Co-optimisation of phosphorus and nitrogen removal in stormwater biofilters: the role of filter media, vegetation and saturated zone

Bonnie J. Glaister, Tim D. Fletcher, Perran L. M. Cook and Belinda E. Hatt

ABSTRACT

Biofilters have been shown to effectively treat stormwater and achieve nutrient load reduction targets. However, effluent concentrations of nitrogen and phosphorus typically exceed environmental targets for receiving water protection. This study investigates the role of filter media, vegetation and a saturated zone (SZ) in achieving co-optimised nitrogen and phosphorus removal in biofilters. Twenty biofilter columns were monitored over a 12-month period of dosing with semi-synthetic stormwater. The frequency of dosing was altered seasonally to examine the impact of hydrologic variability. Very good nutrient removal (90% total phosphorus, 89% total nitrogen) could be achieved by incorporating vegetation, an SZ and Skye sand, a naturally occurring iron-rich filter medium. This design maintained nutrient removal at or below water quality guideline concentrations throughout the experiment, demonstrating resilience to wetting–drying fluctuations. The results also highlighted the benefit of including an SZ to maintain treatment performance over extended dry periods. These findings represent progress towards designing biofilters which co-optimise nitrogen and phosphorus removal and comply with water quality guidelines.

Key words | biofilter, nitrogen, phosphorus, saturated zone, Skye sand, stormwater

Bonnie J. Glaister (corresponding author)
Belinda E. Hatt
CRC for Water Sensitive Cities,
Water for Liveability Centre,
Department of Civil Engineering,
Monash University, Victoria 3800,
Australia
E-mail: *bonnie.glaister@monash.edu*

Tim D. Fletcher
Waterway Ecosystem Research Group,
Department of Resource Management and Geography,
Melbourne School of Land and Environment,
the University of Melbourne, Victoria 3121,
Australia

Perran L. M. Cook
CRC for Water Sensitive Cities,
Water Studies Centre,
School of Chemistry, Monash University,
Victoria 3800,
Australia

INTRODUCTION

Urban stormwater runoff has a significant impact on the health and ecological function of receiving waters (Walsh *et al.* 2004). Discharge of nutrient-rich stormwater into waterways can be particularly detrimental, leading to increased biological productivity and eutrophication (Kadlec & Knight 1996). Stormwater biofilters (also known as biofiltration systems, bioretention systems or raingardens) have the potential to reduce this impact. Extensive laboratory and field testing has demonstrated the effectiveness of biofilters for removing nitrogen and phosphorus from urban stormwater, confirming that these systems reliably meet load reduction targets for total suspended solids (TSS) and nutrients (TSS 80%, total phosphorus (TP) 45%, and total nitrogen (TN) 45% in Victoria, Australia). However, N removal rates remain variable and reported N and P concentrations are near or above typical Australian and New Zealand receiving water guidelines (ANZECC & ARMCANZ 2000; Hunt *et al.* 2006; Davis *et al.* 2009; Hatt *et al.* 2009). To provide effective protection for receiving waters, biofilters must be co-optimised for N and P removal, and achieve effluent concentrations below environmental protection guidelines.

N and P removal are governed by a range of biogeochemical processes. N removal relies on either the transformation of N species into a gaseous form (N_2) through the processes of ammonification, nitrification and denitrification or biological assimilation by plants and microbes (Vymazal 2007). Particulate-associated P is removed predominantly by physical straining and sedimentation. Removal of dissolved P is facilitated by sorption, precipitation and biological uptake (Kadlec & Knight 1996; Hatt *et al.* 2007). While it has been suggested that plant uptake represents only a fraction of overall nutrient removal (Dietz & Clausen 2006) the role of plants in supporting nutrient removal processes has been well established in the literature (Browning & Greenway 2003; Vymazal 2007; Read *et al.* 2008) and demonstrated by several studies (e.g. Henderson *et al.* 2007a; Bratieres *et al.* 2008; Lucas &

doi: 10.2166/wst.2014.117

Greenway 2008). The importance of plant species selection as well as the influence of inter-species competition and planting regime on nutrient removal performance have also been tested (Read *et al.* 2010; Ellerton *et al.* 2012). Australian biofiltration design guidelines (see FAWB 2009) recommend the inclusion of a saturated zone (SZ) to promote anaerobic conditions between wetting events and thus enhance N removal through denitrification. The inclusion of an SZ has also been shown to support plant health and protect biofilters against drying during dry weather periods (Blecken *et al.* 2009). The variable wetting and drying cycles which biofilters experience dramatically alter oxygen concentrations and the distribution of denitrifying bacteria in the SZ (Korom 1992; Chen *et al.* 2013). Seasonality and antecedent dry weather periods therefore have a significant influence on the effectiveness of the SZ, which has achieved mixed success in both field and laboratory experiments (Dietz & Clausen 2006; Hunt *et al.* 2006; Hsieh *et al.* 2007b; Lucas & Greenway 2008; Zinger *et al.* 2012). Furthermore, if not configured correctly, the SZ may become an internal source of P, for instance if P retained in redox sensitive pools (e.g. Fe-bound P) becomes remobilised under reducing conditions (Boström *et al.* 1988), or if the organic carbon added to facilitate denitrification has a high P content. These are important aspects to consider when incorporating an SZ in terms of co-optimising N and P removal.

