Intra-event nutrient removal dynamics in stormwater biofilters: the influence of system design

Les dynamiques intra-événementielles de l'abattement des nutriments dans des biofiltres ; l'influence de la conception

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RÉSUMÉ

Le rendement épuratoire d'un ouvrage de biofiltration est normalement calculé en termes de concentration moyenne évènementielle (CME). Par conséquent, la variation temporelle du traitement et le rôle des facteurs de conception sur cette variation sont encore peu connus. Nous avons donc mené une étude en laboratoire afin de mieux comprendre l'effet des paramètres de conception (substrat, végétal et présence ou non d'une zone saturée) et les conditions de fonctionnement sur les concentrations de nutriments rejetées par les biofiltres. Les résultats montrent que la présence du végétal et d'une zone saturée améliorent le rendement épuratoire du système, et réduisent la variation temporelle des concentrations. La zone saturée est également primordiale pour minimiser le flux des matières en suspension (et les nutriments qui s'y trouvent). L'inclusion d'un sable riche en fer dans le substrat permettait de stabiliser le traitement de l'azote après des périodes sèches. La complexité du comportement de différentes espèces de nutriments met en évidence la difficulté d'optimiser un biofiltre pour tous types de polluants. Les résultats montrent que la performance d'un biofiltre dépend surtout du choix du substrat et du végétal, ainsi que de la présence d'une zone saturée, mais que la même performance peut être atteinte avec un système simple sans drain.

ABSTRACT

Treatment performance of stormwater biofilters is typically reported as an event mean concentration. Consequently, little is currently understood about how pollutant removal fluctuates during events or how biofilter design features affect intra-event treatment. To investigate how design characteristics (filter media, vegetation and a saturated zone) and operational conditions influence intra-event nutrient removal nutrient concentrations from 20 laboratory-scale stormwater biofilter columns were monitored during two simulated rainfall events. The results demonstrate that inclusion of vegetation and a saturated zone enhances nitrogen removal and reduces intra-event treatment variability. Including a saturated zone also minimises mobilisation of particulate-bound nutrients. Nutrient species responded differently to changes in inflow volume and dry weather antecedence, making nutrient removal optimisation a challenge. Biofilters containing iron-rich filter media, 'Skye sand', exhibited greater intra-event nitrogen removal resilience following dry periods than loamy sand. These findings demonstrate that biofilters designed with appropriate filter media, vegetation and a saturated zone can satisfy nutrient treatment objectives with relatively good consistency during rainfall events, which is critical for biofilters servicing ecosystems sensitive to changes in nutrient concentrations. However, these objectives could perhaps be more easily achieved by constructing biofilters without an underdrain.

KEYWORDS

Biofilter, intra-event, nitrogen, phosphorus, saturated zone, Skye sand, stormwater

1 INTRODUCTION

Urban stormwater runoff has been shown to have a detrimental impact on the water quality and hydrology of receiving waterways (Walsh et al., 2005). Nutrient-rich stormwater poses a particularly severe threat to aquatic ecosystems, causing excessive plant growth, depleted oxygen concentrations and eutrophication (Smith et al., 1999). Biofiltration systems (also known as bioretention systems, biofilters, and rain gardens) are recognised as an effective technology for the interception and treatment of stormwater (Davis et al., 2009, Hatt et al., 2009). Previous laboratory and field-scale research has demonstrated that biofilters are capable of achieving effective and reliable phosphorus (P) removal (80-90%) (Davis et al., 2001). However, reported nitrogen (N) removal continues to be variable (Davis et al., 2006, Bratieres et al., 2008), particularly following dry weather periods (Zinger et al., 2007a, Hatt et al., 2007a).

