Advective transport in the porous matrix of sediments surrounding burrows formed by fauna such as *Chironomus plumosus* has been generally neglected. A positron emission tomography study recently revealed that the pumping activity of the midge larvae can indeed induce fluid flow in the sediment. We present a numerical model study which explores the conditions at which advective transport in the sediment becomes relevant. A 0.15 m deep U-shaped burrow with a diameter of 0.002 m within the sediment was represented in a 3-D domain. Fluid flow in the burrow was calculated using the Navier-Stokes equation for incompressible laminar flow in the burrow, and flow in the sediment was described by Darcy’s law. Nonreactive and reactive transport scenarios were simulated considering diffusion and advection. The pumping activity of the model larva results in considerable advective flow in the sediment at reasonable high permeabilities with flow velocities of up to $7.0 \times 10^{-6}$ m s$^{-1}$ close to the larva for a permeability of $3 \times 10^{-12}$ m$^2$. At permeabilities below $7 \times 10^{-13}$ m$^2$ advection is negligible compared to diffusion. Reactive transport simulations using first-order kinetics for oxygen revealed that advective flux into the sediment downstream of the pumping larva enhances sedimentary uptake, while the advective flux into the burrow upstream of the larvae inhibits diffusive sedimentary uptake. Despite the fact that both effects cancel each other with respect to total solute uptake, the advection-induced asymmetry in concentration distribution can lead to a heterogeneous solute and redox distribution in the sediment relevant to complex reaction networks.

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sediments. Most of these models are based on the radially symmetric tube model developed by Aller [1980]. This model describes the sediment as a collection of cylindrical tubes, where the inner radius of the tube corresponds to the average radius of individual burrows in the sediment and the wall thickness of the tube, which corresponds to the distance to the next tube, is a function of the tube density in the sediment [Aller, 1980]. Expansion of Aller’s model has focused on intermittent pumping [Boudreau and Marinelli, 1994], depth-dependent irrigation efficiency of the burrow [Shull et al., 2009], and depth-dependent burrow abundance and geometry [Furukawa et al., 2001] as well as the effect of coupled geochemical reactions on biologically driven solute exchange [Meile et al., 2005] and denitrification [Stief et al., 2010]. While the radially symmetric tube models generally ignore advective transport in the sediment matrix, advection has been recently considered in models describing fauna living in blindly ending burrows like Arenicola marina, which pump water from the burrow into the sediment by peristaltic movements [e.g., Timmerman et al., 2002; Meysman et al., 2006; Wethey et al., 2008].

[6] Only recently, evidence was found that advective solute transport in the sediment may also occur around U-shaped burrows. Roskosch et al. [2010b] performed a tracer study using 18-F fluoride positron emission tomography (PET) to investigate the influence of the pumping activity on the spreading of an inert tracer in the sediment surrounding a burrow inhabited by C. plumosus. It was found that the expansion of the tracer plume at the outlet branch of the burrow was faster than at the inlet branch. This result suggested that the spreading of the tracer is influenced by advection in the sediment matrix driven by the pressure gradients resulting from the pumping activity of C. plumosus. This finding challenges the frequent assumption of negligible advection in such systems.

[7] In this paper, we assess the plausibility of the findings reported by Roskosch et al. [2010b]. We implemented a 3-D model of a U-shaped burrow, which couples the free fluid flow in the burrow with the porous media flow in the surrounding sediment matrix induced by the pumping activity of C. plumosus. Specifically, we investigate the potential consequences of the porous media flow induced by the chironomid on solute dynamics using a simple first-order reaction model as it is frequently applied to simulate oxygen consumption [Bouldin, 1968]. We explore the role of sediment permeability on the transport of inert tracers and the oxygen dynamics at variable sediment reactivity. As a last step, we will investigate the influence of intermittent pumping on the sedimentary oxygen uptake.

2. Model Setup

2.1. Model Domain

[8] The model was implemented using the finite element code COMSOL. We used a 1 m deep 3-D half cylindrical domain symmetric in the x-z plane with a radius of 1 m (Figure 1). The large size of the domain was chosen to avoid boundary effects in the model. The burrow was modeled as a 0.15 m deep U-shaped burrow with a radius of 0.001 m and a distance of 0.04 m between the inlet and outlet branches (Figure 1). The zone in which the chironomid is active was located in the center of the burrow.

