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Zero additional maintenance stormwater biofilters: from laboratory testing to field implementation

Veljko Prodanovic[a,*], Belinda Hatt[b], Harsha Fowdar[c], Mohammed Al-Ameri[d] and Ana Deletic[a,e]

[a] Water Research Centre, School of Civil and Environmental Engineering, UNSW Sydney, Kensington, NSW 2052, Australia
[b] Melbourne Water Corporation, 990 La Trobe Street, Docklands, VIC 3008, Australia
[c] Environmental and Public Health Microbiology Laboratory (EPHMLab), Department of Civil Engineering, Monash University, Wellington Road, Clayton, VIC 3800, Australia
[d] Civil Engineering Department, University of Technology Iraq, Baghdad, Iraq
[e] School of Civil and Environmental Engineering, Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4001, Australia
*Corresponding author. E-mail: prodanovic.veljko@gmail.com; v.prodanovic@unsw.edu.au

VP, 0000-0002-3800-0765

ABSTRACT

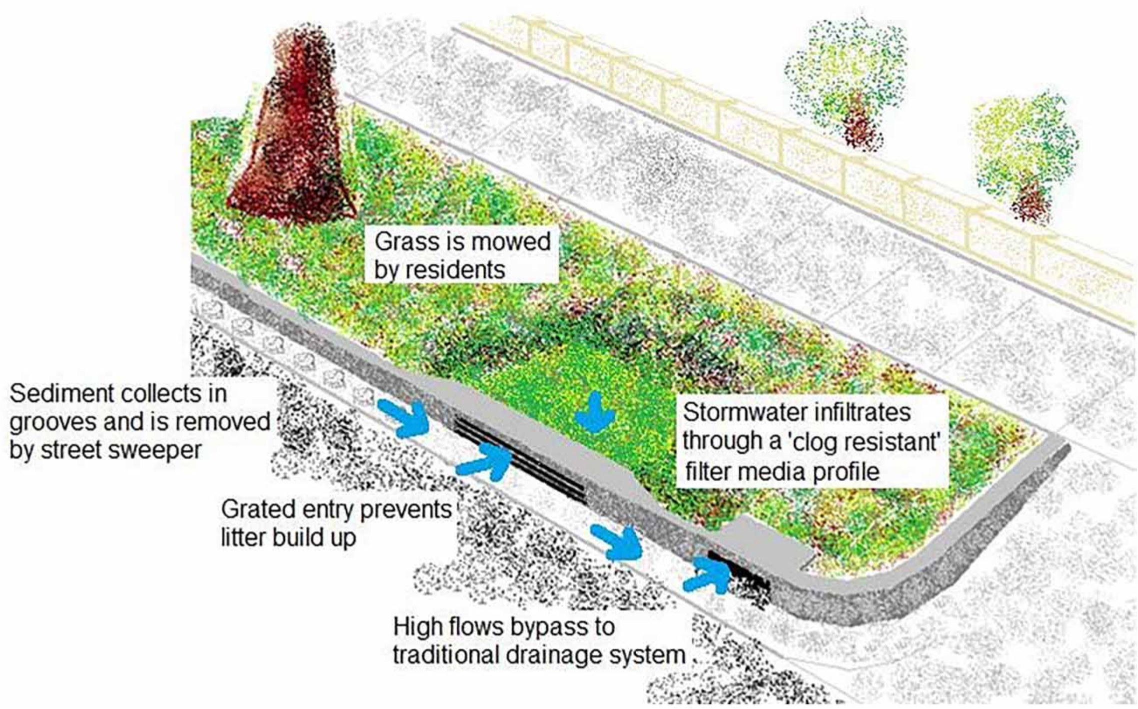
Stormwater biofilters are one of the most widely used nature-based solutions for urban water management. In the last 20 years, biofilters have been extensively studied for their pollutant removal performance; however, their application in the field is limited by high maintenance requirements. In this work, we propose the concept of zero additional maintenance (ZAM) biofilters as a solution to this challenge. To understand the design and operation of ZAM biofilters, a three-stage research programme was conducted to (i) examine filter media configurations that could protect against surface clogging, (ii) test the pollutant removal performance of a variety of lawn grasses, and (iii) validate the laboratory findings through field monitoring. The results showed that a protective filter media layer delayed the onset of clogging. Five lawn grasses – *Kenda Kikuyu*, *Empire Zoysia*, *Santa Ana Couch*, *Village Green Kikuyu* and *Palmetto Soft Leaf Buffalo* – were found to effectively reduce nitrogen concentrations and meet other local pollution reduction requirements. Monitoring of three field-scale ZAM biofilters confirmed their high nutrient and heavy metal removal performance. Overall, the findings of these three studies confirm the potential for well-designed ZAM biofilters to achieve stormwater management requirements with no additional maintenance compared with standard street landscaping.

Key words: heavy metals, nature-based solution, nutrients, rain gardens, water-sensitive urban design

HIGHLIGHTS

- Development of zero additional maintenance biofilters for stormwater management.
- Protective layer was effective against clogging, but practical choice is important.
- Lawn grasses showed high pollutant removal capacity, delayed clogging, and established well.
- Field ZAM biofilters did not clog and had high pollutant removal, complying with guidelines.
- ZAM biofilters successfully managed stormwater, with only streetscape landscaping.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Climate change, rapid urbanisation, and urban densification are significantly changing rainfall runoff in our cities, increasing both the frequency and severity of flooding, as well as pollution in receiving rivers and bays. The traditional approach to managing urban runoff, that is, to convey stormwater away from people and infrastructure as fast as possible is not working any more, and we are seeing the increase in 'at-source' stormwater treatment through decentralised solutions (Iftekhar & Pannell 2022). For this purpose, green, nature-based technologies have been praised for their efficiency and multifunctionality to solve not just stormwater management issues, but also reduce urban heat and increase amenity (Zhang *et al.* 2020).

Biofilters (also known as raingardens, or bioretention systems) are one of the most widely used nature-based solutions for urban stormwater management, especially across Europe and Australia (Oral *et al.* 2020; Kuller *et al.* 2021), due to their flexible sizing and efficacy in managing water quantity and quality (Zinger *et al.* 2021). In the last 20 years, biofilters have been extensively studied for their pollutant removal performance with respect to nutrients (Bratieres *et al.* 2008; Lynn *et al.* 2015; Glaister *et al.* 2017; Zinger *et al.* 2021), heavy metals (Blecken *et al.* 2009a; Hermawan *et al.* 2020; Lange *et al.* 2020; Fang *et al.* 2021), microorganisms (Li *et al.* 2014; Galbraith *et al.* 2019; Shen *et al.* 2020), and, more recently, organic pollutants (Spahr *et al.* 2020). Optimisation of their operational conditions has also been studied (Wu *et al.* 2017; Hermawan *et al.* 2020; Zinger *et al.* 2021), as has their ability to treat other urban water sources, such as greywater and groundwater (Fowdar *et al.* 2017b; Barron *et al.* 2019; Zhang *et al.* 2021a). However, studies that examine longevity and performance of stormwater biofilters in field conditions are limited, and it is even rarer to see data on failures in the field and maintenance needs and challenges. Zhang *et al.* (2021a) recently studied the pollutant removal performance of two field-based biofilters, but did not consider long-term performance or maintenance requirements. Al-Ameri *et al.* (2018) showed that a large number of biofilters constructed in major Australian cities are still showing high efficiency for heavy metal uptake, even after more than 16 years of operation, suggesting that well-designed biofilters in residential catchments might never exceed quality guidelines for heavy metal accumulation. However, this study still highlights high-performing field biofilters, and it is likely that in Australia (and across the world), there are a large number of biofilters that have failed due to design or maintenance issues (Blecken *et al.* 2017; Al-Ameri *et al.* 2018; Beryani *et al.* 2021). Lucke & Nichols (2015) showed highly variable pollutant removal performance of 10-year-old field biofilters, and Beryani *et al.* (2021) showed that at least 40% of tested field biofilters in Sweden need significant maintenance. Maintenance of biofilters still remains a major challenge and obstacle for widespread biofilter implementation, and is generally considered unsatisfactory by experts (Hawken *et al.* 2021). Poor maintenance is usually attributed to asset owners and managers (mostly local governments) lacking financial and human capital to conduct rigorous assessments and repairs (Blecken *et al.* 2017; Hawken *et al.* 2021). Biofilters that are not maintained are more prone to failure by clogging or vegetation damage (die-off, weed ingress), both of which result in reduced pollutant removal performance (Payne *et al.* 2015; Blecken *et al.* 2017).