Biofilters have a finite P retention capacity (Wild 1950; Del Bubba *et al.* 2003; Hsieh *et al.* 2007a). Factors which influence this include native P concentration, depth, chemical composition, particle size and surface area of the filter media, and the presence of other P removal pathways in the system. Presently, our knowledge regarding the role of filter media in facilitating long-term P retention remains limited. Henderson *et al.* (2007a, b) argue that filter media are unlikely to retain nutrients in the long term, but may provide an important function by extending retention time so plant uptake and microbial assimilation can occur. Others have suggested that filter media could enable complex P sorption and precipitation processes through interactions with P attracting ions, which may strongly, or even permanently, bind P to the filter media (Arias *et al.* 2001; Del Bubba *et al.* 2003; Lucas & Greenway 2008). A recent study by Glaister *et al.* (2011) found that under simple laboratory testing a naturally occurring iron- and aluminium- oxide rich sand, known as Skye sand, demonstrated superior phosphate removal performance compared with loamy sand, which is the filter medium currently recommended by Australian biofiltration system guidelines (FAWB 2009). Configuring biofilters with Skye sand may enhance P removal and facilitate long-term P retention. The present study investigates the role of filter media, vegetation and an SZ in co-optimising N and P removal by comparing the nutrient removal performance of biofilters configured with Skye sand and loamy sand in conjunction with and without vegetation and an SZ. Climatic variability imposed during the experiment also investigates the influence of wet and dry periods on filter media durability and treatment resilience.

METHOD

Experimental design

Column construction and filter media selection

Twenty biofilter columns, shown in Figure 1(a), were constructed using PVC pipe (150 mm diameter) and acrylic to create a 200 mm ponding zone. The columns were designed in accordance with Australian biofiltration system guidelines (see FAWB 2009). Columns without an SZ drained freely from the base, while a riser pipe was attached to the outlet of those with an SZ to maintain a 300 mm pool of water in the lower half of the column; Figure 1(b). Elemental characteristics of the Skye sand and loamy sand filter media are described in Table 1. An organic carbon source mixture of pine woodchips (bark removed) (26.5 g) and pine flour ('sawdust') (9.3 g) was blended into the SZ filter medium to facilitate the denitrification process (total material added was equivalent to 5% of the volume of the SZ). These materials were selected on the basis of their biodegradability and low P content (10.2 mg P/kg). The biofilters were configured into four main layers shown in Figure 1(b): (1) filter media (300 mm) loamy sand or Skye sand planted with *Carex appressa*; (2) sand transition layer (200 mm) coarse washed sand; (3) pea gravel drainage layer (70 mm); (4) gravel drainage layer (30 mm).

Column configuration and establishment

Four design configurations were tested (with five replicates of each). The configurations are described in Table 2. Filter media layers 2, 3 and 4 remained constant between configurations. These configurations enabled three key relationships between design characteristics to be analysed: (i) loamy Sand vs. Skye sand vegetated with SZ; (ii) Skye sand non-vegetated with SZ vs. Skye sand vegetated with

