Coupled biomass growth and flow in unsaturated soil

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ABSTRACT: A numerical model based on the finite element method is presented in this paper to describe transient changes in the hydraulic properties of porous media due to bioclogging in the pore space. Physical processes like ground water flow and delivery of nutrients in the domain are considered through the coupling of the Richards equation and the convection-diffusion equation. Biomass growth dynamics is described by the mathematical model defined by the Monod equation. Four theoretical relationships available in the literature are used to estimate the change in hydraulic conductivity due to biomass accumulation in the domain. Variations in the model's predictions due to uncertainty in the Monod coefficients (yield factor, half velocity constant, maximum substrate use rate) are assessed through a sensitivity analysis. The model is validated against results from sand column experiments performed using the bacterium *Beijerinckia indica*. The columns were prepared with a defined initial concentration of bacteria and are subjected to periods of nutrient supply and periods of rest without flow. The columns' effective hydraulic conductivity was determined using a constant head test across the column. Preliminary numerical results are in agreement with the literature showing that bacteria tend to reproduce more readily in nutrient injection points causing reductions in hydraulic conductivity in these regions due to biomass accumulation. The combination of increased biomass content (and corresponding nutrient consumption) and reduction of hydraulic conductivity prevents further flow downstream limiting the growth and possibly increasing the decay of bacteria in those sections of the domain. The effective hydraulic conductivity estimated using coefficient values readily available in the literature and others obtain from ongoing experiments at Cardiff University for the hydraulic conductivity models considered here show noticeable differences attributed to the underlying assumptions in their theoretical formulations. However, one model allows for a good comparison between the numerical results and the experimental measurements thus proving the validity of the mathematical model here proposed. A sensitivity analysis shows a relatively strong dependency on the yield coefficient, followed by the maximum substrate use rate and a negligible effect of the half velocity constant. Further work is ongoing to increase the accuracy of these parameters for the case of *B. indica*.

KEYWORDS: biological clogging, bioclogging, unsaturated porous media, coupled model, finite element method.

1. INTRODUCTION.

Microorganisms in soil influence the chemical balance, organic content, biological processes and hydraulic properties. Baveye et al (1998) offer a comprehensive review of the mechanisms through which microorganisms influence saturated hydraulic conductivity of porous media, laboratory experiments to measure its effects and summarizes traditional uses of biological clogging in soils. More recent efforts to understand and harness the potential use of bacteria in porous media include biocementation of soils (Ivanov and Chu 2008) and maintenance of permeable pavements to prevent reductions in porous properties (Kia et al. 2017).

Under natural conditions bacteria in soils undergo natural cycles of growth and decay controlled by the availability or absence of nutrients. Researchers have tried to propose relationships between the changes in biomass due to its growth dynamics and spatial distribution in the porous media and its hydraulic properties. Some researchers have proposed models of growth that consider the bacteria as forming a film ('biofilm') (Taylor and Jaffé 1990) attached to the soil particles, while others have proposed distributed models that consider the bacteria arranged in discrete colonies ('micro-colonies') (Vandevivere et al. 1995), yet others (Clement et al. 1996) have proposed a compromise between both by proposing models that consider the bacteria initially forming micro colonies but eventually evolving to biofilms under favourable conditions. The variation in time of bacterial spatial distribution (and consequent changes in porous space) is probably related to the flow process detaching and carrying bacterial cells downstream and/or bacteria cells moving towards zones with more beneficial conditions for growth (Purcell 1977).

Mathematical models to describe the growth of bacterial in porous media that have been proposed in the past commonly take into account the transport of nutrients in the media through the use of the transport equation and the growth of bacteria through Monod dynamics. Saturation of the domain can be considered through coupling with the Richard's equation that describes ground water flow. Other phenomena like chemical reactions can also be considered. A summary of modelling techniques for microorganisms in soils is provided by Bradford et al (2014).

