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Assessment of Impact of Filter Design Variables on Clogging in Stormwater Filters

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Abstract Stormwater filters are widely used in stormwater management, sometimes as standalone structures (e.g. stormwater filter beds), or as part of porous pavements, soak ways, infiltration basins and trenches. Due to the high levels of sediment present in stormwater, clogging is the main operational issue for these systems. A laboratory-based study was conducted to investigate the effect of filter bed design variables on the clogging phenomenon in non-vegetated stormwater filters with high infiltration rates. Design parameters studied include: filter media particle sizes (0.5 mm, 2 mm, 5 mm); depth of the filter bed (100 mm, 300 mm and 500 mm); and filter media packing configurations (layered or mixed). The size of filter media particles significantly impact the clogging process, as well as the overall sediment removal performance of the filters; filters with smaller particles had better sediment removal efficiency, but subsequently shorter lifespan. Deeper systems had longer lifespan compared with shallower ones, notwithstanding deeper systems removed more sediment over their life span. Having two layers of distinct sized media in the filter bed improved performance (e.g. volume of water treated; sediment removed) over the single-layered systems. However, the three-layered systems behaved similarly to two-layered systems. Mixed systems also showed improved performance, as compared with single-layered systems, and were similar to the three-layered systems. This study therefore suggests that simple modifications to a stormwater filtration system can help improve sediment removal performance and/or reduce maintenance intervals significantly, while only slightly affecting sediment removal performance.

Keywords Stormwater · Filters · Hydraulic conductivity · Clogging · Sediment treatment · Lifespan

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1 Introduction

Media filtration systems are often employed for treatment of urban stormwater prior to its discharge or infiltration into groundwater systems (Barraud et al. 1999; Tan et al. 2003; and Yong et al. 2013). While these systems can be effective for removal of various stormwater pollutants, they usually clog quickly, and therefore require intensive maintenance (Lindsey et al. 1992; Warnaars et al. 1999; and Bardin et al. 2001). Clogging, which is the decrease in permeability and infiltration rate of a porous media due to physical, biological and chemical processes (Perez-Paricio 2001; Bouwer 2002) usually leads to increased overflows and long periods of ponding of stormwater systems. This eventually results in a range of issues related to public safety (e.g. increased flooding or mosquito breeding), aesthetics, reduction in treatment efficiency, and eventually total failure of the system (Lindsey et al. 1992; Bouwer 2002; Le Coustumer and Barraud 2007).

In water and wastewater treatment practice, it is a well-known fact that the hydraulic conductivity of porous filters and its life-span depends on filter bed design. For example, the coarse gravel bed that used 38 mm particles was found to clog slower than the 19 mm gravel bed in a study that compared different sized gravel media used in leachate collection systems (McIsaac and Rowe 2007). Farizoglu et al. (2003) and Rodgers et al. (2011) found that increasing the depth of filter beds used for wastewater treatment increased the available surface area for the capture of particulate matter, thereby improving its removal rate which has implications for filter lifespan. However, the effect of filter bed design on filtration performance of stormwater filters has seldom been studied and most of the stormwater treatment systems are currently designed using knowledge and experience acquired from other water treatment systems, although stormwater characteristics and system operations are very different.

A few clogging studies that have been conducted for stormwater filtration systems, focused on either very fine filters (e.g. Hatt et al. 2008) and vegetated soil media (e.g. Li and Davis 2008; Le Coustumer et al. 2012) or on coarse gravel systems (e.g. Siriwardene et al. 2007) and complex porous pavement structures (Raimbault et al. 1999; Yong et al. 2013). Clogging of non-vegetated stormwater filter media made from particles sized between 1 mm and 5 mm has not been investigated, although these media are popular in industry. For example zeolite based gravity filters are often used in compact stormwater proprietary systems, such as technologies discussed in Clark and Pitt (1999) or Bratieres et al. (2012). Another recognised gap in the literature is the nature of the reported studies; the work reported so far in stormwater literature mainly uses black-box approach without informing the processes behind the clogging phenomena. Given the specific nature of clogging (Schubert 2002; Mays and Hunt 2005; Mays 2010), it is pertinent to understand clogging processes that govern gravity fed high infiltration rate stormwater treatment filters that are operated intermittently (i.e. only during wet weather). Only such understanding can lead to radical improvements in design and operations of stormwater filters.

