Modeling Bacterial Transport and Removal in a Constructed Wetland System

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Abstract: In this study we evaluate transport, retention and subsistence of Escherichia coli (E. coli), a common fecal indicator bacteria, in a model (2x1m) of a constructed wetland. Transport occurs in the unsaturated and saturated zone. Inactivation is accounted for as a kinetic first-order process. Retention is assumed to be dominated by solid-air-water interface straining and is modeled with a kinetic equation. The relative effluent concentration (C/C_0) equals 1.8 $\log_{10}$ at the system outlet. A forward sensitivity analysis shows that results are highly dependent on water infiltration rates and assumptions on E. coli retention rates. The governing, coupled equations of unsaturated media flow and bacterial transport were solved using COMSOL Multiphysics.

Keywords: Richard's equation, advection-dispersion equation, E. coli, solid-air-water retention, inactivation.

1. Introduction

Constructed wetlands are increasingly being used to handle anthropogenic waster, e.g. pathogen removal from wastewater, storm water and sewage (Langergraber and Simunek, 2005). A vertical flow bed system enables efficient sewage water treatment for subsequent discharge into groundwater (Brix and Arias, 2005). Such a vertical flow reed bed system is modeled in this study. For quantitative assessment of bacterial transport, predictive transport models could provide important tools (WHO, 2008). Improved knowledge on microbial transport could, e.g., contribute to guidelines on treatment requirements regarding single dwellings in rural areas (Brix and Arias, 2005).

1.1. Aim

The aim of this study is to provide an illustrative example of E. coli removal in simple constructed wetland system. The impact of infiltration rates and removal rate coefficients will be evaluated. Results of kinetic retention are compared to the case of instantaneous deposition (Freundlich isotherm).

2. Theory and governing equations

2.1. Flow

Water flow in unsaturated media is generally modeled using Richard's equation (Schijven and Simunek, 2002):

$$\frac{\partial \theta_w(\psi)}{\partial t} = \frac{\partial}{\partial x_i}\left[K(\psi)\left(K_{ij}\frac{\partial \psi}{\partial z} + K_{iz}\right)\right]$$

where ψ is pressure head [L]; x_i are spatial coordinates [L], where $x_i = z$ is positive upwards; t is time [T]; $\theta_w(\psi)$ is volumetric water content [L^3L^{-3}]; $K(\psi)$ is hydraulic conductivity [LT^{-1}]; and K_{ij} are components of an anisotropy tensor [-]. In this paper, expressions for $\theta_w(\psi)$ and $K(\psi)$, as developed by van Genuchten (1980) are used. Further, flow is steady state; hence, the right hands side of the equation is equal to zero.

2.2. Transport

Mass transport in aqueous systems can be described by the Fickian based advection-dispersion equation, derived from mass balance principles. The bacterial flux is proportional to the concentration gradient (Schwartz and Zhang, 2003):

$$\frac{\partial C_w}{\partial t} = \nabla(D\nabla C_w) - \nabla(vC_w)$$

Where D [L^2T^{-1}] is the hydrodynamic dispersion coefficient, v [LT^{-1}] is the average pore water velocity, and C_w [NL^{-3}] is bacterial concentration in the water.

2.3. Removal processes

Removal occurs due to persistence and deposition processes. The latter relate to the exchange of colloids between the gas, liquid and solid phases; however, it is debated which the dominant retention processes in unsaturated media are. Results from a literature review (Engström et al., 2010) showed that deposition is likely to be dominated by solid-air water retention (for solutions of low ionic strength and neutral pH). Moreover, E. coli persistence in saturated media has been found to mainly depend on inactivation (Foppen and Schijven, 2006), likely to apply to the unsaturated zone as well. The advection-dispersion equation above can be adjusted to account for these processes, as well as partial saturation (constant with time):

$$\theta_w \frac{\partial C_w}{\partial t} + \theta_w \left(\frac{\partial C_{ina}}{\partial t} + \frac{\partial C_{ret}}{\partial t} \right) =$$
$$\theta_w \nabla (D \nabla C_w) - \theta_w \nabla (v C_w)$$

where C_{ret} is concentration of retained bacteria [NL^{-3}] and C_{ina} is the concentration of inactivated bacteria [NL^{-3}].

2.3.1. Bacterial inactivation

Inactivation is generally modeled with a first-order kinetic equation (see e.g. Foppen and Schijven, 2006):

$$\frac{\partial C_{ina}}{\partial t} = k_{ina} C_w$$

where k_{ina} [T^{-1}] is the inactivation rate.