This current paper presents a mathematical model to describe the changes in hydraulic conductivity in a porous medium that couples ground water flow (Richard's equation) with the transport equation under unsaturated conditions. Biological growth follows a Monod dynamics. The model is based on the work of Zysset et al (1994) who presented a model for bacteria influenced by the presence of a limiting substrate under saturated conditions and the work of Soleimani et al (2009) who developed a model applicable under unsaturated conditions. Four theoretical relationships between biomass content and relative hydraulic conductivity are considered. The model is validated with experimental data from bioclogging of sand columns produced by others (Alshiblawi 2016).

The development of a theoretical framework including the relationships governing the hydraulic properties of the porous media is presented. The adopted numerical solution of this theoretical formulation of the problem is then detailed. The experimental work performed by others is briefly summarized before being used to validate the proposed numerical model. A sensitivity analysis of the proposed model to variations in the Monod equation parameters is undertaken and finally a discussion of the potential use for the model as well as limitations and future work is made.

2. THEORETICAL FRAMEWORK

This section presents the equations used in the development of a numerical model to describe the growth (and decay) of bacteria in porous media under the influence of water flow and nutrient transport that leads to reductions in hydraulic conductivity and eventual clogging. The model is composed of three governing equations:

- Richard's equation: that describes the flow of water in unsaturated porous media.
- Convection-Diffusion-Reaction (Transport) equation: that describes the transport of a physical quantity due to convection and/or diffusion and the usage and/or generation of this quantity.
- Monod equation: that describes the growth of bacteria under the influence of a limiting substance.

2.1. R*ichards equation*

The standard form of the unsaturated flow equation used in the proposed bioclogging model is known as "mixed" and it is preferred over others (e.g. h-based) since it offers less mass balance errors (Celia et al. 1990). It is given by:

$$\frac{\partial\theta_{tw}}{\partial t} - \nabla\cdot K(h)\nabla h - \frac{\partial h}{\partial z} = 0 \qquad (1)$$

where θ_{tw} (m^3/m^3) is the total moisture content, h (m) is the pressure head and $K(h)$ (m/s) is the unsaturated hydraulic conductivity.

Equation (1) includes two main variables, θ_{tw} and h, however it is modified during the formulation of the numerical solution as part of the temporal discretization to be expressed it in terms of pressure head only. The procedure for this is presented in section 3.

2.2 T*ransport equation*

The transport of non-interacting chemicals through unsaturated soil can be described using the convection dispersion equation (Porro and Wierenga 1993):

$$\frac{\partial(\theta_{fw}C)}{\partial t} = \frac{\partial}{\partial x}\left(\theta_{tw}D\frac{\partial C}{\partial x} - qC\right) + \varphi S \qquad (2)$$

where C (mg/cm^3) is the solution concentration, θ_{fw} is the free water content (the water available to flow in the soil), S ($mg/cm^3{\cdot}s$) is the substrate consumption rate in the pore space, ϕ (cm^3/cm^3) is the soil porosity, D (m^2/s) is the substrate dispersion coefficient, q (m/s) is the volumetric fluid flux density given by Darcy's law:

$$q = -K(h)\frac{\partial h}{\partial z} + K(h) \qquad (3)$$

The sink term, S, in the context of bioclogging is related with the consumption of substrate by the bacteria present in the soil. This is discussed in the next section.

2.3 M*onod equation*

The Monod equation is a mathematical model for the growth of microorganisms (Corman and Pave 1983). This equation is proposed to relate the microbial growth rates in an aqueous environment to the concentration of a limiting substrate. It is given by:

$$\frac{\partial M}{\partial t} = YS - bM \qquad (4)$$

where M (mg/cm^3) is the bacterial concentration in the pore space, Y (mg/mg) is yield coefficient and b (1/s) is decay rate. The amount of substrate utilized by the bacteria, S, is defined as:

$$S = Mq_m\left(\frac{C}{K_s + C}\right) \qquad (5)$$

where q_m (mg substrate/mg biomass · s) is the maximum specific substrate utilization rate, K_s (mg/cm^3) is the half velocity constant

The biomass saturation, S_b, is defined as the volume fraction of pore space occupied by biomass. It is obtained from the concentration of biomass in the pore space as:

$$S_b = \frac{M}{\rho_b} \qquad (6)$$

where ρ_b (mg/cm^3) is the biomass dry density.