Once treated appropriately, urban stormwater can be harvested and used for a range of non-potable urban water uses. The use of treated stormwater could potentially reduce pressures (Grant et al. 2012) on the existing potable urban water supply systems and also assist in adaptation to climate change by improving access to non-potable water supplies. Urban stormwater is of better quality as compared with untreated sewage or industrial wastewater discharge, and hence has better acceptability for re-use (Mitchell et al. 2002; Brown and Farrelly 2007). Furthermore, systems used for treating and/or harvesting stormwater can also provide flood protection and restore flow regimes and water quality in water bodies (Fletcher et al. 2007).

This study aims to develop an understanding of the effect of filter bed design on the rate of clogging of zeolite-based stormwater filters and the nature of clogging. The following hypotheses are therefore proposed:

1. Size of filter media particles in filter bed affects sediment retention within the media and therefore directly impacts upon clogging.
2. Depth of filter bed affects sediment trapping performance of system and therefore clogging.
3. How filter media particles are packed (e.g. layering) affects sediment trapping and clogging behaviour.
4. Distribution of accumulated sediment within the filter bed is non-uniform and clogging layer is formed at the interface between two layers of media of different sizes.

2 Methods

2.1 Experimental Setup

The shape and smoothness of filter media particles has been found to have a limited effect on the clogging performance of most filter media in previous studies (Kandra et al. 2014). Therefore, the following experiments have been conducted using zeolite, which was selected because of its low costs and easy availability (Booker et al. 1996; Wanga and Peng 2010) and frequent use in stormwater filters (e.g. Clark and Pitt 1999; Bratieres et al. 2012).

One hundred millimetre diameter experimental columns were constructed (Fig. 1). Zeolite was placed between a 50 mm layer of coarse gravel at the top (to protect the filter from the

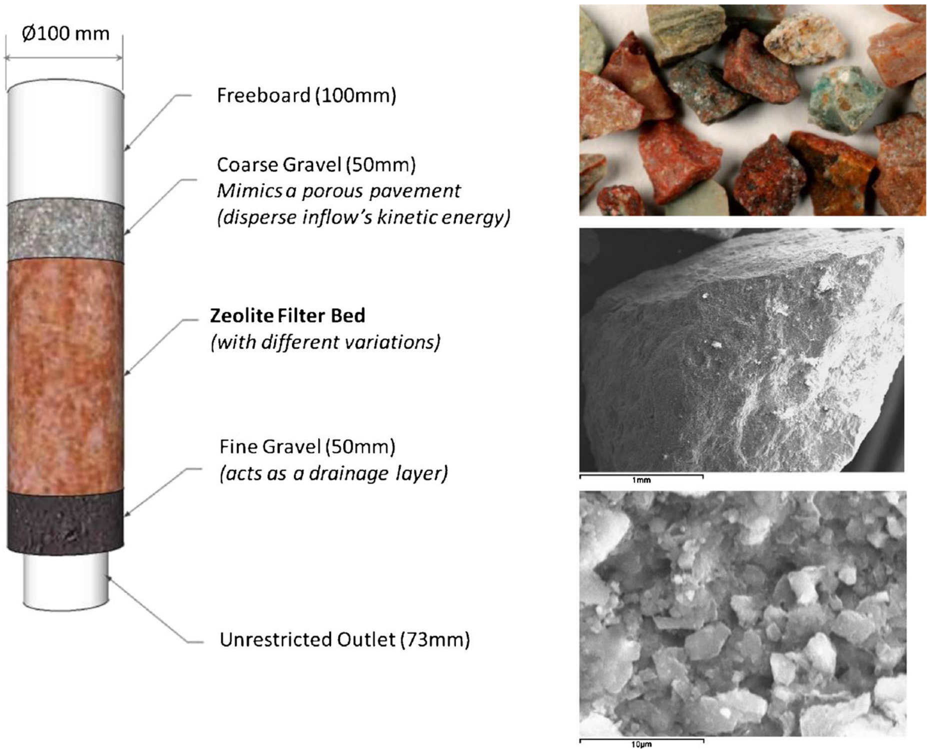

Fig. 1 Design of experimental columns (*left*); Zeolite filter media at different magnifications: normal, 50 times, 5,000 times (*right*: from *top* to *bottom*)