2.3.2. Bacterial retention

It is not yet established how to model solid-air water retention; both kinetic and instantaneous (equilibrium) mechanisms have been proposed. On common method is a kinetic, first-order retention (e.g. Bradford et al., 2004):

$$\frac{\partial C_{ret}}{\partial t} = k_{ret} C_w$$

where k_{ret} [T^{-1}] is the retention rate. Alternatively, if instantaneous retention is assumed, a Freundlich isotherm can be used (e.g. Matthess et al., 1988):

$$C_{ret} = K_d C_w^m$$

where K_d [L^{3}M^{-1}] and m are coefficients applying to a certain combination of filter media, colloids and temperature. Other isotherms, such as Langmuir (Steenhuis et al., 2006) and linear (Tufenkji, 2007) have also been employed to describe microbial transport.

3. Numerical model

In this study, COMSOL Earth science module was used with application modes Richard's Equation (steady state) and Variably Saturated Solute Transport (transient conditions).

3.1. Geometry and boundary conditions

The geometry modeled is depicted in Figure **1;** the top region contained sand and the bottom contains gravel. Infiltration was spread evenly over the top surface, at a steady rate (which could implemented e.g. with a network of pipes and large stones). Outflow occurred from the

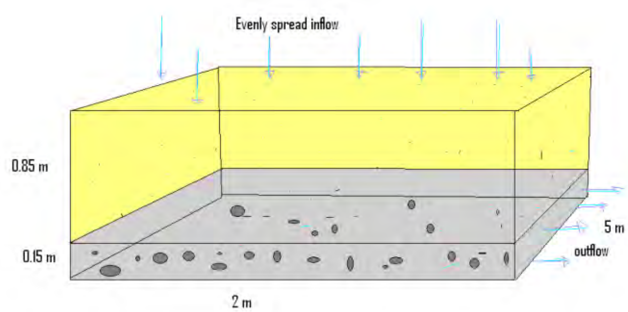

Figure 1. Conceptual sketch of a constructed wetland of vertical flow (not to scale). The upper region (yellow) contains fine grained sand and the bottom layer (grey) contains gravel. Inflow only occurs from the top and outflow only at the bottom right; the remaining boundaries are assumed to be impermeable.

bottom right, in the gravel region (to implement this in reality, tile drains can be used). The filter depth was 1 m, in agreement with Danish guidelines, and the top area was 2*5 m, i.e., two person equivalents, according to Austrian guidelines (Brix and Arias, 2005; Langergraber and Simunek, 2005). As the domain was homogenous in width, a two dimensional geometry (side view) was created. Further, it was assumed that: temperature average was 10° C; pH was approximately neutral; and ionic strength was low (<50 mM). This corresponds with previous findings that artificial sewage has an ionic strength of 3 mM (Powelson and Mills, 2001). Boundary conditions can be found in Table **1** and Table **2**. Initial pressure head was set to -0.05 [m] in the unsaturated subdomain, in accordance with the experimental value used by Mosaddeghi et al. (2009), and varied from 0 to 0.15 in the saturated subdomain (see scalar expressions in **Table 4**). Initial concentration was set to 0 [kg/m^3].

Table 1. Richard's equation boundary conditions

Boundary	**Value**
Top	Inward flux (see constant: qin)
Bottom	Zero flux/symmetry
East (top)	Zero flux/symmetry
East (outlet)	Pressure head (see scalar expression: hh)
West	Zero flux/symmetry

Table 2. Solute transport boundary conditions

Boundary	**Value**
Top	Concentration (c0) after 3600 s
Bottom	Zero flux/symmetry
East (top)	Zero flux/symmetry
East (outlet)	Advective flux
West	Zero flux/symmetry

3.1.1. Subdomain settings and constants used

Primarily, Richard's Equation was solved for steady state flow, and subsequently, transient transport and removal as solved using the first solution as the initial condition. Influx of E. coli was initiated after 1 h and continued for 6 days and 23 h (hence total modeling time was 1 week). The concentration was calculated in kg/m^3: an average weight of E. coli was assumed and multiplied with the initial number of E. coli in the effluent (see constants in **Table 3**). The inactivation rate was assumed to be the same in the saturated and unsaturated zone, whereas the retention coefficient varied between the two regions (see scalar expressions in **Table 4**).