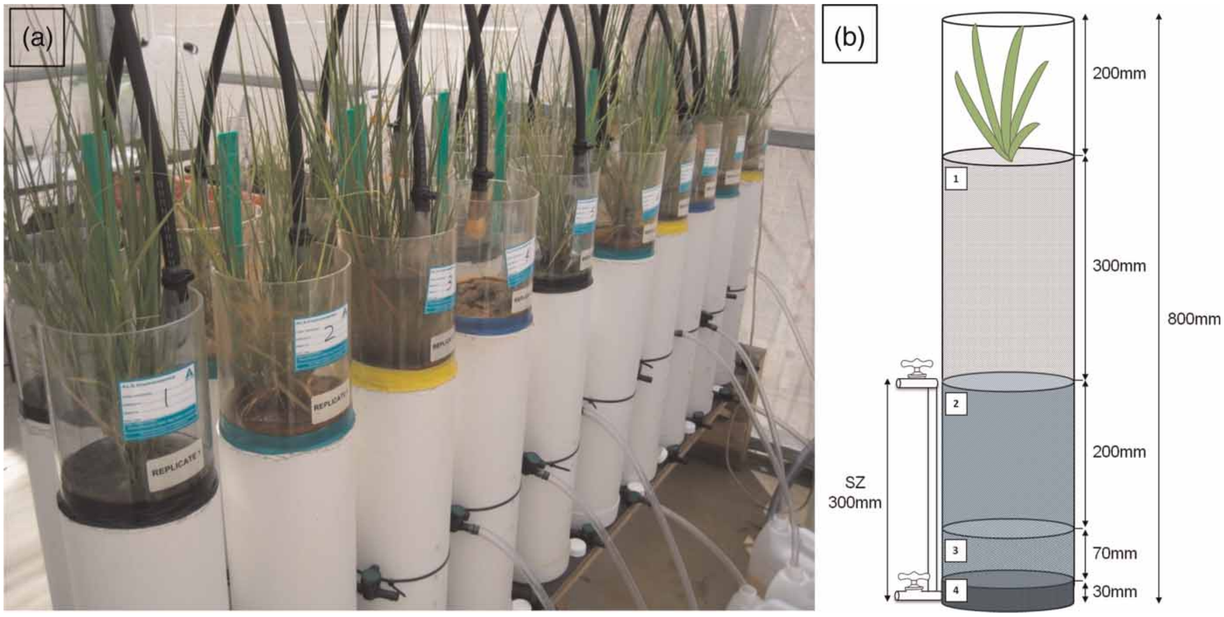

Figure 1 | (a) Experimental set-up of biofilter columns in greenhouse and (b) schematic diagram of the biofilter columns (with SZ riser outlet attached).

Table 1 | Elemental characteristics of loamy sand and Skye sand filter media (parentheses represent range)

Media	Fe^a	Al^a	$Fe_2O_3^b$	$Al_2O_3^b$	SiO_2^b
Loamy sand	1,000 (±200)	900 (±100)	0.21	0.58	99
Skye sand	21,000 (±2,000)	1,000 (±100)	1.8	2.2	94

[a] Analysed using inductively coupled plasma mass spectroscopy (ICP-MS; $n = 2$) (mg/kg).
[b] Analysed using X-ray fluorescence (XRF; %w/w).

SZ; and (iii) Skye sand vegetated with SZ vs. Skye sand vegetated without SZ.

The columns were filled manually then compacted using a weighted hammer (as described by ASTM F1815-11 (2011)). The compaction required was determined by the layer thickness and media porosity. Once filled, vegetation was transplanted into the top 100 mm of the columns. The Australian native species *C. appressa* was selected because of its drought tolerance and resilience to climate fluctuations. Previous biofilter column studies have found that this species maintains very good nutrient removal under high loading conditions and inflow concentrations (Bratieres *et al.* 2008; Read *et al.* 2008). Prior to transplanting the plants were matured in a glasshouse (at 25 °C) for 12 weeks. Following construction the columns were placed in a purpose-built ventilated greenhouse and dosed twice weekly for 5 weeks with semi-synthetic stormwater to establish the plants, inoculate the soil microbial community and flush free particles out of the filter media.

Experimental procedure

Semi-synthetic stormwater

Due to limitations associated with the use of real stormwater, a semi-synthetic stormwater mixture was used instead. This approach minimised inflow concentration variability whilst maintaining realistic composition. Several studies have adopted this method and demonstrated

Table 2 | Biofilter column design configurations

Configuration	Filter medium	Vegetation	Saturated zone
Loamy sand, vegetated, saturated zone (LS-V-S)	Loamy sand	*C. appressa*	SZ
Skye sand, non-vegetated, saturated zone (SS-NV-S)	Skye sand	Non-vegetated	SZ
Skye sand, vegetated, saturated zone (SS-V-S)	Skye sand	*C. appressa*	SZ
Skye sand, vegetated, no saturated zone (SS-V-NS)	Skye sand	*C. appressa*	No SZ

consistency in maintaining target concentrations throughout the experimental period (e.g. Hatt *et al.* 2007). Sediment was collected from a nearby stormwater retarding basin and strained through a 1,000 μm sieve. The concentration of solids in the sieved slurry was measured prior to mixing with a known amount of dechlorinated tap water to ensure the target TSS concentration was achieved. Target concentrations for TSS and nutrients were matched with typical values for worldwide and Melbourne urban stormwater quality reported by Duncan (1999) and Taylor *et al.* (2005) respectively. The mixture was topped up using chemicals where necessary to make up the deficit in nutrient concentrations.

Stormwater dosing, sampling and analysis

The stormwater dosing regimen reflected Melbourne average annual rainfall volumes, for a biofilter sized to 2.5% of its contributing catchment area, based on Australian design guidelines (see Hatt *et al.* 2007). The columns received 3.7 L of stormwater during each dosing event. The dosing campaign simulated wet and dry climate conditions by altering the frequency of events (see Figure 2). Each climate reflected typical Melbourne rainfall patterns (Bureau of Meteorology 2013). During the wet periods (April–November) the columns were dosed twice weekly. During the dry period (December–March) the column dosing gradually transitioned from 6 to 18 antecedent dry days to reduce the risk of plant fatality. Sampling took place for 10 select dosing events over the 12-month period from August 2011 to July 2012. Column effluent was collected until flow ceased (approximately 3.0 of the 3.7 L). This bulk sample was mixed thoroughly then sub-sampled for analysis. Samples were analysed for TSS, TN, TP and their dissolved species. Samples analysed for dissolved nutrients were filtered through a 0.45 μm filter (Bonnet Scientific). All water chemical analyses were undertaken by NATA (National Association for Testing Authorities) certified laboratories using standard analysis methods (APHA/AWWA/WPCF 1998). At several points during the campaign discrete water samples were collected from ports installed along the column to measure dissolved oxygen (DO) concentrations in the SZ before and after dosing events using a fibre-optic oxygen meter (PyroScience FireStingO$_2$).