Table 1 Details of different experiments and experimental column designs

Tested effects	Details of filter bed and nomenclature
Base case	Zeolite, 2 mm sized particles, Single layer, 300 mm deep filter bed
1. Effect of filter media's particle size	Single 300 mm layer of zeolite with various particle sizes: 0.5 mm (Z 0.5), and 5 mm (Z 5)
2. Effect of depth of filter bed	Single layer of 2 mm sized zeolite with other filter bed depths: 100 mm (Z 100), and 500 mm (Z 500)
3. Effect of filter media packing arrangements	*Two-layered system* A 150 mm layer of 0.5 mm sized particles beneath a 150 mm layer of 2 mm sized particles (Z 0.5, 2); A 150 mm layer of 2 mm sized particles beneath a 150 mm layer of 5 mm sized particles (Z 2, 5) *Three-layered system* 100 mm deep layers with 0.5 mm, 2 mm and 5 mm sized particles and the coarsest filter media at the top (Z 0.5, 2, 5) *Mixed-layered system* Filter bed with particle sizes 0.5 mm, 2 mm and 5 mm mixed together (Z mixed)

energy of water applied to the top) and a 50 mm gravel layer at the bottom (to prevent migration of media from the system). At the base of each column, an outlet of 73 mm diameter was provided to allow free-flowing conditions, corresponding to a zero head loss. The ratio of experimental column diameter to filter particle diameter was around 50 (range between 20 and 200), as recommended for filtration studies (Lang et al. 1993).

Filter media particle sizes, depth of filter bed and packing arrangement of filtration media were varied as shown in Table 1. All configurations have been compared with the **Base case** configuration constructed with 300 mm deep zeolite filter bed containing a single layer of 2 mm diameter particle size media (passing 2.36 mm sieve and retained on 2 mm sieve). During construction of these columns, the layers were not compacted, avoiding damage to filter media. This is also true to practice. Five replicates of each experimental configuration were constructed and tested in a glasshouse of Monash University. Unfortunately, cost and space constraints did not permit full factorial experimental design.

2.2 Experimental Procedures

The experiments were undertaken in two steps:

1. Filtration tests using the experimental columns that focus on understanding impact of variations in filter bed design on infiltration and sediment removal, and
2. Sediment profiling of clogged experimental columns to identify the location of clogged material to understand the location of clogging.

2.2.1 Filtration Experiments

Column and Stormwater Preparation After sieving and packing, the columns were dosed in-situ with 6.4 m of tap water (about 50 pore volumes of the media) at the beginning of the experiment to ensure that the filter media was free of any intrinsic dust prior to testing. Initial infiltration rates were determined during this washing phase by measuring flow rates after every 1.75 m of tap water application. The filter bed depth was measured at the end of the cleaning phase, and again at the end of the full clogging experiment, to determine compaction rates, if any.

All columns were then dosed with semi-synthetic stormwater, prepared using potable tap water and sediment harvested from a stormwater pond in Huntingdale (Melbourne, Australia), passed through a 1,000 μm sieve. Although natural stormwater would have been preferable, this was unfeasible for logistical reasons—the high volume required for tests and the timing of rainfall meant that using actual stormwater was impossible. Application of artificial stormwater also ensured a fairly consistent composition of inflow for the experiments and it has been used in earlier clogging studies (e.g. Siriwardene et al. 2007; Bratieres et al. 2012). Particle size distribution of semi-natural stormwater used here (d_{50}=401 μm and d_{90}=448 μm) matched typical stormwater values (e.g. Lloyd et al. 1998). Concentration of sediment in the semi-natural stormwater was targeted at 150 mg/L, based on typical stormwater concentrations from a review of international data (Duncan 1999). Within each dosing event, consistent concentrations were ensured by a mixer installed in the stormwater tank, but concentrations varied between dosing events (100–200 mg/L), reflecting reality (Francey et al. 2010).

Column Dosing Different experimental configurations were tested simultaneously to ensure that the same stormwater was applied to all media, thus avoiding artefacts due to the varying concentrations or particle sizes between treatments. Similar to other studies (Siriwardene et al. 2007; Bratieres et al. 2008, 2012; Kandra et al. 2014), the experiments have been 'compressed in time', where months of operational life of the systems were conducted in several weeks due to time constraints. However, to ensure more realistic behaviour, the systems were not dosed continuously, but storm events were simulated, allowing some drying between events. Using Melbourne's historical rainfall data for 1999–2009 (Bureau of Meteorology, Australia), it was estimated that runoff volume during an 'average storm event' in Melbourne was 5.9 mm/event (the average annual rainfall of 512 mm between 1999 and 2009 resulted in total runoff of 422 mm/year, spread over 72 events). It was assumed that the system represents 0.3 % of its catchment's impervious area, typical of stormwater filters (Bratieres et al. 2008, 2012; Kandra et al. 2014). Therefore the average storm event should be mimicked by applying 15 l (1.91 m) of stormwater daily. Constant head to the top of column was maintained during each dosing session.

