BioRTC: a new model that simulates and explores real time control strategies of stormwater biofilters

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Highlights

- Developed a new model for the simulation of real time control (RTC) in stormwater biofilters
- The model prediction results fitted very well with the observation in laboratory
- The developed model is an effective tool in RTC strategy testing and set-points determination

Introduction

Faecal microbes are the major pollutants that prevent stormwater harvesting. Although stormwater biofilters is effective in faecal microbial removal, their performance was inconsistent. Previous studies mainly focused on the design of biofilters, recent studies found that the operational optimization need to be conducted, and real time control (RTC) is a potential tool to achieve this. Recently, the first attempt of applying RTC in stormwater biofilters has been carried out by developing two RTC strategies and testing them via laboratory experiments (Shen et al., 2020a). Although the two developed RTC strategies were both effective in reducing the risks posed by faecal microbes, the scenarios tested in the laboratory were insufficient; in addition, further RTC strategies need to be developed and tested. However, it is very time-consuming and not economically feasible to test all the potential RTC strategies and scenarios one by one through laboratory experiments or field tests. Instead, modelling could be a potential tool to efficiently evaluate RTC strategies and scenarios. This study therefore aims to analyse the feasibility of using modelling to simulate the results of RTC implementation and assess further options of RTC.

Methodology

Summary of tested RTC strategies

A typical biofilter mainly consists of: (1) ponding zone, (2) unsaturated zone (USZ, consists of filter media with plants grown on the top), and (3) submerged zone (SZ, created by a raised outflow pipe) (**Figure 1**).

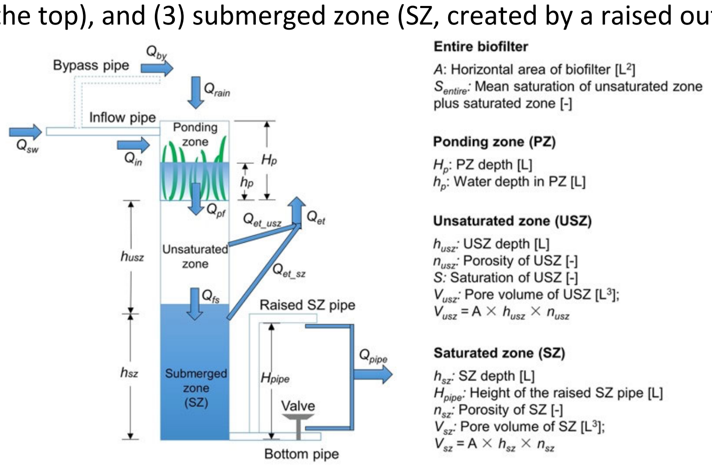

Figure 1. Schematic of a typical biofilter with submerged zone. Rainfall precipitation (Q_{rain}), stormwater inflow (Q_{sw}), stormwater inflow that enters biofilters (Q_{in}), stormwater bypassed (Q_{by}, $Q_{by} = Q_{sw} - Q_{in}$), water flow from PZ to USZ (Q_{pf}), flow from the USZ to SZ (Q_{fs}), evapotranspiration (Q_{et}; divided into the evapotranspiration from USZ (Q_{et_usz}) and from SZ (Q_{et_sz})), and outflow (Q_{pipe}).

The two RTC strategies that developed by Shen et al. (2020a) are modelled in this paper. RTC1 retains water in the biofilter for at least two days before allowing any further inputs into the system (adequate microbial die-off), and the input volume is restricted to the SZ's pore volume. In RTC2, three hours before the next rainfall event, the water in biofilter SZ for at least two days is drained for harvesting through a bottom pipe; when stormwater comes, close the bottom pipe and operate the biofilter without control.

Model selection and modification

The process-based model developed by Shen et al. (2018) is selected for modification, as it includes the major processes and factors in microbial removal, and has been successfully validated with various lab and field study data. However, this model does not include RTC capabilities. Based on this model, a new model, BioRTC, is developed for RTC simulation. Same to the selected "old" model, BioRTC utilises a bucket approach and has two modules: (1) the flow module that governs the flow processes; (2) the microbial quality module that predicts the behaviour of microbes using one-dimensional advection-dispersion equations. The water quality module has four calibration parameters: adsorption rate (k_{att}), desorption rate (k_{det}), standard microbial die-off rate (μ_0), and temperature coefficient for die-off (ϑ).

Table 1. Selected equations in the flow module and microbial quality module of BioRTC.