To address maintenance challenges and increase confidence in biofilters as stormwater management assets, this work proposes a new concept called zero additional maintenance (ZAM) biofilters. The concept of ZAM biofilters was first developed by Manningham Council, a local government area in Melbourne, Australia, and aims to ensure that maintenance implications for asset owners and managers are minimised and comparable to maintenance of common nature strips, i.e. the area of public land situated between a private property boundary and the road kerb, also known as a road verge. This would reduce the need for regular expert control, and better align ZAM biofilter maintenance with regular streetscape maintenance activities compared with traditional biofilter designs (Blecken *et al.* 2017), thus adding benefits of stormwater management to the urban streetscape without increasing the overall maintenance cost. To create ZAM biofilters, three common maintenance challenges need to be addressed: (1) surface clogging of filter media, (2) selection of low-maintenance plants, and (3) ZAM biofilter field design.

Surface clogging of biofilters from excessive stormwater sediment and debris deposition within biofilter media is a known challenge that interferes with hydraulic and pollutant removal processes (Le Coustumer *et al.* 2012; Kandra *et al.* 2014a; Beryani *et al.* 2021). Clogging occurs mostly in the top layer of biofilter media (top 100 mm, Kandra *et al.* (2014a)) and filter media configuration, particularly particle size, is an important factor that influences the rapidity and extent to which clogging occurs (Kandra *et al.* 2014b). However, it is still not clear what top layer biofilter media configuration would be optimal for delaying, and possibly even preventing, clogging. While studies have shown that plants could help with maintaining an appropriate infiltration rate for a longer period (because root growth and die-off helps to maintain porosity (Glaister *et al.* 2017)), it is not clear if the optimal media configuration determined in laboratory conditions will translate to zero maintenance in the field. Some studies have managed to confirm laboratory findings with field experiments (e.g. Pitt *et al.* 2021), however, more research is needed.

When considering ZAM biofilters, vegetation design for minimising maintenance is critical. Firstly, biofiltration plants need to seamlessly blend into the local streetscape so that biofilters do not stand out next to nature strip vegetation. Secondly, common plant types need to be used, with no skill requirement for maintenance, so that mowing and general maintenance can be undertaken by local residents, as is the current practice in Australia. While standard biofilter design guidelines typically recommend sedges (Payne *et al.* 2015), lawn grasses are the most common and simplest plant for asset managers and general community to maintain. Some biofiltration studies have included one or two lawn grass species in plant experiments as a point of comparison to other plants (e.g. Payne *et al.* 2018; Fowdar *et al.* 2022), however, there are no dedicated studies of different lawn grass species for their pollutant removal effectiveness in stormwater biofilters. Little is known about how different lawn grass species affect hydraulic and pollutant removal performance. Additionally, field validation is missing, especially with respect to the maintenance needs of such biofilters planted with lawn grasses (longevity, growth rate, robustness, etc.).

Appropriate selection of anti-clogging media is critical for biofilter longevity, but coarse sediment deposition on top of the biofilter (before it enters the media) is still a significant challenge for maintenance (Beryani *et al.* 2021). Passive sediment pre-removal should be incorporated in the ZAM design to protect the biofilter. Additionally, steep slopes and other safety features (e.g. curbs, fences, gates, etc. (Payne *et al.* 2015)) could be challenging for maintenance, so they should be minimised in ZAM design. This would help to blend biofilters into nature strips. Such exposed design is yet to be trialled in the field for its longevity and pollutant removal performance.

This study, to the best of the authors' knowledge, is the first study that aims to test the development and implementation of the novel ZAM stormwater biofilter concept through a comprehensive series of laboratory experiments and monitoring of field systems. By providing robust experimental design and critical field-scale evidence, this work contributes to stormwater biofilter development through the following research objectives: (1) understand optimal anti-clogging media configuration for ZAM biofilters; (2) identify vegetation that facilitates effective hydraulic and pollutant removal performance with no additional maintenance requirements for nature strips; and (3) validate stormwater ZAM biofilter nutrient and heavy metal pollutant removal performance of field-scale systems with novel elements (passive sedimentation and kerb design). This study further provides understanding of practical implications for the design and operation of ZAM biofilter.

2. MATERIALS AND METHODS

This work validates the ZAM biofilter concept by investigating performance across three studies. *Study 1* utilises a vegetated, laboratory-scale biofilter column experiment to explore how different filter media configurations affect physical clogging from suspended solids in stormwater. The outcomes of this experiment informed *Study 2*, a 12-month vegetated column experiment that explores the hydraulic and pollutant removal performance of six lawn grass species. *Study 3* investigates the treatment performance of three field-scale ZAM biofilters whose design was based on the outcomes of *Studies 1* and *2*. Detailed methodologies for each study are provided below.

2.1. Study 1: surface clogging assessment

2.1.1. Column design

Vegetated biofilter columns were constructed from 100 mm PVC pipe, with a total filter depth of 400 mm and a 200 mm ponding zone (Figure 1). All columns contained a 300 mm treatment zone which overlaid a 50 mm sand transition layer and a 50 mm gravel drainage layer (Figure 1). Within the treatment zone (top 100 mm), six alternative filter media configurations were tested, with five different sand types (Table 1). Five configurations aimed to protect against clogging and the sixth followed standard biofilter design, thus acting as a control. In Australia, a filter medium commonly used in stormwater biofilters is referred to as 'FAWB' engineered media, which was developed and tested specifically for biofilters (Payne *et al.* 2015) consists of triple-washed well graded sand across 0.05–2.00 mm range, and low levels of clay and silt (<3%). Two commercial sand types were also tested, Burdett's 20/30 sand, and Daisy's Coarse White sand, both somewhat coarser than the 'FAWB' media, with more than 80% grading between 0.25 and 1 mm. In addition to these three sand-based media, 2 and 1 mm sands were used, in different mix ratios (Table 1). Detailed particle size gradings for all three commercial sand materials are provided in Supplementary Material, Table S1.

All columns were planted with lawn grass (*Soft Leaf Buffalo*). Prior to planting, the plant roots were washed to remove the soil in which the grass was grown, since this soil would have constrained the infiltration capacity of the system. It should be noted that, although it is proposed to incorporate a saturated zone in the field-scale prototypes (Zinger *et al.* 2021), only the upper, unsaturated layers of filter media were constructed for this study since the focus was on physical clogging. In total, 18 columns (6 designs × 3 replicates) were constructed.

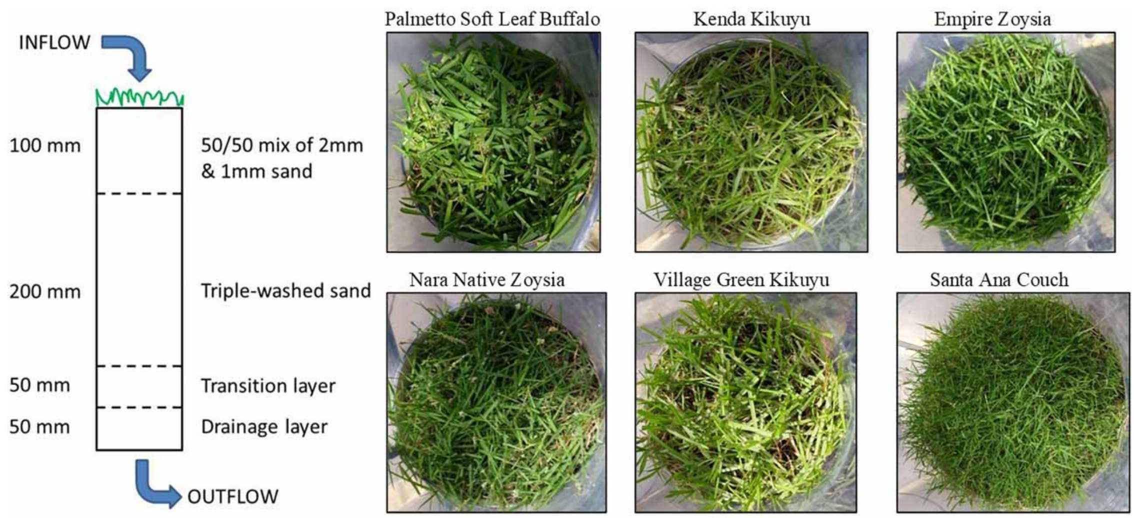


Figure 1 | Biofilter column design with media layering for *Study 1* (left) and lawn grasses tested in laboratory trials in *Study 2* (right).

