Key design characteristics that influence the performance of stormwater biofilters

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ABSTRACT

Biofilters can be used as a tool to treat urban stormwater and help combat the pollution of watercourses, whilst also offering the opportunity to attenuate and retain stormwater flows. However, their large scale implementation is being hindered by lack of knowledge about the key factors that influence their ability to remove pollutants from stormwater. This paper presents the biofilter design characteristics and operating conditions that influence Total Suspended Solids (TSS), Total Phosphorus (TP) and Total Nitrogen (TN) removal efficiency. The significance of these characteristics was identified by analyzing data from three laboratory-scale biofilter column studies. We found that the most significant factors influencing treatment performance are vegetation presence and type, filter media characteristics (orthophosphate and TN contents), filter media depth, and antecedent soil moisture content. This knowledge can later be used to create a simple predictive model of expected TSS, TP and TN treatment by biofilters.

KEYWORDS

Biofilter; design; treatment; Total Suspended Solids; Total Phosphorus; Total Nitrogen

INTRODUCTION

Urban stormwater is a major contributor to the declining health of our waterways. Changes to catchment hydrology as a result of urbanisation can lead to the physical degradation of urban streams, and activities in urban areas generate pollutants that can be carried into receiving bodies of water by stormwater (Leopold, 1968). The increase in the amount of pollutants in streams can lead to eutrophication and reduced aquatic biodiversity (Duncan, 2006). Biofilters have been proposed as a way to treat urban stormwater and mitigate such problems, which are vegetated systems that treat stormwater as it filters vertically through the filter media. The treated water is either collected in an under-drain or is allowed to infiltrate into the surrounding soil. Biofiltration can remove both particulate and dissolved pollutants from urban stormwater by a number of processes including filtration, vegetative uptake, adsorption onto filter media particles and microbial activity (Lucas and Greenway, 2008). Most biofilters are able to achieve removal rates of Total Suspended Solids (TSS) greater than 87% (Hatt *et al.*, 2006). However, in a large scale biofilter column study testing the significance of a number of design characteristics, Bratieres *et al.* (2008) found that due to the large number of physical and bio-chemical processes involved in the removal of nutrients, the selection of a few critical design characteristics such as vegetation and filter media type is critical for effective nutrient removal. For example, Lucas and Greenway (2008) found that vegetation can reduce TP outflow concentrations from 0.21 mg/L (71% reduction) to 0.05 mg/L (96% reduction). Similarly, Henderson *et al.* (2007a) reported that TN outflow concentrations ranged from 6.09 mg/L for non-vegetated gravel filters to 1.23 mg/L for vegetated loam filters (–12% and 77% reduction respectively).

The aim of this study was to build on the work of Bratieres *et al.* (2008), and identify the key design characteristics and operating conditions that impact TSS, TP and TN treatment by biofilters. To do this, statistical tests were conducted on the data set used by Bratieres *et al.* (2008), which was expanded to include two other laboratory-scale column studies.

METHODS

Data collection

Three laboratory-scale column studies were conducted to assess the influence of several design characteristics and operating conditions on the treatment performance of biofilters. Details of these studies can be found in literature (Blecken *et al.*, 2009; Bratieres *et al.*, 2008; Hatt *et al.*, 2008) and are only briefly explained below due to limited space.

Design study. A laboratory-scale column study was conducted to assess the influence of five biofilter design characteristics listed in Table 1 (for further details see Bratieres *et al.*, 2008). In total, there were 24 design configurations, each with five replicates. The treatment performance of the columns was tested using semi-synthetic stormwater, which had target concentrations typical of urban runoff: TSS, 150 mg/L; TP, 0.35 mg/L; and TN, 2.1 mg/L (Duncan, 1999). Each column was dosed twice a week and following a six-month establishment period, inflow and outflow water quality samples were collected approximately every seven weeks over 16 months. All water quality samples were analyzed for TSS, TP, and TN using standard methods (APHA/AWWA/WPCF, 1998; Hosomi and Sudo, 1986) and quality assurance procedures. The analyses were performed by the analytical laboratory in the National Association of Testing Authorities (NATA) accredited (http://www.nata.asn.au/) Monash University Water Studies Centre. The filter media were analyzed also at a NATA-accredited laboratory using standard methods and quality assurance procedures (APHA/AWWA/WPCF, 1998).