Inter-event fluctuations in N removal and instances of N leaching have often been attributed to NO_x production within biofilters due to nitrification of retained ammonium (Cho et al., 2009, Hsieh et al., 2007). Maintaining robust nutrient treatment following dry periods is a critical objective for biofilters, particularly in semi-arid climates like Australia. Inclusion of suitable vegetation and a saturated zone has been shown to enhance N removal, diminish the effects of drying, and reduce inter-event N removal variability (Zinger et al., 2007b, Payne et al., 2014b, Glaister et al., 2014, Kim et al., 2003), but this is sometimes achieved to the detriment of P removal (Zinger et al., 2013). Further, reported effluent concentrations of total nitrogen (TN), total phosphorus (TP) and their dissolved species from biofilters typically exceed Australian water quality guideline trigger levels for aquatic ecosystem protection (ANZECC/ARMCANZ, 2000). Whether nutrient concentrations in biofilter effluent remain above guideline levels during part of or throughout events is unclear, since concentrations are typically reported in terms of an event mean concentration (EMC) (Davis, 2007). While this method provides a good overall estimation of mass load reduction, it does not give insight into the mechanisms that govern nutrient processing or how effluent concentrations fluctuate during events. Intra-event fluctuations in nutrient concentrations have the potential to significantly impact small streams or disturbed ecosystems that are sensitive to concentration changes. As such, determining the extent to which nutrient concentrations fluctuate during events is critical to designing biofilters that provide optimal nutrient processing and protection for urban waterways and predicting how changes in operational conditions influence treatment. Whilst monitoring of consecutive events has been used to examine the influence that previous events have on internal nutrient removal processes (Brown et al., 2013), studies monitoring intra-event fluctuations in nutrient removal are limited (Hatt et al., 2009, Davis, 2007). Moreover, the influence of biofilter design characteristics, such as a saturated zone, on intra-event nutrient removal behaviour is yet to be investigated.

2 METHODS

2.1 Biofilter column design

2.1.1 Column configuration

Four biofilter configurations were designed to compare nutrient removal performance between systems with different filter media, with and without vegetation (*Carex appressa*), and with and without inclusion of a saturated zone and carbon source (see Table 1). Two filter media were tested: loamy sand, currently recommended for use in biofilters (FAWB, 2009), and 'Skye sand', a naturally occurring iron-coated sand. Previous testing has indicated that Skye sand has a greater capacity to adsorb dissolved P than loamy sand (Glaister et al., 2011) and can achieve enhanced N removal in conjunction with vegetation and a saturated zone (Glaister et al., 2014).

Table 1 Biofilter column design configurations

Column ID	Filter Medium	Vegetation (Y/N)	Saturated Zone (Y/N)
LS-V-S	Loamy Sand	Y	Y
SS-V-S	Skye Sand	Y	Y
SS-NV-S	Skye Sand	N	Y
SS-V-NS	Skye Sand	Y	N

2.1.2 Column construction

Twenty biofilter columns, five replicates of each configuration, were constructed using PVC pipes (150mm x 600mm) joined to a transparent Perspex pipe to provide a 200mm ponding zone. The filter media (300mm) was underlain by a coarse washed sand transition zone (200mm) and pea gravel (70mm) and a gravel drainage layer (30mm). A cross section of the columns is shown in Figure 1. Effluent drained freely from the base outlets of the non-saturated columns while a riser pipe was attached to the outlet of those with a saturated zone to maintain a 300mm internal ponding zone in the lower part of the columns.

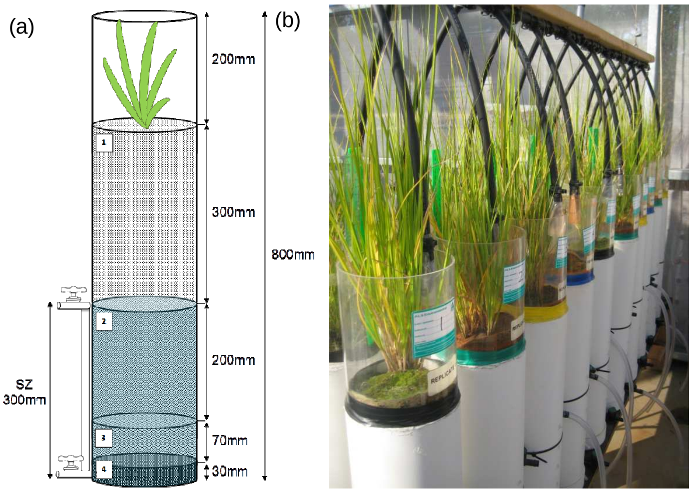

Figure 1 (a) Schematic diagram of the biofilter columns (with SZ rise outlet attached) and (b) experimental set-up of biofilter columns in greenhouse

