A preliminary modelling approach for *Escherichia coli* removal in stormwater biofilters

Approche de modélisation préliminaire pour l'élimination de microbes fécaux des biofiltres d'eaux pluviales

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RÉSUMÉ

Pour réduire les risques causés par les micro-organismes fécaux contenus dans les eaux pluviales, les biofiltres ont été mis au point pour le traitement de microbes. La modélisation est un outil efficace pour mieux comprendre les mécanismes d'élimination de microbes fécaux dans les biofiltres et pour optimiser le fonctionnement des biofiltres sur la base de prévisions de leur élimination à long terme. Dans cette étude, un modèle complet est développé représentant le transport microbien et le sort des microbes à travers les biofiltres, et comprenant les principaux processus et facteurs opérationnels. Le modèle a été calibré avec les données mesurées d'élimination d'*Escherichia coli* (*E. coli*) obtenues lors d'expériences de laboratoire d'une durée de 8 mois. Les hauts taux d'efficacités Nash Sutcliffe (> 0,60) indiquent que le modèle calibré représente bien les données mesurées. En outre, les valeurs des paramètres optimisés sont comparables aux valeurs rapportées dans la littérature et obtenus à partir de travaux de laboratoire.

ABSTRACT

To reduce the risks imposed by faecal microorganisms contained in stormwater, biofilters have been developed for the microbial treatment. To better understand the mechanisms of faecal microbial removal in biofilters, and to optimize the operation of biofilters based on the predictions of long-term removal effects, modelling is an effective tool. In this study, a comprehensive model, which could represent the microbial transport and fate throughout the biofilters and includes the major processes and operational factors, is developed. The model was calibrated with the measured data of *Escherichia coli* (*E.coli*) removal that obtained in 8-month laboratory experiments. Generally high Nash Sutcliffe Efficiencies (>0.60) indicate that the calibrated model is in good agreement with measured data. Also, the optimized parameter values are comparable with values reported in the literature and obtained from lab work.

KEYWORDS

Escherichia coli; faecal microorganism; modelling, Stormwater biofilter

INTRODUCTION

Microorganisms/microbes contained in stormwater runoff have been identified as one of the major pollutants (Ferguson *et al.*, 2003, Ortega *et al.*, 2009), and they are also the main pollutant that impedes stormwater harvesting (Fletcher *et al.*, 2008). In particular, faecal microorganisms, which are sourced from the faeces of animals and humans, are the cause of waterborne diseases and present a higher degree of risk compared to non-faecal microorganisms (NHMRC, 2004, Makepeace *et al.*, 1995).

To reduce to harm caused by faecal microorganisms and other pollutants, stormwater biofilters have been widely applied for stormwater treatment (FAWB, 2009) and proved to be promising for faecal microorganisms removal (Chandrasena *et al.*, 2014a, Chandrasena *et al.*, 2014b). Previous studies indicate that the major processes for faecal microbial removal in biofilters include adsorption, desorption and die-off, and these processes are governed by different operational conditions like temperature.

To better understand the mechanisms of faecal microbial removal in biofilters and to optimize the operation of biofilters based on the predictions of long-term removal, modelling approach is an important tool. Only a few models have been developed for microbial removal in stormwater biofilters, and they all have some inadequacies: Chandrasena *et al.* (2013) developed a model to simulate the outflow concentration continuously, but this model is incapable of revealing the transport of microorganisms throughout the biofilters; in addition, the impact of operational factors are not included. Zhang *et al.* (2010) utilized one-dimensional advection-dispersion equation to model of transport of *E. coli* in biofilter media during 6 hours of continuously simulated run-off conditions, however, this model only considered the processes of adsorption and die-off, and does not reflect any operational factors. Moreover, the simulations were only limited to single wet event. Zhang et al. (2012) used the first order kinetic to model the die-off process in stormwater biofilter media during the dry period, and different temperatures were tested as an operational factor. However, this model did not incorporate any wet weather event.

On the other hand, if it is not confined into biofilters, some models developed for other infiltration applications (e.g. aquifer recharge). The widely used approach for microbial transport in porous media modelling is the adsorption-dispersion equation (Foppen *et al.*, 2007, Tufenkji, 2007). This equation models the movement of microorganisms through advection, dispersion and retention-related processes like adsorption and desorption (Bradford *et al.*, 2006, Gargiulo *et al.*, 2008).

To sum up, there is no available model so far for microbial removal in biofilters that could meet the following requirements: (1) represent the transport and fate of faecal microorganisms throughout biofilters; (2) include the governing processes of microbial removal; (3) reflect the influences of the key factors for microbial removal; (4) represent both wet weather events and dry periods. These requirements are significant for the long-term prediction of faecal microbial removal and the optimization of biofilters. Therefore, the main objective of this study was to develop and test a predictive model that meets all these requirements for the removal of the faecal indicator microorganism, Escherichia coli (E. coli), in the stormwater biofilters.

