Contaminant transport in dual-porosity media with dissolved organic matter and bacteria present as mobile colloids

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Abstract

In riverbank filtration, contaminant transport is affected by colloidal particles such as dissolved organic matter (DOM) and bacterial particles. In addition, the subsurface heterogeneity influences the behavior of contaminant transport in riverbank filtration. A mathematical model is developed to describe the contaminant transport in dual-porosity media in the presence of DOM and bacteria as mobile colloids. In the model development, a porous medium is divided into the mobile and immobile regions to consider the presence of ineffective micropores in physically heterogeneous riverbanks. We assume that the contaminant transport in the mobile region is controlled by the advection and dispersion while the contaminant transport in the immobile region occurs due to the molecular diffusion. The contaminant transfer between the mobile and immobile regions takes place by diffusive mass transfer. The mobile region is conceptualized as a four-phase system: two mobile colloidal phases, an aqueous phase, and a solid matrix. The complete set of governing equations is solved numerically with a fully implicit finite difference method. The model results show that in riverbank filtration, the contaminant can migrate further than expected due to the presence of DOM and bacteria. In addition, the contaminant mobility increases further in the presence of the immobile region in aquifers. A sensitivity analysis shows that in dual-porosity media, earlier breakthrough of the contaminant takes place as the volumetric fraction of the mobile region decreases. It is also demonstrated that as the contaminant mass transfer rate coefficient between the mobile and immobile regions increases, the contaminant concentration gradient between the two regions reverses at earlier pore volumes. The contaminant mass transfer coefficient between the mobile and immobile regions mainly controls the tailing effect of the contaminant breakthrough. The contaminant breakthrough curves are sensitive to changes in contaminant adsorption and desorption rate coefficients on DOM and bacteria. In situations where the contaminant is released in the presence of DOM and bacteria in
dual-porosity media, the early breakthrough and tailing occur due to the colloidal facilitation and presence of immobile regions.

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**Keywords:** Riverbank filtration; Dual-porosity media; Mobile–immobile region; Colloid-facilitated transport; Colloids

### 1. Introduction

The mobilization and transport of colloids in soils and groundwater has been well reported by several researchers (McDowell-Boyer et al., 1986; McCarthy and Zachara, 1989; Ouyang et al., 1996; Sun et al., 2001). The presence of colloidal particles can affect the transport of contaminant in subsurface environments. Highly toxic contaminants such as hydrophobic organic compounds, heavy metals, and radionuclides are strongly sorbed onto colloidal particles with large specific surface areas. The sorption of contaminant on the mobile colloids can greatly increase the mobility of a contaminant when the colloids are highly mobile in the aquifer (Penrose et al., 1990; Magee et al., 1991; Corapcioglu and Jiang, 1993; Saiers and Hornberger, 1996).

Riverbank filtration is widely used in alluvial aquifers, hydraulically connected to a river, for the production of drinking water. In riverbank filtration, colloidal particles such as dissolved organic matter (DOM) and bacteria can affect the transport of an organic contaminant. Organic and inorganic contaminants have strong affinity to DOM. The mobility of contaminant is enhanced in the presence of DOM (Lafrance et al., 1994; Jordan et al., 1997; McCarthy et al., 1998). The aquifer where the riverbank filtration is practiced is generally saturated with organic matter due to continuous input of DOM from the river water (McCarthy et al., 1996). Therefore, DOM as mobile carriers can facilitate the contaminant transport in riverbank filtration. Bacteria can be also involved in the enhancement of the contaminant transport in the aquifers (Lindqvist and Enfield, 1992; Jenkins and Lion, 1993; Corapcioglu and Kim, 1995). In riverbank filtration, bacteria can utilize the organic contaminant and DOM as food source. In the presence of bacteria and DOM, the subsurface system can be conceptualized as a four-phase medium: an aqueous phase, a solid matrix, and two mobile colloidal phases.

The nonideality of the contaminant transport due to the presence of physical (pore-scale) heterogeneity in porous media has been addressed by several researchers (Coats and Smith, 1964; Rao et al., 1980; van Genuchten and Wagenet, 1989; Saxena et al., 1994; Selim and Ma, 1995). Brusseau et al. (1989) have discussed that nonideal transport of contaminant in heterogeneous soils is mainly due to the physical and chemical nonequilibrium. The physical nonequilibrium is related to the presence of immobile regions in porous media while the chemical nonequilibrium occurs due to rate-limited sorption processes. Jarvis et al. (1991) have demonstrated that the movement of a conservative tracer such as chloride in unsaturated soils could be described well by the dual-porosity approach. Gerke and van Genuchten (1993) have used the dual-porosity approach to describe the preferential movement of solutes in structured porous media. Corapcioglu and Wang (1999) have applied the dual-porosity model to simulate the colloid-facilitated...
Fig. 1. Schematic diagram of riverbank filtration.
contaminant in heterogeneous soils. In the presence of pore-scale heterogeneity, the solute transport in porous media is characterized by early breakthrough and late tailing.

In this study, the dual-porosity approach is used to describe the contaminant transport in the presence of bacteria and DOM in riverbank filtration (Fig. 1). In this approach, the porous media is divided into mobile and immobile regions. The mobile region is a dynamic water flow region where the pore-water can flow through the effective macropores. In this region, the advection and mechanical dispersion control the contaminant transport. In contrast, the immobile region is a stagnant water region where pore-water flow is negligible due to the ineffective micropores. The immobile region plays a significant role as a reservoir of contaminant and impacts on the behavior of contaminant in porous media. The molecular diffusion is a dominant phenomenon for the contaminant transport in the immobile region. In addition, the difference of the contaminant concentration between the mobile and immobile regions can cause the mass transfer of contaminant by diffusive exchange. In saturated porous media, both mobile and immobile regions are saturated, and so no mass transfer of water occurs between two regions. Thus, no water at the immobile region affects the water flow at the mobile region.

2. Mathematical model development

2.1. DOM and bacteria transport in dual-porosity media

As mentioned earlier, the aquifer is generally saturated with organic matter owing to continuous input of DOM from river water in riverbank filtration. Therefore, we assume that DOM concentration is constant in the aqueous phase of the mobile and immobile regions, and so no mass transfer of DOM occurs between two regions.

The existence of physical heterogeneity in porous media can influence the bacterial transport. Smith et al. (1985) have reported that *E. coli* moved rapidly through macropores in well-structured soils with small retention on the soil matrix. Fontes et al. (1991) have demonstrated that the presence of preferential flow path in porous media could greatly increase the extent of bacterial transport in soils. Harvey et al. (1993) have noted that bacteria could move faster than a nonreactive tracer due to the physical heterogeneity of the aquifer. We assume in the model development that bacteria are present only in the mobile region. In the model developed, the flow condition between the river and the pumping well(s) is idealized as a one-dimensional horizontal flow (see Fig. 1). This idealization can be justified due to the use of a set of pumping wells placed along the river in a riverbank filtration operation (Kuehn and Mueller, 2000). Then, the one-dimensional mass balance equation for bacteria suspended in the aqueous phase of the mobile region can be described as:

\[
\frac{\partial (\phi \theta^{\text{ma}} C_b^{\text{ma}})}{\partial t} = - \frac{\partial}{\partial x} \left[ -D_b \frac{\partial (\phi \theta^{\text{ma}} C_b^{\text{ma}})}{\partial x} + \phi v_w \phi^{\text{ma}} C_b^{\text{ma}} \right] - \phi Q_{\text{bs}}^{\text{ma}} - \phi Q_{\text{bs}}^r \phi^{\text{ma}} + \phi Q_{\text{gm}}^{\text{ma}} - \phi Q_{\text{dm}}^{\text{ma}} + \phi Q_{\text{go}}^{\text{ma}}
\]  

