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Stormwater biofilter treatment model for faecal microorganisms

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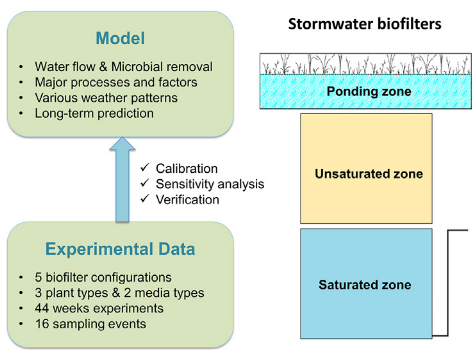
HIGHLIGHTS

- Key processes and factors for microbial removal in biofilters were modelled.
- The prediction fitted well with the observation on five biofilter configurations.
- Microbial behavior under various operational conditions could be well simulated.
- Sensitivity analysis and validation were conducted for each biofilter configuration.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a new model to simulate long-term microbial removal in stormwater biofilters. The water flow module uses a 'three-bucket' approach to describe the flow processes in biofilters, while the microbial quality module employs the one-dimensional advection-dispersion equation to represent microbial transport and fate under different design and operational conditions. Three governing processes for microbial removal, adsorption, desorption and die-off, are included; temperature is also incorporated as a key factor for die-off. The model was tested using long term monitoring data collected from laboratory columns in which five different biofilter configurations were studied over a period of 44 weeks. A multi-objective calibration with the balance of instantaneous ponding levels and event outflow volumes was implemented on the water flow module, and the Nash-Sutcliffe Efficiency (E) values ranged from 0.82 to 0.95. The microbial quality module was tested using the effluent *Escherichia coli* concentration data, and the E values obtained for different configurations were between 0.46 and 0.68. The optimized parameter values agreed with those presented in literature. However, sensitivity analyses suggested that the model's prediction was not sensitive to all parameters, the explanation for which was hypothesized to be data paucity rather than model structural uncertainties. Model validation was also conducted by splitting the data into calibration and validation datasets. The results further reinforced the needed for more data for model calibration.

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1. Introduction

Faecal microorganisms contained in stormwater runoff have been identified as one of the major pollutants impacting and degrading waterways around the globe (Burton and Pitt, 2002; Ferguson et al.,

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2003). They are also the main pollutant that impedes stormwater harvesting due to the risks they pose when they come into contact with humans (Fletcher et al., 2008).

To reduce the harm caused by stormwater pollutants, biofilters (also known as rain gardens or bioretention systems) are widely applied as a part of Water Sensitive Urban Design (FAWB, 2009). While biofilters' sediment and nutrient removal capabilities are well documented, their promising ability to remove faecal microorganisms from stormwater has only recently been reported (Chandrasena et al., 2016; Chandrasena et al., 2014; Hathaway et al., 2011; Li et al., 2012). Previous studies indicated that the governing processes for the removal of faecal microbes in biofilters include adsorption, desorption and die-off (Bradford et al., 2006; Hathaway et al., 2011; Zhang et al., 2011).

Adsorption could be explained by the double layer theory, which describes the repulsive and attractive forces between microbes and media (Stevik et al., 2004). Since adsorption is reversible within the neutral pH range (Schijven and Hassanizadeh, 2000), which is also the pH range of stormwater (Duncan, 1999), desorption also occurs in biofilters. Adsorption and desorption govern the exchange of the mass of microbes between the liquid phase and solid phase in biofilters. These two processes are governed by different design and operational conditions such as media type, plant type, and flow conditions. Die-off controls the survival of microbes that are trapped by the soil and vegetation, and it is the dominant process during dry weather periods between wet weather events (Chandrasena et al., 2013). The effects of die-off are influenced by various abiotic (e.g. temperature and moisture content) (Ferguson et al., 2003; Schijven and Hassanizadeh, 2000; Zhang et al., 2011) and biotic conditions (e.g. predation and competition) (Flint, 1987; Zhang et al., 2010). Among these conditions, temperature is one of the most significant factors (Chandrasena et al., 2014).