2.4 H*ydraulic properties*

The hydraulic conductivity used in the Richard's equation (1) and Darcy's equation (3) is defined as:

$$K(h) = K_{sat}K_r(h) \qquad (7)$$

where K_{sat} (m/s) is the soil's saturated hydraulic conductivity, K_r (nondimensional) is the soil relative hydraulic conductivity.

The relation between pressure head, h, and total moisture content, θ_{tw}, is based on the relationship proposed by Van Genuchten (1980):

$$\theta_{tw} = (\theta_s - \theta_r)[1 + (\alpha|h|)^n]^{-m} + \theta_r \qquad (8)$$

where α, n and m are fitting parameters. m is defined in relation to n as:

$$m = 1 - \frac{1}{n} \qquad (9)$$

In this work four theoretical relationships between biomass concentration and relative hydraulic conductivity were used.

The first approach in order to relate the biomass growth with changes in the hydraulic conductivity properties of the soil the work of Lenhard and Parker (1987) is used, they studied the change in hydraulic conductivity in porous media for three-phase flow systems such as water, air and oil that could form bubbles that occlude the pore space. This model has been developed by Soleimani et al (2009) for the case of a two-phase flow system (e.g. water and air) and applied for a bioclogging scenario. It is defined as:

$$K_r(h) = S_{etw}^{1/2}\left[\left(1 - S_{eb}^{1/m}\right)^m - \left(1 - S_{etw}^{1/m}\right)^m\right]^2 \qquad (10)$$

where S_{etw} (nondimensional) is the effective total moisture content defined as:

$$S_{etw}(h) = \frac{\theta_{tw}(h) - \theta_r}{\theta_s - \theta_r} \qquad (11)$$

where θ_s is the saturation moisture content, θ_r is the residual moisture content

The second theoretical approach is based on the work of Clement et al (1996) and is defined by:

$$K_r(h) = (1 - S_b)^{19/6} \qquad (12)$$

The third approach is based on the work of Okubo and Matsumoto (1979) and is defined by:

$$K_r(h) = (1 - S_b)^2 \qquad (13)$$

The fourth and final relationship between biomass and relative hydraulic conductivity is defined by Vandevivere (1995), who assumed that porous media could be represented by a bundle of parallel pores all having the same radius and biomass growth as plugs or aggregates respectively, as:

$$K_r(h) = \gamma(1 - S_b)^2 + (1 - \gamma)\frac{k_c}{k_c + S_b(1 - k_c)} \quad (14)$$

where k_c is the relative hydraulic conductivity of the plug and γ is defined as:

$$\gamma = \exp\left[-0.5\left(\frac{S_b}{S_{bc}}\right)^2\right] \quad (15)$$

where S_{bc} is a critical biomass saturation factor.

Figure 1 shows a comparison of the changes in relative hydraulic conductivity with biomass saturation estimated using the equations presented in this section for a degree of saturation of 1 and using parameter values listed in Table 2.

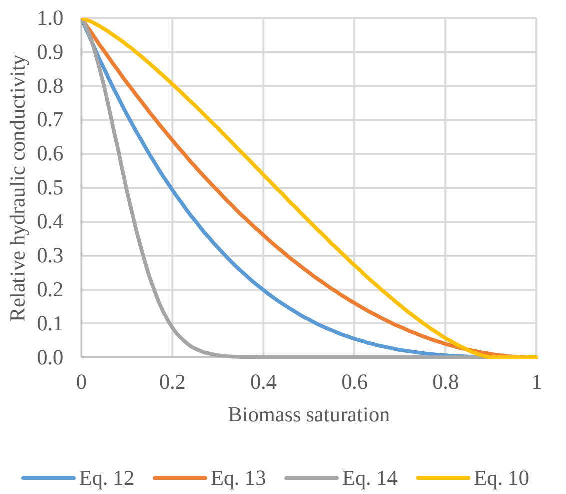

Figure 1 – Variation of relative hydraulic conductivity with biomass saturation estimated using four theoretical relationships.