(1)
where the superscript \( ma \) stands for the mobile region, \( \phi \) is the volume fraction of the mobile region in the total volume of porous media (\( = V_{T}^{ma}/V_{T} \)), \( \theta^{ma} \) is the water content in the mobile region (\( = V_{w}^{ma}/V_{T}^{ma} \)), \( C_{b}^{ma} \) is the concentration of bacteria suspended in the aqueous phase of the mobile region, \( \nu_{w}^{ma} \) is the pore-water velocity in the mobile region, \( D_{B} \) is the hydrodynamic dispersion coefficients of bacteria (L\(^{2}\) T\(^{-1}\)), \( Q_{bs}^{r,ma} \) and \( Q_{bs}^{ir,ma} \) represent the reversible and irreversible deposition of bacteria on the solid matrix in the mobile region (ML\(^{-3}\) T\(^{-1}\), respectively, \( Q_{gm}^{ma} \) denotes the growth rate of the bacteria suspended in the aqueous phase of the mobile region with the contaminant as a food source, \( Q_{go}^{ma} \) indicates the decay rate of the bacteria suspended in the aqueous phase of the mobile region, and \( Q_{go}^{ma} \) denotes the growth rate of the bacteria suspended in the aqueous phase of the mobile region with DOM as the other food source.

The deposition of bacteria on the solid matrix is affected by the physical and chemical properties of porous media and the surface characteristics of bacteria. When the net forces of attractive London-van der Waals forces and repulsive electrostatic forces become attractive, the attachment of bacteria to the solid surfaces can occur at the secondary minimum. Bacteria can reversibly attach to the surfaces by the long-range forces and be readily detached from the surfaces by shear forces. In the potential energy curve for the bacterial attachment on the solid matrix, the primary minimum is located close to the solid surfaces and responsible for the strong attachment of bacteria. The secondary minimum is situated at a larger distance from the solid surfaces. Bacteria attach weakly on the solid matrix at the secondary minimum (Rijnaarts et al., 1995). The mass balance equation for the bacteria reversibly deposited on the solid matrix in the mobile region can be written as:

\[
\frac{\partial (\phi \rho_{b} \sigma_{r,ma}^{b})}{\partial t} = \phi Q_{bs}^{r,ma} + \phi Q_{gi}^{r,ma} - \phi Q_{di}^{r,ma} \tag{2}
\]

where \( \rho_{b} \) is the density of bacteria, \( \sigma_{r,ma}^{b} \) is the volumetric fraction of the bacteria deposited reversibly on the solid matrix (volume of bacteria deposited per unit volume of porous media, L\(^{-3}\)), and \( Q_{gi}^{r,ma} \) and \( Q_{di}^{r,ma} \) denote the growth and decay rates of the reversibly attached bacteria, respectively. The reversible mass transfer of bacteria between the aqueous phase and the solid matrix can be given as:

\[
Q_{bs}^{r,ma} = k_{c}^{ma} \theta^{ma} C_{b}^{ma} - k_{r}^{ma} \rho_{b} \sigma_{r,ma}^{b} \tag{3}
\]

where \( k_{c}^{ma} \) and \( k_{r}^{ma} \) are the deposition and release rate coefficients of bacteria on the solid matrix (T\(^{-1}\)), respectively.

When hydrophobic interactions and polymer bridging affect bacteria attached to the secondary minimum, they can transfer to the primary minimum. The bacteria held at the primary minimum due to these non-DLVO forces can irreversibly attach to the matrix surfaces. The mass balance equation for bacteria deposited irreversibly on the solid matrix of the mobile region can be described as:

\[
\frac{\partial (\phi \rho_{b} \sigma_{ir,ma}^{b})}{\partial t} = \phi Q_{bs}^{ir,ma} + \phi Q_{gi}^{ir,ma} - \phi Q_{di}^{ir,ma} \tag{4}
\]

where \( \sigma_{ir,ma}^{b} \) is the volumetric fraction of the bacteria deposited irreversibly on the solid matrix of the mobile region (volume of bacteria deposited per unit total volume of porous
media, \(L^{-1} L^{-3}\), and \(Q^{ir,ma}_{gi}\) and \(Q^{ir,ma}_{di}\) denote the growth and decay rates of the irreversibly attached bacteria, respectively. The irreversible attachment of bacteria can be described as a time-dependent process in which bacteria are permanently removed from the aqueous phase. The irreversible mass transfer of bacteria from the aqueous phase to the solid matrix can be presented as:

\[
Q^{ir,ma}_{bs} = k^{ma}_{ci} \theta^{ma}_{b} C^{ma}_{b}
\]

where \(k^{ma}_{ci}\) is the irreversible deposition rate coefficient of bacteria on the solid matrix (\(T^{-1}\)).

2.2. Contaminant transport in dual-porosity media

The mass balance equations of the contaminant dissolved in the aqueous phase of the mobile and immobile regions can be expressed as:

\[
\frac{\partial (\phi \theta^{ma}_{c} C^{ma}_{c})}{\partial t} + \frac{\partial (\phi \rho_{s} \sigma^{ma}_{cs} C^{ma}_{c})}{\partial x} = - \frac{\partial}{\partial x} \left[ -D_{c} \frac{\partial (\phi \theta^{ma}_{c} C^{ma}_{c})}{\partial x} + \phi v^{ma}_{w} \theta^{ma}_{c} C^{ma}_{c} \right] - \phi Q^{ma}_{cd} - \phi Q^{ma}_{cbm} - \phi Q^{ir,ma}_{cbi} - \phi Q^{r,ma}_{cbi} - \phi Q^{ma}_{a} - \phi Q^{ma}_{s} - \phi \Gamma_{c} \tag{6a}
\]

\[
\frac{\partial [(1 - \phi) \theta^{mi}_{c} C^{mi}_{c}]}{\partial t} + \frac{\partial [(1 - \phi) \rho_{s} \sigma^{mi}_{cs}]}{\partial t} = - \frac{\partial}{\partial x} \left\{ -D_{B} \frac{\partial [(1 - \phi) \theta^{mi}_{c} C^{mi}_{c}]}{\partial x} \right\} - (1 - \phi) Q^{mi}_{cd} + (1 - \phi) \Gamma_{c} \tag{6b}
\]