The solute transport subdomain variables were coupled with the flow variables in Richard's equation. Removal was implemented by defining reaction solid to – k_rem *c (see **Table 4**), where k_rem represented the sum of inactivation and retention (per unit time). The infiltration rate of 0.4 cm/h, corresponded to the rate used by Mosaddeghi et al. (2009). It was near the Austrian standards on wetlands: a daily loading rate of 40 liters over 1 m^2 during 6 h, i.e., 0.2 cm/h (Langergraber and Simunek, 2005). Scale dependent dispersion has been accounted for, as it has been reported that dispersion increase systematically with observation scale (Gelhar et al., 1992). The value of ε can be compared with Bunsri et al. (2008) who found that the max longitudinal dispersivity was 1.13 cm in 20 cm of sand, corresponding to ε = 0.0565.

The assigned E. coli influx concentration (1.2e6 CFU/100 ml), found in septic tank effluent (Pang et al., 2004), was about half of the value reported for liquid swine manure (1e6.38 CFU/100 ml) (Unc and Goss, 2003), which is reasonable.

Regarding attenuation in sand, Mosaddeghi et al. (2009) reported that the total E. coli removal rate was 5.74/m (corresponding to 1.72/day), at 86% saturation. This value accounted for retention as well as inactivation processes; since the average E. coli inactivation rate has been found to be 0.15/day (average at 10° C) (Foppen and Schijven, 2006), retention in sand was set to 1.57/day.

Total removal in saturated gravel has been reported to be 0.14/day for sewage bacteria (Harvey and Garabedian, 1991). This value is very close to the assumed E. coli inactivation rate (0.15/day), which indicates that retention is insignificant in this region. Accordingly, it has often been reported that removal in saturated, coarse grained filter media is considerably lower than in unsaturated, fine grained filter media (see e.g. Jiang et al., 2007). Consistently, Foppen and Schijven (2006) reported that decay dominates total removal in coarse-grained material. Hence, in the lower subdomain, removal was assumed to occur due to inactivation only.

Table 3. Constants used in the modeling

Constant	**Value [unit]**	**Description**	**Reference**
Contaminant source			
qin	0.4 [cm/h]	Infiltration rate	Mosaddeghi et al., 2009
tstart	3600 [s]		Start time of E. coli infiltration
Soil characteristics			
eps	0.06	Longitudinal dispersivity/distance ratio	Pang et al., 2004
disp_Lot	eps*0.85[m]	Longitudinal dispersivity (top)	
dispTrt	disp_Lot*0.1	Transverse dispersivity (top)	
disp_Lob	eps *1[m]	Longitudinal dispersivity (bottom)	
dispTrb	disp_Lob*0.1	Transverse dispersivity (bottom)	
Ks_g	420 [cm/h]	Saturated hydraulic conductivity (gravel)	Pang, 2009 (estimated value)
Ks_s	26.6 [cm/h]	-“- (sand)	Kim et al., 2008
thetas_s	0.375	Saturated liquid fraction (sand)	Kim et al., 2008
thetar_s	0.053	Residual liquid fraction (sand)	Kim et al., 2008
alpha_s	2.7 [1/m]	van Genuchten parameter (sand)	Ghanbarian-Alavijeh et al., 2010
n_s	2.38	-“-	
m_s	0.58	-“-	Ghanbarian-Alavijeh et al., 2010 (sand)
l_s	0.5	-“-	
E. coli indicators			
Eckg	9.5e-16 [kg]	Wet weight of 1 E. coli	Milo, 2010
k_ina	0.15 [1/day]	E. coli inactivation rate sand and gravel	Foppen and Schijven, 2006
k_ret_s	1.57 [1/day]	E. coli retention rate unsaturated sand	Mosaddeghi et al., 2009 Harvey and Garabedian, 1991
k_ret_g	0 [1/day]	E. coli retention rate saturated gravel	Harvey and Garabedian, 1991 Foppen and Schijven, 2006
c0	1.2e6 CFU/ 100 ml	E. coli concentration septic tank effluent	Pang et al., 2004
Kd	0.003 [mL/g]	Freundlich parameter (sand)	Jiang et al., 2007
m	1.37	-“-	Jiang et al., 2007
R	1.02	Retardation factor (sand)	Jiang et al., 2007

Table 4. Scalar expressions

Name	**Expression**	**Description**
ctime	t>tstart	Time of infiltration
Sflag	Se_esvr>0.99	Flag saturated zone
k_rem	theta_esvr*(k_ina + (1-Sflag)* k_ret_sand+ Sflag*k_ret_gravel)	Total E. coli removal rate
hh	0.15[m]-y	Initial pressure head (gravel)

4. Results and discussion

The average saturation was 69 % in the top subdomain and 100% in the bottom subdomain. As expected, velocity was much higher in the top region: the average velocity was 0.4 cm/h and 2.5 cm/h in the unsaturated sand and saturated gravel, respectively (see **Figure 2** for a plot of the velocity field).