Selected flow module equation	Eq. No.
Stormwater that enters biofilters	
$Q_{in} = \begin{cases} Q_{sw}, & \text{no control} \\ 0, & \text{inflow pipe is fully closed} \\ Q_{in\_control}, & \text{inflow is partly closed} \end{cases}$	(1)
Stormwater that bypassed without treatment:	
$Q_{by} = Q_{sw} - Q_{in}$	(2)
Outflow through raised outflow pipe or bottom pipe	
$Q_{pipe} = \begin{cases} \min\left(A \times K_s \dfrac{h_p + h_{usz}}{h_{usz} + h_{sz}}, \dfrac{(h_{sz} - h_{pipe}) n_{sz} A}{dt} + Q_{fs} - Q_{hc} - Q_{et_{sz}}\right), h_{sz} > h_{pipe} \text{ and no control} \\ 0, h_{sz} \le h_{pipe} \text{ or outflow pipe is fully closed} \\ C_d \left(\dfrac{1}{4}\pi D^2\right) \sqrt{2g\left(h_p + h_{usz} + h_{sz} - h_{pipe}\right)}, \text{outflow pipe is partly closed} \end{cases}$	(3)
Selected microbial quality module equation	**Eq. No.**
Stormwater that enters biofilters	
$c_{in} = c_{sw}, \text{if } Q_{in} > 0$	(4)
Stormwater that bypassed without treatment	
$c_{by} = c_{sw}, \text{if } Q_{by} > 0$	(5)
Microbial mass balance in the water phase in Unsaturated zone (USZ)	
$\dfrac{\partial (S n_{usz} c_{usz})}{\partial t} + (S n_{usz} k_{att} c_{usz} - \rho k_{det} M_1) = \dfrac{\partial}{\partial z}\left(S n_{usz} D_1 \dfrac{\partial c_{usz}}{\partial z}\right) - \dfrac{\partial (q_1 c_{usz})}{\partial z} - S n_{usz} \mu c_{usz}$	(6)
Adsorption, desorption and die-off of adsorbed microbes in the soil phase in Unsaturated zone (USZ)	
$\dfrac{\partial M_1}{\partial t} = \dfrac{n_{usz} S}{\rho} k_{att} c_{usz} - k_{det} M_1 - \mu M_1$	(7)

The newly developed model for RTC simulation based on modification is named BioRTC (Table 1). Compared to the selected "old" model, the following elements are added/revised in BioRTC to represent RTC behaviours: (a) the restriction of inflow and outflow pipes (Eq. (1) and (3)), (b) the effects caused by control, such as the bypass of stormwater due to inflow restriction (Eq. (2), (4) and (5)), and (c) the key parameters that associated with control strategies (e.g., the controlled inflow rate $Q_{in\_control}$ in Eq. (1)).

Model calibration, sensitivity analysis, and validation

Laboratory experiments were conducted for RTC1 and RTC2 in Shen et al. (2020a). Ten biofilter columns were divided into RTC biofilters and non-RTC biofilters (without control), with five replicates each. All the columns had a same size (USZ length: 500 mm, SZ length: 440 mm, diameter: 240 mm, pore volume: 20 L), plants (*Carex appressa*), and filter media (washed sand). Two rounds of experiments (respectively for RTC1 and RTC2 testing) were conducted. In each round, 11 sampling events with various rainfall sizes, antecedent dry lengths, and inflow concentrations were designed based on Melbourne's historical rainfall. Biofilters were dosed with semi-natural stormwater that spiked with *Escherichia coli* (*E. coli*).

The data collected in all the 22 events were employed in model calibration. The model calibration and sensitivity analysis were based on a modified Monte-Carlo based method, using Nash Sutcliffe Efficiency (E_c) criterion. For model validation, the 3179 parameter sets (reported in Shen et al. (2020b)) that calibrated with the data collected from various laboratory experiments and field tests for non-RTC biofilters were adopted, to simulate the RTC testing results and compared with the reality.

Exploration of RTC potential using BioRTC in hypothetical system simulation

To explore the potential of RTC, BioRTC was utilised to analyse the performance when RTC1 and RTC2 were respectively implemented in a hypothetical biofilter system that represents the reality. The hypothetical system was assumed to locate in the outlet of the Hawthorn Main Drain West Catchment (with 597 ha surface area, of which 45% is impervious) in Melbourne. With Melbourne's rainfall information, the flows and *E. coli* concentrations from this catchment for a two-year time series with 126 rainfall events were generated. These data were used as the inflow conditions of the hypothetical system. The hypothetical system was simulated by BioRTC to test different RTC scenarios, with the best-fit parameter set from calibration results. For each RTC strategy, the minimum required retention time T_{min} was re-evaluated, as the optimum T_{min} might be different when being applied in different systems. Thirteen T_{min} values were tested: 1 h, 2 h, 3 h, 4 h, 5 h, 6 h, 12 h, 18 h, 24 h, 30 h, 36 h, 42 h, and 48 h. The results under different T_{min} were also compared with those when RTC was not implemented (non-RTC).

Results and discussion

Model calibration, sensitivity analysis and validation results

3086 parameter sets were selected as after calibration. When using this best-fit parameter set for prediction, the predicted outflow concentrations fitted the observation well, as a high Nash Sutcliffe Efficiency value is achieved (E_c = 0.80), and the majority of data points were scattered around the 1:1 line (Figure 2). With all the 3086 parameters sets, E_c ranged from 0.65 to 0.80, which were higher than those obtained in previous studies on the selected "old" model (E_c = 0.46~0.55) or other stormwater *E. coli* modelling studies. In addition, the peak in the diagonal histograms of k_{att}, k_{det}, ϑ and μ_0 in the matrix plot (Figure 3) suggested that the model was sensitive to all the 3086 parameter sets in the water quality module.