3. NUMERICAL FORMULATION

Equation (1) and (2) form a couple transient system that is solved spatially using the finite element method with linear elements. To optimise the stability of the solution the Petrov-Galerkin method is used for the transport equation while Galerkin method is used for Richard's equation.

Time discretization is performed using the finite difference method for both Richard's and transport equation. In particular, equation (1) is discretized in time in the following way in order to express it as a function of pressure head only:

$$\begin{aligned} &\theta_{tw}^{n+1} - \theta_{tw}^{n} \\ &-\Delta t\eta\nabla\cdot\left[K\left(h^{i+1}\right)\cdot\left(\nabla h^{i+1}+1\right)\right] \\ &-\Delta t(1-\eta)\nabla\cdot\left[K\left(h^{i}\right)\cdot\left(\nabla h^{i}+1\right)\right] = 0 \end{aligned} \quad (16)$$

where η defines the time discretization scheme used, i is a time stepping index and Δt is the time step.

Utilising the Pickard iteration method, solutions for the main variables are calculated iteratively using coefficients estimated with the solutions obtained from previous iterations. That is, solutions at t=i+1 and iteration j+1 are calculated using coefficients estimated with solution values at iteration j. This can be expressed as:

$$\begin{aligned} &\theta_{tw}^{i+1,j+1} - \theta_{tw}^{i} \\ &-\Delta t\eta\nabla\cdot\left[K\left(h^{i+1,j}\right)\cdot\left(\nabla h^{i+1,j+1}+1\right)\right] \\ &-\Delta t(1-\eta)\nabla\cdot\left[K\left(h^{i}\right)\cdot\left(\nabla h^{i}+1\right)\right] = 0 \end{aligned} \quad (17)$$

Equation (17) can be reformulated with a single main variable by expanding the total moisture content using a truncated Taylor expansion with respect to h about the expansion point $h^{i+1,j}$:

$$\begin{aligned} \theta_{tw}^{i+1,j+1} &= \theta_{tw}^{i+1,j} \\ &+ \left.\frac{\partial\theta_{tw}}{\partial h}\right|^{i+1,j}\left(h^{i+1,j+1} - h^{i+1,j}\right) + O(\delta^2) \end{aligned} \quad (18)$$

Substituting (17) in (16) and rearranging:

$$\begin{aligned} &C_w^{i+1,j}\left(h^{i+1,j+1} - h^{i+1,j}\right) \\ &-\Delta t\eta\nabla\cdot\left[K\left(h^{i+1,j}\right)\cdot\left(\nabla h^{i+1,j+1}+1\right)\right] \\ &-\Delta t(1-\eta)\nabla\cdot\left[K\left(h^{i}\right)\cdot\left(\nabla h^{i}+1\right)\right] \\ &\qquad = -\left(\theta_{tw}^{i+1,m} - \theta_{tw}^{i}\right) \end{aligned} \quad (19)$$

where

$$C_w^{i+1,j} = \left.\frac{\partial\theta_{tw}}{\partial h}\right|^{i+1,j} \quad (20)$$

Equation (19) is solved for $h^{i+1,j+1}$ using the relationships for hydraulic conductivity and moisture content presented earlier.

3.1 Boundary conditions

In order to solve the coupled numerical system formed after space and time discretization of equations (1) and (2) the following boundary conditions are assumed:

For the Richard's equation, (1), a fixed pressure difference, Δh, is defined between the inlet and outlet of the domain to ensure an initial constant flow rate, q_0, that is:

$$q_0 = -K(h)\left(\frac{\Delta h}{\Delta z} + 1\right) \quad (21)$$

where Δz is the vertical distance between inlet and outlet.