Monitoring Hydraulic and Sediment Removal Performance The infiltration rate of each column was calculated by measuring the outflow volume per unit time using the constant head method (ASTM international D2434-68) as per Darcy's Law. This was repeated after every 0.75 m of water was passed through each column. During each dosing event, composite water samples were taken from the inflow and the columns' outlets; the entire outflow was collected in a 25 l bucket after which a composite sample was withdrawn. This ensured that the first flush of the effluent was captured, giving a better estimate of sediment removal efficiency. The inflow and outlet samples were analysed for suspended sediment concentrations (ASTM D5907-09). These results were then used to determine the total load of sediment applied to and retained by each column. Particle size distribution (PSD) to assess the range of particle sizes in the inflow and outflow from the columns was undertaken using AccuSizer V Autodiluter Particle Sizing Systems.

2.2.2 *Profiling of Sediment in Clogged Columns*

Three replicates of each design configuration were profiled to analyse the location of clogged material within the filter bed. However, profiling could not be undertaken for designs that use filter media with a particle size of 0.5 mm as the size of trapped sediment and filter media were comparable, hence it was not possible to differentiate between them.

To examine contents of clogged filters, a detachable column that opened longitudinally was constructed (please refer Supplementary Figure I (left)). The clogged column was inverted and the contents transferred into this detachable column. This transfer was undertaken carefully, so that the layers within the filter media were not disturbed significantly. The clogged filter bed was then separated into 5–6 layers of equal depths (depending on filter bed design) by carefully inserting metal sheets into the filter bed (Supplementary Figure I (right)). A representative sample (1/6th of the entire volume) was removed from each sliced layer carefully using scoops. Two samples weighing about 80–100 g were removed, one of which was then oven dried to estimate moisture content and another used to measure sediment trapped in the respective layer.

In order to measure the sediment in the sample drawn from each layer, thorough washing of sampled media was undertaken. About 400–500 mL of de-ionised water was first added to the filter media and the solution was mixed thoroughly, both manually as well as using a 'Vortex' machine for 30 s. This helped in separating the sediment from filter media. This partially washed filter media was then cleaned again with another 400–500 mL of de-ionised water; this time, the filter media was placed on a 1 mm sieve that avoided any ingress of filter media particles into the collection chamber below. Thus, about 800–1,000 mL of deionised water was collected during the washing process. This solution was analysed for TSS (as per standard method ASTM D5907-09). Total sediment load in the filter media sample was calculated based on the TSS observed in sediment solution and volume of de-ionised water used for washing. This eventually led to assessing grams (g) of sediment load per gram of filter media (dried weight) in each layer.

2.3 Data Analysis

Evolution of clogging was examined in relation to the cumulative volume of applied water. For all configurations, median values and 95 % confidence intervals were then reported for the following variables:

- Initial infiltration rate (IIR) in m/hr representing hydraulic performance at the beginning of filter life (measured using potable water)
- The normalised volume of stormwater (in metres or litres) that causes total clogging of the system (i.e. when the infiltration rate dropped to 5 % of IIR). Normalisation was done by dividing the total mass of sediment applied by 150 mg/L (the target inflow TSS concentration) and then expressing all results in *Equivalent meters (or litres) of treated water*
- Sediment removed by the configuration during its operational lifespan in grams (g)
- Overall sediment removal efficiency of the media over its life span, defined as the ratio between total mass of TSS removed and total mass applied to each column (%)
- Sediment trapped in different layers of filter bed has been normalised per unit weight of filter media and reported in milligrams of sediment trapped per gram of filter media

Standard ANOVA tests were done to examine statistical difference between five replicates of different designs for a particular performance parameter (such as the effect of different filter bed designs on total sediment removed). Data has been tested for independence, normality and homogeneity of variances prior to undertaking the significance tests, as assumed for Standard ANOVA tests. Probability values less than 0.05 have been considered to imply a significant difference among designs.