Data analysis

All statistical analyses were performed using SPSS (version 20. IBM, USA). Analysis of variance (ANOVA) was used to compare performance between biofilter configurations and climate periods, with post-hoc tests used to compare individual pairs (Tukey's HSD where inequality of variance occurred and Tamhane's where not). Data reported below detection limits (e.g. <0.001) were analysed at half the limit of reporting value (e.g. 0.0005). Data from the first sample event (September) were omitted from the analysis because at this stage the columns were still establishing. Additionally, sample data from the SS-V-NS columns were omitted for the eighth event (May), as infiltration had ceased due to sediment clogging of the surface layer. This sediment layer was disturbed manually by gently scraping the surface, allowing regular infiltration to resume.

RESULTS AND DISCUSSION

Phosphorus removal performance of alternative biofilter designs

The influence of filter media

Analysis of TP outflow concentrations from the loamy sand (LS-V-S) and Skye sand (SS-V-S) columns suggests that filter medium type did not significantly influence TP removal (Figure 3). This finding is at least partially attributed to the fact that very effective TSS (86–99%) removal was achieved by both filter media and approximately ~70% of TP is associated with particulates. However, all design configurations also consistently achieved very good removal of PO_4^{3-} (>96%, Table 3) and there were no significant differences between the two filter media types. Perhaps it is not altogether unsurprising that no differences in PO_4^{3-} removal

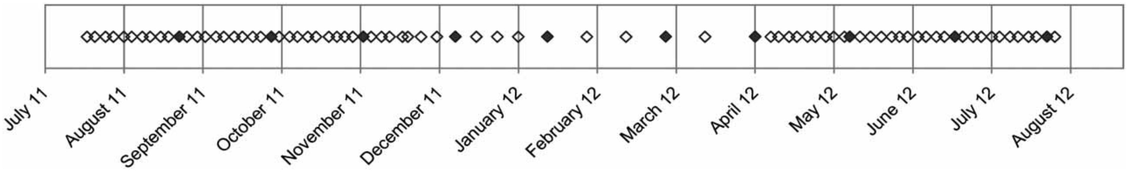

Figure 2 | Stormwater dosing and sampling regime (filled markers denote sampled events).