For the transport equation, a flow with fixed concentration C_{ext} is defined at the inlet:

$$\hat{n}\cdot\left(\theta_{tw} D\frac{\partial C}{\partial x} - \vec{q}C\right) = -(\hat{n}\cdot\vec{q})C_{ext} \quad (22)$$

3.2 Initial conditions

The model assumes the following initial conditions: a homogeneous pressure head field equal to the value at the outlet boundary, zero concentration of substrate is assumed in the domain while a constant initial concentration of biomass, M_0, is assumed through the domain.

3.3 Solution procedure

The following steps are followed in the solution of the proposed model:

i. Estimation of hydraulic properties based on current presence of bacteria in the domain.
ii. Solution of Richard's equation, (1).
iii. Solution of Transport equation, (2), using velocities estimated from the pressure head field.
iv. Solution of Monod equation, (4), using substrate values calculated in step iii.
v. Steps i-iv are repeated iteratively until convergence, defined as a change smaller than $2\text{x}10^{-7}$ in the

transport solution l_2-norm between iterations, is achieved.

4. EXPERIMENTAL WORK

An experimental study aimed to investigate the bioclogging process in porous media and related changes in its hydraulic properties has been carried out (Alshiblawi, 2016). The long-term objective was to understand how flow is affected by processes of biomass grow and decay, and how these processes could be influenced to enhance or deter the development of preferential flow paths ultimately allowing control of flow in the porous media.

The bioclogging process was investigated through a series of sand column experiments with two homogeneous particle size fractions of 150 and 300 µm. The bacterium *B. indica* was used in this study due to its ability to produce a copious amount of tough and strongly adhesive exopolysaccharide material (EPS) (Dennis and Turner 1998).

Sand fractions were prepared in acrylic tubes 20 cm long with inner diameter of 2.6 cm. Sand packing in the columns was performed using a wet pluviation method whereby dry, sterile sand was poured into a bacterial suspension (Alshiblawi 2016). Each sand fraction experiment was repeated in six identical columns, three of them as control columns with dead cells (killed by autoclaving), whereas the other columns were operated with live cells.

The nutrient solution was delivered by a peristaltic pump containing 30.0 g/l of glucose in a nitrogen free media. The pump effectively applied a constant pressure head that produced an initial flow rate of 2.5 ml/min, applied for 16 minutes per day. This flow rate was selected to provide a total flow of 40 ml for each sand fraction. The initial number of cells ranged from 1.53×10^6 to 1.66×10^6 cells/gram dry sand. The hydraulic conductivity was measured three times a week using a Mariotte bottle. Additional results and further details can be found in Alshiblawi (2016).

5. VALIDATION

Experimental results from two sand columns experiments briefly summarized in section 4 are used to validate the proposed numerical model proposed in this paper.

The model is applied to a one-dimensional domain composed of 128 homogeneous bi-linear elements. Initial time step is set equal to 1 s but is allowed vary between 1 and 10 s in order to speed up convergence.

An initial homogeneous biomass concentration of 500 mg/L (void space) is used in the domain considering a production of 7.8E-11 grams of EPS per cell based on recent initial experimental results obtained at Cardiff University. Outlet pressure head is set to 1 cm (at the top of the sand column). The domain is assumed to be subjected to periods of nutrient flow (16 min per day) during which the inlet pressure is set in a way that the pressure difference ensures an initial flow rate of 2.5 ml/min (Table 1, note that the flow will vary as the hydraulic conductivity changes over time due to biomass growth), otherwise the inlet pressure head is set to 21 cm (to consider the weight of water in the sand column). A value of 0.83 has been used for Y as a theoretical maximum estimated from the assumption that *B. indica* consumes the entire amount of glucose (chemical formula $C_6H_{12}O_6$) used as substrate and converts it to EPS (chemical formula $C_{40}H_{53}O_{29}$), this gives a ratio of 20 molecules of glucose needed to produce 3 molecules of EPS.