2.2 Stormwater preparation, dosing and sampling

Because of the uncertainty and inconsistency associated with the use of natural stormwater, this study utilised methods described by prior studies (e.g. Glaister et al., 2014, Hatt et al., 2007b) to produce a semi-synthetic stormwater of a quality consistent with reported stormwater pollutant concentrations (Duncan, 1999, Taylor et al., 2005). Stormwater dosing occurred over a 12 month period with volumes designed to reflect rainfall received by a biofilter sized to 2.5% of its catchment area in Melbourne, Australia, where the annual effective rainfall is approximately 540mm. During the 12 month dosing period two sequential sampling experiments were conducted to measure intra-event nutrient concentration variability in biofilters' effluent. Samples were collected sequentially in order to capture the transition in biofilter effluent from 'old' stormwater retained in the system from the previous dosing to 'new', freshly applied stormwater. The first experiment took place in 8 months after column establishment following 18 antecedent dry days (ADD). This experiment utilised twenty biofilter columns (n=5) and represented a standard stormwater dosing volume (3.7L) equivalent to 5mm of rainfall (where the biofilter surface area represented 2.5% of its contributing catchment). Three consecutive effluent samples of approximately 1L were collected during the first experiment. The second experiment was conducted after 12 months of dosing and following 2 ADD. In this instance, 12 biofilter columns were sampled (n=3) after dosing with 7.4L of stormwater (representative of a 10mm rainfall event). At least 12 consecutive 500mL samples were collected from the columns, of which every second was analysed; approximately 6.0-6.5L of stormwater was recovered overall. This sampling regime enabled an event 'pollutograph' to be produced, providing greater insights into intra-event fluctuations in effluent nutrient concentrations.

2.3 Water quality testing and data analysis

The effluent samples were analysed for TP, TN, total dissolved phosphorus (TDP) and nitrogen (TDN), ammonia (NH_3), nitrate and nitrite (NO_x) and filterable reactive phosphorus (FRP) using flow injection analysis (Lachat, QuikChem® 8000). Concentrations of dissolved and particulate organic nitrogen (DON, PON) and particulate phosphorus (PP) were determined from these results. Samples for dissolved nutrient analysis were filtered immediately following collection (0.45µm Bonnet Scientific). Water analyses were undertaken in a NATA (National Association for Testing Authorities) certified laboratory using standard methods and quality control procedures (APHA/AWWA/WPCF, 2001). Treatment performance between the biofilter configurations was evaluated statistically using a 2-Independent sample non-parametric test (Mann Whitney), where significance was defined as $p \leq 0.05$.

3 RESULTS AND DISCUSSION

3.1 Standard-volume stormwater dosing event

Nutrient concentrations in the biofilter effluent collected during the standard-volume dosing event are illustrated in Figure 2. The three-stage sampling scheme revealed that nutrient concentrations in biofilter effluent fluctuate during events. Excellent FRP removal (>98%) was exhibited by each of the biofilter configurations throughout the event (data not shown), which consistently achieved the water quality targets for ecosystem protection (<0.02mg/L) (ANZECC/ARMCANZ, 2000). Total dissolved phosphorus (TDP) concentrations were consistently below detection limits (<0.1mg/L) in all configurations (data not shown). This performance emphasises the capacity of these recently constructed systems to readily remove phosphate. However, this capacity will diminish as the systems age, at which point the influence of filter media type on phosphate removal will likely become more apparent. Illustrating the results in terms of TP constituents shows that the phosphorus in biofilter effluent is largely particulate associated (PP), and that fluctuations in phosphorus removal are driven by variations in the efflux of particulates (Figure 2). The results for TP suggest that this variability can be reduced by inclusion of vegetation and a saturated zone. Inclusion of these design elements reduces the mobilisation of phosphorus-bound particulates from the biofilters upon rewetting, which is particularly apparent following dry periods. These design elements also maintain effluent TP concentrations below ecosystem protection guideline concentrations (0.05mg/L). Total phosphorus removal was largely unaffected by the choice of filter media. Although, as discussed with regard to FRP, filter media is likely to have more bearing on TP removal as the systems mature.