4.1. Removal rates assuming kinetic retention

After 1 week, effluent over influent concentration (C_{eff}/C_0), was equal to 1.8$\log_{10}$ (se **Figure 2**), assuming kinetic retention rates. In **Figure 3** relative concentrations at different depths are plotted over time. Removal mainly took place in the unsaturated zone, which was expected considering the higher retention rate and lower flow velocity in this subdomain. After 1 week, the effluent concentration (at the outlet boundary) stabilized at 2.1e4 CFU/100 ml (see **Figure 4**).

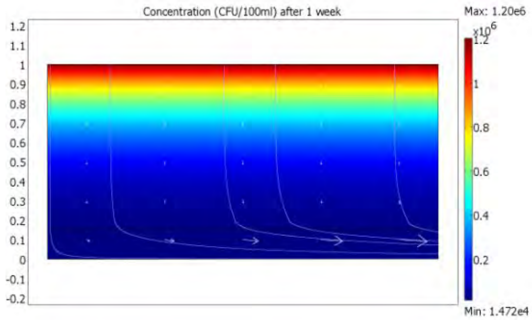

Figure 2. Concentration (in CFU/ml) of E. coli (surface) and velocity field (arrows and streamlines) after 1 week (kinetic retention). Influent concentration was 1.2e6 CFU/100 ml. The average effluent concentration at the outlet was 2.1e4 CFU/100 ml; hence, the $\log_{10}$ removal was 1.8.

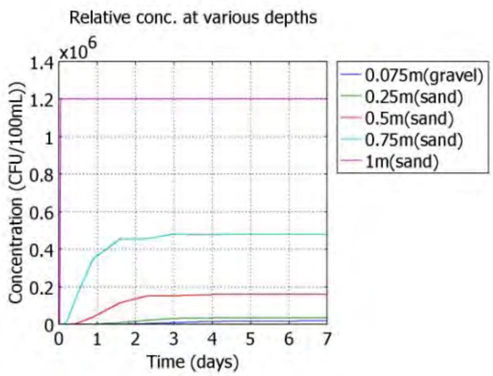

Figure 3. Breakthrough curves (C_{eff}/C_0) at coordinates (x,y) = (1,1) purple; (1,0.75) turquoise; (1,0.5) red; (1,0.25) green; and (1,0.075) blue. It is clear that removal mainly occurs in the unsaturated zone.

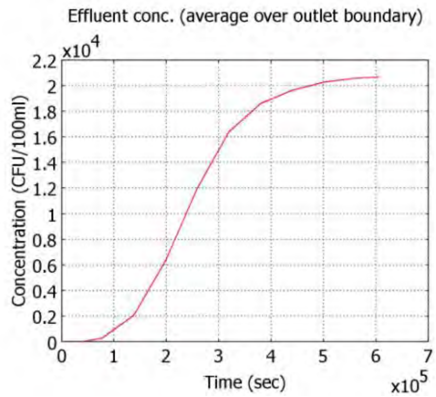

Figure 4. Average concentration at the outlet (0-1 week). After one week concentration stabilized at C_{eff} = 2.1e4 CFU/100ml.

4.2. Forward sensitivity analysis

The effect of infiltration rate on relative effluent concentration is shown in **Table 5**. In this forward sensitivity analysis, removal was considered a kinetic process and the coefficients were the same as in the previous section. Clearly, inward flux has large impact on removal: e.g., for an infiltration rate of 0.04 cm/h, it would take approximately 200 days for the bacteria to reach the outlet (assuming they travel with the water). After that time, it is likely that most bacteria would have died. The impact of kinetic retention rate in unsaturated sand can be seen in **Table 6** (the infiltration rate is set at 0.4 cm/h). For very high retention rates (7.85/day) there is no E. coli left in the effluent.

Table 5. Impact of infiltration rate on relative effluent concentration (C_0 = 1.2e6 CFU/100 ml) after 1 week.

Infiltration rate	**Resulting relative removal (C_{eff}/C_0)**
0.04 [cm/h]	0 E. coli in effluent (C_{eff} = 0)
0.4 [cm/h] (used in previous model runs)	1.8 $\log_{10}$ (C_{eff} = 2.1e4 CFU/100 ml)
4 [cm/h]	0.6 $\log_{10}$ (C_{eff} = 7.7e5 CFU/100 ml)

Table 6. Impact of retention coefficient (unsaturated sand) on relative effluent concentration (C_0 = 1.2e6 CFU/100 ml) after 1 week.