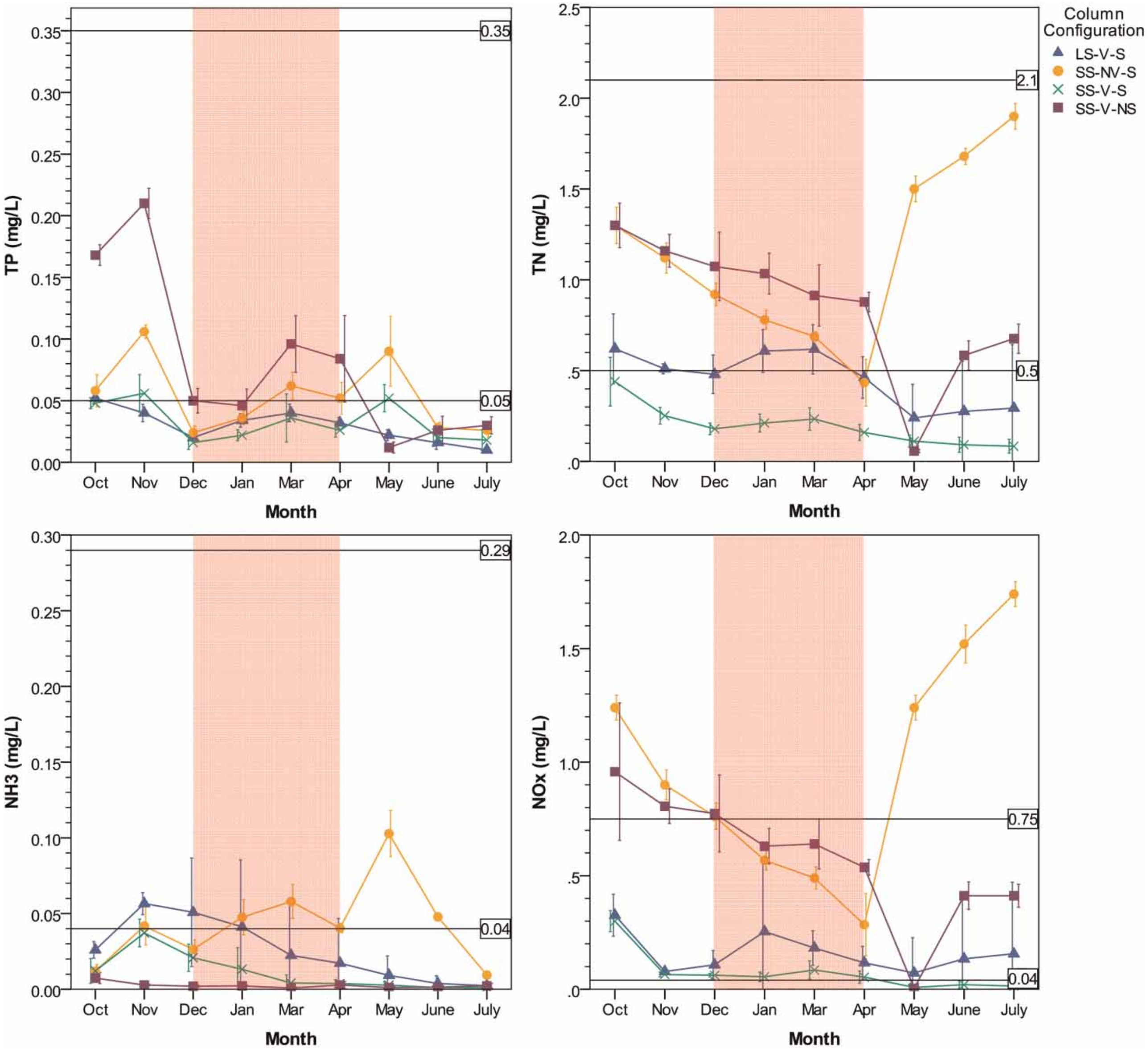

Figure 3 | Biofilter column outflow concentrations (mg/L) from October 2011 to July 2012 (TP, top left; TN, top right; ammonia, NH3, bottom left; and nitrous oxides, NOx, bottom right). Data points represent the mean ($n = 5$) and error bars represent ±1 standard deviation from the mean. Upper horizontal reference line denotes inflow concentration; lower horizontal reference line represents the water quality guideline concentration for slightly disturbed lowland rivers in South-Eastern Australia (ANZECC & ARMCANZ 2000). Shaded area represents the dry dosing period.

were observed given that the testing period (1 year) was relatively short and neither loamy sand nor Skye were likely to approach PO_4^{3-} saturation during this time. The role of filter media may become more important as plants reach maturity and P uptake and release (due to plant senescence) approach equilibrium. Given that Skye sand has higher concentrations of Fe and Al oxides, to which PO_4^{3-} is readily adsorbed, the sorption capacity and life-span of this medium is expected to extend beyond that of loamy sand (Glaister *et al.* 2011).

Interactions with vegetation and SZ

Vegetation had a significant effect on PO_4^{3-} removal ($p < 0.001$) but not TP. This is perhaps not surprising, given that PO_4^{3-} is chemically and biologically driven, while TP removal is primarily related to removal of TSS. TP removal was improved by the addition of vegetation (Figure 3). Vegetation provides a removal pathway for dissolved nutrients through plant uptake, and supports biological activity in the rhizosphere, which also contributes

Table 3 | Average outflow nutrient concentrations for wet and dry dosing periods (mg/L)

		LS-V-S	**SS-NV-S**	**SS-V-S**	**SS-V-NS**
TP	Wet[a]	0.046 (88)	0.082 (79)	0.052 (87)	0.19 (52)
	Dry	0.032 (92)	0.044 (89)	0.025 (93)	0.069 (82)
	Wet[b]	0.016 (95)	0.048 (86)	0.030 (91)	0.028 (92)
PO_4^{3-}	Wet[a]	0.003 (99)	0.002 (99)	0.002 (99)	0.004 (98)
	Dry	0.002 (99)	0.003 (98)	0.003 (99)	0.003 (98)
	Wet[b]	0.002 (98)	0.002 (97)	0.001 (98)	0.003 (98)
TN	Wet[a]	0.56 (70)	1.2 (35)	0.34 (82)	1.2 (33)
	Dry	0.54 (69)	0.71 (60)	0.20 (89)	0.97 (44)
	Wet[b]	0.27 (85)	1.7 (8)	0.096 (95)	0.63 (66)
NH_3	Wet[a]	0.041 (89)	0.027 (93)	0.026 (93)	0.005 (99)
	Dry	0.037 (88)	0.043 (84)	0.012 (96)	0.002 (99)
	Wet[b]	0.005 (99)	0.053 (85)	0.002 (99)	0.001 (100)
NO_X	Wet[a]	0.20 (80)	1.1 (−10)	0.18 (81)	0.88 (9)
	Dry	0.17 (81)	0.53 (41)	0.064 (93)	0.65 (27)
	Wet[b]	0.13 (86)	1.5 (−59)	0.013 (99)	0.41 (59)

[a] Wet period August–November.

[b] Wet period April–July.