Table 1 | Matrix of alternative column designs for *Study 1*

Configuration	Filter media		Vegetation
	Depth (mm)	Details	
1	300	'FAWB' engineered media	Lawn grass
	50	Transition layer	
	50	Drainage layer	
2	50	2 mm coarse sand	Lawn grass
	50	1 mm coarse sand	
	200	'FAWB' engineered media	
	50	Transition layer	
	50	Drainage layer	
3	100	50/50 mix of 2 and 1 mm coarse sand	Lawn grass
	200	'FAWB' engineered media	
	50	Transition layer	
	50	Drainage layer	
4	100	50/50 mix of 1 mm and 0.5 mm coarse sand	Lawn grass
	200	'FAWB' engineered media	
	50	Transition layer	
	50	Drainage layer	
5	100	Burdetts 20/30 sand	Lawn grass
	200	'FAWB' engineered media	
	50	Transition layer	
	50	Drainage layer	
6	100	Daisy's Coarse White Sand	Lawn grass
	200	'FAWB' engineered media	
	50	Transition layer	
	50	Drainage layer	

2.1.2. Establishment and stormwater dosing protocol

The biofilter columns were allowed to stabilise for one week following construction. During this time, they were irrigated periodically with tap water. Following this establishment period, the columns were dosed with semi-synthetic stormwater using an accelerated dosing approach. Semi-synthetic stormwater was prepared by mixing a slurry of sediment collected from the sediment pond of a local constructed wetland with tap water in a tank to achieve a target total suspended solids (TSS) concentration of 150 mg/L typical for stormwater (Zhang *et al.* 2021a).

The aim of the stormwater dosing regime was to load the biofilter columns with the equivalent of 18 months of inflow over 15 days. To achieve this, the biofilter columns needed to be dosed with 16 L of stormwater per day (2 L was added at hourly intervals eight times per day). The volumetric inflow equivalency was calculated using typical biofilter design (2% of the catchment area, Payne *et al.* (2015)) and rainfall characteristics for Melbourne (effective annual rainfall = 550 mm).

To assess the development of clogging, outflow rates were manually measured three times a day. Inflow samples were also collected on a daily basis and analysed using a standard method (APHA/AWWA/WPCF 1998) to check the inflow sediment concentration. It should be noted that there were some differences in cumulative inflow volumes across column replicates because, as the columns began to clog, some did not fully drain between dosing intervals. When this occurred, the hourly dosing volume was the volume of water that filled the ponding space.

2.2. Study 2: lawn grasses hydraulic and pollutant removal testing

2.2.1. Lawn grass species tested

Six lawn grass species (Figure 1) were tested for their nutrient removal ability and hydraulic performance in a laboratory-scale column study. Their selection was based on their physical characteristics, as well as their sun and humidity tolerance, both of which were tested in a separate, preliminary field trial. *Palmetto Soft Leaf Buffalo* was found to be suitable for shady and moist sites while *Kenda Kikuyu* showed excellent survival in sunny sites (defined as <20% shade). *Santa Ana Couch* was also likely to be tolerant of sunny sites. *Empire Zoysia* showed very good survival but was expected to be better suited to sites with part shade. *Nara Native Zoysia* may be suitable for areas with high environmental values because it is less invasive than Couch and Kikuyu, and part shade. *Kenda Kikuyu* and *Village Green Kikuyu* offer good wear tolerance, while *Nara Native Zoysia* and *Empire Zoysia* are suitable for sites with low-to-medium pedestrian traffic.

2.2.2. Experimental set-up

Thirty-five columns were constructed (five replicates of each lawn grass species and five non-vegetated controls) in an open-air greenhouse with a clear, impermeable roof. The columns were constructed from 240 mm diameter PVC pipe, with a transparent Perspex top section allowing for plant growth and ponding of water (Figure 2). The insides of the columns were sand-blasted to reduce preferential flow along the column edges. Columns were filled with different layers of media (Figure 2) based on the results of Study 1. Freshly sourced lawn grasses were laid into a total of 30 columns. The remaining five columns were left unvegetated, thereby acting as both controls and to simulate the performance of bare systems with poor grass survival. The saturated zone was 300 mm deep (created by raising the outlet pipe) and comprised the gravel and transition layer. Liquid fertiliser was added after planting, as one-off help for plant establishment.

2.2.3. Experimental procedure

Following construction, plants were allowed to establish 6 weeks. For the first 2 weeks, the grasses were watered with approximately 2 L of tap water three times per week. The watering frequency was then reduced to twice per week. Lawn grasses were mowed as required during the trial period.

In early June 2017, dosing of the columns with 9.4 L of semi-synthetic stormwater twice weekly commenced. This dosing regime was based on an annual average effective rainfall of 540 mm for Melbourne and using a biofilter sized to 2.5% of its contributing catchment. Use of semi-synthetic stormwater allowed us to minimise variations in inflow concentration while maintaining realistic composition. It contained sediment from a local stormwater wetland, sieved to 1 mm and mixed with dechlorinated tap water to achieve the target TSS concentration. Laboratory chemicals (potassium nitrate, ammonium chloride, nicotinic acid, potassium sulphate, and sodium thiosulphate) were added to match any deficit in targeted nutrient concentrations, as detailed in Bratieres *et al.* (2008) and Zinger *et al.* (2021). Target nutrient concentrations are shown in Supplementary Material, Table S2.

Over the 10-month study period (12 months from planting), both wet and dry weather conditions were simulated, with 8 months of wet conditions, when columns were dosed twice weekly with semi-synthetic stormwater, and 2 months of dry conditions, when columns were dosed once per fortnight. A total of six water quality sampling runs were conducted (four during wet conditions and two after 1 month of dry conditions), along with three infiltration tests during wet events (experimental timeline in Supplementary Material, Figure S1).

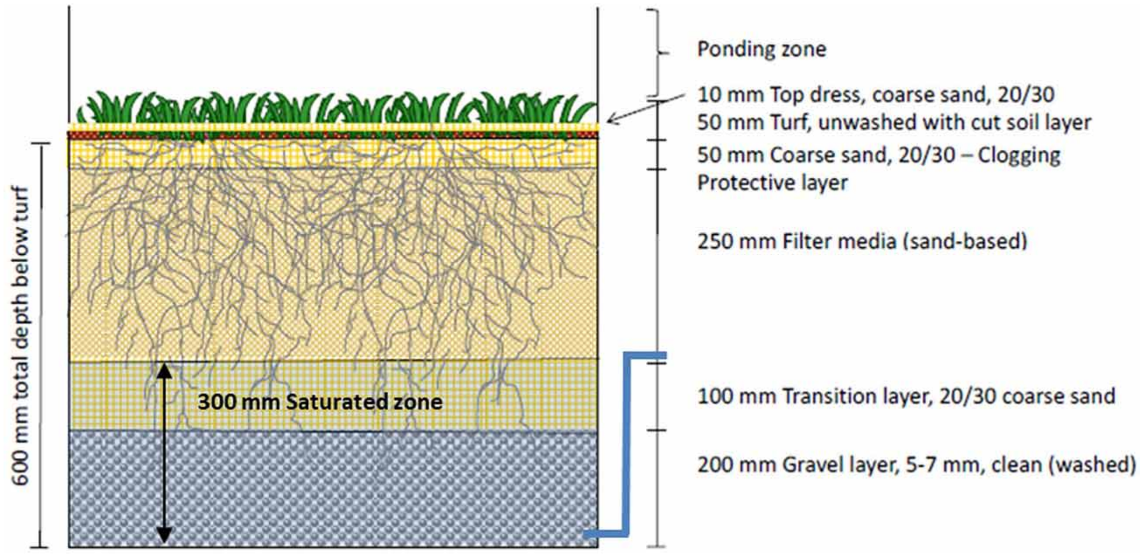


Figure 2 | Schematic drawing of biofilter cross-sectional profile for Study 2.

To assess the infiltration rate of each column, the drop in ponded water level (i.e. the water level above the filter media surface) was measured every 60 s for at least 15 min, depending on the rate of drainage of the column. The infiltration rate was calculated as the average decrease in water level over the measurement time. During each sampling run, inflow and outflow water samples were collected for pollutant analysis. A composite outflow sample was taken after the column finished draining. This was sub-sampled into a 1 L bottle. All samples were analysed in a NATA (National Association of Testing Authorities, Australia) accredited laboratory according to standard methods (APHA/AWWA/WPCF 1998). All sampling runs were analysed for Total Nitrogen (TN), ammonia (NH_3), and oxidised nitrogen (NO_x). Total Dissolved Nitrogen (TDN) was measured for the first four sampling runs and Dissolved Organic Nitrogen (DON) was calculated as the difference between TDN and $NH_3 + NO_x$. In the Week 26 (dry) and Week 30 (wet) sampling runs, water quality samples were also analysed for Total Phosphorus (TP), Total Dissolved Phosphorus (TDP), and Filterable Reactive Phosphorus (FRP, a measure of orthophosphate, PO_4^{3-}). The difference between TP and TDP is a measure of particulate phosphorus.