Figure 2 shows results from sand column experiments for a sand fraction of 300 µm subjected to bacterial clogging (Alshiblawi 2016) compared with numerical results obtained with the proposed numerical model using the four relationships for relative hydraulic conductivity as a function of biomass saturation presented in section 2.4 using the parameters listed in Table 2. Similar results are shown in Figure 3 for a sand fraction of 150 µm.

It can be seen that the four different theoretical relations between relative hydraulic conductivity and biomass saturation estimate a reduction in hydraulic conductivity, the zig-zag nature in each transient is due to the decay rate factor b producing an increase in hydraulic conductivity during the periods without feeding (it is assumed that the EPS associated with a bacterium dissolves in the liquid when this dies).

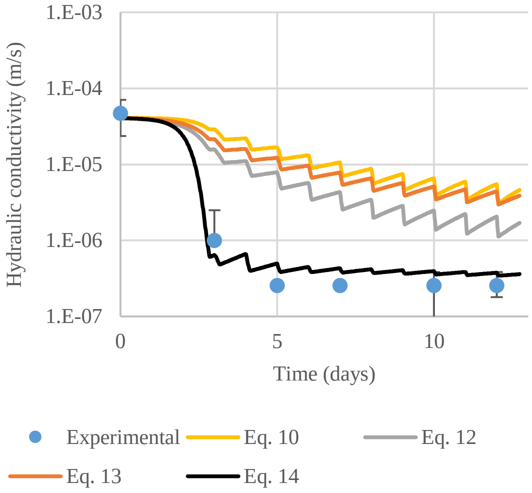

Figure 2 – Experimental observations of hydraulic conductivity in a sand fraction of 150 µm subjected to bioclogging compared with numerical results obtained with the proposed numerical model using four different relative hydraulic conductivity relationships.

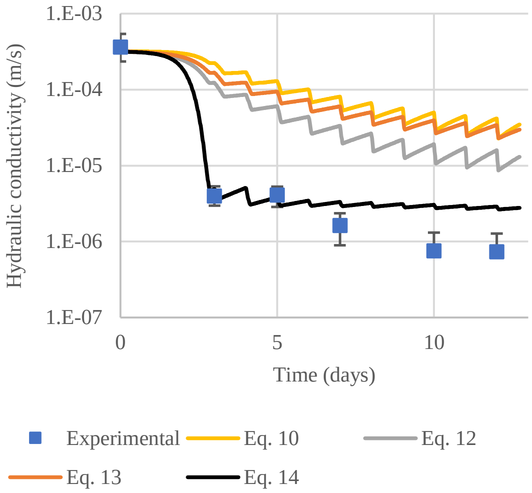

Figure 3 - Experimental observations of hydraulic conductivity in a sand fraction of 300 µm subjected to bioclogging compared with numerical results obtained with the proposed numerical model using four different relative hydraulic conductivity relationships.

The most notable difference observed in Figure 2 is the rate of decrease of the sand column hydraulic conductivity, particularly for Vandevivere (1995) model. This could be due to the different assumptions used to develop each theoretical relationship. It seems like the substantial production of EPS from *B. indica* lends itself to be represented by Vandevivere's model (14) perhaps because it takes into account the possibility of a rapid transition between biofilm attached in the solid grains to the formation of biomass plugs in the pore throats. Although for this particular case, equation (14) offers a good match with experimental observations, due to the complexity of bacterial growth dynamics involving different bacterial strains and growth conditions, it is difficult to categorically say that a particular theoretical approach is superior to others and efforts should be made to test alternative models. However, for the subsequent sensitivity analysis equation (14) is used to explore the impact of the variation of selected Monod parameters in the change of hydraulic conductivity of sands.

Table 1. Saturated hydraulic properties, porosity for two sand fractions used in the column experiments described in section 4. The pressure head difference set between domain inlet and outlet (equation (21)) to produce an initial flow rate of 2.5 ml/min is also included.