2.2. Governing Equations

[9] Different flow and reactive transport regimes were implemented for the burrow and surrounding sediment. The flow inside the burrow was calculated using the Navier-Stokes equation for incompressible laminar flow:

\[
\frac{\partial u}{\partial t} + u \cdot \nabla u = -\nabla p + \mu \nabla^2 u + F,
\]

where \( u \) denotes the velocity field, \( p \) is the pressure, \( \rho \) is the density of water (1000 kg m\(^{-3}\)), \( \mu \) is the dynamic viscosity of water (0.001 Pa s), \( I \) is the identity matrix, and \( F \) is the volume force. The fluid flow in the sediment was calculated using Darcy’s law:

\[
\rho \frac{\nabla \cdot u}{\rho} = 0,
\]

where \( \kappa \) denotes the permeability of the porous medium.
Figure 2. Steady-state distribution of oxygen around the outlet branch at 0.05 m depth calculated with dispersion introduced to fulfill the Peclet criterion (stabilized) for transient calculations and without dispersion (not stabilized). The thin vertical lines indicate the burrow wall.

[10] The solute transport was calculated using the advection-diffusion equation:

\[
\frac{\partial c}{\partial t} + \nabla \cdot \left( - \varepsilon (D_{\text{disp}} + D_{\text{mol}}) \nabla c \right) + \mathbf{u} \nabla c = R. \tag{3}
\]

where \( c \) is the solute concentration, \( D_{\text{disp}} \) is the dispersion coefficient, \( D_{\text{mol}} \) is the molecular diffusion coefficient in water, \( \varepsilon \) is the sediment porosity, and \( R \) is the reaction rate. We used a \( D_{\text{mol}} \) value of \( 1.97 \times 10^{-9} \text{ m}^2/\text{s} \), which corresponds to the diffusivity of oxygen at 20°C for all model calculations and a porosity \( \varepsilon \) of 0.8, which is typical for unconsolidated sediments [e.g., Maerki et al., 2004]. We also used the diffusion coefficient of oxygen for the calculations of the transport of the hypothetical inert tracer. In the sediment, \( R \) was described using first-order kinetics:

\[
R = -kc \tag{4}
\]

when a reactive solute—we use oxygen as a model reactive solute—was considered. The parameter \( k \) is the reaction rate coefficient. In the burrow we assumed that no reaction is taking place, and \( R \) is zero. In the case of inert tracer transport, \( R \) was set to zero.

[11] In order to ensure numerical stability a dispersion coefficient was introduced to describe solute transport inside the burrow to fulfill the Peclet criterion for transient model runs:

\[
D_{\text{disp}} = \frac{|u|^2 \Delta x}{2}, \tag{5}
\]

where \( \Delta x \) is the grid size, which was set to the largest grid size used in the burrow subdomain (0.0003 m). This stabilization is necessary to avoid nonphysical, oscillating solutions with negative concentrations which occur when the grid Peclet number \( Pe_{gs} = \frac{|u|^2 \Delta x}{D_{\text{mol}}} \) is smaller than two. Figure 2 compares the steady-state oxygen concentrations at the outlet branch and its close surroundings with and without the stabilization term (equation (5)). The non-stabilized solution also shows a distinct oxygen gradient within the burrow. In contrast, the oxygen concentration is relatively constant across the burrow when the stabilization term is introduced, and oxygen concentrations at the burrow wall decrease from 133 to 129 mmol m\(^{-3}\). In the center of the burrow, the stabilization term results in a dispersion coefficient of \( 1.7 \times 10^{-6} \text{ m}^2/\text{s} \) which is 3 orders of magnitude higher than the molecular diffusion coefficient of oxygen.

[12] Hydrodynamic dispersion is an additional, diffusion-like physical process which is induced by advection in porous sediments, since the fluid follows different flow paths around grains. In order to assess whether this effect is important in our system, we applied the analysis of Meyrman et al. [2006] who uses the grain size Peclet number \( Pe_{gs} = \frac{d_50|u|^2}{D_{\text{mol}}} \) as a criterion: even if we assume a median grain size of \( d_{50} = 250 \mu \text{m} \), which corresponds to the upper limit of fine sand, and a velocity of \( 7 \times 10^{-6} \text{ m s}^{-1} \), which corresponds to the maximum of observed velocities in our study (Figure 3), the resulting \( Pe_{gs} \) is 0.88. Since \( d_{50} \) of the sediment used in the present study is smaller than 250 \( \mu \text{m} \), \( Pe \) is also smaller. A \( Pe < 1 \) indicates negligible hydrodynamic dispersion. Therefore, we can omit hydrodynamic dispersion in the sediment matrix.