Non-vegetated media study. A smaller laboratory-scale column study was conducted to test the influence of filter media properties in non-vegetated systems under distinct wet and dry periods, with dry periods ranging from 2 to 32 days. Six filter media types were tested in the non-vegetated media study; however, the results for only three media types were used here because the other three media types differed from those used in the design study. The three media types tested were sandy loam (SL), sandy loam with 5% (by weight) organic matter (SLCM), and sandy loam with vermiculite and perlite (10% by volume of each) (SLVP). Prior to the commencement of stormwater dosing, the chemical composition of these filter media were tested using the same procedure as in the design study (Table 2). As in the design study, semi-synthetic stormwater, with the same target influent pollutant concentrations was used. During dry periods, water quality samples were collected at the first dosing after a dry spell, while samples were collected weekly or fortnightly during wet periods (for further details see Hatt *et al.*, 2008).

Table 1. Characteristics tested in the design study (adapted from Bratieres *et al.*, 2008). See Table 2 for characterisation of the filter media types.

Design characteristic	Varieties tested
Vegetation	*Carex appressa*, *Melaleuca ericifolia*, *Leucophyta brownii*, *Dianella revoluta*, *Microlaena stipoides*, Non-vegetated
Filter media type	Sandy Loam (SL) Sandy Loam with 10% vermiculite and 10% perlite (by volume) (SLVP) Sandy loam with 10% leaf compost and 10% mulch (by volume) with low pH (SLCMpH) Sandy loam with 10% leaf compost and 10% mulch (by volume) (SLCM)
Filter media depth	300 mm, 500 mm, 700 mm
Influent pollutant concentration	standard (target concentrations outlined in above), double (twice of standard)

Table 2. Characterisation of filter media in the design study and non-vegetated media study.

Study	Design Study				Non-vegetated Media Study		
	SL	SLVP	SLCMpH	SLCM	SL	SLVP	SLCM
OM (by weight) (%)	<5%	<5%	≥5%	≥5%	<5%	<5%	≥5%
Orthophosphate (mg/kg)	35	54	67	92	Not tested	Not tested	Not tested
TP (mg/kg)	167	133	149	160	18	94	94
Ammonia (mg/kg)	<5	<5	<5	<5	Not tested	Not tested	Not tested
Nitrite and Nitrate (mg/kg)	<5	<5	<5	<5	28	13	57
TN (mg/kg)	997	733	683	1200	270	290	660
Total Organic Carbon (mg/kg)	40700	19300	13000	13000	6200	5400	17000
pH	8	8.1	7.4	7.7	5.6	6.1	6.3

Submerged zone study. The effect of a submerged zone on biofilter treatment performance was tested in a separate study. During the first stage, 18 biofilter columns with a 400 mm sandy loam filter media (the same SL filter media used in the design study) overlaying a 400 mm sand transition layer were tested. All columns were vegetated with *Carex appressa*. A carbon source was incorporated into the transition layer of some columns, comprised of 5% by volume organic material, two-thirds being hardwood woodchips and the remainder pea straw. The volume required was stoichiometrically calculated to provide the necessary carbon to support denitrification over a twenty year period (ie. the systems were designed for realistic long-term performance). In total, there were six design configurations, with three replicates of each, based on different depths of the submerged zone (i.e., 0, 150, 450, 600 mm) and the presence or absence of the carbon source. Each column was dosed twice a week using semi-synthetic stormwater with the same target concentrations as the previous two studies (for further details see Blecken *et al.*, 2009). In the second stage, twelve of the eighteen columns were reconfigured to have a submerged zone of 450 mm and a carbon source. The remaining six columns had no submerged zone or carbon source. The columns were subjected to drying and to test three different wetting and drying regimes, the columns were separated into three groups, with dry periods between 3 and 49 days. Moisture probes (*Theta Probes*, model ML2x, Delta-T Devices, Cambridge, UK) were placed 250 mm deep in two columns from each group (one with a submerged zone, and one without) and soil moisture was recorded at 10-minute intervals (Zinger *et al.*, 2007).