Sand fraction (μm)	K_{sat} (cm/s)	φ	Δh (cm)
300	$3.2\text{x}10^{-2}$	0.408	24.9
150	$4.1\text{x}10^{-3}$	0.42	58.3

Table 2. Values of different parameters used in the proposed numerical model. † from Ohashi and Harada (1994).

Parameter	Value	Parameter	Value
Y	0.83	ρ_b	$1\text{x}10^{2}$ †
q_m	$2\text{x}10^{-5}$	θ_r	0.04
K_s	100	n	4
b	$6\text{x}10^{-7}$	α	0.04
D	$1\text{x}10^{-5}$	η	0.5
k_c	$2.5\text{x}10^{-4}$	S_{bc}	0.1

6. SENSITIVITY ANALYSIS

The Monod growth kinetics defined by equation (4) are a function of different parameters that are typically estimated from experimental observations (Corman and Pave 1983). In this paper the values for these parameters have been obtained from the literature (Table 2) and at the moment there is ongoing work at Cardiff University to refine their values. In order to give insight about the impact on the estimations obtained with the proposed numerical model of variations in three of Monod parameters a simple one-a-at-time sensitivity analysis is performed using the theoretical relationship proposed by Vandevivere (1995) for the changes in relative hydraulic conductivity as a function of biomass saturation. Three parameters are studied: maximum substrate use rate (q_m), half velocity constant (K_s) and yield coefficient (Y). Note that although q_m and Y appear as factors in equation (4), only q_m is included in equation (2), through S, coupling the growth of biomass with the change of substrate in the domain given by the transport equation.

Figure 4 shows the impact of variation of the yield coefficient (Y) in the estimations of hydraulic conductivity. It can be seen that reducing the value of this parameter delays the reduction of hydraulic conductivity in the sand column and at the same time allows smaller values to be obtained by the end of the experiment. This is because with smaller values of Y, more substrate is needed to produce the same amount of EPS. Smaller values of hydraulic conductivity are obtained by the end of the experiment because since the biomass takes longer to grow at the inlet section, the substrate is able to penetrate the column and produce a more homogeneous growth that translates in higher average hydraulic conductivity as opposed to the base case where the majority of the growth occurs at the column inlet (results not shown for brevity).

Figure 5 shows the impact of variation of the maximum specific substrate utilization rate (q_m) in the estimations of hydraulic conductivity. It can be seen that a decrease of this parameter also delays the reduction of hydraulic conductivity in the sand column. This could be explained since q_m is present as a factor in equation (4) effectively giving the same effect as reducing parameter Y as explained before, more substrate is needed to produce the same amount of biomass. However, q_m is also part of the sink term in the transport equation (2). A reduction of q_m would allow more substrate to be available for the biomass. Figure 5 seems to indicate that the former effect is dominant in the system.

Figure 6 shows the impact of variation of the half velocity constant (K_s) in the estimations of hydraulic conductivity. This parameter defines the value of the soluble substrate concentration at a one-half the maximum specific substrate utilization rate (q_m). Effectively, if the substrate concentration, C, in equation (5) is much higher than K_s, the production of biomass given by equation (4) is independent of the substrate concentration. By increasing its value the production of biomass becomes in principle more restricted by the substrate concentration, this explains the delay in the reduction of hydraulic conductivity in the sand column observed in Figure 6, however, it can be seen that compared with the changes produced by Y and q_m, K_s has a comparatively smaller impact.