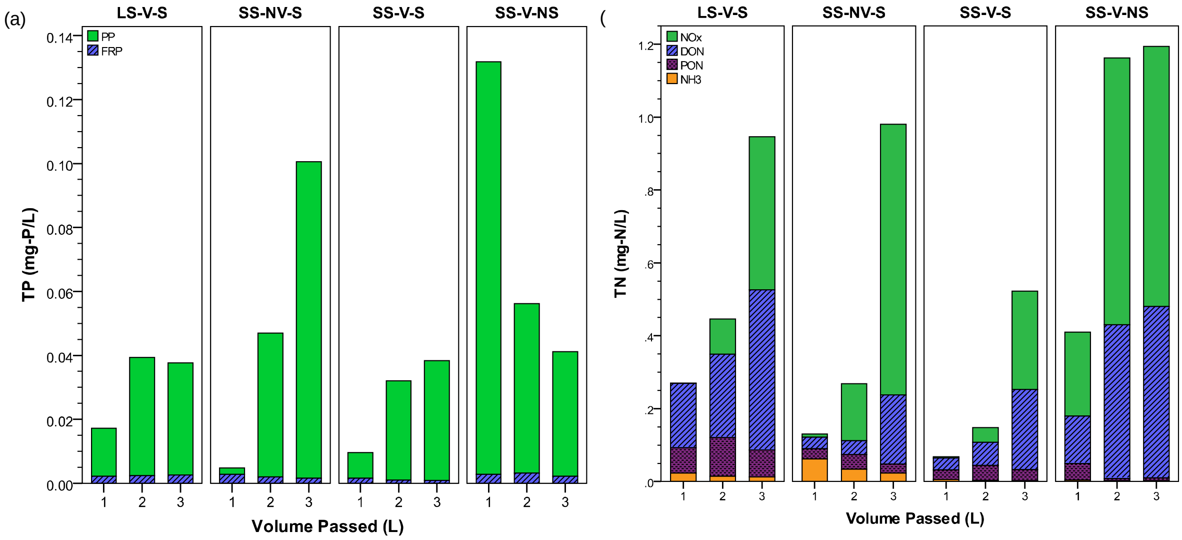

Figure 2 (a) TP (mg/L) and (b) TN (mg/L) concentrations in consecutive effluent samples (L) collected from the biofilter columns after a standard-volume dosing event represented in terms of constituent species. Particulate phosphorus (PP) concentration measured as TP-FRP. Bars represent the mean of five replicates. Panels left to right represent the biofilter configurations (LS: loamy sand, SS: Skye sand, V/NV: vegetated/non-vegetated, S/NS: saturated zone/no saturated zone)