2.3. Study 3: field implementation of ZAM biofilters

2.3.1. Description of field implementation sites

In *Study 3*, three constructed ZAM biofiltration systems located within the Manningham Council local government area were monitored. Two systems were in Hummel Way, Doncaster, in a Council office car park (HW1 and HW2), and one biofilter in a residential area in Edwin Road, Templestowe (ER) (see Supplementary Material, Figure S2 for a map of the site locations). The total areal footprint of each biofilter was around 6.75 m^2 while the treatment surface area was 2 m^2, equivalent to 1–2% of the impervious catchment area (Figure 3(a)). The filter media configuration and layering were the same as for *Study 2* (Figure 2), except for the ER biofilter, which did not contain a saturated zone. *Palmetto Soft Leaf Buffalo* grasses were planted in all systems, as per findings

Figure 3 | Hummel Way 1 system's details: (a) Raingarden system, (b) sediment grooves, (c) outlet-pit, and (d) outlet pipe.

of the *Study 2*. This turf species was used as it is tolerant to drought, shade, frost, and wear, and has a slow growth rate and low growth height, both of which reduce the required maintenance frequency.

To reduce the amount of sediment deposits on top of the biofilter and thus delay the onset of surface clogging, sedimentation grooves were installed in the concrete channel upstream of each system (Figure 3(b)). These sediment grooves were designed to be cleaned by street sweepers every 5–6 weeks as part of Manningham Council's regular sweeping programme. Square bars were installed in the inlet with 18–20 mm gaps between bars to prevent large litter (>20 mm in size) from entering the ZAM biofilter and allow collection by a street sweeper or disposal into a downstream side-entry pit (Figure 3(c)).

2.3.2. Experimental procedure

Beginning in September 2017, the pollutant removal performance was evaluated at each site using simulated inflow events. Each system was dosed with 500 L of semi-synthetic stormwater per event, which is equal to two pore volumes (PVs) of the filter media. Semi-synthetic stormwater was prepared following the method described for *Study 2*, with the addition of heavy metal dosing (see Supplementary Material, Table S2 for further details).

Five inflow events were simulated at each site over a period of 8 months (in September and December 2017, and January, February, and April 2018). The first sampling point was upstream of the sediment grooves, to characterise the untreated stormwater. The second one was between the sediment grooves and biofilter inlet, to assess the removal efficacy of the sediment grooves. The last sampling location was the biofilter's outflow pipe inside the side-entry pit (Figure 3(d)). Complete outflow volume was measured at the outflow to understand volumetric reduction within the systems. Discrete samples were collected from the outlet at 50 L intervals, then combined to create a composite sample. Three composite water samples were collected into 1 L bottles during each event. All samples were analysed for copper (Cu), zinc (Zn), TSS, TN, and TP by a NATA (National Association of Testing Authorities, Australia) accredited laboratory according to standard methods. In addition, two filter media samples (surface and subsurface) and plant leaf and root samples were collected during each event at all three sites and analysed for Cu and Zn.

2.3.3. Data analysis

Box plots were used to present metals concentrations and removal in the water quality samples, filter media, and the different lawn parts. Shapiro–Wilk *W* test was performed to check the normality of data. Univariate analysis of variance (ANOVA) test was used to assess the statistical significance of differences between inflow and outflow metal concentrations as well as metal concentration in the filter media and plant parts. Welch and Brown-Forsythe were used when the homogeneity was rejected to be confident that the data were statistically significant. Log-transformed data was used to perform the analysis when the data were not normally distributed. Statistical significance was accepted when the p-value was <0.05. Box plots and statistical tests were produced using IBM SPSS Statistics (Version 25).

3. RESULTS AND DISCUSSION

3.1. Performance of alternative surface filter media configurations in clogging prevention

The change in outflow rate across the dosing period of six different media configurations is shown in Figure 4. In all cases, there was a rapid initial decline in outflow rate (over the first 50 L) followed by a slow decline up to the end of the dosing period (full graph in Supplementary Material, Figure S3). This rapid decline is typically observed during the establishment period of filters, even though the filter media was compacted during construction, because particles rearrange and settle as water flows through the media profile (Zinger *et al.* 2021). There was generally close agreement between replicates, except for one replicate each in Configurations 2 and 5 (Figure 4). This is not entirely unsurprising given the heterogeneity of the filter media and the inherent level of uncertainty associated with the flow measurements.

Generally, all designs containing a protective layer delayed the onset of clogging compared with the design with no protective layer. The extent to which clogging was delayed appeared to be partially determined by particle size distribution; designs whose protective layers were comprised of a smaller mean particle size had higher outflow rates, perhaps because they were better able to trap and distribute incoming sediment across the full

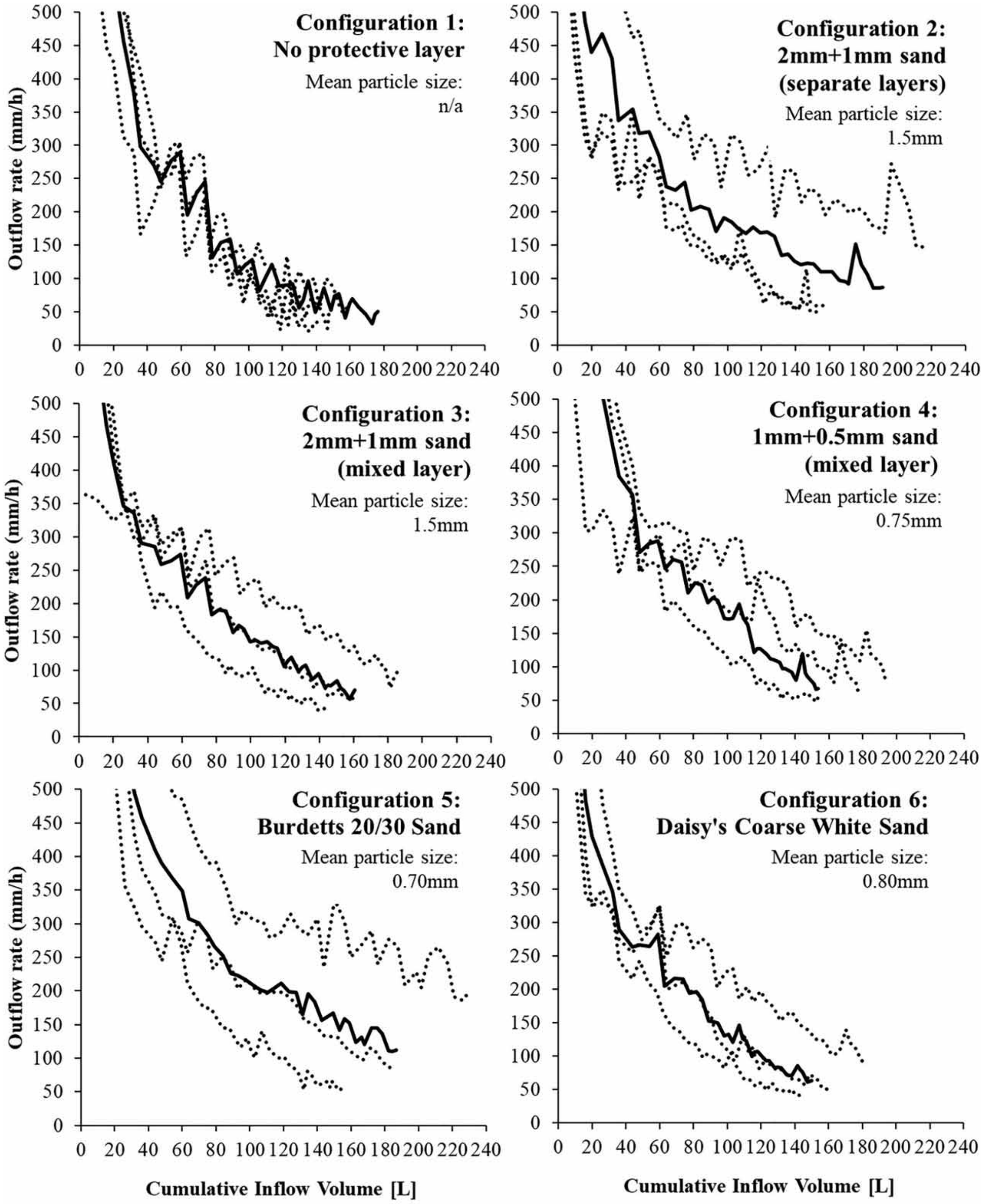


Figure 4 | Change in outflow rate against cumulative inflow for six filter media configurations. Results for individual replicates are shown for each configuration (dotted lines) and average across all three replicates (solid line). Initial infiltration rate cut for clarity at low range.

depth of the protective layer (Figure 4). The average infiltration rates for Configurations 1 (no protective layer), 3 (2 mm + 1 mm mixed), 4 (1 mm + 0.5 mm mixed), and 6 (Daisy's Coarse White Sand) dropped below 100 mm/h after 120–130 L of stormwater application (equivalent to a cumulative hydraulic loading of ∼10 m). This is consistent with the findings of Kandra *et al.* (2014b) who reported that biofilters tested under an accelerated loading regime, like in this work, experienced a rapid drop in the infiltration rate across the first 10 m of water applied, after which it stabilised. Configurations 2 (2 + 1 mm separate layers) and 5 (Burdetts 20/30 sand) showed somewhat higher resistance to clogging, especially across one outlier replicate in each configuration (Figure 4). This suggests that layers of coarser filter media at the top of the biofilter can help with surface clogging.