3 Results and Discussion

3.1 Effect of Filter Media Particle Size

The initial infiltration rates of the three systems were different (Fig. 2), reflecting the differences in media particle sizes and hence porosities (Hillel 1998). As a result, the sediment removal efficiencies also varied, with finer systems being most efficient at retaining particles compared with the coarser ones. Similar to that of Yong et al. (2013), infiltration rates of all configurations decreased over time (Fig. 2) because of the cumulative retention of particles in the filter media, causing pore spaces to reduce, which also meant the sediment removal performances were enhanced (data not shown).

As found by many authors, such as McIsaac and Rowe (2007) and Knowles et al. (2011), the finer designs clogged more quickly due to their higher sediment retention efficiencies as compared with the coarse designs. As a result, the total amount of water treated by each design was significantly different (p=6E-18, Fig. 3, left). However, the relationship between overall sediment removal performances and the amount of stormwater that could be treated by a filter bed design was not linear. The sediment removal performance of the coarser design was around three times lower than that of the finer design, yet capable of treating more than 30 times the amount of stormwater (and did not clog completely). This could be because the coarser filter bed was unable to remove finer particles or the flow through rate led to re-suspension of particles responsible for clogging.

The particle sizes of the effluent also varied with filter media size and with time. For instance, d_{50} particle sizes in the outflow of Base case reduced from 251 μm (d_{50} in inflow: 401 μm) to less than 100 μm at the end of its operational life. However, a more significant change was observed for the finest media with the d_{50} outflow particles sizes dropping to just 11 μm. These results align with the above discussion; indeed, as the systems clog, their pore

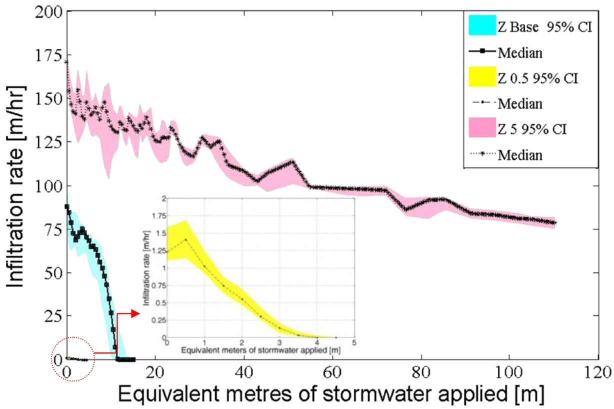

Fig. 2 Evolution of hydraulic performance in the three configurations with different particle sizes over their lifespan *(lines represent median values and shaded areas represent 95 % confidence intervals for the five replicates of this design)*

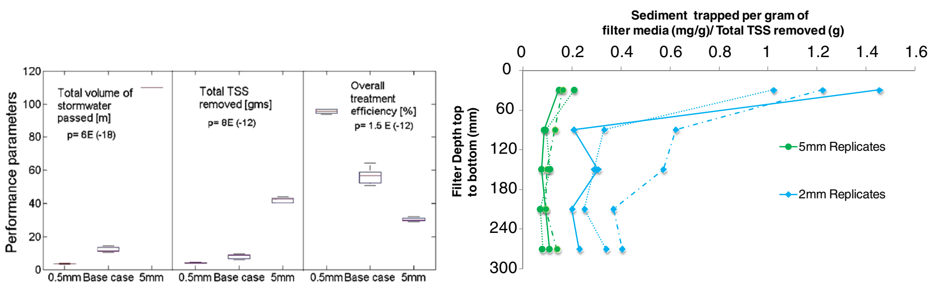

Fig. 3 Box plots comparing performance of filter beds made with different particle sizes (*left*) and; Distribution of sediment within different depths/layers of filter bed with 2 mm and 5 mm sized particles (*right*). *(Note: Top-most layer of the 300 mm deep filter bed is represented as 0–60 mm section and bottom most layer as 240–300 mm section of the filter bed)*

spaces reduce hence capturing smaller particle sizes. Outflow particle sizes from the coarsest filter media was relatively stable over time, probably because this design hardly clogged.

Profiling of the clogged columns suggests that most of the sediment removal occurs within the top-most layer (Fig. 3, right); aligning with relevant literature which states that surface clogging dominates (Hatt et al. 2008; Haselbach 2010). However, these results also suggest that some deeper clogging still occurs, meaning that a combination of cake and depth filtration; adsorption and interception contribute to the clogging of these systems, partly confirming the results of Li and Davis (2008). The differences observed in the sediment profiles between the two designs could be related to variations in shear stresses imposed onto each design; indeed, the coarse media has higher shear stresses (because of higher flow rates) which could force particles further into the media as compared with finer filter media. Another possibility is that the governing processes in the two designs differ. For example, straining of the <1 mm sized influent particles could be dominant in the 2 mm particle design, which according to Herzig et al. (1970) could lead to surface clogging, while straining is not dominant in the coarser design because 5 mm particle sizes are less effective at straining <1 mm particle sizes.