Total nitrogen concentrations varied considerably during the standard dosing event. The inclusion of vegetation and a saturated zone maintained TN and NO_x concentrations below the water quality guideline concentration initially (0.5mg/L and 0.04mg/L respectively), although all configurations exceeded these values after 2L of effluent had passed. Total nitrogen removal variability was attributed mostly to increasing NO_x concentrations in the effluent. The presence of a saturated zone significantly improved NO_x removal (Table 2), reflecting the benefit of having an internal water storage to provide prolonged retention and enhanced treatment between events, in this instance 18 days. However, once the water retained in the saturated zone was exhausted and effluent transitioned to fresh stormwater, NO_x removal performance declined rapidly. At this point the effect of vegetation on NO_x treatment became more evident. Indeed, ongoing monitoring of the biofilters after recommencement of regular dosing (every 2-3 days) showed that without a plant uptake pathway, or sufficient time between events for microbial processes to occur, leaching of internally produced NO_x quickly becomes an issue in non-vegetated biofilters (Glaister et al., 2014). This leaching of NO_x from the non-vegetated systems implied that complete denitrification was not occurring. On this basis we hypothesise that plant-uptake is the primary pathway for NO_x removal. This conclusion is supported by the findings of Payne et al. (2014a) who determined through the application of an N tracer that NO_x uptake is predominately facilitated by assimilation. These findings suggest that NO_x retained in biofilters, or produced within the system between events, can almost be completely removed through biological assimilation prior to the next dosing event, provided there is sufficient retention time between events. Therefore, in order to achieve optimum NO_x removal and minimise intra-event variability in effluent concentrations, biofilters should be vegetated and include a saturated zone large enough to capture inflow of a standard size rainfall event.

The presence of a saturated zone affected DON removal in a similar way to NO_x, whereby the extended retention time in the system allowed DON stored in the saturated zone to undergo further treatment via biological assimilation or biochemical processing (i.e. ammonification, nitrification, and denitrification). The use of Skye sand filter media also affected DON removal significantly, providing enhanced treatment compared to loamy sand filter media (Table 2). This was also the case for PON, for which the best removal consistency was maintained in the Skye sand filter media columns with a saturated zone included. Indeed, effluent concentrations of all nitrogen species were lower from the vegetated, saturated zone Skye sand biofilters (SS-V-S) than the loamy sand biofilters (LS-V-S), suggesting that Skye sand provides better N removal, or perhaps better resilience to the effects of drying than loamy sand. Ammonia (present in stormwater as ammonium NH_4^+) was the only nitrogen species for which the presence of vegetation had a significant influence on treatment performance during the standard dosing event (Table 2). Each of the vegetated biofilter configurations maintained excellent NH_3 removal throughout the event, with effluent concentrations consistently remaining below the ecosystem protection guideline target of 0.02mg/L. However, without vegetation NH_3 concentrations fluctuated somewhat, and despite decreasing, consistently remained above the guideline target. These findings emphasise the critical role plants play in providing a removal pathway for nutrients, particularly during dry periods, when microbial processing slows down.

Table 2. Identification of design elements which had a significant influence on nutrient removal in the biofilter columns during the standard-dosing event as determined by the Mann-Whitney U test for 2-independent non-parametric samples. Significant values (*p<0.05*) are presented in bold. See Table 1 for configuration IDs.

Configurations	TP	FRP*	TN	NH_4^+	NO_x	DON	PON
LS-V-S v. SS-V-S	0.377	**<0.001**	**0.001**	**0.016**	0.780	**<0.001**	**<0.001**
SS-V-S v. SS-NV-S	0.290	**0.001**	0.057	**<0.001**	0.112	0.425	0.561
SS-V-S v. SS-V-NS	**0.001**	**<0.001**	**<0.001**	0.683	**<0.001**	**<0.001**	0.158

* Statistical significance may be due to there being almost zero error between the results