1 MATERIALS AND METHODS

1.1 Model description

The schematic of a typical stormwater biofilter for modelling is shown in Figure 1. This biofilter was divided into three zones: ponding zone (PZ), unsaturated zone (USZ), and saturated zone/submerged zone (SZ). h_p, h_{over} and A_p represent the water depth in PZ, the threshold of water level when overflow occurs, and surface area of PZ respectively; S, n_{usz}, h_{usz} represent the saturation, porosity and depth of USZ respectively; n_{sz} and h_{sz} represent the porosity and depth of SZ respectively; A is the surface area of the biofilter.

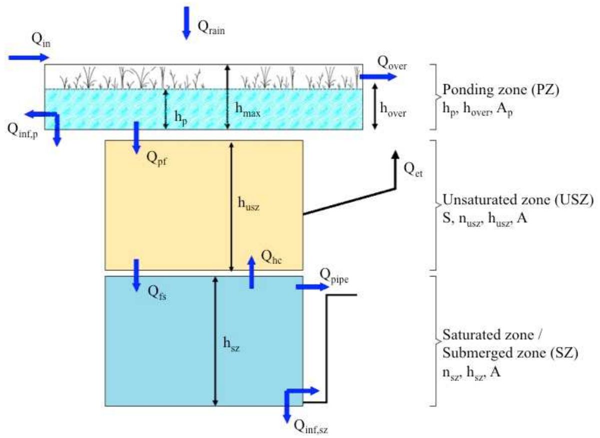

Figure 1 Schematic of a typical stormwater biofilter for modelling

The model simulates advection and dispersion of faecal microorganisms, as well as the three governing processes of faecal microbial removal in biofilters: adsorption, desorption and die-off. Especially, the die-off process is governed by temperature. These processes are modelled using a so-called 'three tank' approach (also known as a bucket approach). The three zones (i.e. PZ, USZ, SZ) by represented three tanks respectively. The major modelling equations are shown in Table 1.

Table 1 Major modelling equations

Major modelling equations	Eq. No.
The die-off rate:	
$\mu = \mu_0 \theta^{T-20°C}$	(1)
Unsaturated zone:	
$\frac{\partial(S \cdot n_{usz} c_{usz})}{\partial t} + \underbrace{n_{usz} S \cdot k_{att} c_{usz}}_{adsorption} - \underbrace{\rho k_{det} M_1}_{desorption} = \underbrace{\frac{\partial}{\partial z}\left(S \cdot n_{usz} D_1 \frac{\partial c_{usz}}{\partial z}\right)}_{dispersion} - \underbrace{\frac{\partial(q_1 c_{usz})}{\partial z}}_{advection} - \underbrace{S \cdot n_{usz} \mu c_{usz}}_{die-off}$	(2)
Adsorption, desorption and die-off of adsorbed microbes in the soil phase:	
$\frac{\partial M}{\partial t} = \frac{n_{usz} S}{\rho} k_{att} c_{usz} - k_{det} M - \mu M$	(3)
Saturated zone:	
Microbial mass balance in the water phase in SZ:	
$\frac{\partial(n_{sz} c_{sz})}{\partial t} + \left(\underbrace{n_{sz} k_{att} c_{sz}}_{adsorption} - \underbrace{\rho k_{det} M'}_{desorption}\right) = \underbrace{\frac{\partial}{\partial z}\left(n_{sz} D_2 \frac{\partial c_{sz}}{\partial z}\right)}_{dispersion} - \underbrace{\frac{\partial(q_2 c_{sz})}{\partial z}}_{advection} - \underbrace{n_{sz} \mu c_{sz}}_{die-off}$	(4)
Adsorption, desorption and die-off of adsorbed microbes in the soil phase:	
$\frac{\partial M'}{\partial t} = \frac{n_{sz}}{\rho} k_{att} c_{sz} - k_{det} M' - \mu M'$	(5)

Where S is saturation; n_{usz} and n_{sz} are porosities of USZ and SZ respectively (-); c_{usz} and c_{sz} are *E. coli* concentrations in liquid phase of USZ and SZ respectively (MPN/100ml); k_{att} and k_{det} are adsorption and desorption rate respectively (s^{-1}); M_1 and M'_1 are *E. coli* concentrations in the solid phase due to adsorption/desorption in USZ and SZ respectively (MPN/100ml); D_1 and D_2 are the dispersion coefficients in USZ and SZ respectively (m^2/s); q_1 and q_2 are the specific flows/fluxes in USZ and SZ respectively (m/s); μ is the die-off rate (s^{-1}); μ_0 is the first order die-off rate coefficient at given reference conditions of the system of interest (e.g. standard temperature) (s^{-1}), θ is the correction coefficient for temperature in die-off (-).