where the superscript \(mi\) stands for the immobile region, \(C^{ma}_{c}\) and \(C^{mi}_{c}\) are the concentrations of the dissolved contaminant in the mobile and immobile regions, respectively, \(\rho_{s}\) is the dry bulk density of the solid matrix, \(\sigma^{ma}_{cs}\) and \(\sigma^{mi}_{cs}\) are the mass fractions of the contaminant sorbed onto the solid matrix in the mobile and immobile regions, respectively (mass of contaminants sorbed per unit solid mass of porous media, \(MM^{-1}\)), \(D_{c}\) is the hydrodynamic dispersion coefficient of contaminant (\(L^{2} T^{-1}\)), \(D_{B}\) is the Brownian molecular diffusion coefficient of contaminant (\(L^{2} T^{-1}\)), \(Q^{ma}_{cd}\) and \(Q^{mi}_{cd}\) denote the contaminant mass transfers between the aqueous phase and DOM in the mobile and immobile regions (\(ML^{-3} T^{-1}\)), respectively, \(Q^{ma}_{cbm}\) indicates the contaminant mass transfer between the aqueous phase and the mobile bacteria in the mobile region, \(Q^{ma}_{cbi}\) represents the contaminant mass transfer between the aqueous phase and the reversibly attached bacteria in the mobile region, \(Q^{ir,ma}_{cbi}\) denotes the contaminant mass transfer between the aqueous phase and the irreversibly attached bacteria in the mobile region, and, \(Q^{ma}_{a}\) and \(Q^{ma}_{s}\) are the utilization rates of the dissolved contaminant and the contaminants sorbed onto the solid matrix of the mobile region, respectively. As noted earlier, bacteria are present only in the mobile region. Therefore, the contaminant present in the immobile region is not available for microbial
degradation. $\Gamma_c$ is the contaminant mass transfer between the mobile and immobile regions and represented as:

$$\Gamma_c = a(C_c^{ma} - C_c^{mi})$$  \hfill (7)$$

where $a$ is the first-order mass transfer rate coefficient of the contaminant ($T^{-1}$).

If the sorption relationship between the aqueous phase and the solid matrix is assumed to be an equilibrium-controlled process and represented by a linear isotherm, the mass fractions of contaminant sorbed onto the solid matrix in the mobile and immobile regions can be given as:

$$\sigma_{cs}^{ma} = K_{1}^{ma}C_c^{ma}$$ \hfill (8a)$$

$$\sigma_{cs}^{mi} = K_{1}^{mi}C_c^{mi}$$ \hfill (8b)$$

where $K_{1}^{ma}$ and $K_{1}^{mi}$ are the equilibrium distribution coefficients of contaminant between the aqueous phase and the solid matrix in the mobile and immobile regions ($L^3 M^{-1}$), respectively.

The mass balance equation for the contaminant sorbed to DOM in the mobile and immobile regions can be described as:

$$\frac{\partial (\phi \theta^{ma} C_d^{ma} \sigma_{cd}^{ma})}{\partial t} = - \frac{\partial}{\partial x} \left[ -D_d \frac{\partial}{\partial x} (\phi \theta^{ma} C_d^{ma} \sigma_{cd}^{ma}) + \phi v_w^{ma} \theta^{ma} C_d^{ma} \sigma_{cd}^{ma} \right] + \phi Q_{cd}^{ma} - \phi Q_{cd}^{ma}$$ \hfill (9a)$$

$$\frac{\partial [(1 - \phi) \theta^{mi} C_d^{mi} \sigma_{cd}^{mi}]}{\partial t} = (1 - \phi) Q_{cd}^{mi}$$ \hfill (9b)$$

where $C_d^{ma}$ and $C_d^{mi}$ are the concentrations of DOM in the mobile and immobile regions, respectively, $\sigma_{cd}^{ma}$ and $\sigma_{cd}^{mi}$ are the mass fractions of contaminant sorbed to DOM in the mobile and immobile regions (mass of contaminant sorbed to DOM per unit mass of DOM, MM$^{-1}$), $D_d$ is the hydrodynamic dispersion coefficient of DOM ($L^2 T^{-1}$), $Q_{d}^{ma}$ is the utilization rate of contaminant sorbed to DOM in the mobile region. As noted previously, in riverbank filtration, the aquifer is generally saturated with DOM. Therefore, for practical purposes of riverbank filtration, we can assume that DOM concentration is constant in the mobile and immobile regions. In addition, no diffusion of DOM and DOM-attached contaminant occurs in the immobile region due to constant DOM concentration. The mass transfer of contaminant between the aqueous phase and DOM can be expressed as:

$$Q_{cd}^{ma} = k_p^{ma} \theta^{ma} C_c^{ma} - k_q^{ma} \theta^{ma} C_d^{ma} \sigma_{cd}^{ma}$$ \hfill (10a)$$

$$Q_{cd}^{mi} = k_p^{mi} \theta^{mi} C_c^{mi} - k_q^{mi} \theta^{mi} C_d^{mi} \sigma_{cd}^{mi}$$ \hfill (10b)$$
where \( k_p^{\text{ma}} \) and \( k_q^{\text{ma}} \) are the adsorption and desorption rate coefficients of the contaminant on DOM in the mobile region \((T^{-1})\), respectively, and \( k_p^{\text{mi}} \) and \( k_q^{\text{mi}} \) are adsorption and desorption rate coefficients of the contaminant on DOM in the immobile region \((T^{-1})\), respectively.

The mass balance equation for the contaminant sorbed to the mobile bacteria in the mobile region can be presented as:

\[
\frac{\partial (\phi \theta^{\text{ma}}_{\text{b}} C^{\text{ma}}_{\text{cbm}} \sigma^{\text{ma}}_{\text{cbm}})}{\partial t} = -\frac{\partial}{\partial x} \left[ -D_b \frac{\partial}{\partial x} (\phi \theta^{\text{ma}}_{\text{b}} C^{\text{ma}}_{\text{cbm}} \sigma^{\text{ma}}_{\text{cbm}}) + \phi v^{\text{ma}}_{\text{w}} \theta^{\text{ma}}_{\text{b}} C^{\text{ma}}_{\text{b}} \sigma^{\text{ma}}_{\text{cbm}} \right]
\]

\[
+ \phi Q^{\text{ma}}_{\text{cbm}} - \phi Q^{\text{ma}}_{\text{bm}}
\]

where \( \sigma^{\text{ma}}_{\text{cbm}} \) is the mass fraction of the contaminant sorbed to the mobile bacteria (mass of contaminants sorbed to mobile bacteria per unit mass of mobile bacteria, \( \text{MM} / C_0 \)), and \( Q^{\text{ma}}_{\text{bm}} \) is the utilization rate of the contaminant sorbed to the mobile bacteria. The mass balance equation for the contaminant sorbed to the reversibly attached bacteria in the mobile region can be given as:

\[
\frac{\partial (\phi \rho_b \sigma^{\text{r,ma}}_{\text{b}} \sigma^{\text{r,ma}}_{\text{cbi}})}{\partial t} = \phi Q^{\text{r,ma}}_{\text{cbi}} - \phi Q^{\text{r,ma}}_{\text{bi}}
\]

where \( \sigma^{\text{r,ma}}_{\text{cbi}} \) is the mass fraction of the contaminant sorbed to the reversibly attached bacteria (mass of contaminant sorbed to reversibly attached bacteria per unit mass of reversibly attached bacteria, \( \text{MM} / C_0 \)), and \( Q^{\text{r,ma}}_{\text{bi}} \) is the utilization rate of the contaminant sorbed to the reversibly attached bacteria. The mass balance equation for the contaminant sorbed to the irreversibly attached bacteria in the mobile region can be written as:

\[
\frac{\partial (\phi \rho_b \sigma^{\text{ir,ma}}_{\text{b}} \sigma^{\text{ir,ma}}_{\text{cbi}})}{\partial t} = \phi Q^{\text{ir,ma}}_{\text{cbi}} - \phi Q^{\text{ir,ma}}_{\text{bi}}
\]

where \( \sigma^{\text{ir,ma}}_{\text{cbi}} \) is the mass fraction of the contaminant sorbed to the irreversibly attached bacteria (mass of contaminant sorbed to irreversibly attached bacteria per unit mass of irreversibly attached bacteria, \( \text{MM} / C_0 \)), and \( Q^{\text{ir,ma}}_{\text{bi}} \) is the utilization rate of the contaminant sorbed to the irreversibly attached bacteria.

