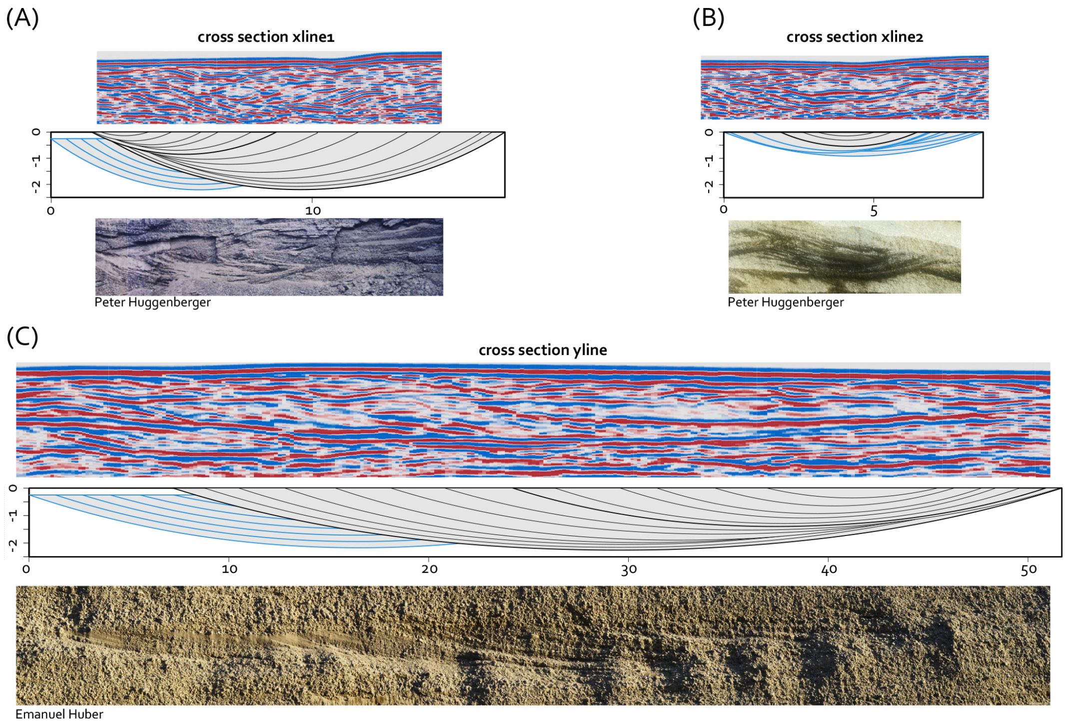

Figure 4. (a)–(c) Ground-penetrating radar data, sections of the geometric model and, for comparison purposes, vertical outcrop exposures (northeast Switzerland). The two trough fills are here represented by the blue and the grey truncated ellipses.

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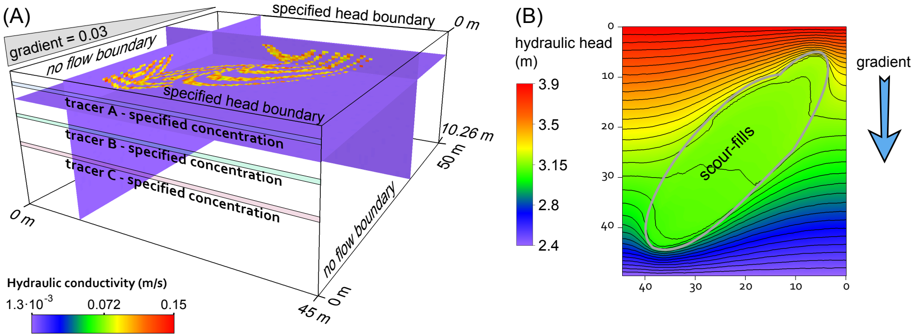

Figure 5. (a) Hydrogeological model setup with spatial distribution of the hydraulic conductivity values. **(b)** Hydraulic head at the upper model boundary (top view, contour every 0.05 m).