In addition to performance, selection of the protective layer configuration needs to consider complexity of construction, cost, and capacity to support healthy plant growth as well as ability to delay the onset of clogging. A single-layer protective system is far more practical to build than a mixed layer system. The cost of the commercially available Burdetts and Daisy's sand products is approximately 20% of the engineered sands, which is significant when considering the scale at which biofilters are built. Finally, the use of a coarser material for the top 100–150 mm of the media profile is unlikely to impact plant growth as even the root systems of shallow-rooted plants, such as lawn grasses, penetrate well beyond this depth. This was also observed in our experiment, where grasses on all configurations remained unaffected. In a separate laboratory study of plant species in biofiltration systems, it was found that 95% of the root system of Soft Leaf Buffalo occupied the entire unsaturated zone (300 mm deep) and some roots were sufficiently long to penetrate well into the saturated zone (>300 mm deep, Payne *et al.* 2013). Considering these practical criteria, along with sediment removal performance, it is recommended that Configuration 5 (Burdetts 20/30 sand) be used as the protective layer for future ZAM biofilter design.

3.2. The performance of lawn grass species in ZAM biofilters

3.2.1. Hydraulic performance

Infiltration rates were measured three times over the first 6 months of the study to monitor clogging and identify any species associated with slow or fast drainage. 15 weeks after planting (August 2017, about 8 weeks into the stormwater dosing period), the average infiltration rate was 456 mm/h and there were no significant differences between grass types (Figure 5). Rates slightly increased in September 2017 (i.e. after about 14 weeks of stormwater dosing) and significantly increased from September 2017 to November 2017 for all grass species (Figure 5). This increase is likely due to the development of grass roots in the filter media over time, especially during spring, when plants are in their active growth phase (Le Coustumer *et al.* 2012). In contrast, a decrease in infiltration rate was observed for the non-vegetated columns over time. This could stem from an accumulation of sediments on the surface of the filter media over time. The above results confirm the positive effect that biofilter vegetation has in alleviating clogging issues. It also suggests that the use of a protective layer (Configuration 5 from Study 1) in combination with lawn grasses, retained high hydraulic performance over time.

The average infiltration rates were statistically similar across grass species ($p > 0.05$) after 15, 21, and 28 weeks of planting, respectively. Interestingly, particularly in November 2017, planted columns had significantly higher infiltration rates than unplanted columns (Figure 5). Vegetation indeed loosens up filter media with roots. *Santa Ana Couch* and *Kenda Kikuyu* had the least variation in infiltration rates across replicates while *Empire Zoysia* was the greatest (Figure 5).

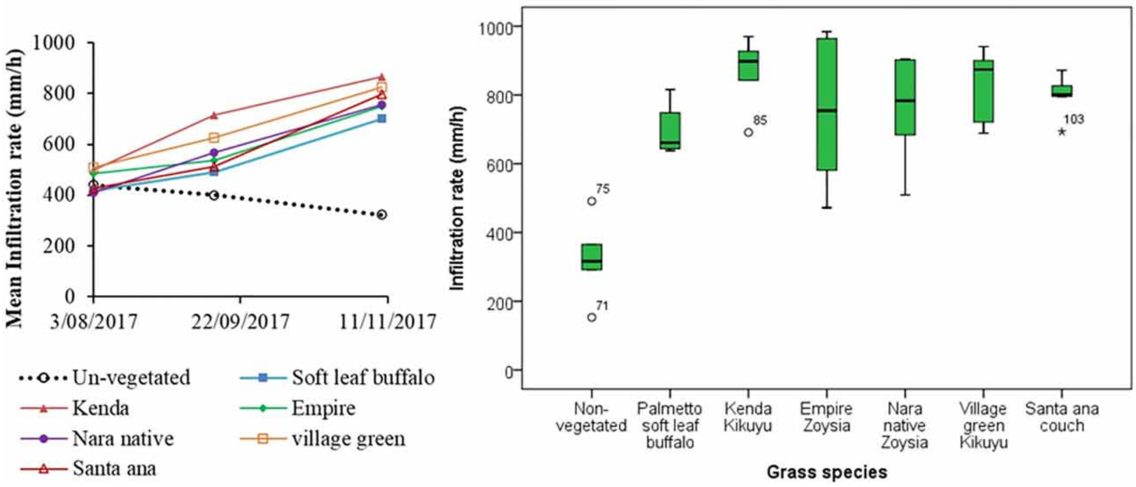


Figure 5 | Evolution of mean infiltration rate over time for the different grass species (left) and variation across grass species after 6 months of stormwater inflow (November 2017) (right).

It should be noted the high infiltration rates observed in this trial may not be reflective of field conditions because the biofilter columns were not subjected to vehicular and/or human traffic or litter accumulation. Nevertheless, these results give a clear comparison of the hydraulic behaviour of different lawn grasses in the field.

3.2.2. Pollution removal performance

3.2.2.1. Nitrogen. The TN removal efficiency, calculated as a percentage of the difference in inflow and outflow concentrations, and the variation of outflow NO_x, NH_3, and DON concentrations over time are shown in Figure 6. A net TN removal was observed for all grass species in every sampling event, except for the non-vegetated and *Nara Native Zoysia* columns in the third sampling event (at week 26, where outflow concentrations were greater than inflow concentrations). In general, planted columns performed better than the unvegetated controls. While TN removal was 14–46% at week 15, greater variation in TN removal was observed during the winter months (week 22 to week 30), presumably because most grass varieties went into dormancy. From week 30 to week 51, all lawn grass species rapidly increased nitrogen uptake (29–63% removal in week 30, and 67–80% removal in week 51), which coincided with the spring and summer growing season. Unvegetated columns, however, only removed on average 23% of TN in week 51.

The two dry weather periods, one imposed during winter and the other in summer, had different effects on nitrogen removal. Week 26 sampling occurred after 4 weeks of dry conditions, and lower TN removal was observed for all grass species except *Santa Ana Couch* and *Empire Zoysia*, with *Nara Native Zoysia* and unvegetated columns leaching TN. Reduced nitrogen removal performance is typical after dry weather spells and is attributed to root die-off, leaching from filter media, and reduced microbial activity as a result of desiccation (Zinger *et al.* 2021). It is likely that *Nara Native Zoysia* had not well established at that time (it went into a state of dormancy during winter) which resulted in a decrease in its performance. Interestingly, the two-week