The mass transfer of contaminant between the aqueous phase and the mobile bacteria and between the aqueous phase and the immobile bacteria can be presented with the following kinetic expressions:

\[
Q^{\text{ma}}_{\text{cbm}} = k_3^{\text{ma}} \theta^{\text{ma}} C^{\text{ma}} - k_4^{\text{ma}} \theta^{\text{ma}} C^{\text{ma}} \sigma^{\text{ma}}_{\text{cbm}} - k_3^{\text{ma}} \theta^{\text{ma}} C^{\text{ma}} \sigma^{\text{ma}}_{\text{cbm}} + k_4^{\text{ma}} \theta^{\text{ma}} C^{\text{ma}} \sigma^{\text{ma}}_{\text{cbm}}
\]

\[
Q^{\text{r,ma}}_{\text{cbi}} = k_3^{\text{ma}} \theta^{\text{ma}} C^{\text{ma}} - k_4^{\text{ma}} \rho_b \sigma^{\text{r,ma}}_{\text{cbi}} + k_3^{\text{ma}} \theta^{\text{ma}} C^{\text{ma}} \sigma^{\text{ma}}_{\text{cbi}} - k_4^{\text{ma}} \rho_b \sigma^{\text{r,ma}}_{\text{cbi}}
\]

\[
Q^{\text{ir,ma}}_{\text{cbi}} = k_3^{\text{ma}} \theta^{\text{ma}} C^{\text{ma}} - k_4^{\text{ma}} \rho_b \sigma^{\text{ir,ma}}_{\text{cbi}} + k_3^{\text{ma}} \theta^{\text{ma}} C^{\text{ma}} \sigma^{\text{ma}}_{\text{cbi}}
\]

where \( k_3^{\text{ma}} \) and \( k_4^{\text{ma}} \) are the adsorption and desorption rate coefficients of the contaminant on bacteria \((T^{-1})\), respectively. Note that the detachment rate coefficient of the
contaminant on the mobile bacteria is assumed to be equal to that of the contaminant on
the immobile bacteria.

2.3. Bacterial growth and decay and contaminant utilization

The specific growth rate of bacteria can be described by the Monod equation. Assuming that the contaminant concentration in the aqueous phase is low ($K_s \gg C_c^{ma}$), the growth rates of the mobile and immobile bacteria with contaminant as a food source can be described as:

\[ Q_{gm}^{ma} = \mu \left( \frac{C_c^{ma} + \rho_s \sigma_{cs}^{ma}}{\theta^{ma}} + C_d^{ma} \sigma_{ed}^{ma} \right) (\theta^{ma} C_b^{ma}) \]  \hspace{1cm} (17)

\[ Q_{gi}^{r,ma} = \mu \left( \frac{C_c^{ma} + \rho_s \sigma_{cs}^{ma}}{\theta^{ma}} \right) (\rho_b \sigma_{b}^{r,ma}) \]  \hspace{1cm} (18)

\[ Q_{gi}^{ir,ma} = \mu \left( \frac{C_c^{ma} + \rho_s \sigma_{cs}^{ma}}{\theta^{ma}} \right) (\rho_b \sigma_{b}^{ir,ma}) \]  \hspace{1cm} (19)

where $\mu = \mu_{max}/K_s$, $\mu_{max}$ is the maximum growth rate of the mobile bacteria (T$^{-1}$), and $K_s$ is the half-constant which is the substrate concentration where the specific growth rate has a half of its maximum value (ML$^{-3}$). The growth rate of bacteria with DOM as a food source can be expressed with the following first-order kinetic expression (Borden and Bedient, 1986):

\[ Q_{go}^{ma} = k_o Y \theta^{ma} C_d^{ma} \]  \hspace{1cm} (20)

where $k_o$ is the first-order decay rate coefficient for DOM (T$^{-1}$), and $Y$ is the yield factor, which is the mass of bacteria formed per unit mass of food source utilized (MM$^{-1}$).

The decay rates of the mobile and immobile bacteria can be given by the following first-order kinetic expressions:

\[ Q_{dm}^{ma} = k_{dm} \theta^{ma} C_b^{ma} \]  \hspace{1cm} (21)

\[ Q_{di}^{r,ma} = k_{di}^{r} \rho_b \sigma_{b}^{r,ma} \]  \hspace{1cm} (22)

\[ Q_{di}^{ir,ma} = k_{di}^{ir} \rho_b \sigma_{b}^{ir,ma} \]  \hspace{1cm} (23)

where $k_{dm}$, $k_{di}^{r}$ and $k_{di}^{ir}$ are the decay rate coefficients for the mobile, reversibly attached and irreversibly attached bacteria (T$^{-1}$), respectively.
The utilization rates for the dissolved contaminant and the contaminant sorbed onto the solid matrix can be written as:

\[ Q_{ma} = \frac{\mu C_c^m a}{Y} (\theta^m a C_b^m + \rho_b \sigma_b^{r,ma} + \rho_b \sigma_b^{ir,ma}) \]  

(24)

\[ Q_{s} = \frac{\mu \rho_s^m \sigma_s^m}{Y \theta_{ma}} (\theta^m a C_b^m + \rho_b \sigma_b^{r,ma} + \rho_b \sigma_b^{ir,ma}) \]  

(25)

\[ Q_{d} = \frac{\mu C_d^m \sigma_d^m}{Y} (\theta^m a C_b^m) \]  

(26)

Note that the utilization rates of the contaminant sorbed onto bacteria are assumed to be negligible (i.e. \( Q_{bm}^{ma} = Q_{bi}^{ma} = Q_{bm}^{ir,ma} = 0 \)) because they are higher-order expressions (Kim and Corapcioglu, 1996).

### 3. Governing equations

The substitution of Eqs. (3), (5), (17), (20) and (21) into Eq. (1) yields the transport equation for the mobile bacteria as:

\[
\frac{\partial (\phi \theta^m a C_b^m)}{\partial t} = -\frac{\partial}{\partial x} \left[ -D_b \frac{\partial (\phi \theta^m a C_b^m)}{\partial x} + \phi v_w \theta^m a C_b^m \right] - \phi k_{c}^m \theta^m a C_b^m \\
+ \phi k_{r}^m \rho_b \sigma_b^{r,ma} - \phi k_{ci}^m \theta^m a C_b^m \\
+ \phi \mu \left( C_c^m + \rho_b \frac{K_1}{\theta^m a} + \sigma_d \sigma_{cd}^m \right) (\theta^m a C_b^m) \\
- \phi k_{dm} \theta^m a C_b^m + \phi k_{d} Y \theta^m a C_d^m 
\]

(27)

With the substitution of Eqs. (3), (18) and (22) into Eq. (2), the mass balance equation for the reversibly attached bacteria can be written as:

\[
\frac{\partial (\phi \rho_b \sigma_b^{r,ma})}{\partial t} = \phi k_{c}^m \theta^m a C_b^m - \phi k_{r}^m \rho_b \sigma_b^{r,ma} + \phi \mu C_c^m \left( 1 + \frac{\rho_b K_1^m}{\theta^m a} \right) (\rho_b \sigma_b^{r,ma}) \\
- \phi k_{di} \rho_b \sigma_b^{r,ma} 
\]