2.3. Boundary Conditions and Modeling Strategy

[13] The conditions for the various boundaries between the individual domains and subdomains are given in Table 1. For the location of the individual boundaries see Figure 1. The coupling between the burrow wall and the sediment was implemented by equalizing the pressure between burrow and sediment. This means that the pressure exerted by the pumping chironomid is the driving force of the advective flow in the sediment. Fluid loss from the burrow to the sediment by leaking through boundary 3 is negligible for the calculation of the laminar flow inside the burrow, since the Darcy velocity is much smaller compared to the free flow. Therefore, the no-slip condition (\( u = 0 \)) was applied at the burrow wall (boundary 3) for the calculation of the laminar flow.

[14] The pumping activity of the chironomid was mimicked by setting the horizontal (\( x \)) component of the volume force \( \mathbf{F} \) to 2400 N m\(^{-3}\) in the zone of pumping activity.
et al. respectively) closely correspond to the values reported between both phases. The steady-state pumping cycle was similar to the average pumping behavior of the chironomid.

Run 1: In order to investigate the occurrence of advective flow in the porous matrix of the sediment, steady-state velocity fields were calculated for different permeabilities \( \kappa \) ranging from \( 3 \times 10^{-12} \) to \( 10^{-14} \) m\(^2\). These values cover the range typical for fine sandy sediments to unconsolidated loamy fine sediments [Bear, 1972].

Run 2: The temporal development of an inert tracer of similar diffusivity to oxygen was calculated for the various \( \kappa \) using the steady-state solution of the velocity field with continuous pumping activity.

Run 3: Steady-state solutions for reactive transport of oxygen were calculated for various \( \kappa \) and a reaction constant of \( k = 40 \, \text{h}^{-1} \).

Run 4: Steady-state solutions were calculated for oxygen with \( \kappa \) ranging from 1 to 40 h\(^{-1} \) and a permeability of \( \kappa = 3 \times 10^{-12} \) m\(^2\).

Run 5: Behavior of intermittent pumping activity was modeled using \( \kappa = 3 \times 10^{-12} \) m\(^2\) and \( k = 40 \, \text{h}^{-1} \). The pumping cycle was similar to the average pumping behavior reported by Roskosch et al. [2011] with a 90 s pumping period followed by a 60 s resting period. The steady-state velocity field was used to model the flow field during the pumping phase, while \( \mathbf{u} \) was set to zero throughout the domain during the resting phase. A transition period of 10 s with a sigmoidal change of the velocity was included between both phases.

3. Results

3.1. Pressure Fields and Fluid Flow

In order to maintain an average fluid flow velocity of \( 0.004 \) m s\(^{-1}\) against viscous forces in the burrow, the chironomid had to exert a volume force of \( 2400 \) N m\(^{-3}\) in \( x \) direction, which corresponds to a pumping pressure of 6 Pa. The pumping activity results in a negative pressure in the inlet branch which is decreasing from the surface to the zone of active pumping from 0 to \(-6\) Pa. In the sediments surrounding the outlet branch the pressure is positive and decreases from the zone of active pumping to the surface from 6 to 0 Pa. The pressure field in the burrow propagates into the sediment (Figure 4). About 10% of the pressure occurring in the burrow penetrates up to 0.05 m into the surrounding sediment, while the Darcy velocity in 0.01 m distance from the burrow wall is still 10% of the velocity at the burrow wall. This pressure field is the driving force for the Darcy flow in the sediment (Figure 3). The highest flow velocities in the sediment (2.3 \( \times \) \( 10^{-8} \) m s\(^{-1}\) for \( \kappa = 10^{-14} \) m\(^2\) to 7 \( \times \) \( 10^{-6} \) m s\(^{-1}\) for \( \kappa = 3 \times 10^{-12} \) m\(^2\)) are observed close to the zone of chironomid pumping activity (deepest point of the burrow). The values decrease nonlinearly with distance from this location (Figure 3) with the highest flow velocities generally occurring between the two branches of the burrow. The pore water flow is directed from the outlet branch toward the inlet branch, while water flows from the sediment-water interface (SWI, boundary 1) into the sediment in the vicinity of the inlet and out of the sediment across the SWI in the vicinity of the outlet. Figure 5a shows the integrated water fluxes into the inlet branch and out of the outlet branch. At \( \kappa = 3 \times 10^{-12} \) m\(^2\) the water flux is 2.8 \( \times \) \( 10^{-9} \) m\(^3\) s\(^{-1}\), while the flux is 9 \( \times \) \( 10^{-12} \) m\(^3\) s\(^{-1}\) at \( \kappa = 1 \times 10^{-14} \) m\(^2\). In other words, the pore water residence time in a 0.17 m deep cylinder with a radius of 0.02 m surrounding the inlet or the outlet branch of the burrow is 0.9 days for \( \kappa = 3 \times 10^{-12} \) m\(^2\) and 270 days for \( \kappa = 1 \times 10^{-14} \) m\(^2\) (Figure 5b).