3.2 High-volume stormwater dosing event

Total phosphorus and total nitrogen concentrations in the biofilter effluent collected during the high-volume stormwater dosing event are illustrated in **Erreur ! Source du renvoi introuvable.** and**Erreur ! Source du renvoi introuvable.** respectively in terms of their constituent species. This event occurred 4 months after the standard-dosing event, since which regular stormwater dosing (every 2-3 days) had been reinstated. Similar trends in TP removal were observed in the all the Skye sand filter media biofilters during the event. In the Skye sand configurations with a saturated zone (SS-V-S, SS-NV-S) TP concentrations increased until 2.5L of effluent had passed then decreased until the cessation of outflow. This occurred sooner in the Skye sand biofilters without a saturated zone (SS-V-NS) as fresh stormwater containing P-associated particulates mobilised upon rewetting entered the effluent more quickly. As such, including a saturated zone diminished the peak TP concentration and more evenly spread the event pollutograph. The presence of vegetation also reduced particle migration thereby increasing TP removal by approximately 20% overall. However, neither vegetation nor inclusion of a saturated zone was found to have a significant effect on TP removal, suggesting that the influence of filter media is the driving TP removal (Table 3). Visual examination of the biofilter effluent samples indicated that fluctuations in TP concentrations correlated with increasing turbidity of the effluent. This relationship was not surprising since Skye sand has a strong affinity for P-sorption and a high concentration of very fine particles (25% clay) compared with loamy sand (2% clay) (Glaister et al., 2011). Wash-out of phosphorus associated Skye sand particles may explain why TP removal was better and less variable in the loamy sand biofilters (LS-S-V) during the high-volume event. Because mobilisation of particulates is exacerbated by drying (Blecken et al., 2009, Hatt et al., 2007a) it follows that higher TP effluent concentrations were observed during the standard-dosing event, which occurred after an 18 day dry period. However, the additional establishment time between the events (4 months) could also have influenced the extent of particulate mobilisation. Evidently, mitigating particulate migration is critical to reducing effluent TP concentrations. Measures should therefore be taken to mitigate filter media mobilisation and wash-out during events. For example, filter media should be well graded and strategies to reduce the effects of drying should be considered (i.e. inclusion of a saturated zone or allowing for treatment of other wastewater sources during dry weather periods). Drying of filter media between events also affects the extent to which particles are mobilised upon stormwater dosing. Other than when fresh stormwater containing resuspended particles initially entered the effluent, the Skye sand biofilters maintained TP concentrations below ecosystem protection guidelines concentrations (<0.05mg/L) during the high-volume event. The loamy sand filter media biofilters however maintained concentrations below the target throughout. Excellent FRP removal (>98%) was observed during the high-volume dosing event, indicating that neither of the filter media has reached phosphate saturation and is not likely to some time. Water quality targets for FRP (<0.02mg/L) were also achieved by all configurations throughout.

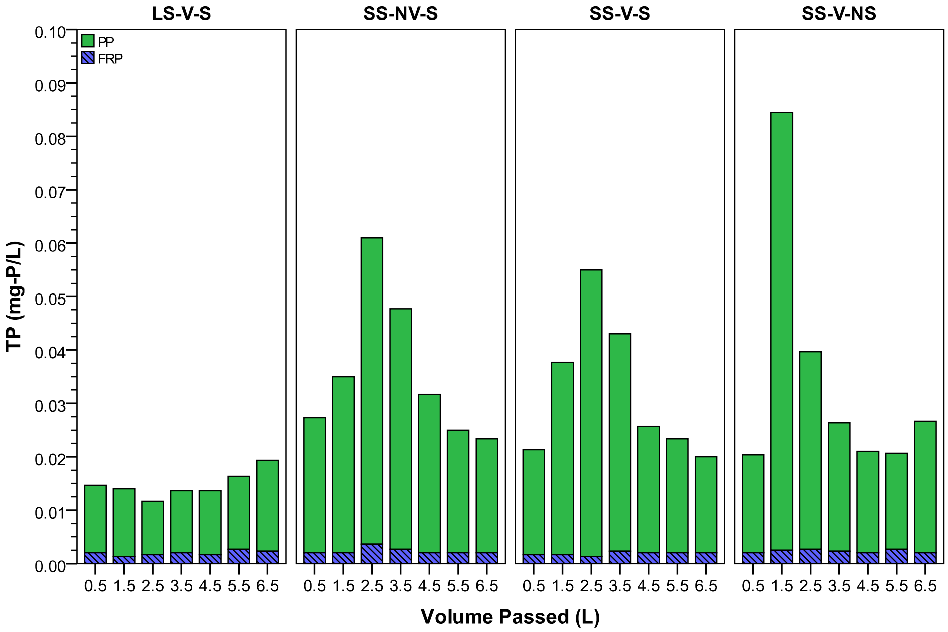

Figure 3 TP (mg/L) concentrations in consecutive effluent samples (L) collected from the biofilter columns after a high-volume dosing event represented in terms of constituent species. Particulate phosphorus (PP) concentration measured as TP-FRP. Bars represent the mean of five replicates. Panels left to right represent the biofilter configurations (LS: loamy sand, SS: Skye sand, V/NV: vegetated/non-vegetated, S/NS: saturated zone/no saturated zone)