Modelling is an important tool for better understanding the mechanisms of the removal of faecal microbes in biofilters, and for optimizing their design and operation. However, models for microbial removal in stormwater biofilters are very rare and not fully developed. Zhang et al. (2010) utilized a one-dimensional advection-dispersion equation to model the transport of *E. coli* in bioretention media during six hours of continuously simulated run-off conditions. Unfortunately, they only considered the processes of adsorption and die-off during a single rainfall event, without describing the influence of any operational factors or simulating dry periods, even though these are known to govern microbial removal in stormwater biofilters (Chandrasena et al., 2014; Chandrasena et al., 2014). Zhang et al. (2012) used the first order kinetic model to simulate the die-off process in stormwater biofilter media during dry periods. Although different temperatures were tested as an operational factor, no wet weather events were incorporated. As a result, governing processes for microbial removal that mainly take place during wet weather events, such as adsorption and desorption, were neglected. Therefore, this model was not able to simulate processes that occur during the period between two storm events that are important for overall system performance. Chandrasena et al. (2013) developed a model to simulate the outflow concentrations continuously, but this model is incapable of revealing the true transport of microorganisms throughout the biofilters as only a conceptual transport model was used. In addition, the impact of some operational factors such as temperature was not included. In summary, there is no available model that can continuously predict microbial removal in stormwater biofilters over extended periods.

Randelovic et al. (2016) presented a biofilter model for the treatment of micropollutants: a three-bucket approach was used to simulate biofilters; water flow and pollutant transport were modelled separately; the adsorption-dispersion equation was utilized to simulate pollutant transport. The model is capable of predicting the removal of different micro-pollutants in field-scale biofilters. However, the model was established for micropollutants removal and is unlikely to be suitable for microbial removal; furthermore, the model could neither simulate the differences in evapotranspiration rate between different plants, nor reflect the plant roots' capability of adsorbing water from different parts of a biofilter.

The main objective of this study is to develop and test a predictive model for microbial removal in stormwater biofilters. This model should (1) represent the transport and fate of faecal microorganisms through biofilters; (2) include the governing processes for microbial removal; (3) reflect the influences of the key factors for microbial removal; (4) represent both wet weather events and dry periods, as these requirements are significant for the long-term prediction of the removal of faecal microbes and the optimization of biofilters. In addition, the model should be able to simulate different types of biofilter with various design (e.g. different plant types and media types). It should also be noted that, considering the complexity of microbial removal mechanisms, and data availability, complicated model structure may not always provide better results for microbial behavior modelling; alternatively, the uncertainty and stochasticity could be reflected in parameter values. Therefore, a parsimonious model with well-calibrated parameter values is favored, rather than an over-parameterized model. The model developed in this study will have a water flow module and a microbial quality module, and will be tested using the data collected from a 44 weeks long laboratory column experiments on five different configurations.

2. Methods

2.1. Model description

The model consists of two modules: the water flow module and the microbial quality module.

(1) Water flow module

The water flow module describes the major flow processes in biofilters. It was adapted from Randelovic et al. (2016) with some modifications. A "three-bucket" approach is employed, where the buckets represent the major parts of a biofilter: (1) the ponding zone (PZ) – a temporary pond on the top of the filter media, (2) the unsaturated zone (USZ) – the unsaturated filter media, and (3) the saturated/submerged zone (SZ) – the consistently saturated part of a biofilter created by a raised outflow pipe (Fig. 1). This method is simple in terms of computational requirement and coding difficulty (e.g. compared to the Richards equation), and it has been proved to be efficient enough to simulate the water flow in biofilters (Randelovic et al., 2016). The equations and parameters in the water flow module are listed in Tables 1 and 2-left, respectively.

In PZ, the water depth (h_p) is governed by inflow rate (Q_{in}), rainfall precipitation (Q_{rain}) and the infiltration to USZ (Q_{pf}) (Eq. (4)). Q_{pf} is determined by the hydraulic conductivity (K_s) and the degree of saturation in USZ (S) (Eq. (1)). S is assumed uniform over the entire USZ, and it is governed by Q_{pf}, evapotranspiration from USZ (Q_{et_usz}) and capillary rise (Q_{hc}) (Eq. (10)).

This paper uses a more comprehensive function to describe evapotranspiration compared to that implemented by Randelovic et al. (2016): the function introduced in FAO-56 (Eq. (6)) (Allen et al., 1998) was employed; the potential evapotranspiration for each plant type was calculated as the daily reference evapotranspiration (ET_0) that could be easily obtained from the Bureau of Meteorology for any Australian capital city (BOM, 2017), multiplied with a plant coefficient for evapotranspiration, K_c (Allen et al., 1998). This method considers the different water consumption ability between different plants, which was neglected by Randelovic et al. (2016). Moreover, Q_{et} is assumed to have impacts on both USZ and SZ, as the plant roots could adsorb water directly from both USZ and SZ, irrespective of capillary rise (Le Coustumer et al., 2012). This was also neglected by Randelovic et al. (2016). Therefore, Q_{et} is calculated as the degree of entire

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