3.2. Solute Transport With Continuous Irrigation

3.2.1. Inert Tracer

The impact of the advective flow on the solute transport in the sediment can be considerable. Figure 6 compares the temporal development of the tracer distribution along the horizontal transect in 0.05 m depth (Figure 1). At a permeability of \( 3 \times 10^{-12} \) m\(^2\), the development of the tracer distribution varies significantly between inlet and outlet branches (Figure 6a). The difference is most pronounced in the sediment region between both branches. While the tracer is transported advectively in the sediment close to the outlet branch, the diffusive transport into the sediment from the inlet branch is suppressed by the opposite-directed advection of tracer-free pore water. The same effect is observed on the sides of inlet and outlet branches.

Table 1. Boundary Conditions for the Domain and Subdomain Boundaries as Indicated in Figure 1\(^a\)

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Free Flow</th>
<th>Darcy Flow</th>
<th>Solute Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>( p = 0 )</td>
<td>( p = 0 )</td>
<td>( c = c_0 )</td>
</tr>
<tr>
<td>B2</td>
<td>No flow</td>
<td>No flux</td>
<td>Not applicable</td>
</tr>
<tr>
<td>B3</td>
<td>( u = 0 )</td>
<td>( p_{sol} \neq p_{surround} )</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

\(^{a}\) \( p \), \( c \), and \( u \) are pressure, concentration, and velocity vector, respectively. \( p_{surround} \) is the hydraulic pressure in the burrow and \( p_{sol} \) is the pressure in the surrounding sediment.
facing the domain boundaries even though it is much less pronounced in these areas. In contrast, for a permeability of $10^{-14}$ m$^2$, the development of the tracer distribution is practically identical at inlet branch and outlet branch, and diffusion is the dominant transport process (Figure 6b).

The influence of advective transport also becomes evident in the temporal development of the tracer front (Figure 7). The speed at which the tracer front moves away from the burrow decreases with increasing permeability, while the speed of the tracer front increases at the outlet. Under close to purely diffusive conditions ($\kappa = 10^{-14}$ m$^2$), the tracer front at the inlet moved even farther than at the outlet due to the higher concentrations at the inlet burrow. Still, this effect is more than overcompensated by advection when the permeabilities are higher.

### 3.2.2. Oxygen

Pore water advection also determines the oxygen distribution around the burrow. This effect becomes more pronounced with decreasing reaction rates. Figure 8 shows steady-state distributions of oxygen with a reaction coefficient of $k = 1$ h$^{-1}$ for the close to purely diffusive case ($\kappa = 1 \times 10^{-14}$ m$^2$, Figure 8a) and for a permeability of $\kappa = 3 \times 10^{-12}$ m$^2$ (Figure 8b). For the close to purely diffusive case the oxygen distribution is constant along the burrow and the penetration depth of oxygen into the sediment, which we define as the location where the concentration is 10% of the concentration at the burrow wall, is constantly 0.004 m along the whole course of the burrow. For a permeability of $\kappa = 3 \times 10^{-12}$ m$^2$ (Figure 8b), the distribution of oxygen is characterized by a high asymmetry between the inlet branch and the outlet branch of the burrow. This asymmetry stems from the transport of water toward the burrow at the inlet branch and the transport of water into the sediment at the outlet branch. The highest intrusion of oxygen is observed at the outlet branch close to the zone of chironomid pumping activity, where the oxygen intrudes...
more than 0.01 m from the burrow wall into the sediment. The penetration depth decreases with distance from the larva along the outlet branch. In contrast, the intrusion depth of oxygen along the inlet branch increases with distance from the larva (Figure 8b). Interestingly, the intrusion of oxygen from the SWI into the sediment is higher in the zone around the inlet compared to the zone around the outlet (Figure 8c). This is due to the negative pressure at the inlet, which results in an advective transport of oxygen into the sediment, while oxygen-containing water is advected into the water column in the vicinity of the outlet which counteracts the diffusive transport into the sediment. In both cases, this effect decreases with distance from the chironomid burrow opening. It is evident that the influence of the pressure-induced advection in the sediment is highly dependent on the permeability of the sediment.