(28)

With the substitution of Eqs. (5), (19) and (23) into Eq. (4), the mass balance equation for the irreversibly attached bacteria can be presented as:

\[
\frac{\partial (\phi \rho_b \sigma_b^{ir,ma})}{\partial t} = \phi k_{ci}^m \theta^m a C_b^m + \phi \mu C_c^m \left( 1 + \frac{\rho_b K_1^m}{\theta^m a} \right) \rho_b \sigma_b^{ir,ma} - \phi k_{di}^i \rho_b \sigma_b^{ir,ma} 
\]

(29)
After the substitution of (Eqs. (7), (8a), (10a), (7), (8a), (10a), (14), (15), (16), (24) and (25)) into Eq. (6a), the transport equation for the contaminant dissolved in the aqueous phase of the mobile region can be finalized as:

\[
\frac{\partial (\phi R_{c}^{ma} \theta^{ma} C_{c}^{ma})}{\partial t} = - \frac{\partial}{\partial x} \left[ -D_{c} \frac{\partial (\phi \theta^{ma} C_{c}^{ma})}{\partial x} + \phi v_{w}^{ma} \theta^{ma} C_{c}^{ma} \right] - \phi k_{p}^{ma} \theta^{ma} C_{c}^{ma} + \phi k_{q}^{ma} \theta^{ma} C_{d}^{ma} \sigma_{cd}^{ma} - 3 \phi k_{s}^{ma} \theta^{ma} C_{c}^{ma} + \phi k_{4}^{ma} \theta^{ma} C_{b}^{ma} \sigma_{cb}^{ma} + \phi k_{4}^{ma} \rho_{b}^{r,ma} \sigma_{cbi}^{r,ma} + \phi k_{4}^{ma} \rho_{b}^{ir,ma} \sigma_{cbi}^{ir,ma} - \phi k_{4}^{ma} \theta^{ma} C_{b}^{ma} \sigma_{cb}^{ma} - \phi \mu \left( 1 + \rho_{s} K_{1}^{ma} / \theta^{ma} \right) \times (\theta^{ma} C_{c}^{ma} + \rho_{b}^{r,ma} + \rho_{b}^{ir,ma}) C_{c}^{ma} - \phi a (C_{c}^{ma} - C_{c}^{ma})
\]

where \( R_{c}^{ma} \) is the contaminant retardation factor at the mobile region (= 1 + \( \rho_{s} K_{1}^{ma} / \theta^{ma} \)).

With the substitution of (Eqs. (7), (8b) and (10b) into Eq. (6b), the transport equation for the contaminant dissolved in the aqueous phase of the immobile region can be written as:

\[
\frac{\partial ((1 - \phi) R_{c}^{mi} \theta^{mi} C_{c}^{mi})}{\partial t} = - \frac{\partial}{\partial x} \left\{ - D_{B} \frac{\partial ((1 - \phi) \theta^{mi} C_{c}^{mi})}{\partial x} \right\} - (1 - \phi) k_{p}^{mi} \theta^{mi} C_{c}^{mi} + (1 - \phi) k_{q}^{mi} \theta^{mi} C_{d}^{mi} \sigma_{cd}^{mi} + (1 - \phi) a (C_{c}^{mi} - C_{c}^{mi})
\]

where \( R_{c}^{mi} \) is the contaminant retardation factor at the immobile region (= 1 + \( \rho_{s} K_{1}^{mi} / \theta^{mi} \)).

The substitution of Eqs. (10a) and (26) into Eq. (9a) yields the transport equation for the contaminant sorbed to DOM in the mobile region as:

\[
\frac{\partial (\phi \theta^{ma} C_{b}^{ma} \sigma_{cb}^{ma})}{\partial t} = - \frac{\partial}{\partial x} \left[ -D_{b} \frac{\partial (\phi \theta^{ma} C_{b}^{ma} \sigma_{cb}^{ma})}{\partial x} + \phi v_{w}^{ma} \theta^{ma} C_{b}^{ma} \sigma_{cb}^{ma} \right] + \phi k_{3}^{ma} \theta^{ma} C_{c}^{ma} - \phi k_{4}^{ma} \theta^{ma} C_{b}^{ma} \sigma_{cb}^{ma} + \phi k_{c}^{ma} \theta^{ma} C_{b}^{ma} \sigma_{cb}^{ma} + \phi k_{r}^{ma} \rho_{b}^{ma} \sigma_{cbi}^{ma}
\]

The substitution of Eq. (14) into Eq. (11) produces the transport equation for the contaminant sorbed to the mobile bacteria as:

\[
\frac{\partial (\phi \theta^{ma} C_{b}^{ma} \sigma_{cbi}^{ma})}{\partial t} = - \frac{\partial}{\partial x} \left[ -D_{b} \frac{\partial (\phi \theta^{ma} C_{b}^{ma} \sigma_{cbi}^{ma})}{\partial x} + \phi v_{w}^{ma} \theta^{ma} C_{b}^{ma} \sigma_{cbi}^{ma} \right] + \phi k_{3}^{ma} \theta^{ma} C_{c}^{ma} - \phi k_{4}^{ma} \theta^{ma} C_{b}^{ma} \sigma_{cbi}^{ma} + \phi k_{c}^{ma} \theta^{ma} C_{b}^{ma} \sigma_{cbi}^{ma} + \phi k_{r}^{ma} \rho_{b}^{ma} \sigma_{cbi}^{ma}
\]

The substitution of Eq. (14) into Eq. (15) produces the transport equation for the contaminant sorbed to the immobile bacteria as:

\[
\frac{\partial (\phi \theta^{mi} C_{b}^{mi} \sigma_{cbi}^{mi})}{\partial t} = - \frac{\partial}{\partial x} \left[ -D_{b} \frac{\partial (\phi \theta^{mi} C_{b}^{mi} \sigma_{cbi}^{mi})}{\partial x} + \phi v_{w}^{mi} \theta^{mi} C_{b}^{mi} \sigma_{cbi}^{mi} \right] + \phi k_{3}^{mi} \theta^{mi} C_{c}^{mi} - \phi k_{4}^{mi} \theta^{mi} C_{b}^{mi} \sigma_{cbi}^{mi} + \phi k_{c}^{mi} \theta^{mi} C_{b}^{mi} \sigma_{cbi}^{mi} + \phi k_{r}^{mi} \rho_{b}^{mi} \sigma_{cbi}^{mi}
\]