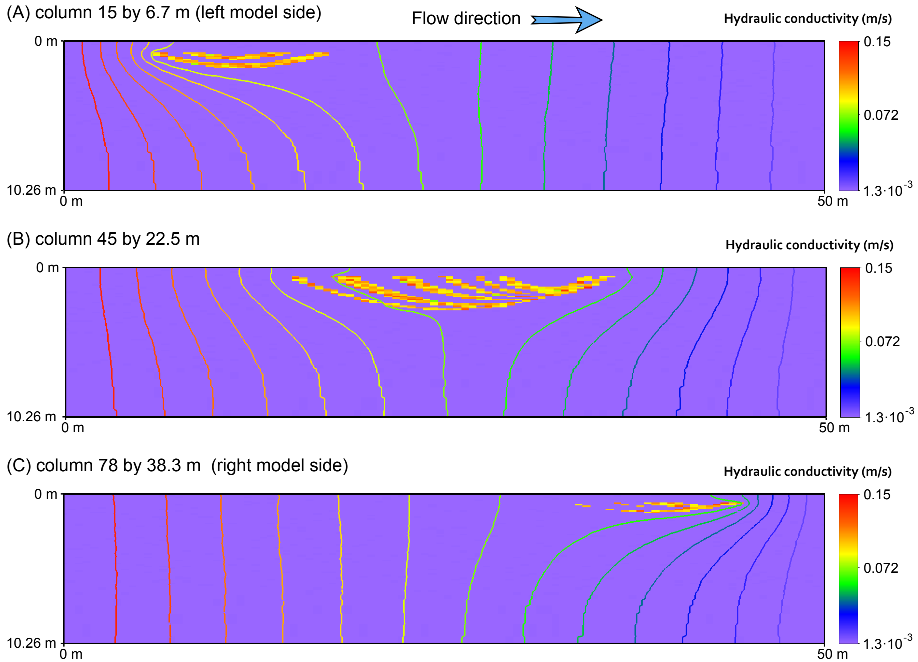

Figure 6. Cross sections of the hydrogeological model along the *y* axis (see Fig. 3). Hydraulic head contours (every 0.1 m) superimposed on the hydraulic conductivity values.

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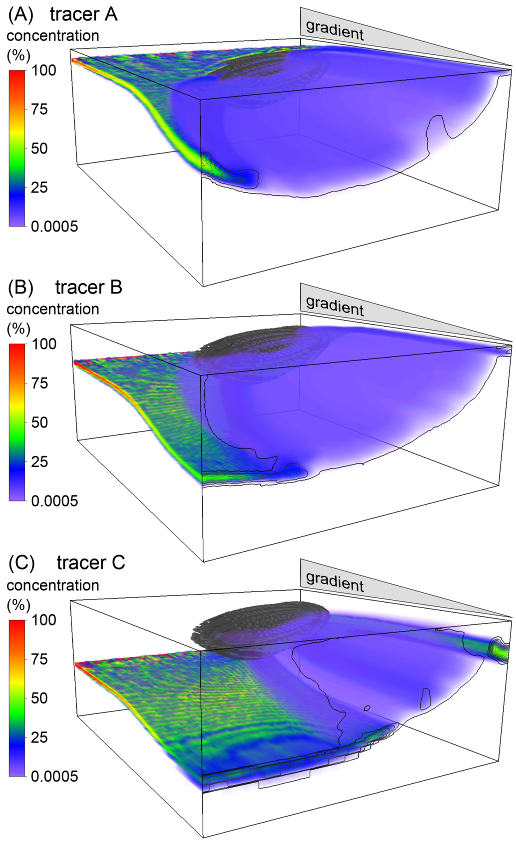

Figure 7. (a)–(c) spatial distribution of the tracer concentration for tracers A, B and C. They grey body represents the overlapping trough fills.

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Subsurface flow mixing

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