Data Analysis

The data was analysed to identify the factors that significantly influence TSS, TP and TN removal by biofilters. Results from the design study and stage 1 of the submerged zone study were grouped such that they differed by only one design characteristic. One-way Analysis of Variance (ANOVA) with Tukey's post-hoc test was used to identify the significant design characteristics (significance was accepted at $p<0.05$). These tests were used after verifying the assumptions of normality and homogeneity of variance using the Kolmogorov-Smirnov test and the F-test, respectively ($\alpha = 0.05$ for both). Where the assumption of normality was not satisfied, the data was log-transformed and where the assumption of homogeneity of variance was not satisfied, the separate variance t-test ($\alpha = 0.05$) was used instead of ANOVA. The significance of antecedent soil moisture was tested using regression analysis. PHSTAT version 2.5 and Microsoft Excel 2007 were used for the F-test, t-tests and regression analyses, while SPSS version 18.0 was used for the Kolmogorov–Smirnov tests.

Before conducting these statistical analyses, the data was screened to identify outliers and to eliminate data from unestablished systems. Any data points that were confirmed as recording, laboratory analytical or typing errors were removed. One biofilter column from the design study was ignored because it was planted late (resulting in poor plant establishment) and was thus deemed to be non-representative. The five columns planted with *Leucophyta brownii* in this data set were analysed as non-vegetated columns because the vegetation had died before dosing began. Finally, results from one group in stage 2 of the submerged zone study were excluded because the plants died during the first extended dry period. Similarly, we only wanted to assess 'mature' systems, as biofilters can take some time to reach their optimal nutrient removal performance due to the time required for roots to fully exploit the filtration media (Bratieres *et al.*, 2008). Therefore time was also assessed as a factor in the ANOVA and only data from these 'mature' systems were considered. In the design study, columns with *C. appressa* and *Melaleuca ericifolia* reached optimal performance approximately eight months after the start of the experiment. Conversely, the treatment performance of the non-vegetated columns and those with *Microlaena stipoides* and *Dianella revoluta* stabilised after approximately four months. The columns in the non-vegetated media study and stage 1 of the submerged zone study took approximately five months to become fully established but all results from stage 2 of the submerged zone study were from mature systems.

RESULTS AND DISCUSSION

TSS

For all three studies, TSS removal was high and soil moisture was the only significant explanatory factor. As indicated in Figure 1, regression analysis showed an inverse relationship between the antecedent dry weather period and TSS outflow concentrations from non-vegetated systems ($p<0.001$, $R^2 = 0.48$). This is likely due to the shrinkage and cracking within the soil matrix as soil moisture decreases. This not only results in increased porosity, which reduces the ability of the filter media to capture the finer particulates, but it also creates macropores and preferential flow paths, allowing water from the next dosing event to move through the filter profile at a faster rate and mobilise filter media particles in the process (Hatt *et al.*, 2007).