The substitution of Eq. (14) into Eq. (16) produces the transport equation for the contaminant sorbed to the DOM as:

\[
\frac{\partial (\phi \theta^{mi} C_{d}^{mi} \sigma_{cd}^{mi})}{\partial t} = - \frac{\partial}{\partial x} \left[ -D_{d} \frac{\partial (\phi \theta^{mi} C_{d}^{mi} \sigma_{cd}^{mi})}{\partial x} + \phi v_{w}^{mi} \theta^{mi} C_{d}^{mi} \sigma_{cd}^{mi} \right] + \phi k_{3}^{mi} \theta^{mi} C_{c}^{mi} - \phi k_{4}^{mi} \theta^{mi} C_{d}^{mi} \sigma_{cd}^{mi} + \phi k_{c}^{mi} \theta^{mi} C_{d}^{mi} \sigma_{cd}^{mi} + \phi k_{r}^{mi} \rho_{b}^{mi} \sigma_{cd}^{mi}
\]
With the substitution of Eq. (15) into Eq. (12), the mass balance equation for the contaminant sorbed to the reversibly attached bacteria can be finalized as:

\[
\frac{\partial (\phi \rho_b \sigma_{\text{r,ma}}^b / \sigma_{\text{ci},b})}{\partial t} = \phi k_3^{\text{ma}} \theta^{\text{ma}} C_{c}^{\text{ma}} - \phi k_4^{\text{ma}} \rho_b \sigma_{\text{ci},b}^{\text{r,ma}} + \phi k_5^{\text{ma}} \theta^{\text{ma}} C_{b}^{\text{ma}} \sigma_{\text{cm},b}^{\text{ma}}
\]

Finally, with the substitution of Eq. (16) into Eq. (13), the mass balance equation for the contaminant sorbed to the irreversibly attached bacteria can be given as:

\[
\frac{\partial (\phi \rho_b \sigma_{\text{ir,ma}}^b / \sigma_{\text{ci},b})}{\partial t} = \phi k_3^{\text{ma}} \theta^{\text{ma}} C_{c}^{\text{ma}} - \phi k_4^{\text{ma}} \rho_b \sigma_{\text{ci},b}^{\text{ir,ma}} + \phi k_5^{\text{ma}} \theta^{\text{ma}} C_{b}^{\text{ma}} \sigma_{\text{cm},b}^{\text{ma}}
\]

### 4. Solutions of governing equations

Eqs. (27)–(36) constitute a complete set of governing equations with 10 unknowns: \( C_b^{\text{ma}}, \sigma_{\text{r,ma}}^b, \sigma_{\text{ci},b}^{\text{r,ma}}, C_c^{\text{mi}}, \sigma_{\text{r,ma}}^c, \sigma_{\text{cm},b}^{\text{ma}}, \sigma_{\text{cm},b}^{\text{r,ma}}, \sigma_{\text{cm},b}^{\text{ma}}, \sigma_{\text{cm},b}^{\text{r,ma}} \). In this study, a fully implicit finite difference method is used to solve the governing equations numerically with the following initial and boundary conditions:

\[
\begin{align*}
C_b^{\text{ma}}(x,0) &= C_c^{\text{ma}}(x,0) = C_c^{\text{mi}}(x,0) = \sigma_{\text{r,ma}}^b(x,0) = \sigma_{\text{r,ma}}^c(x,0) = C_d^{\text{ma}}(x,0) = C_d^{\text{mi}}(x,0) = 0 \\
- D_b \frac{\partial C_b^{\text{ma}}}{\partial x}(0,t) + v_w^{\text{ma}} C_b^{\text{ma}}(0,t) &= \begin{cases} \\
\nu_{w,b} C_{b,0} & \text{at } 0 < t \leq t_0 \\
0 & \text{at } t > t_0 \\
\end{cases} \\
- D_c \frac{\partial C_c^{\text{ma}}}{\partial x}(t_0,t) + v_w^{\text{ma}} C_c^{\text{ma}}(t_0,t) &= \begin{cases} \\
\nu_{w,c} C_{c,0} & \text{at } 0 < t \leq t_0 \\
0 & \text{at } t > t_0 \\
\end{cases} \\
\frac{\partial C_b^{\text{ma}}}{\partial x}(L,t) + \frac{\partial C_b^{\text{ma}}}{\partial x}(L,t) &= \frac{\partial C_c^{\text{mi}}}{\partial x}(L,t) + \frac{\partial C_d^{\text{ma}}}{\partial x}(L,t) + \frac{\partial C_d^{\text{mi}}}{\partial x}(L,t) \\
&= 0
\end{align*}
\]

where \( C_{b,0} \) is the influent concentration of bacteria at \( x = 0 \), \( C_{c,0} \) is the influent concentration for contaminants at \( x = 0 \), \( L \) is the distance between the river and the pumping station, and \( t_0 \) is the duration of bacteria and contaminant flux injection.

Eqs. (27)–(36) are solved sequentially at each time step. First, the bacterial transport Eq. (27) is solved for \( C_b^{\text{ma}} \) at time step \((n+1)\), where \( n \) is the previous time step at which
all variables are known. Then, the mass balance equations for the reversibly and irreversibly attached bacteria (28) and (29) are solved for \( r_b^{r,ma} \) and \( r_b^{ir,ma} \), respectively, at the time step \((n+1)\). In case of the contaminant transport, the model equations are also solved sequentially. Eqs. (30) and (31) are solved for \( C_c^{ma} \) and \( C_c^{mi} \), respectively. Then, Eqs. (32) and (33) are solved for \( r_{cd}^{ma} \) and \( r_{cd}^{mi} \), respectively. Finally, Eqs. (34)–(36) are solved for \( r_{cbm}^{ma} \), \( r_{cbi}^{r,ma} \), and \( r_{cbi}^{ir,ma} \), respectively.

5. Model results and sensitivity analysis

The partial verification of the proposed model is performed for the contaminant transport in the absence of colloids in dual-porosity media. The measured data from the column experiments of the 2,4,5-trichlorophenoxyacetic acid transport by van Genuchten et al. (1977) are used to verify the model. They performed the column experiments using the unsaturated columns with the length of 30 cm to investigate the transport behavior of herbicides. The parameter values available by van Genuchten et al. (1977) at their experiments 1–4 are \( q_w = 5.91 \times 10^{-5} \) cm, \( D_c = 9.72 \times 10^{-5} \) cm² s⁻¹, \( \theta = 0.473 \), \( \phi = 0.940 \), and \( \rho_b = 1.36 \times 10^6 \) mg l⁻¹. The influent concentration of the contaminant is 10 mg l⁻¹, and the duration of the contaminant injection is 7.672
days. The simulation result shows a good match-up with the experimental data (Fig. 2) when $K_{1\text{ma}}$, $K_{1\text{mi}}$, and $\alpha_c$ are $1.96 \times 10^{-7}$, $4.38 \times 10^{-6}$ l mg$^{-1}$, and $1.50 \times 10^{-6}$ s$^{-1}$, respectively.

The model equations are used to simulate the contaminant transport in dual-porosity media in the presence of DOM and bacteria in riverbank filtration. The water content, pore-water velocity, and volume fraction of the mobile region are assumed to be constant. In addition, the hydrodynamic dispersion coefficients of bacteria and DOM are assumed to be equal to that of the contaminant. The parameters and the range of parameters used in the simulation (see Table 1) mainly come from Borden and Bedient (1986); Corapcioglu and Jiang (1993); Hendry et al. (1999), and Corapcioglu and Wang (1999).