Therefore, these experiments confirm that clogging performance of filter media is strongly dependent on the size of filter particles (which has been shown often for wastewater and water treatment filters in the past). The nature of clogging for these filters is a mixture of surface and deep clogging and is governed by the inter relation between sizes of filter media and particles in the influent. There is a trade-off between longevity and sediment removal efficiency of the system. For instance, coarse media filter beds would remove stormwater runoff quickly and would hardly need any maintenance, but would be less effective in sediment removal (and vice versa). The choice of the filter media's particle size has to be guided by the project's objective, whether focussed towards flow control or treatment.

3.2 Effect of Filter bed Depth

Similar performance trends were observed for all three designs, as described above, infiltration rates decreased with time (Fig. 4, left), while sediment removal efficiencies increased. The sediment removal performance increased with filter depth- 42 % for 100 mm depths; 57 % for 300 mm and; 62 % for 500 mm (Fig. 4, right). Particle size analysis of the outflows also suggests that the deepest filter bed was able to remove finer sediment as compared with other configurations. Considering the initial hydraulic head of these three systems is similar, better sediment removal efficiency of the deep systems confirms that surface clogging is not the only

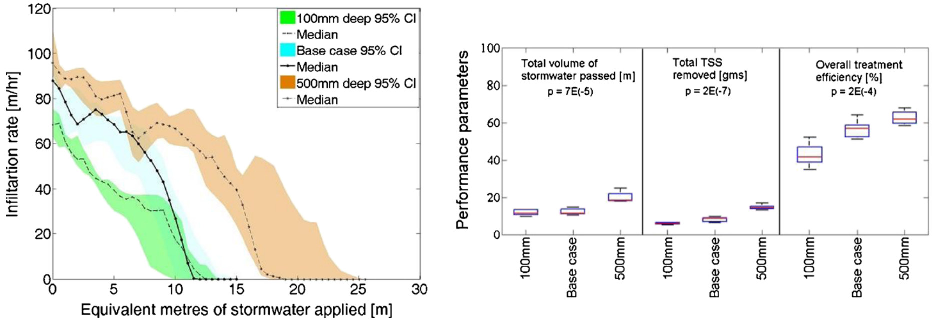

Fig. 4 Performance of 100 mm, 300 mm (Base case) and 500 mm deep filters made from 2 mm Zeolite particles- Hydraulic performance over filter lifespan (*left*) and; Box plots of total stormwater volume passed, total sediment retained and overall sediment removal efficiency over their lifespan (*right*) *(lines represent median values and shaded areas represent 95 % confidence intervals for the five replicates of this design)*

important process that occurs. Indeed, the better performance of the deeper filter configurations is the result of increased contact time with the media, which may enhance processes such as adsorption/adhesion or particle interception; this aligns with many other findings in water treatment literature (e.g. Farizoglu et al. 2003 and Rodgers et al. 2011).

The 100 mm and 300 mm (Base case) systems performed almost identically in terms of treated stormwater volumes before clogging, while the 500 mm system was capable of processing 60 % more water even though it also had the highest sediment removal efficiency (Fig. 4, right). The hypothesis is that the shallow systems fail *mainly* due to surface clogging. The deeper columns have the largest ponding depth (Table 1), which means that there is more pressure on the 'thin' surface clogging layer (once formed). This increased pressure could mobilise and drive particles from this layer deeper into the column, thereby reducing surface clogging and increasing their lifespan. This hypothesis was partly confirmed by Fig. 5, which shows that while surface clogging was still dominant in all configurations, the deeper columns had the lowest proportion of sediment retained in the surface layer (37 % as opposed to 50 % and 59 % in the 300 mm and 100 mm