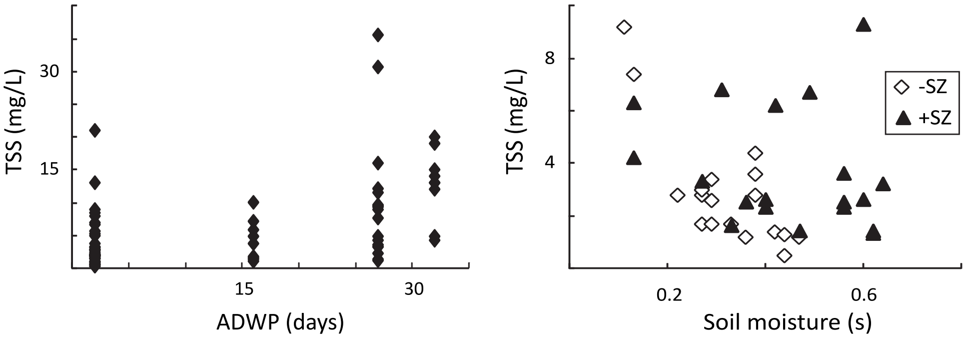

Figure 1. (a) TSS outflow concentrations from the non-vegetated media study as a function of ADWP. (b) TSS outflow concentrations as a function of antecedent soil moisture from stage 2 of the submerged zone study from columns with no carbon source and no submerged zone (-SZ) as well as from columns with a carbon source and a submerged zone of 450 mm (+SZ).

Likewise, stage 2 of the submerged zone study indicated that for biofilters with no submerged zone the antecedent soil moisture impacted TSS removal (Figure 1). Although data is sparse, TSS outflow concentrations appear relatively constant when the soil is moist (above a threshold between 0.2 and 0.3) and when soil moisture is lower than this threshold, there appears to be an inverse relationship between TSS outflow concentration and antecedent soil moisture. The lack of correlation between antecedent soil moisture and the outflow TSS concentration in systems with a submerged zone could be due to leaching of fine particulate matter from the carbon source. It could also be due to the fact that during the experiment, the moisture probe was not within the submerged zone layer. Thus, even after a dry period the soil moisture reading may have underestimated the actual soil moisture in the lower layers of the biofilter column and would not reflect the continued presence of a submerged zone (albeit at a smaller depth), which would minimize the formation of cracks and macropores in the filter media.

TP

TP removal was found to be a function of only four factors. First, vegetation type is important; systems with *C. appressa* or *M. ericifolia* were found to remove TP from stormwater more effectively than non-vegetated systems or systems with *D. revoluta* and *M. stipoides* ($p = 0.00 - 0.04$). This is consistent with the findings of Read *et al.* (2008), who found that systems with shallow rooted plants such as *D. revoluta* and *M. stipoides* provide less effective treatment. Second, increasing the filter media orthophosphate content significantly increased the TP outflow concentration ($p < 0.01$). It is likely that a fraction of the native phosphorus in the media will be in leachable forms, while another portion will be attached to exchange sites on the filter media particles, limiting the capacity to adsorb phosphorus in the stormwater (Henderson *et al.*, 2007b). In addition, microbial processes will transform some of the particulate phosphorus to more labile forms, which may then be washed out of the system (Baldwin and Mitchell, 2000). Third, increasing the submerged zone depth from 150 mm to 600 mm led to a significant increase in TP outflow concentrations ($p < 0.01$). This is probably due to leaching of phosphorus from the carbon source in the submerged zone. This is supported by the finding that, in the absence of a carbon source, increasing the submerged zone depth did not lead to differences in TP outflow concentrations ($p = 0.11$). It is also likely that desorption of P from sediment occurred under the reducing conditions caused by extended period of saturation.

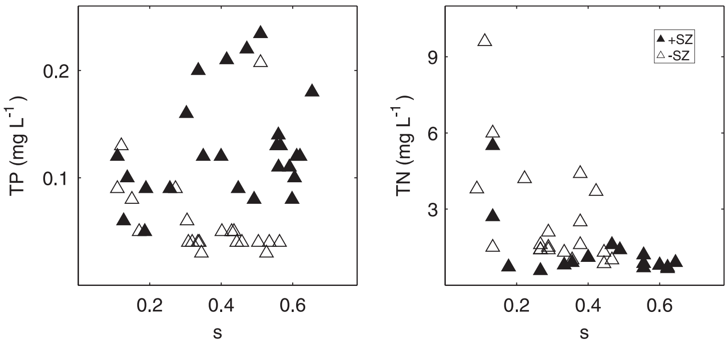

Figure 2. TP and TN outflow concentrations from stage 2 of the submerged zone study. Outflow concentrations from columns with no carbon source and no submerged zone (-SZ) as well as from columns with a carbon source and a submerged zone of 450 mm (+SZ) are shown.