Value of retention rate in sand: k_ret_s	**Resulting C_{eff}/C_0**
0.5*1.57 =0.79 [1/day]	1 log_{10} removal (C_{eff} = 1.2e5 CFU/100 ml)
1.57 [1/day] (used in previous model runs)	1.8 log_{10} removal (C_{eff} = 2.1e4 CFU/100 ml)
5*1.57 =7.85 [1/day]	100% removal (C_{eff} = 0 CFU/100 ml)

4.3. Kinetic vs. equilibrium retention

When using an equilibrium model to describe retention in the unsaturated sand (Freundlich isotherm), and laboratory coefficients fitted by Jiang et al. (2007), C_{eff} was found to be 7.6e5 CFU/100 ml. Thus, the removal was only 0.2 log_{10}. However, inference from these results are limited by a low degree of fit of experimental breakthrough curves to the Freundlich model: 0.58 (Jiang et al., 2007). Additionally, no other studies on E. coli transport in the unsaturated zone that apply Freundlich isotherms have been found; hence, it is difficult to verify the relevance of this result.

5. Discussion on parameter values and results

Retention coefficients of E. coli varies largely in the literature (Engström et al., 2010). Moreover, values are generally much higher in the laboratory than in the field; in a literature study of microbial removal, Pang (2009) found that removal rates were 1-3 orders of magnitude lower in the field. Therefore, laboratory values should be considered carefully; on the other hand, field data are hard to obtain. One such field study was implemented Mosaddeghi et al. (2009), who evaluated E. coli removal in lysimeters. They found that the total removal rate was 1.72/day, which is the value used in this study; however, the filter media was finer (sand containing silt and clay) than in the present study, which generally increases E. coli retention (see e.g. Jiang et al., 2007). On the other hand, average saturation was higher (86%, as compared to 69% in the current study), which generally decreases retention (e.g. Won et al., 2007). Moreover, the value used in this study is consistent with laboratory findings of Powelson and Mills (2001): a removal rate of 1.73 /day (26 % saturation in sand of size 0.4-0.7 mm). However, the fact that this was a laboratory result indicates that removal rate in the field is actually higher (see the impact of higher retention rates in section 4.2 above). Nevertheless, the result in the present study is consistent with findings that removal rates of microbes in superficial soil (normally considered unsaturated) is a few log_{10}/m for most soil types (Pang, 2009). Accordingly, in the present study, removal was 1.8 log_{10} for 0.85 m transport in the unsaturated zone, i.e., removal was approximately 2.1 log_{10}/m (4.8 natural log/m).

An invariable retention rate was applied in this study; however, E. coli retention rates have frequently been reported to relate to saturation (see e.g. Chen et al., 2010). On the other hand, findings on E. coli retention in silica sand indicate that this relationship is *linear* in a range of approximately 20% - 95% saturation (Chen, 2008). This suggests that in a region of varying saturation a retention rate that corresponds to average saturation in the region can be applied. In this study, saturation was in the range of 46% - 95% in a major part of the unsaturated region (82%); therefore, a constant retention rate was assumed.

The effluent concentration found in this study (2.1e4 CFU/100 ml) is two orders of magnitude larger than guidelines for fresh bathing in New Zeeland of <126 CFU/100ml (Pang et al., 2004). This result indicates that constructed wetlands should be designed with deeper unsaturated zones, i.e., at least one more meter than the 0.85 m considered in this study (assuming a removal of 2.1 log_{10}/m); lower infiltration rates (<0.4 cm/h); or finer filter media (containing a larger share of silt) in order to filter septic tank effluent in a way that complies with bathing guidelines.

6. Summary and future studies

Kinetic first-order removal rate was used to calculate E. coli removal efficiency of unsaturated sand and saturated gravel. Removal mainly occurred in the unsaturated sand and total removal was found to be 1.8 $\log_{10}$ in a 1 m deep system. However, retention depends highly on infiltration rate as well as assumptions on removal rates.

Constructed wetlands provide promising low cost bacterial filters; however, their removal capacity needs better understanding for improved guidelines on construction and use. The effect of heterogeneous filter media, containing macropores, e.g., corresponding to plant roots, is likely to be significant; however, the related processes are not yet fully understood and development of related mobile-immobile region macro-scale models needs further research. Further, the impact of biological factors, such as pore biofilm formation and clogging of flow paths, are yet insufficiently investigated. Additionally, improved models would include the impact of passive aeration through vertical pipes, commonly practiced in constructed wetland systems (Brix and Arias, 2005).

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