In order to investigate the influence of advection on sediment oxygen uptake, we calculated steady-state solutions for different permeabilities and a reaction coefficient of 40 h \(^{-1}\). This reaction coefficient results in an oxygen penetration depth of 0.001 m as it is typical in mesotrophic lakes [e.g., Brand et al., 2009]. At such high reaction rates, changes in permeability result only in minute changes of the sediment concentration profiles (compare black lines in Figures 9a and 9b).

The oxygen concentration at the burrow walls in 0.05 m depth at the inlet and outlet changes only slightly. At the inlet, the concentration decreases from 214 to 208 mmol m \(^{-3}\) when \(\kappa\) is increased from \(10^{-14}\) to \(3 \times 10^{-12}\) m \(^{2}\), while the concentration at the outlet is almost constant around 130 mmol m \(^{-3}\) at the same time (Figure 10a). Especially the independence of the outlet concentration from the permeability is surprising. As we will show later in this chapter this constancy of concentration at the outlet is due to the fact that the influence of advection at the inlet and outlet branches cancel each other. Darcy flow velocities were increasing strongly from \(5.4 \times 10^{-9}\) to \(1.6 \times 10^{-6}\) m s \(^{-1}\) at the observation points at the burrow walls in 0.05 m depth with increasing permeability (Figure 10a).

The change in the concentration gradient is also reflected in the diffusive component of the oxygen flux (Figure 10b). The decrease of the concentration gradient at the outlet results in a lower diffusive flux, while advective transport overcompensates for the decrease in diffusive flux. In contrast, the diffusive flux increases at the inlet due to the increase of the concentration gradient, while the Darcy flow toward the inlet branch of the burrow decreases the total flux (Figure 10b). Compared to the close to purely diffusive case, where the total normal flux into the sediment is \(8.9 \times 10^{-4}\) mmol m \(^{-2}\) s \(^{-1}\) at the inlet and \(5.7 \times 10^{-4}\) mmol m \(^{-2}\) s \(^{-1}\) at the outlet, advective transport decreases the total flux by 43% at the inlet branch and increases the flux by 22% at the outlet branch for a permeability of \(3 \times 10^{-12}\) m \(^{2}\). Still, as the symmetry of the fluxes at the observation points already suggests, the contrasting influence of fluxes at the inlet and outlet branches compensates each other when the flux across the whole burrow is considered. The presence of advection decreases the overall flux by only 3.1% compared to the close to purely diffusive case at a permeability of \(3 \times 10^{-12}\) m \(^{2}\) (Figure 11a). While advective transport results in a decrease of total sediment oxygen uptake, a significant enhancement of oxygen uptake

---

**Figure 8.** Concentration distribution for oxygen with a reaction coefficient of 1 h \(^{-1}\) for a permeability of (a) \(\kappa = 10^{-14}\) m \(^{2}\) and (b and c) \(\kappa = 3 \times 10^{-11}\) m \(^{2}\). The \(x-y\) plane was located at \(z = -0.05\) m.

**Figure 9.** Concentration distribution of oxygen along a cross section in 0.05 m depth for different first-order reaction coefficients. (a) Sediment permeability of \(\kappa = 3 \times 10^{-11}\) m \(^{2}\) and (b) close to diffusive transport (\(\kappa = 10^{-14}\) m \(^{2}\) ) in the sediment. The lower concentrations at the outlet branch result from the sedimentary oxygen uptake.
is only observed in the curved, lower part of the burrow at a permeability of $3 \times 10^{-12}$ m$^2$ (Figure 11b). The small change in total oxygen uptake with increasing influence of advection also explains the relatively small change of oxygen concentration inside the burrow with increasing permeability. The maximum concentration inside the burrow in 0.05 m depth at the outlet branch decreases from 157 to 153 mmol m$^{-3}$ when the permeability increases from $1 \times 10^{-14}$ to $3 \times 10^{-12}$ m$^2$. For the concentration profile is barely visible for highly reactive solutes, the formation of an asymmetry of the oxygen distribution between inlet and outlet due to advective transport becomes increasingly evident with decreasing reaction rates. In the close to purely diffusive case, a reaction rate $k = 1$ h$^{-1}$ results in a solute penetration depth of approximately 0.004 m (Figure 9b) as it is typical for oxygen in oligotrophic lakes or nitrate in mesotrophic lakes [Brand et al., 2009].