Consecutive effluent sampling during the high-volume stormwater dosing event revealed that intra-event nitrogen removal variability was greatest in the absence of vegetation and a saturated zone. These design elements were also found to significantly affect overall TN removal performance (Table 3). Throughout the event, NO_x concentrations in the non-vegetated configuration's effluent exceeded the inflow (0.82mg/L) and were well in excess of the water quality guideline concentration (0.04mg/L). The NO_x leaching was particularly evident in the first 3.5L of effluent, due to the release of NO_x produced between events through nitrification, which without a plant uptake pathway is retained in the system until being flushed out by the next dosing event. The inverse was apparent for NH_3, which gradually increased in concentration during the event as the supply of water retained in saturated zone was exhausted and fresh stormwater, which has had limited time for treatment, entered the effluent (approx. >2.5L). This is however of limited practical importance, considering that all biofilter configurations demonstrated excellent NH_3 removal during the high-volume event (>85%) and achieved water quality guideline targets throughout (0.02mg/L). Nevertheless, these results emphasise the importance of a plant uptake pathway to reduce TN concentrations, in particular NO_x, and maintain an effective level of treatment throughout events.

Dissolved organic nitrogen removal was not significantly affected by absence of vegetation (Table 3) and was almost completely removed in the first 2.5L of outflow from the non-vegetated Skye sand columns (SS-NV-S). This illustrates that in the absence of vegetation, which can be a source of DON, DON can almost be completely removed between events in non-vegetated biofilters when a saturated zone is included. However, as fresh stormwater passes through the biofilter (>2.5L), effluent concentrations increase as there is insufficient time for DON turn-over to be completed. In the vegetated Skye sand biofilter columns with a saturated zone (SS-V-S) DON concentrations also increased with the outflow of 'new' stormwater, although the peak DON concentration in the effluent from this configuration was lower and the pollutograph more evenly spread than that of the non-vegetated system. Concentrations of DON from the loamy sand configuration showed the least intra-event variability, although this configuration did not achieve DON concentrations as low as the Skye sand columns with a saturated zone did in the first 2.5L. In the absence of a saturated zone DON concentrations decreased marginally over the event, suggesting that if we were to extend the pollutograph we would perhaps see DON concentrations in the saturated zone inclusive systems start to decrease.

Particulate organic nitrogen removal was more variable during the high-volume event in the non-saturated configuration, emphasising again the role the saturated zone plays in mitigating particle efflux. Removal of PON was otherwise consistent throughout the high-volume event with similar concentrations being achieved regardless of filter media type or the presence of vegetation. Interestingly, several of the nutrient species found to be significantly affected by filter media type in the standard-volume stormwater dosing event were not in the high-volume event (e.g. NH_3, FRP and PON). This suggests that the influence of design characteristics on nutrient treatment is dynamic, and can become more or less critical under certain operational or environmental conditions than others. For example, NH_3 and FRP removal via sorption to the filter media appears to become more critical during dry periods when plant-uptake and microbial processing slows down.