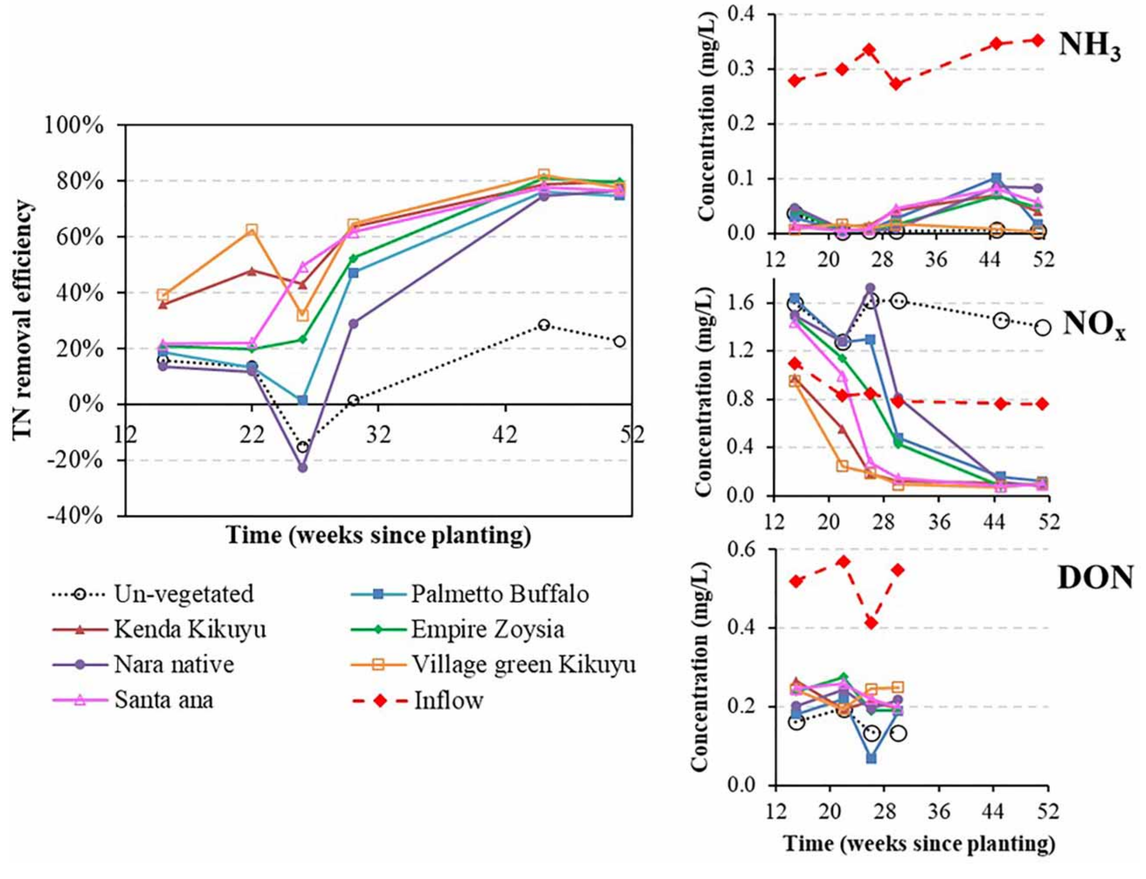


Figure 6 | Average total nitrogen (TN) removal efficiencies over time for different lawn grasses (left) and effluent concentrations in column outflow of dissolved nitrogen species (ammonia, NH_3; oxidised nitrogen, NO_x, and dissolved organic nitrogen, DON) across lawn grasses (right).

drying period in summer had no significant effect on nitrogen removal (during sampling events at weeks 45 and 51 (Figure 6)). It is likely that the more mature plants were less impacted by this dry period because it was shorter than the winter dry period and also because they were able to draw water from the saturated zone and thus sustain nitrogen removal performance. A similar is seen in Zinger *et al.* (2021) where 2 weeks of drying had no significant effect on biofilter columns with a saturated zone.

Effluent NH_3 concentrations were low in all cases (Figure 6). NH_3 is mainly removed through adsorption and microbial processing via nitrification which occurred effectively (Zhang *et al.* 2021b). There was a consistent net reduction in DON concentrations across by all column configurations, both vegetated and unvegetated. In contrast, effluent NO_x concentrations varied across the study period, ranging from leaching to effective removal. Where leaching occurred, it is possible that this was due to net production via nitrification (the microbial conversion of NH_3 to NO_x) and insufficient plant uptake. An overall decrease in effluent NO_x concentration was observed with time, matching plant growth and development of root systems. In fact, TN removal was influenced by the extent of NO_x removal and/or production.

There was a significant difference in TN removal and effluent NO_x concentrations across grass type ($p < 0.001$) in the initial four sampling runs, with some species performing better than others (Figure 6). This difference could be attributed to the growth pattern of the different lawn grasses. For instance, some species were dormant during winter while others experienced active growth (particularly the two Kikuyu species), leading to higher initial removal performance. Previous studies have found that plant uptake plays a key role in nitrogen removal by stormwater biofilters (Payne *et al.* 2014b). The growth rate of the lawn grasses is likely another factor influencing nitrogen removal. *Nara Native Zoysia* is known to be slow growing which explains its lower performance in the first half of the experiment. It also becomes dormant during drought, which explains the poor performance during the first dry period (week 26). Interestingly, after establishment and under more mature state, the difference in performance across lawn grasses became insignificant.

The results indicate that all tested lawn grasses were able to achieve a TN removal efficiency of up to 70–80%, which meets the 45% reduction recommended by Australian best practice guidelines for stormwater management. Species such as *Santa Ana Couch* and *Kenda Kikuyu* have shown to be robust, high performers throughout the experimental period.

3.2.2.2. Phosphorus. Phosphorus is usually well-removed from stormwater by biofiltration since it is mostly associated with sediments and thus removed through physical processes (Fowdar *et al.* 2017b). To verify the performance of TP in systems planted with lawn grasses, TP was analysed for only two sampling events: during October (dry period) and November (wet period). The results are presented in Figure 7. During the dry period (week 26), TP reduction ranged from −13% (*Nara Native Zoysia*) to 26% (bare column). FRP removal ranged from 54% (*Nara Native Zoysia*) to 91% (*Kenda Kikuyu*). Since FRP was mostly well-removed and most of the TDP was in the form of FRP, this indicates that the poor TP removal performance was due to leaching of particulate phosphorus (see Figure 7, right). Potential sources of this include the filter media and desiccated plant matter (Zinger *et al.* 2021). During the wet period (week 30), a major improvement in phosphorus concentration reductions was recorded, with TP reductions ranging from 14% (*Nara Native*) to 53% (bare column) while FRP ranged from 40% to 82% (Figure 7). Since more than 70% of the phosphorus in the outflow is bound to particles and thus potentially less bioavailable, this may reduce the environmental risk. In the future, a deeper transition layer comprising coarse sand could be implemented to better trap fine particles migrating downwards from the filter media. There was no significant difference in TP removal across grass species ($p > 0.05$). Poorer removal of vegetated columns compared with non-vegetated columns could be due to leaching of plant matter.

3.2.3. Design choice of lawn grasses

Design choice of lawn grass species will depend on several criteria, including pollutant removal performance, maturation speed, site conditions, clogging risk, and aesthetics. Because of their faster growth rate and sustained growth during winter, *Kenda Kikuyu* and *Village Green Kikuyu* were the best performing lawn species during the initial trial period, and optimal species if fast establishment is required. At maturity, all species were universally effective at pollutant removal. However, it appears that lawn grasses may be more susceptible to seasonal variation in comparison with other species (e.g. native shrubs, sedge, or ornamental plants) (Fowdar *et al.* 2017a).

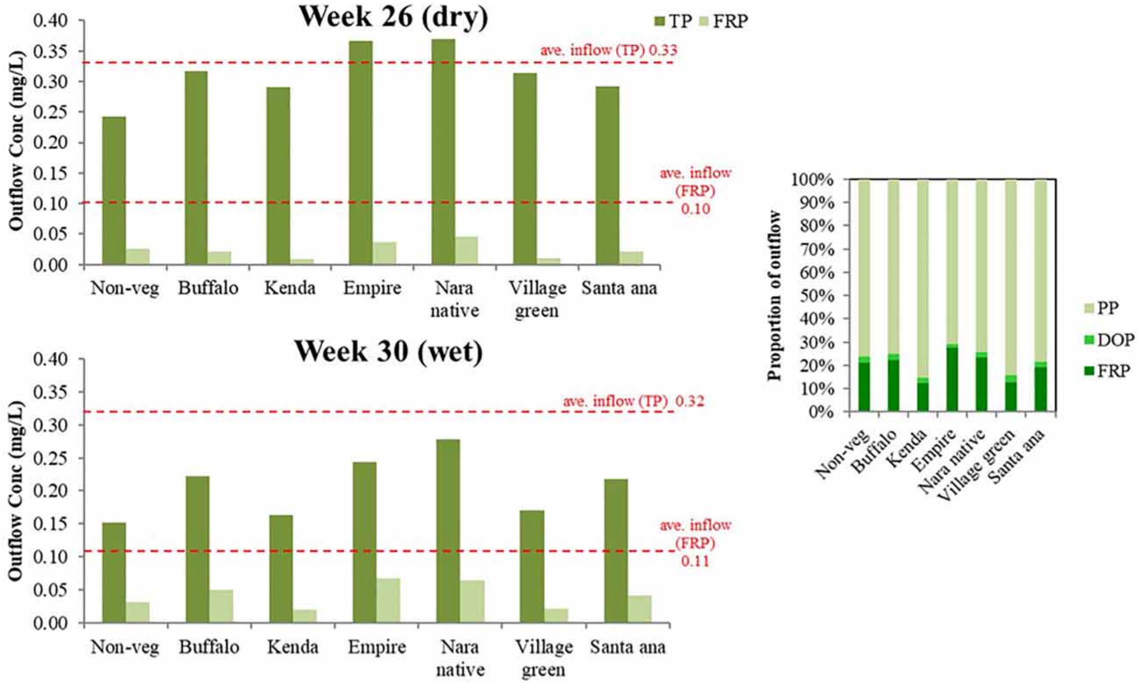


Figure 7 | Comparison of average outflow total phosphorus (TP) and filterable reactive phosphorus (FRP, a measure of orthophosphate) concentrations across lawn grasses during dry and wet weather conditions (left), and proportion of outflow TP concentration as FRP, dissolved non-reactive P (DOP), and particulate P (PP) (right).

For example, *Nara Native Zoysia*, *Santa Ana Couch*, and *Empire Zoysia* may go dormant during winter, which might cause some performance issues, particularly in winter rainfall-dominated climates.