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3.3. Oxygen Transport With Intermittent Irrigation

The transient model runs were started with no oxygen in the burrow as well as in the sediment matrix as initial condition. After two pumping and resting cycles, the temporal development of oxygen concentrations and fluxes remained identical for each pumping and resting cycle. The concentrations of oxygen of the third cycle are shown in Figure 14c for three different observation points (compare Figure 1). The pumping activity starts at 390 s. The first increase in the flux (indicated by A in Figure 14a) occurs simultaneously at all three observation locations. This first peak is due to the gradient steepening caused by increased

Figure 10. (a) Steady-state oxygen concentrations $C$ and horizontal Darcy velocities $u_{\text{Darcy}}$ at the burrow walls in the $x$-$z$ plane in 0.05 m depth at inlet and outlet. Note that the graphs for $u_{\text{Darcy}}$ at inlet and outlet plot above each other. The right axis refers to the concentrations and the left one to velocities. (b) Normal total and diffusive oxygen fluxes at the same locations as in (a). Calculations were performed for a reaction coefficient of $40$ h$^{-1}$. Total fluxes ($J_{\text{tot}}$) are lower than the diffusive fluxes ($J_{\text{diff}}$) at the inlet and higher at the outlet due to advective fluxes.

Similar to the results already presented for $k = 40$ h$^{-1}$ the effects of advection at inlet and outlet compensate each other, and the contribution of advection to the overall flux across the burrow walls is negligible also for lower reaction coefficients (Figure 12b). Even though the influence of advection on total fluxes proves to be negligible in our model study, the sediment area, which is affected by oxygen, can be highly dependent on advection (Figure 13). In total, the affected sediment area increases by 28% when the permeability increases from $1 \times 10^{-14}$ to $3 \times 10^{-12}$ m$^2$ for a reaction rate of $k = 1$ h$^{-1}$. When only the outlet branch is considered, the changes in volume are even higher and increase by more than factor 2 when the permeability increases (Figure 13b).

Figure 11. Steady-state average oxygen fluxes across the burrow walls. (a) Advective, diffusive, and total fluxes of the whole burrow, and (b) advective fluxes across bend and straight parts of the burrow. Positive values denote fluxes into the sediment, and negative values denote fluxes into the burrow.
mixing due to the dispersion introduced in the burrow (equation (5)). The subsequent drop in oxygen flux is a consequence of the decreasing oxygen gradient caused by the proceeding intrusion of oxygen into the sediment. The second peak (B) occurs with an increasing time lag at different observation points with increasing distance from the inlet. The second peak is due to the occurrence of surface water with a higher oxygen concentration in the specific section of the burrow which has entered the burrow right at the beginning of the pumping activity. Subsequently, the oxygen flux decreases again and fluxes approach asymptotically a constant value as the oxygen concentration in the sediment approaches the steady-state distribution for continuous pumping in the sediment. The pumping activity starts to decrease at 490 s and stops completely at 500 s. The peak in oxygen flux, which is observed during this period at the inlet branches (C), is due to the cessation of advective flow from the porous sediment into the inlet branch of the burrow, which counteracts the diffusive transfer of oxygen into the sediment. In contrast, no peak is observed at the outlet branch, but a much earlier decrease of the flux, while the pumping activity decreases. After 500 s, the oxygen flux is only governed by diffusive transport of the oxygen contained in the stagnant burrow water. The total flux in the burrow averaged over one pumping and resting cycle is 28% lower than the fluxes calculated from the steady-state model runs representing the case of continuous pumping activity (Figure 14b). Time-averaged transient fluxes are higher than steady-state fluxes at the inlet, since no advection opposes the flux into the sediment matrix during the resting periods. At the outlet, normal fluxes are much lower for the transient model runs. On the one hand, this is due to the decreased enhancement of solute transport by advection when the pumping activity is only intermittent. In addition, oxygen concentrations at the burrow walls are much lower at the outlet when pumping is only intermittent (Figure 14c). While the oxygen concentration in 0.05 m depth is 130 mmol m\(^{-3}\) at steady state, it never exceeds 108 mmol m\(^{-3}\) during transient conditions (Figure 14c). The calculations were performed for typical pumping and resting cycles as they were observed by Roskosch et al. [2011]. The lower flux during the 60 s resting period is partly compensated by the gradient steepening at the beginning of the pumping period due to mixing and the second peak in oxygen flux due to the flushing with surface water. Longer resting periods would result in a stronger decrease of the time-averaged transient fluxes.