### Table 1
Model parameters used in the simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{b0}$ = 5 mg l$^{-1}$</td>
<td>influent bacterial concentration</td>
</tr>
<tr>
<td>$C_{c0}$ = 0.1 mg l$^{-1}$</td>
<td>influent contaminant concentration</td>
</tr>
<tr>
<td>$C_d$ = 10 mg l$^{-1}$</td>
<td>DOM concentration in the aqueous phase</td>
</tr>
<tr>
<td>$\phi_{\text{ma}}$ = 0.4</td>
<td>water content in mobile region</td>
</tr>
<tr>
<td>$\phi_{\text{mi}}$ = 0.4</td>
<td>water content in immobile region</td>
</tr>
<tr>
<td>$\phi$ = 0.8</td>
<td>volume fraction of mobile region (Corapcioglu and Wang, 1999)</td>
</tr>
<tr>
<td>$\rho_s$ = $1.6 \times 10^6$ mg l$^{-1}$</td>
<td>dry bulk density of solid matrix</td>
</tr>
<tr>
<td>$\rho_b$ = $1.0 \times 10^6$ mg l$^{-1}$</td>
<td>density of bacteria (Corapcioglu and Kim, 1995)</td>
</tr>
<tr>
<td>$q_{\text{ma}}$ = $1.2 \times 10^{-3}$ cm s$^{-1}$</td>
<td>specific discharge in mobile region</td>
</tr>
<tr>
<td>$D_c$ = $7.5 \times 10^{-3}$ cm$^2$ s$^{-1}$</td>
<td>hydrodynamic dispersion coefficient</td>
</tr>
<tr>
<td>$D_B$ = $4.0 \times 10^{-6}$ cm$^2$ s$^{-1}$</td>
<td>Brownian molecular diffusion coefficient</td>
</tr>
<tr>
<td>$a$ = $1.0 \times 10^{-6}$ s$^{-1}$</td>
<td>first-order mass transfer rate coefficient (Corapcioglu and Wang, 1999)</td>
</tr>
<tr>
<td>$K_{1\text{ma}}$ = $1.2 \times 10^{-5}$ l mg$^{-1}$</td>
<td>contaminant distribution coefficient in mobile region (Corapcioglu and Wang, 1999)</td>
</tr>
<tr>
<td>$K_{1\text{mi}}$ = $1.2 \times 10^{-4}$ l mg$^{-1}$</td>
<td>contaminant distribution coefficient in immobile region (Corapcioglu and Wang, 1999)</td>
</tr>
<tr>
<td>$k_{\text{cma}}$ = $2.0 \times 10^{-5}$ s$^{-1}$</td>
<td>bacterial deposition rate coefficient (Hendry et al., 1999)</td>
</tr>
<tr>
<td>$k_{\text{cma}}$ = $2.0 \times 10^{-6}$ s$^{-1}$</td>
<td>bacterial release rate coefficient (Hendry et al., 1999)</td>
</tr>
<tr>
<td>$k_{\text{ci}}$ = $1.0 \times 10^{-5}$ s$^{-1}$</td>
<td>bacterial irreversible deposition rate coefficient (Hendry et al., 1999)</td>
</tr>
<tr>
<td>$k_3$ = $3.0 \times 10^{-5}$ s$^{-1}$</td>
<td>contaminant adsorption rate coefficient onto bacteria (Kim and Corapcioglu, 1996)</td>
</tr>
<tr>
<td>$k_4$ = $1.5 \times 10^{-5}$ s$^{-1}$</td>
<td>contaminant desorption rate coefficient from bacteria (Kim and Corapcioglu, 1996)</td>
</tr>
<tr>
<td>$k_p$, $k_{\text{pi}}$ = $3.0 \times 10^{-4}$ s$^{-1}$</td>
<td>contaminant adsorption rate coefficient on DOM (Corapcioglu and Jiang, 1993)</td>
</tr>
<tr>
<td>$k_q$, $k_{\text{qi}}$ = $1.5 \times 10^{-4}$ s$^{-1}$</td>
<td>contaminant desorption rate coefficient from DOM (Corapcioglu and Jiang, 1993)</td>
</tr>
<tr>
<td>$k_b$ = $3.1 \times 10^{-11}$ s$^{-1}$</td>
<td>first-order decay rate coefficient for DOM (Borden and Bedient, 1986)</td>
</tr>
<tr>
<td>$\mu$ = $2.1 \times 10^{-11}$ cm$^3$ mg$^{-1}$ s$^{-1}$</td>
<td>coefficient related with bacterial growth rate (Corapcioglu and Kim, 1995)</td>
</tr>
<tr>
<td>$Y$ = 0.098</td>
<td>yield factor (Corapcioglu and Kim, 1995)</td>
</tr>
<tr>
<td>$k_{\text{dm}}$, $k_{\text{di}}$, $k_{\text{di}}$ = $1.7 \times 10^{-8}$ s$^{-1}$</td>
<td>decay rate coefficient of bacteria (Corapcioglu and Kim, 1995)</td>
</tr>
</tbody>
</table>
Fig. 3 illustrates the temporal variation of the total aqueous phase contaminant concentration in the mobile and immobile regions in the presence of DOM and bacteria. Concentration values are normalized by the influent concentration. In the simulation, bacteria are present at all times while the contaminant is pulse-loaded for 5 pore volumes (pv). In the dual-porosity model, the total concentration of contaminant in the aqueous phase of the mobile region, $C_{ct}^m$, is the sum of the contaminant dissolved in the aqueous phase, the contaminant sorbed to DOM, and the contaminant sorbed to the mobile bacteria (i.e. $C_{ct}^m = C_c^m + C_d^m + C_{cb}^m$). And the total concentration of contaminant in the aqueous phase of the immobile region, $C_{ct}^i$, is the sum of the contaminant dissolved in the aqueous phase and the contaminant sorbed to DOM (i.e. $C_{ct}^i = C_c^i + C_d^i$). Fig. 3 shows that the contaminant mobility increases in the presence of DOM and bacteria in the mobile region. When no colloids are present, the peak position in the mobile region is at 40.0 pv. In the presence of DOM, the peak position in the mobile region is at 16.0 pv. The mobility of the contaminant increases greatly when DOM is present in the aqueous phase. If bacteria and DOM are present together, the peak position shifts from 16.0 to 14.7 pv. In riverbank filtration, the contaminant mobility increases due to the presence of DOM and bacteria. As shown in Fig. 3, the tailing appears at later pore volumes due to the presence of an immobile region. The contaminant concentration in the immobile region increases slowly by the mass transfer from the mobile region. After the concentration gradient between the mobile and immobile regions reverses, the immobile region serves as a contaminant reservoir and releases the contaminant into the mobile region. Therefore, at later pore volumes, the contaminant concentration in the mobile region is affected by the

![Figure 3](image_url)

Fig. 3. Temporal variation of total aqueous phase contaminant concentration in the mobile region, $C_{ct}^m$, and immobile region, $C_{ct}^i$ (at $x=L$).
rate of mass transfer from the immobile region. In the presence of DOM and bacteria, the tailing effect occurs at earlier pore volumes than in the absence of colloids. In the mobile region, the contaminant can move faster in the presence of colloids than in the absence of colloids. Thus, the concentration gradient between two regions reverses at earlier pore volumes in the presence of colloids.