Percentage removed is given in parentheses.

to P removal through microbial assimilation. Furthermore, vegetation improves soil structure, which provides resilience to cracking and the formation of preferential flow pathways during dry periods. The SZ was also found to have a significant influence on P removal (TP and PO_4^{3-}). Inclusion of the SZ reduced the infiltration rate by decreasing the hydraulic head, effectively creating a buffer to high-velocity flow, thereby minimising mobilisation of P-laden particles into the effluent. Retention of stormwater in the SZ also increases detention time between dosing events, allowing P to undergo further biological uptake and chemical complexation. The sustained PO_4^{3-} removal throughout the campaign suggests that biodegradation of the carbon source did not contribute to P leaching and that reduction of Fe-bound P in the filter media did not occur.

Nitrogen removal performance of alternative biofilter designs

The influence of filter media

TN removal trends were similar for LS-V-S and SS-V-S throughout the campaign, although concentrations were consistently lower from the SS-V-S configuration (see Figure 3). ANOVA confirmed this, indicating a significant difference in TN and NH_3 removal between LS-V-S and SS-V-S ($p <$ 0.001). This may be attributed to greater adsorption of ionised ammonia (NH_4^+) in the Skye sand filter medium, which has a higher clay content than loamy sand. Filter medium type did not have a significant influence on NO_x removal, as was discussed in relation to PO_4^{3-}, and this is not surprising, given that NO_x removal is chemically and biologically driven. The very low TN and NO_x concentrations recorded in May (following clogging of the columns) highlights the sensitivity of these systems to changes in hydraulic conductivity and emphasises the influence of detention time on treatment performance. While the clogging may appear to have been beneficial for N treatment it is important to remember that under these conditions the biofilters were not operating within the infiltration rate guidelines of 200–400 mm/h.

Interactions with vegetation and SZ

Vegetation and the inclusion of an SZ had a significant influence on NO_x treatment (and subsequently TN). This was exemplified by the results for the non-vegetated (SS-NV-S) and non-saturated (SS-V-NS) configurations, which both showed poor NO_x removal throughout the experimental period (see Figure 3). Inclusion of vegetation supports biological removal pathways for NO_x captured from incoming stormwater and produced between events through nitrification. Mean DO concentrations in the SZ before (2.1 mg/L) and after (3.7 mg/L) dosing events indicated that conditions were not depleted to the point where denitrification would occur (<0.5 mg/L). However, it is nevertheless possible that anaerobic microsites exist within the SZ where denitrifying bacteria are active (Parkin 1987). The improved NO_x removal demonstrated in the SZ inclusive columns may also be explained by the extended detention time imposed between events, providing further opportunity for biological uptake to occur. NH_3 removal was not affected by the presence or absence of the SZ, presumably because it was retained or nitrified in the upper aerobic layers. However, given the important role which the SZ plays in NO_x removal, its inclusion is recommended to ensure effective overall N removal.

Resilience to variable inflow hydrology

Outflow concentrations from the biofilters during the three climate periods, wet^a (October–November), dry (December–March), and wet^b (April–July) are summarised in Table 3. Treatment performance for all nutrients remained relatively consistent between the periods in configurations inclusive of vegetation and SZ (i.e. LS-V-S and SS-V-S). TP concentrations from the SS-V-S columns increased marginally when wet dosing resumed. This was attributed to particulate P mobilisation upon re-wetting. TP concentrations returned to pre-rewetting concentrations in the next sample (June). Therefore, both filter media tested were found to be resilient over extended dry periods when coupled with vegetation and an SZ. The SZ supported nutrient-removal processes during the extended dry period by providing access to a permanent pool of water to sustain plant health, increasing detention time for biological removal processes to occur, and supporting hydro-chemical conditions to facilitate denitrification. The absence of vegetation had a persistent effect on NH_3 removal performance, which gradually declined over the dry and into the second wet period. The vegetated configurations show that NH_3 removal can otherwise be maintained throughout wet and dry periods, with or without the inclusion of an SZ. Vegetation provides a pathway for NH_3 removal under dry conditions, when biological processes slow down and limit nitrification. The impact of wetting and drying in the non-vegetated configuration (SS-NV-S) was most detrimental to NO_x removal (and consequently TN). NO_x removal was maintained over the extended dry period when increased retention time allowed the SZ to become anaerobic and promote denitrification. Extended detention also facilitated advanced biological uptake of NO_x. When regular dosing resumed, the non-vegetated systems responded immediately and began to leach NO_x, which continued for the remainder of the experiment. This suggests that NO_x removal can be maintained over dry periods in non-vegetated SZ inclusive columns, but when dosing frequency increases, oxygen conditions change and detention time in the SZ is reduced, compromising NO_x treatment. Conversely, very good NO_x removal was maintained in the LS-V-S and SS-V-S configurations (>80% removal). This highlights the role of biological uptake in N removal and the importance of coupling vegetation with the inclusion of an SZ.