4. Discussion

Our model study has shown that the pumping activity of macrofauna such as *C. plumosus* in U-shaped, open ended burrows can indeed induce pore water advection in...
the surrounding sediments and therefore corroborates the laboratory observations reported recently [Roskosch et al., 2010b]. Roskosch et al. [2010b] reported an average expansion of the tracer front around the burrow by approximately 0.0078 m at the inlet and 0.009 m at the outlet in 10 h, resulting in a difference of 0.0012 m between both branches. Our model runs with the inert tracer shows a similar qualitative behavior. The inert tracer front in 0.05 m depth proceeds in 10 h 0.0072 m at the inlet and 0.0088 m at the outlet for a permeability of $7 \times 10^{-13}$ m$^2$ (Figure 7).

This shows that advective effects indeed occur around U-shaped burrows and confirm our modeling approach. Nevertheless, the aim of our model study in the present paper was to investigate the relevance of advective transport and its potential consequences for the geochemistry of the sediments next to an idealized, U-shaped burrow. A more in-depth analysis of the experiment performed by Roskosch et al. [2010b] using numerical models including intermittency of pumping and potential gradients in conductivity with an exact representation of burrow geometry is part of our ongoing research.

[27] The model study based on the inert tracer also suggested that pore water advection becomes relevant at permeabilities $>7 \times 10^{-13}$ m$^2$. At lower conductivities as they are encountered in many muddy sediments, our model study confirms that advection is negligible and that models which ignore pore water advection can be confidently used in most cases. Since the effects of advection at the inlet and outlet branch compensate each other as long as the considered solutes follow simple rate laws, the classic radially symmetric tube models provide reasonable estimates of uptake rates in the burrows even under conditions when pore water advection becomes important. However, these models may fail when more complex, coupled reaction networks which describe, for example, denitrification or the mineralization of organic matter using variable electron acceptors are considered.

[28] The low pressure magnitudes as well as the high reactivity of the sediment are two reasons for the low detectability of advective effects in chironomid burrows. For studies of bioirrigation, oxygen is one of the most common tracers [e.g., Volkenborn et al., 2010] since there exists a suite of methods to monitor oxygen at very high temporal and spatial resolution ranging from microelectrodes [e.g., Revsbech, 1989; Klimant et al., 1995] to 2-D-planar optodes [e.g., Glud et al., 1996]. Still, our model runs with $k = 40$ h$^{-1}$, a value typical for O$_2$ consumption in organic-rich sediments, reveal that the influence of advection by burrow ventilating macrozoobenthos is hardly observable under these conditions, and the changes in oxygen concentration distribution are much smaller than the analytical uncertainties.

[29] Our model results show that the influence of pore water advection on the total oxygen uptake rate in comparison with the purely diffusive case can be negligible since the enhanced uptake at the outlet branch is compensated by a reduced uptake at the inlet branch. Even though the total uptake rates may not be influenced, pore water advection alters the distribution of oxygen especially between the inlet and outlet branches in a contrasting way. While pore water advection enhances the intrusion and uptake of oxygen in the surroundings of the outlet branch, it compresses the concentration distribution and opposes oxygen uptake. This different pattern can play an important role by defining distinct microenvironments in the sediment close to inlet and outlet branches depending on the reactivity of the solute. Steady-state calculations with a permeability of $3 \times 10^{-12}$ m$^2$ with variable reaction coefficients have shown that the dependence of solute distribution on pore water advection changes with sediment reactivity (Figure 9).

Figure 14. (a) Time series of oxygen fluxes into the sediment under intermittent pumping activity at different locations of the burrow wall shown in Figure 1. Capital letters indicate characteristic events during the pumping cycle. (A) Peak formation due to gradient steepening in the burrow by dispersive mixing, (B) breakthrough of oxygen-rich water from the surface, and (C) change of transport regime due to cessation of advective transport. (b) Comparison between steady-state oxygen fluxes and fluxes averaged over a pumping/resting cycle at different locations in the burrow (“in” denotes the inlet branch, and “out” denotes the outlet branch). Note that “burrow” denotes the integrated flux across the burrow wall and has the units mmol s$^{-1}$. (c) Oxygen concentrations during the pumping and resting cycle. The line colors correspond those of (a). All calculations of this figure were performed for a permeability of $k = 3 \times 10^{-12}$ m$^2$ and a reaction coefficient of $k = 40$ h$^{-1}$. 