Clogging was not found to be an issue, hence the choice of any of the tested lawn species would be suitable for ZAM biofilter design in that respect, although it is acknowledged that the 12-month monitoring period represents only a small proportion of the expected lifespan of stormwater biofilters. However, it is evident that lawn species with poor survivability would result in poor nutrient removal, and particularly nitrogen. Lawn species that are healthy will provide the greatest treatment benefit. Always choose lawn species that will grow well in the particular location (although slow growing species can be expected to initially render lower nutrient removal) for effective nutrient removal. For example, it is likely that installing *Kenda Kikuyu* in a shady location (which prefers sunny conditions) will facilitate lower removal rates than *Palmetto Soft Leaf Buffalo*, which is more shade tolerant. From this study, while it can be speculated that nutrient removal of the lawn grasses is a function of grass health and growth rate, plant growth and vegetation mass changes were only visually observed during this study (Supplementary Material, Figure S4). A summary of lawn grass performance and characteristics for consideration in field application is provided in Supplementary Material, Table S4.

3.3. Performance of field-scale ZAM biofilters

3.3.1. Stormwater pollution treatment

Outflow concentrations of TSS, TP, Cu, and Zn were significantly lower than inflow concentrations ($p < 0.05$) at all three sites (Figure 8), with an average reduction of TSS >88%, TP >55%, Cu >91%, and Zn >99%. This is not surprising, considering that ZAM biofilters were designed with the protective top filter media layer, which would also efficiently capture these particulate pollutants. This is based on the previous field and laboratory studies (Hatt *et al.* 2008; Blecken *et al.* 2009b; Fowdar *et al.* 2017b; Kluge *et al.* 2018) which found that particulate nutrients and heavy metals accumulated in the top 5–10 cm, then dropped dramatically with increasing depth. TP removal performance in the field-scale ZAM biofilters increased in comparison to the column trials in *Study 2*, and this performance is consistent with the literature (Wu *et al.* 2017).

In contrast, removal of TN was highly variable, in the range of 28–64% at both Hummel Way sites. Effluent concentrations of TN from the Edwin Road biofilter (ER) were very high and leaching was observed in some cases, resulting in an average removal of 11%. The low removal of TN at the ER biofilter was likely due to the

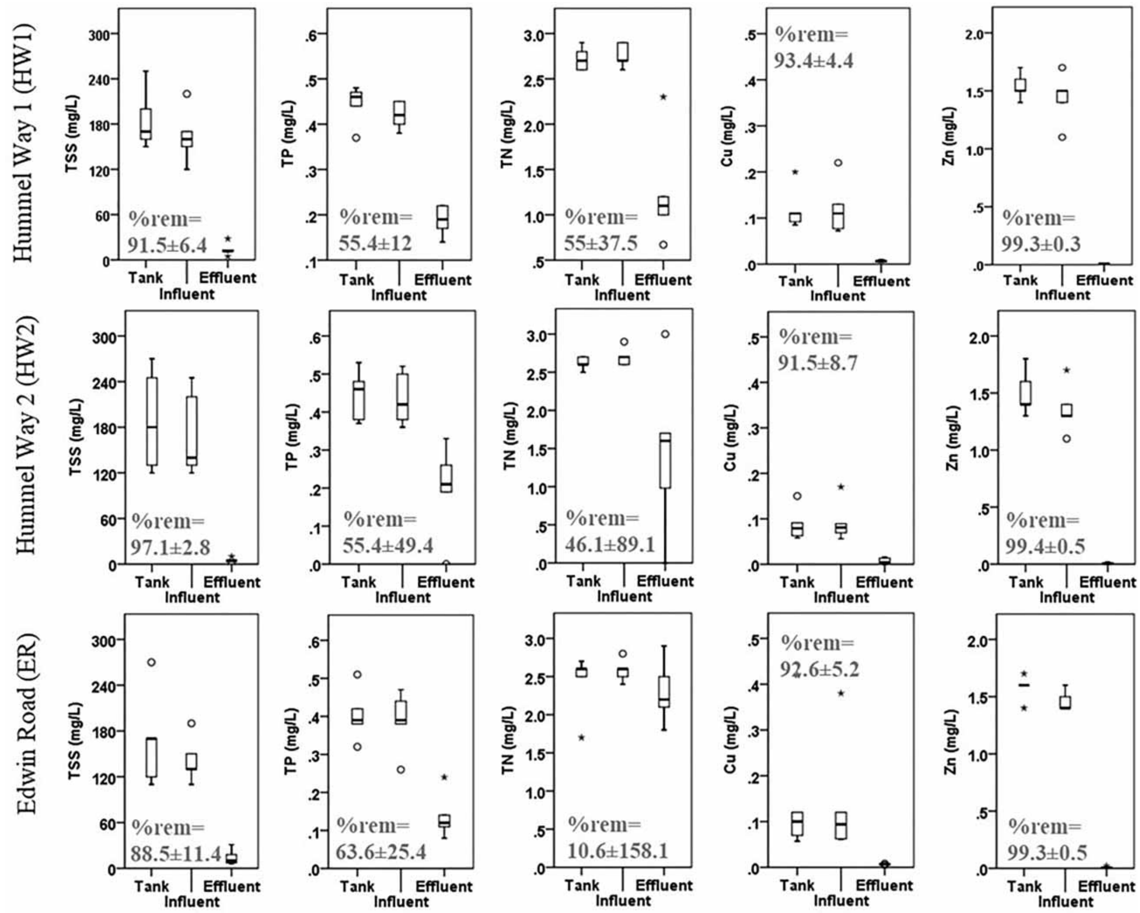


Figure 8 | Range of pollutants concentrations at Hummel Way 1 & 2 (HW1 and HW2) and Edwin Road (ER); Sampling positions were 'Tank' before the sediment grooves, 'Influent' after the sediment grooves, and 'Effluent' at the system outlet. Cu and TP *y*-axis is <1 mg/L. Removal rates between inflow and outflow are given.

absence of a saturated zone, which is known to sustain denitrification in stormwater biofilters (Igielski *et al.* 2019) and promote plant removal of NO_x (Payne *et al.* 2014a). In addition, dense patches of clover were observed at the ER biofilter, which had invaded the raingarden from the surrounding area. Clover is a known nitrogen-fixing plant (Bolger *et al.* 1995) and is thus an undesirable plant species for biofiltration because the potential addition of nitrogen to the system via fixation of atmospheric nitrogen very likely counteracts nitrogen removal from stormwater. The higher TN concentrations in the HW2 effluent compared with HW1 may also be attributed to the presence of clover in this system. Despite the poor reduction in TN concentrations, the ER system still demonstrated reliable removal of other pollutants (Figure 8).

The presented data in Figure 8 showed that, while statistically not significant, TSS, TP, and Zn pollutant concentrations in the influent (after sediment grooves) were somewhat lower, compared with concentrations in the tank (before sediment grooves). This indicates minor accumulation of the suspended particles inside sedimentation grooves. For the grooves to be effective, either flow velocities in the gutter should be kept low to avoid scouring the grooves, or the sediment grooves need more frequent cleaning, which would increase maintenance costs. For instance, the TSS reduced by 30% in one simulated inflow event at ER, when the grooves were clean, but in another inflow event at the same site, the TSS concentration increased from 120 mg/L before the sediment grooves to 130 mg/L after the grooves, indicating that collected sediment was scoured from the grooves and washed into the biofilter.

The median stormwater runoff volume reduction in HW1, HW2, and ER biofilters were 60, 53, and 78%, respectively. Reductions in runoff volumes were highest at ER (83% on average), due to the absence of an impervious liner, and this reduction was enough to counter TN leaching. The volumetric reductions observed in this study were within the range of a previous field study which reported that the monitored bioretention basin

Table 2 | Pollutant removal performance according to the load reduction (mean ± coefficient of variation), in comparison to local stormwater treatment targets

	Load reduction (%)			
Pollutant	**Hummel Way 1**	**Hummel Way 2**	**Edwin Rd**	**Treatment targets**[a]
TSS	97 ± 1.8	99.1 ± 0.7	98.2 ± 1.4	80
TP	83.3 ± 4.8	83.3 ± 16.5	92.8 ± 4.3	45
TN	83.4 ± 7.9	82.5 ± 16	78.6 ± 14.7	45
Cu	97.7 ± 1.2	97.1 ± 3.5	98.7 ± 0.9	–
Zn	99.7 ± 0.13	99.8 ± 0.2	99.9 ± 0.05	–

[a]EPA Victoria (2021).

retained 25–89% of the inflow volume (Mangangka *et al.* 2015). Similarly, the effluent volume reduction was 33–84% from five lined bioretention systems (Lucke & Nichols 2015). The high volumetric reduction observed in the present study, combined with pollutant concentration reductions, translated to high pollutant load reductions (Table 2). The performance of these systems thus complied with the local stormwater treatment targets of 80, 45, and 45% reductions in loads of TSS, TN, and TP, respectively (EPA Victoria 2021). Even the ER system, where some leaching of TN and the lowest mean concentration reduction were observed, still delivered a high TN load reduction and reliable performance because the system was able to retain a high quantity of water.