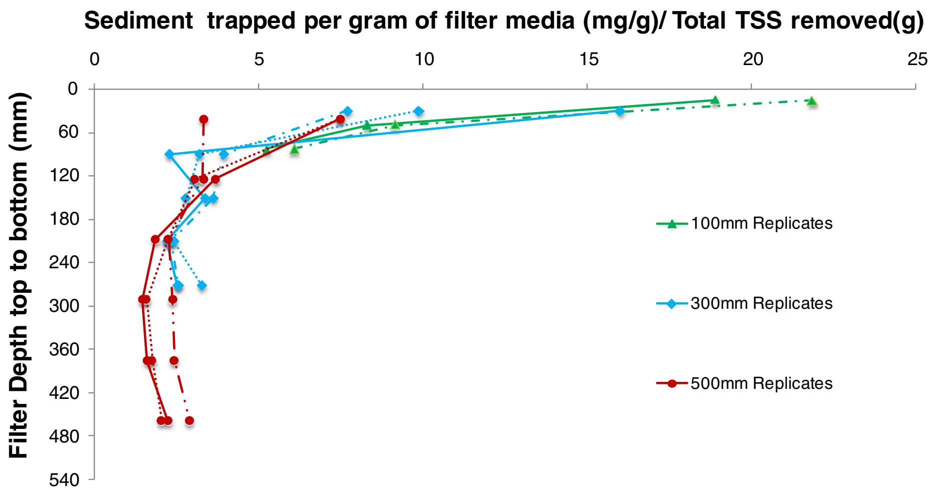

Fig. 5 Distribution of sediment within different depths/layers of filter bed for 100 mm, 300 mm and 500 mm deep filters

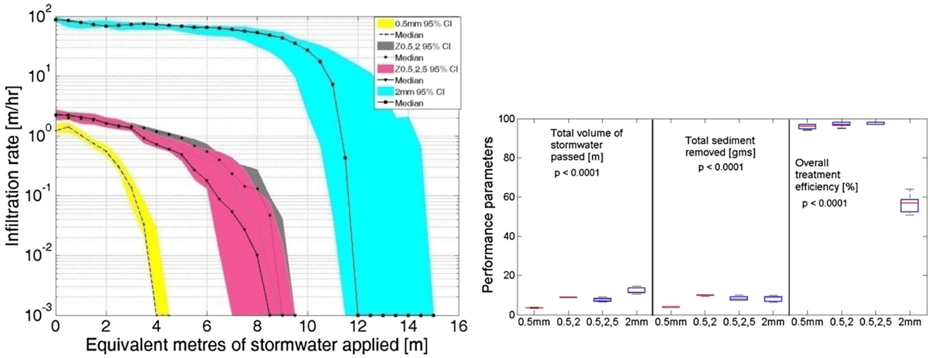

Fig. 6 Comparison of hydraulic performance of filter bed with 1, 2 and 3 layers of filter media (log plots) *(lines represent median values and shaded areas represent 95 % confidence intervals for the five replicates of this design)* (*left*) and; Box plots of the total stormwater volume passed, total sediment retained and overall sediment removal efficiency of the filter beds with 1, 2 and 3 layers of filter media (*right*)

configurations, respectively). Deeper systems should therefore be preferred in practice, especially if large hydraulic gradients (similar to those used here) are possible.

3.3 Effect of Packing Arrangement

3.3.1 Layering Arrangement

The initial hydraulic conductivity and sediment removal efficiency performances of multiple layered systems were comparable to the single layered systems, which had particle sizes equal to the bottom-most layer (Fig. 6, left). For instance, Z 0.5,2 had similar initial hydraulic conductivities and overall sediment removal performances as the single-layered Z 0.5 systems. This is because, for both designs, the bottom 0.5 mm layer governs both infiltration and sediment trapping processes. However, the evolution of infiltration rate was different (Fig. 6, left), resulting in different lifespans of the multiple layered systems compared with single layered systems (Fig. 6, right). It is hypothesised that the enhanced performance of layered systems is due to most sediment removal occurring in the upper layer, which protects the bottom layer from clogging, as also found in patented air and gas filters, such as US Patent 4,011,067 (1977) and US Patent 5,427,597 (1995). However, the 2-layered system (Z 0.5,2) performed similarly to the 3-layered system (Z 0.5,2,5) (Fig. 6, right). This may be because the coarse media at the top hardly removes any fine sediment from the inflow, especially since the influent is sieved to <1 mm.

3.3.2 Mixing Arrangement

The performance differences between mixed (Z mixed) and the multiple layered systems (Z 0.5,2,5) for total volume of stormwater passed before clogging and total sediment retained are statistically insignificant (see p-values in Fig. 7). However, both these systems removed more sediment and treated more water than the single-layered Z 0.5 system. Z 0.5,2,5 and Z mixed respectively treated 105 % and 86 % more water and; removed 103 % and 76 % more sediment before clogging as compared with Z 0.5. Analysis of results for particle size distribution of sediment in outflows of the subject configurations suggests that having a filter bed with diverse range of particle sizes helped trap finer sediment with d_{50} in outflows reducing overtime.