[30] Adective transport in the sediment matrix induced by organisms living in U-shaped, open ended burrows surrounded by sediment with medium to low permeability has rarely been addressed until now. One of the few exceptions is the study recently published by Volkenborn et al. [2012] on the ghost shrimp Neotrypea californiensis which occasionally builds U-shaped burrows. They observed that pressure exerted by pumping activity in U-shaped burrows protrudes into the surrounding sediment and is related to enhanced oxygen transport into the sediment. They also observed dynamic and asymmetric pressure fields with positive and negative pore water pressurization in different regions of the sediment. This study confirms qualitatively the results of our modeling study like the deep penetration of the pumping pressure by more than 0.05 m into the sediment which results in an occurrence of 10% of the Darcy flow magnitude in 0.01 m distance from the burrow wall. Still, chironomids exert a significantly lower pumping pressure compared to the ghost shrimp, which exerts an approximately tenfold higher pumping pressure during normal pumping activity.

[31] Pore water advection also increases the zone of reactive solutes, such as oxygen, close to other reactive solutes in the vicinity of the outlet branch of the burrow (Figure 13b). This change of redox regime can influence the dynamics of a suite of biogeochemical reactions. Especially the zones and rates of nitrate and sulfate reduction as well as methanogenesis and the dissolution of iron(III) and manganese(IV) minerals can be heavily inhibited under the presence of more energetically efficient electron acceptors [e.g., Wang and Van Cappellen, 1996; Meile et al., 2005] when advection in the sediments occurs. Another important aspect is the occurrence of zones with variable redox regimes due to the intermittent pumping activity, especially denitrification processes may be influenced by these redox shifts resulting in the buildup and release of reaction intermediates like nitrate and nitrous oxides [Brand et al., 2009; Polerecky et al., 2007].

[32] As a model simplification we assumed that the chironomid itself does not act as an oxygen consumer. Brodersen et al. [2004] reported oxygen consumption rates for chironomids of up to 4.7 µg h⁻¹ mg⁻¹ (chironomid dry weight). If we assume a dry weight of 1 mg for a single chironomid, this corresponds to an oxygen consumption rate of 4.1 × 10⁻⁸ mmol s⁻¹. The total uptake rates in our model runs range between 5 × 10⁻⁷ and 10 × 10⁻⁷ mmol s⁻¹ (Figure 12). Therefore, the contribution of the chironomid respiration to the total oxygen consumption is around 5% and thus negligible in our model. Another assumption was the neglect of burrow linings in our model. For many marine organisms these linings are of high importance to avoid reflux of pore water into the burrow [Meysman et al., 2005] or to retain toxic substances like ammonia [Aller, 1983]. While these linings built by marine organisms are of a significant thickness of several hundred micrometers, the linings built by C. plumosus consist of a more loosely tied net made of strands of salivary secretions [Walshe, 1947]. Due to the thin nature and mesh structure of these nets, we assume that the hydraulic resistance of these lining is negligible. The linings are made of the same material as the net in the center of the burrow which is used to trap particles for food of the chironomid [Walshe, 1947].

In our laboratory experiments, we observed that the chironomids always pumped in the same direction. Consequently, our modeling approach which does not consider direction changes in pumping is in agreement with these laboratory observations.

[33] Simulations considering intermittent irrigation with a cycle of 90 s pumping and 60 s resting resulted in 28% lower oxygen fluxes when compared to simulations of continuous irrigation. In this case, the decrease in solute flux during resting periods is partly compensated by elevated fluxes at the beginning of the pumping period and with the advent of freshly pumped surface water. Still, the compensating effect is getting weaker with increasing length of the resting periods as they have sporadically been observed in our laboratory experiments [Roskosch et al., 2011]. These results will change when different pumping and resting patterns occur. Stief et al. [2010] observed pumping periods of up to 15 min followed by resting periods of up to 15 min. The reasons for this deviation are not quite clear and such long pumping and resting cycles have never been observed in our system even under a wide range of environmental conditions [Roskosch et al., 2012]. In general, longer pumping cycles will allow the system to get closer to steady state, while longer resting cycles will further decrease the overall fluxes.

[34] The approach presented in this paper is a first step toward a more mechanistic understanding of bioirrigation in permeable sediments inhabited by organisms living in U-shaped burrows. Still, there is more work necessary to develop a comprehensive understanding of advective porous media flow induced by burrow ventilation and its consequence for solute dynamics. The data basis on pumping induced pore water advection is still very poor. We suggest the combination of numerical modeling as described in this paper with noninvasive investigations of inhabited sediments with methods like PET [Roskosch et al., 2010b] and the use of pressure sensors as they have been used for the study of marine organisms [e.g., Volkenborn et al., 2012, 2010] in order to gain further insight into the importance and mechanisms of bioadvection. Another important aspect which needs to be addressed in future studies is the importance of advective flow for solutes released from the sediment like ammonia and as well as the response of complex reaction networks on continuous and intermittent advection. The expansion of the present model by such networks will be a first step in this direction.

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