Performance relative to ecosystem protection guidelines

Table 4 summarises biofilter performance relative to typical Australian and New Zealand receiving water nutrient guideline concentrations (ANZECC & ARMCANZ 2000). TP concentrations less than or equal to the guideline targets were successfully achieved by the SS-V-S and LS-V-S columns throughout the experiment. At the time of the last sampling event all configurations were meeting the TP water quality guideline concentrations. All configurations maintained PO_4^{3-} concentrations below the guideline throughout the experiment. TN concentrations were maintained below guidelines throughout the experiment by the SS-V-S columns. Minimal variation between SS-V-S replicates and consistent results over the sampling events represents a success as studies often cite variability in this regard. LS-V-S outflows also remained close to the TN target concentration, increasing only marginally during the transition into the dry climate. Conversely, TN concentrations from the non-vegetated (SS-NV-S) and non-saturated (SS-V-NS) configurations remained above the guideline for the duration of the experiment. Similar trends were apparent in terms of NO_x removal, although only the SS-V-S configuration achieved the target values. The non-vegetated columns (SS-NV-S) did not achieve the NH_3 targets, although the non-saturated, vegetated configuration (SS-V-NS) achieved this target consistently. The SS-V-S and LS-V-S began to meet the NH_3 target concentration halfway through the experiment, most likely coinciding with the growth of plant roots into the SZ where trapped NH_3 could be accessed.

Table 4 | Summary of success in achieving Australian and New Zealand Environment Conservation Council water quality guideline concentrations (based on trigger guideline values for lowland rivers) (ANZECC & ARMCANZ 2000)

Column	TP	PO_4^{3-}	TN	NO_x	NH_3
LS-V-S	✓	✓	✓	✗	✓
SS-NV-S	✓	✓	✗	✗	✗
SS-V-S	✓	✓	✓	✓	✓
SS-V-NS	✓	✓	✗	✗	✓

CONCLUSIONS

This study investigated nutrient removal performance of biofilter columns under the influence of design modifications (filter media type, vegetation and SZ) and variable climate conditions. The results demonstrated that a vegetated biofilter configured with Skye sand and an SZ can maintain very good N and P removal, and achieve receiving water protection targets in wet and dry climates. The importance of vegetation and an SZ to maintain co-optimised N and P removal under variable climate conditions was also highlighted. However, this experiment was undertaken over a relatively short time period, during which the plants experienced substantial growth. The nutrient removal performance exhibited by these biofilter columns should therefore be verified by research quantifying N and P removal performance as system establishment stabilises and as filter media approach P saturation. In practice, these results may have significant relevance when designing biofilters in areas which experience prolonged dry periods, or where the protection of receiving waters is a priority.

ACKNOWLEDGEMENTS

We appreciate the financial support of Melbourne Water (State Government of Victoria). Special thanks are also extended to Richard Williamson and Tony Brosinsky (Monash University Civil Engineering Hydraulics Laboratory). We acknowledge our partners at Monash University in the School of Biological Sciences, and the School of Chemistry (Water Studies Centre) for support and advice. Fletcher is supported by an ARC Future Fellowship. Two anonymous reviewers are thanked for their constructive comments.

REFERENCES

APHA/AWWA/WPCF 1998 *Standard Methods for the Examination of Water and Wastewater*. Washington, DC, USA.

Arias, C. A., Del Bubba, M. & Brix, H. 2001 Phosphorus removal by sands for use as media in subsurface flow constructed reed beds. *Water Research* **35** (5), 1159–1168.

ASTM F1815-11 2011 Standard test methods for saturated hydraulic conductivity, water retention, porosity, and bulk density of athletic field rootzones. American Society for Testing and Materials.

ANZECC & ARMCANZ 2000 *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*, Australian and New Zealand Environmental and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Blecken, G.-T., Zinger, Y., Deletic, A., Fletcher, T. D. & Viklander, M. 2009 Influence of intermittent wetting and drying conditions on heavy metal removal by stormwater biofilters. *Water Research* **43** (18), 4590–4598.

Boström, B., Andersen, J. M., Fleischer, S. & Jansson, M. 1988 Exchange of phosphorus across the sediment-water interface. *Hydrobiologia* **170** (1), 229–244.

Bratieres, K., Fletcher, T. D., Deletic, A. & Zinger, Y. 2008 Nutrient and sediment removal by stormwater biofilters: a large-scale design optimisation study. *Water Research* **42** (14), 3930–3940.

Browning, K. & Greenway, M. 2003 Nutrient removal and plant biomass in a subsurface flow constructed wetland in Brisbane, Australia. *Water Science and Technology* **48** (5), 183–189.

Bureau of Meteorology 2013 Climate Data [Online]. Available: www.bom.gov.au (accessed September 2013).

Chen, X., Peltier, E., Sturm, B. S. M. & Young, C. B. 2013 Nitrogen removal and nitrifying and denitrifying bacteria quantification in a stormwater bioretention system. *Water Research* **47** (4), 1691–1700.

Davis, A. P., Hunt, W. F., Traver, R. G. & Clar, M. 2009 Bioretention technology: overview of current practice and future needs. *Journal of Environmental Engineering* **135** (3), 109–117.