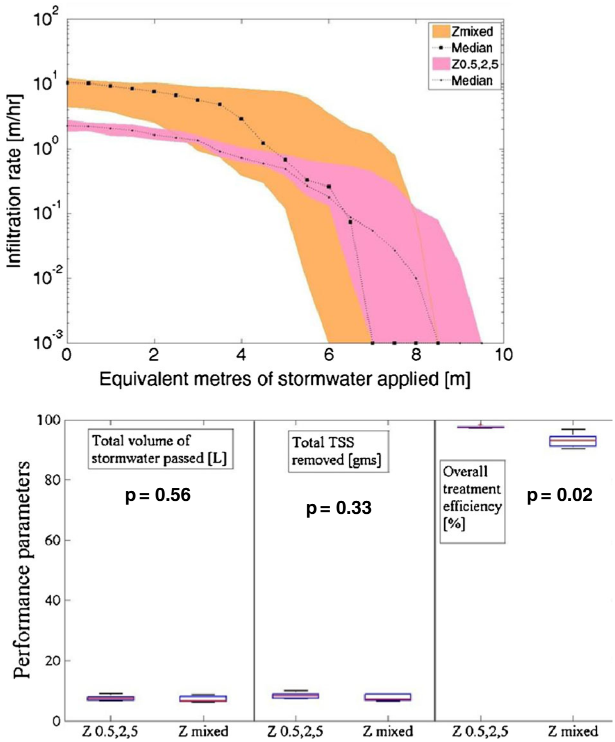

Fig. 7 Comparison of hydraulic performance of filters with three layers and mixed filter bed over their lifespan (log plots) (*left*); Box plots of total stormwater volume passed, total sediment retained and overall sediment removal efficiency performance of filters with three layers and mixed filter bed over their lifespan (*right*)

The above results suggest that it is better to have a filter bed with a diverse range of particle sizes than uniform size. However, multiple layering does not provide significant improvements to mixing particles of different sizes. Since layering is usually not a practical solution (costs to layer are higher) it is recommended that mixing different fractions is the best approach to designing stormwater filters with high flow rates. However, it should be noted that an optimum design of a mixed system (such as the number of particle fractions and their sizes) should be optimised in relation to the size of particles in the inflow.

4 Conclusions

Clogging of granular stormwater filters has been studied for a range of design configurations: filter media particle sizes; depth of the filter bed and; different filter media packing configurations (single layer of a specific filter media size and multiple layers of different particle sizes). Analysis of comparative performances of configurations suggests that filter bed design certainly affects the clogging rate and sediment removal performance of non-vegetated high flow rate stormwater filters.

A decrease in particle size of filter media reduces hydraulic conductivities of the filter and improves its sediment removal. There is a trade-off between longevity and sediment treatment efficiency of the system, but this trade-off is not linear. Filter bed with coarser media had onethird sediment removal efficiency yet treated more than 30 times the amount of stormwater treated by the design using fine media. The choice of filter media's particle size in filter bed therefore has to be guided by the objective of treatment, whether it is focussed more toward flow control or treatment of stormwater.

An increase in depth of filter bed enhanced the life and sediment removal performance. The better sediment removal performance of the deeper filter configurations is the result of increased contact time with the media. Deeper systems were also able to treat a significantly larger volume of stormwater possibly because shallower systems clogged at the surface and the deeper system had greater ponding depth, which effectively disrupted the surface layer. Deeper systems should be preferred in practice, especially if large hydraulic gradients (similar to those used here) are possible.

Layered filters eventually offered greater resistance and passed almost double stormwater while also removing much more sediment before clogging as compared with single layered systems. It is hypothesised that the enhanced performance of layered systems is because of the protection to the bottom layer with most of removal processes/sediment removal occurring in the upper layer. No net benefit of a three-layered system was observed over a two-layered one, probably because the additional layer had a media size five times the maximum influent particle size. Further, a filter bed prepared by mixing particles of diverse sizes behaved similarly to a three-layered system. These results therefore suggest that it is better to have a filter bed with diverse range of particle sizes, since multiple layering may not be a practical solution because of the costs involved.

This study therefore suggests that simple modifications to stormwater filtration systems with high infiltration rates can help improve the sediment removal performance and/or reduce maintenance intervals significantly.

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