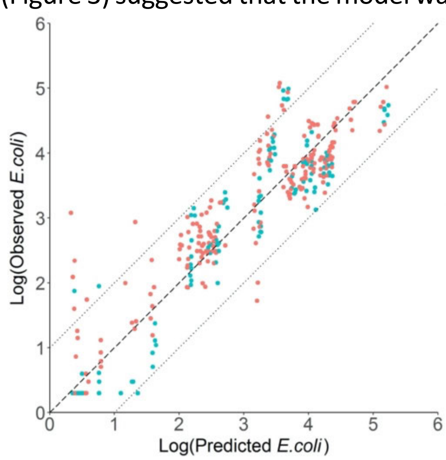

Figure 2. Comparison of observed and predicted outflow *E. coli* concentrations of all the columns in all the events. Dashed line indicates the 1:1 line between prediction and observation, while dotted lines indicate +/- one order of magnitude bars.

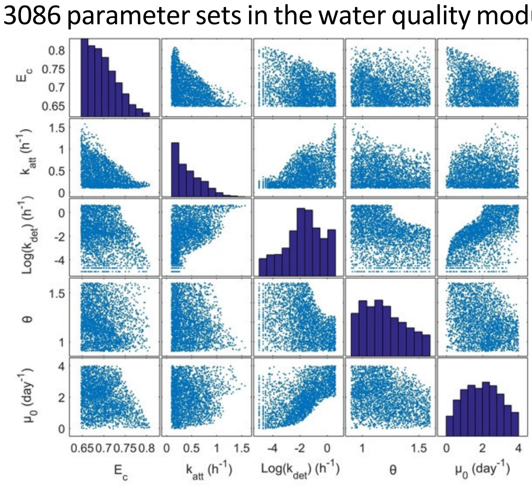

Figure 3. Matrix plot for parameter distributions of the 3086 parameter sets. The diagonal histograms represent the distributions of E_c and all the parameters, while the scatter plots between parameters reveal the parameter interactions.

For BioRTC validation, when the 3179 previously calibrated parameter sets were adopted to predict outflow concentrations of *E. coli*, the E_c values ranged from -0.07 to 0.70, and 64 % of E_c values were above 0.40. These promising results indicated a high parameter transferability of BioRTC.

Scenario testing results of BioRTC for hypothetical system simulation

Since similar findings were obtained during the scenario testing with RTC1 and RTC2, only the RTC1 performance in the hypothetical system simulation is discussed here. For RTC1 scenario testing, with the increase of T_{min} value, the quality of the hypothetical system outflow (i.e., harvested water) increased (the median *E. coli* concentrations decreased), as longer retention time enhanced microbial die-off in biofilters; at the same time, the proportions of harvested water volume (harvested water volume/total stormwater volume) decreased, as more stormwater has to be bypassed when longer T_{min} was required (Figure 4).

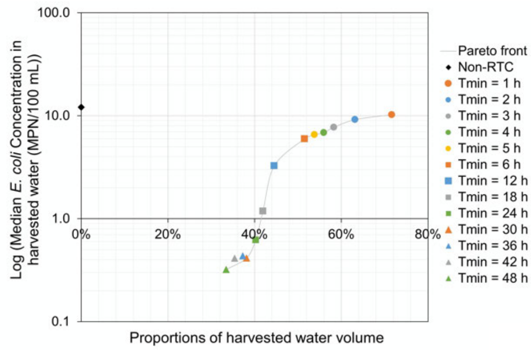

Figure 4. The best-fit prediction of median *E. coli* concentrations in harvested water against the proportions of harvested water volume, under various T_{min} values in RTC1.

A Pareto front was found in Figure 4, which means it was impossible to optimize one objective (e.g., quality of harvested water) without making the other objective (e.g., the volume of harvested water) worse. The Pareto front could help to decide the optimum T_{min}, according to the specific case of interest. For example, the water is harvested for irrigation of commercial food crops in Australia (median concentration < 1 *E. coli*/100 mL), the optimum T_{min} was 24 h, as this set-point could help us collect the highest water volume under this water quality requirement (Figure 4); while if the harvested water is for municipal use with unrestricted access or irrigation of non-food crops in Australia (requirement: median concentration < 10 *E. coli*/100 mL), the optimum T_{min} was 2 h (Figure 4). These results demonstrated the necessity to testing T_{min} before implementing RTC in a new system, and BioRTC could be an efficient tool to fulfill this goal.

Conclusions and future work

The newly developed model in this study, BioRTC, has been proved to be effective in representing the outcome of RTC implementation. Therefore, this model could be employed to explore RTC strategies and test RTC scenarios. In addition, since the benefits of a same RTC strategy and the corresponding optimum set-points might vary for different systems (e.g., with various inflow concentrations and dry lengths) and different treatment requirements (e.g., end uses), BioRTC could be an efficient tool to select the most suitable RTC strategy and determine the optimum set-points to maximise the benefits of RTC.

References

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