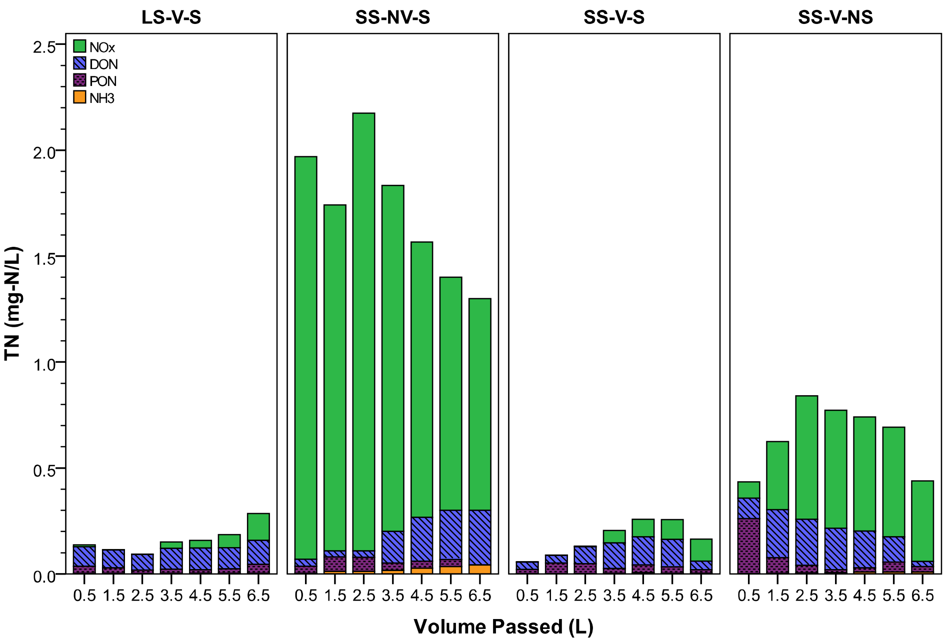

Figure 4 TN (mg/L) concentrations in consecutive effluent samples (L) collected from the biofilter columns after a high-volume dosing event represented in terms of constituent species. Particulate phosphorus (PP) concentration measured as TP-FRP. Bars represent the mean of five replicates. Panels left to right represent the biofilter configurations (LS: loamy sand, SS: Skye sand, V/NV: vegetated/non-vegetated, S/NS: saturated zone/no saturated zone)

Table 3. Identification of design elements which had a significant influence on nutrient removal in the biofilter columns during the high-dosing event as determined by the Mann-Whitney U test for 2-independent non-parametric samples. Significant values (*p<0.05*) are presented in bold. See Table 1 for configuration IDs.

Configurations	TP	FRP	TN	NH_3	NO_x	DON	PON
LS-V-S v. SS-V-S	**<0.001**	0.737	0.403	0.957	0.207	0.037	0.109
SS-V-S v. SS-NV-S	0.225	**0.013**	**<0.001**	**<0.001**	**<0.001**	0.272	0.182
SS-V-S v. SS-V-NS	0.574	**0.012**	**<0.001**	**0.006**	**<0.001**	0.023	0.251

3.3 Recommendations for the use of Skye sand in stormwater biofilters

Based on the results of this study it would be recommended that rather than full substitution of loamy sand with Skye sand it would be better to apply Skye sand to biofilters as an amendment (i.e. blending Skye sand with loamy sand). This would improve the grading of the filter media and thus reduce particle efflux. Nevertheless, since P sorbed to Skye sand is relatively immobile, washout of P-bound Skye sand particles should not pose a serious threat to the water quality of aquatic environments. These very fine particles may however cause discolouration of drains and perhaps more critical issues over time if, following burial of particles in deoxygenated aquatic sediments, dissimilatory iron reduction causes P to be released into the water column.

4 CONCLUSIONS

Using a sequential effluent sampling method, this study assessed the intra-event variability of effluent nutrient concentrations from laboratory-scale biofilter columns following a standard-volume and high-volume stormwater dosing event. The results demonstrated that nutrient concentrations in biofilter effluent vary during events and that the extent of this variation was affected by system design, particularly the absence of vegetation or a saturated zone, and the antecedent dry period. These findings suggest that biofilters can achieve co-optimised intra-event N and P removal and maintain effluent concentrations close to or below water quality guideline values for ecosystem protection under varying hydrologic conditions, provided that suitable vegetation, filter media and a saturated zone are included. However, the best way to ultimately address the challenge of intra-event variability and satisfy the water quality guidelines is to wherever possible use infiltration-based systems that extend detention times by infiltrating water into underlying soils, such that the biofiltration process continues.

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