Finally, TP removal for vegetated systems with no submerged zone was related to the antecedent soil moisture content (Figure 2). TP outflow concentrations decrease with increasing soil moisture, but remain constant once the moisture content exceeds a certain point. As for TSS outflow concentrations (Figure 1), this transition point appears to be between 0.2 and 0.3. It seems likely that in the case of TP, when vegetation and the microbial community start to suffer water stress, the system is no longer able to efficiently perform its nutrient removal functions. As described above, drying has a detrimental impact on particulate removal, and it is possible that the elevated TP levels are due to particulate-bound P being washed out. It is possible that this process also occurs in systems with submerged zones, but is being masked by leaching of P from the carbon source or by the misrepresentation of the soil moisture readings due to the positioning of the soil moisture probe, as described previously.

TN

Three design elements significantly affected TN treatment. TN outflow EMCs were higher from systems without vegetation or systems vegetated with *M. stipoides* and *D. revoluta* ($p < 0.001$) as compared to systems with *C. appressa* or *M. ericifolia*. Also, TN removal was substantially lower when the TN filter media content was greater than 1000 mg/kg ($p < 0.01$). There was also an inverse relationship between filter media depth and TN outflow EMCs for systems with *M. stipoides* ($p < 0.02$). We hypothesize that due to its shallow roots, this plant is unable to take up TN in the deeper layers of the soil, resulting in leaching of nitrogen from lower parts of the filter media profile (Read *et al.*, 2010).

TN removal was also influenced by changes in antecedent soil moisture. TN outflow EMCs were consistently low when the soil moisture was greater than a certain threshold (between 0.2 and 0.3) (Figure 2). After a dosing event, when the soil is moist, the rate of N uptake by plants most likely exceeds nitrification rates, so that N is not significantly accumulated in the soil. However, when the soil is dry, outflow concentrations increase with decreasing soil moisture. We hypothesize that as soil moisture decreases, plants begin to experience drought stress and their uptake of N decreases (Manzoni and Porporato, 2007), likely resulting in accumulation of N in the soil. Part of this N is washed out from the system during the subsequent dosing event. However, the performance of non-vegetated systems are also adversely affected by drying ($p < 0.001$, $R^2 = 0.763$). Thus, drought stress of vegetation is not the only mechanism contributing to the decline in TN removal performance, but is likely combined to other processes, such as declining bacterial activity, cell lysis, and the conversion of NH_4^+ to NO_x in aerobic conditions (Baldwin and Mitchell, 2000; Henderson *et al.*, 2007b).

CONCLUSIONS

Four factors significantly impact a biofilter's ability to remove TSS, TP and TN from stormwater. One factor common to all three pollutants was soil moisture. In vegetated systems, there appears to be a soil moisture threshold (between 0.2 and 0.3), above which the treatment of TSS, TP and TN is unaffected by antecedent soil moisture. However, below this point, treatment performance deteriorates with decreasing antecedent soil moisture. In non-vegetated systems there was a positive relationship between antecedent dry weather days and the TSS and TN outflow EMCs. Additionally, nutrient removal was greatly influenced by vegetation type and the filter media nutrient (orthophosphate and TN) content. Furthermore, TN removal was affected by filter media depth, but only for systems with shallow rooted plants such as *M. stipoides*.

This study has highlighted the complexities of the biochemical processes within the submerged zone and that further investigation is required to fully understand the treatment processes in submerged zones. Finally, in a further study, these findings will be used to create a predictive model of TSS, TP and TN treatment performance of biofiltration systems, given their specific design characteristics and operating conditions.

ACKNOWLEDGEMENTS

This work was funded by the Victorian Government's Science, Technology and Innovation grant scheme, and a number of industry partners.

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