Fig. 4 presents the temporal variation of the total aqueous phase effluent contaminant concentration in the mobile region in single- and dual-porosity media. Fig. 4 shows that the contaminant can breakthrough earlier in dual-porosity media than in single-porosity media. In the presence of DOM and bacteria, the normalized peak concentration is 0.20 at \( \text{pv} = 17.3 \) in single-porosity media while it is 0.23 at 14.7 \( \text{pv} \) in dual-porosity media. The pore space available for the contaminant transport in dual-porosity media is smaller than in single-porosity media. It indicates that the pore velocity in dual-porosity media is larger than in single-porosity media in case of constant flow rate. Therefore, the contaminant can migrate to further distances in dual-porosity media than in single-porosity media. Fig. 4 also demonstrates that there is no tailing in single-porosity media. The contaminant concentration decreases rapidly from the peak concentration at later pore volumes in single-porosity media. However, the tailing effect is observed in dual-porosity media. The contaminant breakthrough curves in dual-porosity media show the early breakthrough and tailing. In the contaminant transport in dual-porosity media, the early breakthrough of the contaminant is closely related with the volumetric fraction of the mobile region. The pore space available for contaminant transport will be reduced when the volumetric fraction of the mobile region becomes smaller. Therefore, the

Fig. 4. Temporal variation of the total aqueous phase effluent contaminant concentration in single- (\( \phi = 1.0 \)) and dual-porosity media (\( \phi = 0.8 \)). \( \phi \) is the volume fraction of the mobile region.
earlier breakthrough of the contaminant occurs as the volumetric fraction of the mobile region decreases.

Fig. 5 shows the effect of the adsorption and desorption rate coefficients of contaminant on DOM, \( k_p \) and \( k_q \), on total aqueous phase effluent contaminant concentration in the mobile region, \( C_{ct} \). As \( k_p \) increases from \( 1.5 \times 10^{-4} \) to \( 1.5 \times 10^{-3} \) s\(^{-1}\), the peak concentration increases sharply from 0.17 to 0.57 while the peak position moves from 20.5 to 6.7 pv (Fig. 5a). As \( k_p \) increases, the contaminant sorbed onto DOM increases, and so the contaminant mobility increases. When \( k_q \) increases from \( 3.0 \times 10^{-5} \) to \( 3.0 \times 10^{-4} \) s\(^{-1}\), the normalized peak concentration decreases from 0.39 to 0.20, and the peak position shifts from 5.9 to 21.0 pv (Fig. 5b). As \( k_q \) increases, the contaminant mobility decreases since more contaminant mass is released from DOM. Fig. 5 demonstrates that the contaminant breakthrough curve is very sensitive to changes in \( k_p \) and \( k_q \).

Fig. 6 presents the effect of the adsorption and desorption rate coefficients of contaminant on bacteria, \( k_3 \) and \( k_4 \), on total aqueous phase effluent contaminant concentration in the mobile region, \( C_{ct} \). If \( k_3 \) increases from \( 1.5 \times 10^{-5} \) to \( 1.5 \times 10^{-4} \) s\(^{-1}\), the normalized peak concentration increases from 0.23 to 0.24 and the peak position shifts from 15.5 to 9.3 pv (Fig. 6a). As \( k_3 \) increases, more contaminant mass can sorb onto bacteria, and so the contaminant mobility increases. As \( k_4 \) increases from \( 3.0 \times 10^{-6} \) to \( 3.0 \times 10^{-5} \) s\(^{-1}\), the normalized peak concentration increases from 0.19 to 0.24, and the peak position moves from 13.6 to 14.7 pv (Fig. 6b). As expected, the contaminant mobility decreases as \( k_4 \) increases.

Fig. 7 illustrates the effect of bacterial deposition and release rate coefficients, \( k_c \) and \( k_r \), on the total aqueous phase effluent contaminant concentration in the mobile region. As \( k_c \) increases, the concentration of the mobile bacteria decreases, and so the contaminant facilitation by the mobile bacteria decreases (Fig. 7a). To the contrary, the mobile bacterial concentration increases as \( k_r \) increases. Because more bacterial particles are available as the mobile carriers, the contaminant mobility increases (Fig. 7b). As \( k_{ci} \) increases, more bacteria become immobile, and so the bacterial facilitation effect is reduced (Fig. 7c).

Fig. 8 demonstrates the effect of contaminant mass transfer rate coefficient, \( a \), on total aqueous phase contaminant concentration in the mobile and immobile regions. According to Gerke and van Genuchten (1993), the mass transfer rate coefficient for the contaminant can be defined as \( a=(\alpha/\beta^2)D_B \). \( \alpha \) is the dimensionless geometry factor which is related to the properties of the soil matrix. \( \beta \) denotes the characteristic diffusion path length (L). It represents the distance between the interface of the mobile–immobile region and the center of the immobile region. \( D_B \) indicates the molecular diffusion coefficient (L\(^2\) T\(^{-1}\)). The extent that the presence of the immobile region affects contaminant transport in the mobile region is closely related to the mass transfer rate coefficient. If the contaminant mass transfer rate coefficient is too small, the effect of the immobile region on the transport of the contaminant in the mobile region becomes negligible. As \( a \) increases, the contaminant mass transfer between the mobile and immobile regions increases, and the immobile region more actively involves with the contaminant transport in the mobile region. When \( a \) increases from \( 5.0 \times 10^{-7} \) to \( 5.0 \times 10^{-6} \), the total aqueous phase contaminant concentration in the immobile region (at 90 pv) increases from \( 1.3 \times 10^{-4} \) S.-B. Kim, M.Y. Corapcioglu / Journal of Contaminant Hydrology 59 (2002) 267–289 283
to $1.2 \times 10^{-3}$. Fig. 8 demonstrates that at larger mass transfer rates, the contaminant concentration in the immobile region increases faster, and so the reversal of the contaminant gradient between the mobile and immobile regions takes place at earlier
pore volumes. As $a$ increases from $5.0 \times 10^{-7}$ to $5.0 \times 10^{-6}$, the total aqueous phase effluent contaminant concentration in the mobile region (at 90 pv) increases from $7.2 \times 10^{-7}$ to $6.7 \times 10^{-5}$. It indicates that the tailing occurs at higher contaminant
Fig. 7. The effect of the (a) reversible deposition rate coefficient of bacteria, $k_{cm}^{ma}$, (b) release rate coefficient of bacteria, $k_{r}^{ma}$, and (c) irreversible deposition rate coefficient of bacteria, $k_{ci}^{ma}$, on total aqueous phase effluent contaminant concentration in the mobile region, $C_{ct}^{ma}$. 
concentrations when the contaminant mass transfer rate coefficient becomes larger. In contaminant transport in dual-porosity media, the contaminant mass transfer coefficient between the mobile and immobile regions mainly controls the tailing effect of contaminant breakthrough.

6. Conclusions

In this study, a mathematical model is developed to describe the contaminant transport in the presence of DOM and bacterial particles in physically heterogeneous aquifers during riverbank filtration. To consider the role of immobile regions (ineffective micropores) in physically heterogeneous aquifers, the dual-porosity (mobile–immobile region) approach is applied. The mobile region is conceptualized as a four-phase medium: two mobile colloidal phases, an aqueous phase, and a solid matrix. The model results demonstrate that in riverbank filtration, the presence of colloidal particles and ineffective micropores in aquifers causes the early breakthrough and tailing in the contaminant transport. The presence of bacteria and DOM in aquifers enhances the contaminant mobility in riverbank filtration. When the volumetric fraction of the mobile region in aquifers diminishes, earlier contaminant breakthrough occurs in riverbank filtration. The tailing in contaminant breakthrough curves is mainly controlled by the contaminant mass transfer coefficient between the mobile and immobile regions. The model presented in this study can help predict the contaminant transport in riverbank filtration.

Fig. 8. The effect of contaminant mass transfer rate coefficient, $a$, on total aqueous phase contaminant concentration in the mobile region, $C_{ct}^{ma}$, and immobile region, $C_{ct}^{mi}$ at $x = L$. 
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References