1.2 Laboratory measurements used for model testing

The model was tested with the data obtained from 8-month laboratory experiments. The biofilters (5 replicates) used washed sand as filter media, and no plant was cultivated on the top of the biofilters. The depth of PZ, USZ and SZ are 280 mm, 400 mm and 440 mm separately.

Semi-natural storm water was used to dose the columns. The stormwater runoff volume and the lengths of dry periods were respectively simulated by the dosing scheme of the dosing quantity and dosing frequency.

There were 16 sampling events. For each event, the outflow was separated into two segments (1) "old water" - the water remains in the SZ after previous dry days, which could be generally clean due to the sufficient time for die-off; (2) "new water" - the treated newly-dosed water. Both old and new water samples were analyzed for the concentrations of an indicator of faecal microbes, *E. coli*.

1.3 Model calibration

In this model, four parameters need to be calibrated: katt, kdet, θ, and μ0. A modified Monte-Carlo based method (Vezzaro *et al.*, 2013) was used for calibrated. Nash Sutcliffe Efficiency criterion (E) is utilized for parameter selection/model evaluation (Nash and Sutcliffe, 1970):

$$E = 1 - \frac{\sum_{t=1}^{T}(U_0^t - U_m^t)^2}{\sum_{t=1}^{T}(U_0^t - \bar{U}_0)^2}$$

Where $\bar{U}_0$ is the mean of observed value; U_m is modeled value; U^t_0 is observed value at time t.

The four were calibrated altogether, with the data obtained from old and new water samples collected in the 16 sampling events (174 data in total).

2 RESULTS AND CONCLUSIONS

All the modelled and measured data (i.e. *E. coli* concentrations) were logged for the calibration process. That is because, the *E. coli* concentrations vary significantly in different events (e.g. 60 ~ 18000); with the logged concentrations, the error term/residuals could be normalized and so that the peaks would not be overemphasized for the calculation of Nash-Sutcliffe Coefficient (E).

For the best-fit parameter set, E = 0.60 was achieved. Figure 2 shows the model performance using the best-fit parameter set. It is evident that the model performed well as the majority of the measured concentrations are scattered around the 1:1 line.

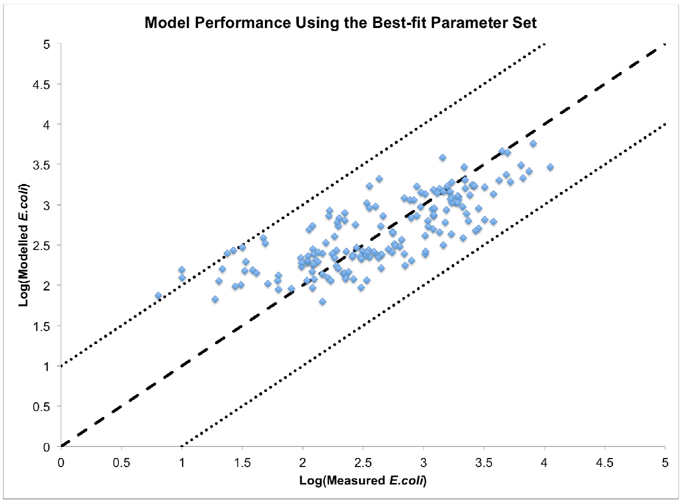

Figure 2 Model performance using the best-fit parameter set (Dashed lines indicate the 1:1 line between modelled and measured *E. coli* concentrations, while dotted lines indicate error bars (+/- one order of magnitude))

The calibrated parameter values were also compared with those measured in the laboratory experiments and reported in the literature (Table 2). The results indicate that, for the best-fit parameter set, the modelled data and measured data fit very well. In addition, the ranges of parameter values are generally located in the ranges obtained from literatures and experiments.

Table 2 Calibrated values of key parameters

	k_{att} (h^{-1})	k_{det} (h^{-1})	θ (-)	μ_0 (day^{-1})
Best-fit (modelled)	2.15	0.094	1.226	0.54
Calibrated range (modelled)	1.33 ~ 3.95	0.00007 ~ 0.960	1.041 ~ 1.791	-0.03 ~ 2
Literature/Measured	0.20 ~ 5.862	0.00006 ~ 2.028	1.105 ~ 1.133	0.22 ~ 1.23

CONCLUSIONS AND FUTURE WORK

The model developed in this study of *E. coli* removal performance by stormwater biofilters showed good agreement with the measured performance. Hence, it can be concluded that faecal microbial removal in the stormwater biofilters can be adequately simulated using the selected processes (adsorption, desorption and die-off) and operational factor (temperature). However, this model still needs to be calibrated and tested against other types of biofilters to represent the influence of filter media types and plants.

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