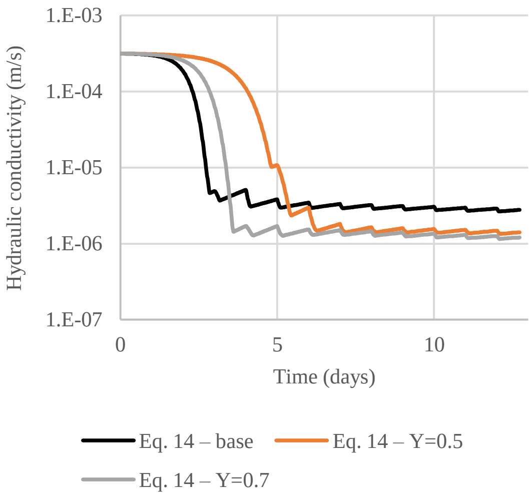

Figure 4 – Impact of variation of yield coefficient, Y, in (4) in the estimation of hydraulic conductivity changes using Vandevivere (1995) relation between relative hydraulic conductivity and biomass saturation.

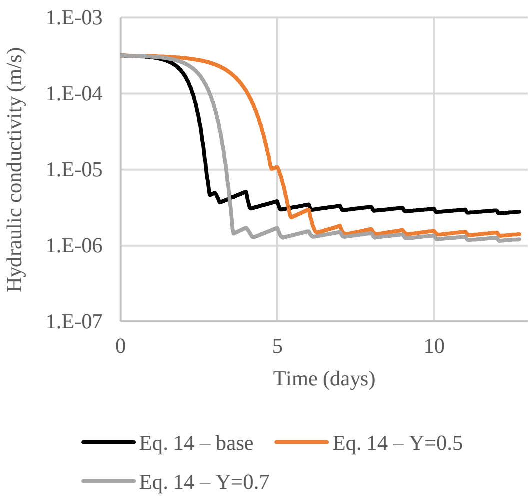

Figure 5 – Impact of variation of maximum specific substrate utilization coefficient in (5) in the estimation of hydraulic conductivity changes using Vandevivere (1995) relation between relative hydraulic conductivity and biomass saturation.

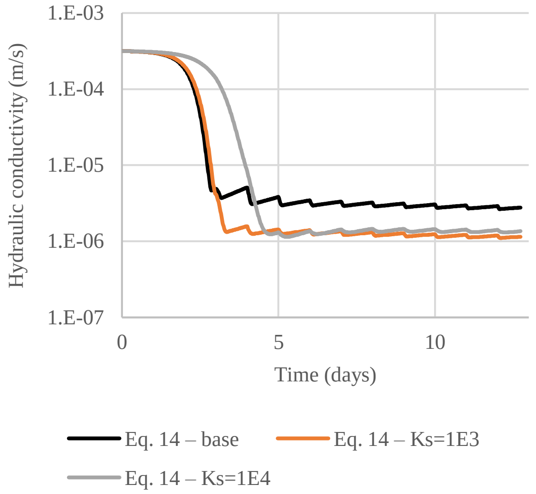

Figure 6 – Impact of variation of half velocity constant coefficient in (5) in the estimation of hydraulic conductivity changes using Vandevivere (1995) relation between relative hydraulic conductivity and biomass saturation.

7. CONCLUSION

This paper has presented the development of a numerical model based on the finite element method to describe the reduction of hydraulic conductivity in soils due to the grow dynamics of bacteria. Four theoretical relationships found in the literature that estimates the changes in relative hydraulic conductivity as a function of biomass saturation in the pore space are compared.

The numerical model is validated using experimental data obtain from bioclogging sand column experiments using B. indica performed by others (Alshiblawi 2016). Good agreement is found with at least one theoretical relationship for the experimental setup considered. However, due to the complexity of bacterial growth dynamics possibly involving different bacterial strains and growth conditions, it is difficult to categorically say that a particular theoretical approach is superior to others and efforts should be made to test alternative models.

A simple one-at-a-time sensitivity analysis was performed to test the impact of three selected parameters found in the Monod growth dynamics equation: maximum substrate use rate, half velocity constant and yield coefficient. It was shown that reductions on the maximum substrate use rate and yield coefficient have the effect of delaying the decrease of hydraulic conductivity in the sand column due higher amounts of substrate required to produce a unit of EPS. The impact of varying the half velocity constant was found to be comparatively smaller.

8. ACKNOWLEDGEMENTS

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