3.3.2. Pollutant accumulation in ZAM biofilters

Heavy metal concentrations were significantly higher at the surface of the filter media compared with the subsurface ($p < 0.05$; Figure 9), which means the metals are mainly trapped in the top layer (0–2 cm) and do not ingress too far into the filter media. However, surface concentrations of Cu and Zn were below the Australian soil quality guidelines for ecological health (Cu = 100 and Zn = 200 mg/kg) (NEPC 1999), with the exception of one Zn measurement taken at HW2 (Figure 9). It can also be seen that metal concentrations in the filter media at the ER system were lower than the two HW systems (Figure 9). This could be attributed to the ER system being located within a residential area whereas the two HW systems receive runoff from a busy carpark catchment, and heavy metals in stormwater runoff are associated with vehicular traffic (Al-Ameri *et al.* 2018). Some accumulation variations between HW1 and HW2 (HW1 had less accumulated metal concentrations) could be caused by micro-location of the systems within the carpark, since HW2 received higher volumes of direct runoff from the car lanes (see Supplementary Material, Figure S5). In comparison with the field data literature (Al-Ameri *et al.* 2018), ZAM-WSUD systems have lower metals concentrations in the filter media within a similar operation period.

The results indicate that *Palmetto Soft Leaf Buffalo* lawn was able to prevent the accumulation of metals in biofilters. Similar to the study by Yeh *et al.* (2009), metal concentrations were higher in the *Palmetto Soft Leaf Buffalo* roots compared with shoots at all sites. This is not surprising because plant roots are in direct contact with the filter media and the point at which metals enter the plants. However, this correlation was only significant for Zn concentrations at ER ($p = 0.02$; Figure 9), while ($p > 0.12$) in the other cases. Plants tissues usually have different growth rates and properties that affect nutrient concentrations, therefore, there was no clear correlation between metal concentrations in the leaves and roots. Visual observation of the *Palmetto Soft Leaf Buffalo* grass during the study indicated that it was well suited to the site conditions. The grass was green, healthy, and completely covered the filter media. However, having a ZAM biofilter incorporated within a nature strip and exposed to pedestrian traffic could impact system performance and longevity due to compaction of the filter media compaction and vegetation damage. While this issue was not observed during this study, perhaps because pedestrian traffic was light, this should be assessed, particularly for systems installed in locations with higher pedestrian traffic loads. There was no surface clogging observed over the 8-month monitoring period, proving the effectiveness of ZAM biofilter design. However, it is acknowledged that these were quite new systems, only about 3 years old when the study was conducted. Therefore, it is possible that the continuous accumulation of sediments on the surface layer of the systems with time might reduce the infiltration rate.

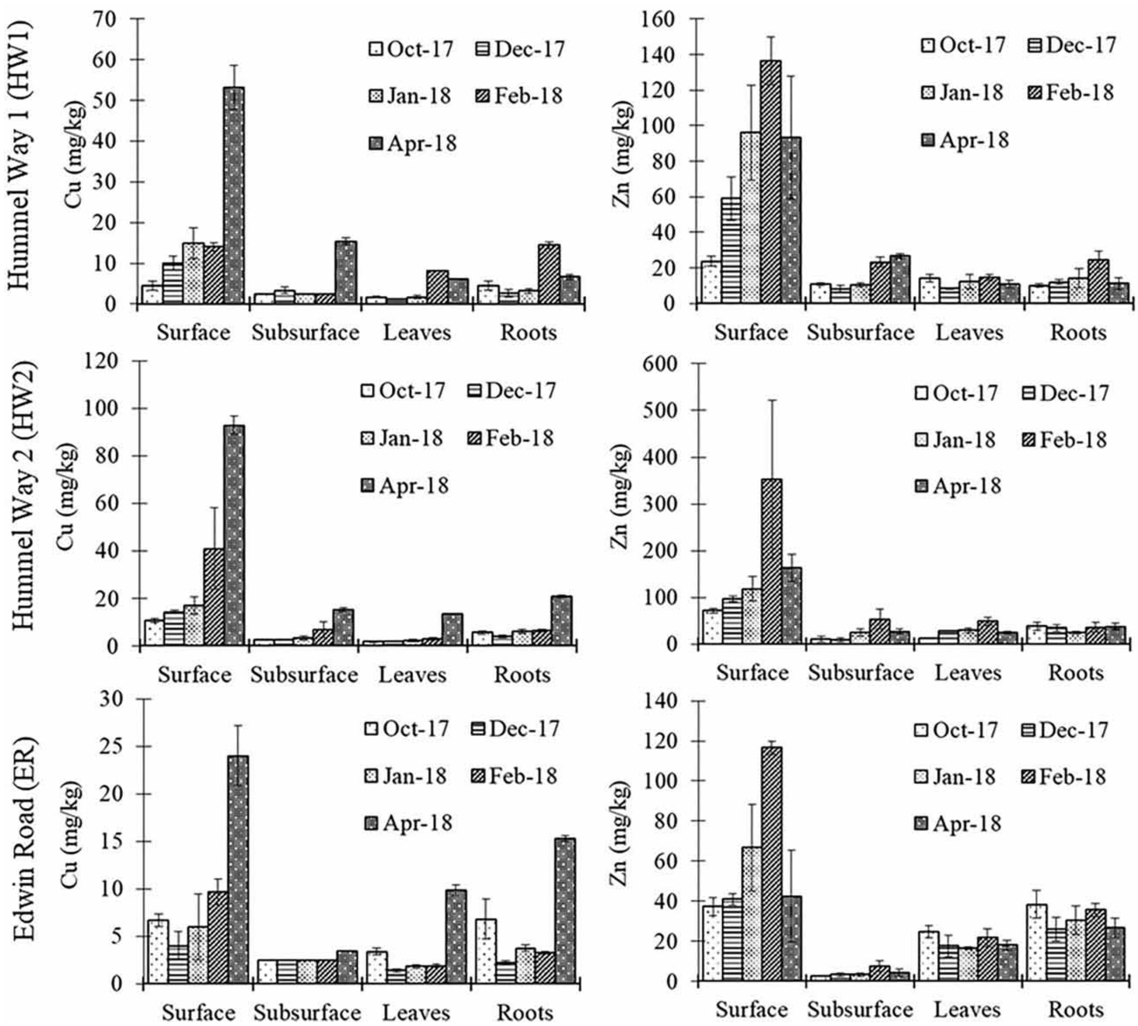


Figure 9 | Range of heavy metal concentrations in the filter media (surface and subsurface) and grass (leaves and roots), with accumulation over time, for each ZAM biofilter.

4. CONCLUSION

This study tested the development and implementation of novel concept called ZAM biofilters for stormwater management through a series of laboratory experiments and monitoring of field systems that examined the performance of filter media configurations designed to protect against clogging, plant choice, and field operation of ZAM systems. The results showed that the protective media layer delayed the onset of clogging compared with the design with no protective layer. The extent to which clogging was delayed appeared to be partially determined by particle size distribution favouring designs whose protective layers were comprised of a smaller mean particle size. However, the recommended protective layer configuration also considered cost, availability, and construction complexity.

The choice of easy-to-maintain lawn grasses for ZAM biofilter revealed that biofilters planted with lawn grass species, including *Kenda Kikuyu*, *Empire Zoysia*, *Santa Ana Couch*, *Village Green Kikuyu*, and *Palmetto Soft Leaf Buffalo*, could be effective for reducing nitrogen concentrations from stormwater. Some species, such as *Kenda Kikuyu* and *Santa Ana Couch*, established faster than others and showed less variable performance during dry conditions. If the preferences of the chosen lawn grass matched the site conditions, lawn grasses can meet local regulatory requirements and best practice standards for stormwater management.

The field study of three ZAM biofilters confirmed their high nutrient and heavy metal removal from stormwater. Designs with a submerged zone had higher TN removal, however, all designs achieved significantly higher pollutant load reductions than required by guidelines for stormwater treatment targets. Surface accumulation of sediments and heavy metals was observed, however no clogging was present after 3 years of system operation. The *Palmetto Soft Leaf Buffalo* grass used in the system was performed well, both visually and in terms of pollution removal, however, sediment grooves in the kerb upstream of the systems delivered only minor pre-treatment benefits. Overall, the findings of these three studies confirm the potential for well-designed ZAM biofilters to achieve stormwater management requirements with no additional maintenance requirements compared with standard streetscape landscaping. It is recommended that future monitoring of infiltration rates and lawn grass health over the long term be undertaken to provide further field-scale validation of this technology.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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