Del Bubba, M., Arias, C. A. & Brix, H. 2003 Phosphorus adsorption maximum of sands for use as media in subsurface flow constructed reed beds as measured by the Langmuir isotherm. *Water Research* **37** (14), 3390–3400.

Dietz, M. E. & Clausen, J. C. 2006 Saturation to improve pollutant retention in a rain garden. *Environmental Science & Technology* **40**, 1335–1340.

Duncan, H. P. 1999 *Urban Stormwater Quality: A Statistical Overview*. Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia.

Ellerton, J., Hatt, B. E., Fletcher, T. D., Cook, P. L. M. & Denton, M. 2012 Mixed plantings of Carex appressa and Lomandra longifolia improve pollutant removal over monocultures of L. Longifolia in stormwater biofilters. In: *Seventh International Conference on Water Sensitive Urban Design*. Melbourne, Australia.

FAWB 2009 *Adoption Guidelines for Stormwater Biofiltration Systems*. Facility for Advancing Water Biofiltration, Monash University, Melbourne, Australia.

Glaister, B., Fletcher, T. D., Cook, P. L. M. & Hatt, B. E. 2011 Can stormwater biofilters meet receiving water phosphorus targets? A pilot study investigating metal-oxide enriched filter media. In: *15th International Conference of the IWA Diffuse Pollution Specialist Group on: Diffuse Pollution and Eutrophication*. Rotorua, New Zealand.

Hatt, B. E., Fletcher, T. D. & Deletic, A. 2007 Stormwater reuse: designing biofiltration systems for reliable treatment. *Water Science and Technology* **55** (4), 201–209.

Hatt, B. E., Fletcher, T. D. & Deletic, A. 2009 Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. *Journal of Hydrology* **365** (3–4), 310–321.

Henderson, C., Greenway, M. & Phillips, I. 2007a Removal of dissolved nitrogen, phosphorus and carbon from stormwater by biofiltration mesocosms. *Water Science and Technology* **55** (4), 183–191.

Henderson, C., Greenway, M. & Phillips, I. 2007b Sorption behaviour of nutrients in loamy-sand bioretention media subject to different conditions (vegetation, enrichment and incubation time). In: *13th International Rainwater Catchment Systems Conference and 5th International Water Sensitive Urban Design Conference*. Sydney, Australia.

Hsieh, C. H., Davis, A. P. & Needelman, B. A. 2007a Bioretention column studies of phosphorus removal from urban stormwater runoff. *Water Environment Research* **79** (2), 177–184.

Hsieh, C. H., Davis, A. P. & Needelman, B. A. 2007b Nitrogen removal from urban stormwater runoff through layered bioretention columns. *Water Environment Research* **79** (12), 2404–2411.

Hunt, W., Jarrett, A., Smith, J. & Sharkey, L. 2006 Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. *Journal of Irrigation and Drainage Engineering* **132** (6), 600–608.

Kadlec, R. H & Knight, R. L. 1996 *Treatment Wetlands*. CRC Lewis Press, Boca Raton.

Korom, S. F. 1992 Natural denitrification in the saturated zone – a review. *Water Resources Research* **28** (6), 1657–1668.

Lucas, W. & Greenway, M. 2008 Nutrient retention in vegetated and nonvegetated bioretention mesocosms. *Journal of Irrigation and Drainage Engineering* **134** (5), 613–623.

Parkin, T. B. 1987 Soil microsites as a source of denitrification variability. *Soil Science Society of America Journal* **51** (5), 1194–1199.

Read, J., Fletcher, T. D., Wevill, P. & Deletic, A. 2010 Plant traits that enhance pollutant removal from stormwater in biofiltration systems. *International Journal of Phytoremediation* **12** (1), 34–53.

Read, J., Wevill, T., Fletcher, T. D. & Deletic, A. 2008 Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Research* **42** (4–5), 893–902.

Taylor, G. D., Fletcher, T. D., Wong, T. H. F., Breen, P. F. & Duncan, H. P. 2005 Nitrogen composition in urban runoff – implications for stormwater management. *Water Research* **39** (10), 1982–1989.

Vymazal, J. 2007 Removal of nutrients in various types of constructed wetlands. *Science of The Total Environment* **380** (1–3), 48–65.

Walsh, C. J., Leonard, A. W., Ladson, A. R. & Fletcher, T. D. 2004 *Urban Stormwater and the Ecology of Streams*. Melbourne Water Studies Centre, CRC for Freshwater Ecology, CRC for Catchment Hydrology, Melbourne, Australia.

Wild, A. 1950 The retention of phosphate by soil. A Review. *Journal of Soil Science* **1** (2), 221–238.

Zinger, Y., Blecken, G. T., Deletic, A., Fletcher, T. D. & Viklander, M. 2012 Retrofitting a saturated zone (RSAZ) in stormwater biofilters; impact on pollutants removal. In: *7th International Conference on Water Sensitive Urban Design*, Melbourne, Australia.

First received 18 July 2013; accepted in revised form 19 February 2014. Available online 6 March 2014