Performance of the enviss™ filtration media: Laboratory trial

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ABSTRACT

An experimental study was undertaken by Monash University to develop and test enviss™ stormwater treatment and harvesting technologies - non-vegetated filtration systems with an extremely low footprint. This paper focuses on the water quality and hydraulic performance of two systems tested over a year of operation in a Melbourne climate: (1) REUSE enviss™ filters, designed for stormwater harvesting systems for non-potable supply substitution, and (2) WSUD enviss™ filters, developed to treat urban stormwater prior to discharge to downstream systems. The presence of chlorine as a disinfection agent proved to be very efficient for the removal of microorganisms in REUSE enviss™ filters. WSUD enviss™ filters had the benefit of providing an elevated nutrient treatment performance, due to an extended depth of filter media. However, nutrient outflow concentrations (TN in particular) were found to increase during the testing period. Also, dry weather periods were found to have an important negative effect on the treatment performance of almost all pollutants for both filters (nutrients, *E. coli* and heavy metals). Although hydraulic conductivity results indicated 2 or 3 sediment trap replacements per year are required to maintain filtration rates, it is expected that the experimental design overestimated this maintenance frequency.

KEYWORDS

Filter media, hydraulic conductivity, pollutant treatment performance, stormwater harvesting, water quality, WSUD

INTRODUCTION

Water Sensitive Urban Design (WSUD) technologies have been widely implemented around the world (1) for the protection of receiving aquatic ecosystems (water quality and hydrology), (2) for stormwater harvesting purposes and, to a lesser extent, (3) for distributed flood protection. However, most WSUD systems still need improvement in some areas depending on their end-use purposes. For example, pathogen treatment levels are often insufficient for re-use scenarios (e.g. Bratieres *et al.*, 2008) and most WSUD technologies have a relatively large footprint, which can be problematic for retrofitting scenarios in highly urbanised areas.

An experimental study was undertaken by Monash University to develop and test enviss™ stormwater treatment and harvesting technologies. These stormwater filtration systems are non-vegetated filtration systems with an extremely low footprint (around 7 times smaller than that of a typical biofilter), and a design hydraulic conductivity of 2000mm/hr. This technology is one of just few available which can treat stormwater to a level which is acceptable for reuse, and the only known which has undergone independent testing for this purpose in Australia.

This paper will focus on the water quality and hydraulic performance of two systems with different end-use applications: (1) REUSE filters, designed for stormwater harvesting systems for non-potable supply substitution (e.g. irrigation and toilet flushing), and (2) WSUD filters, developed to treat urban stormwater prior to discharge to downstream systems.

METHODS

Experimental set-up

enviss™ filters consist of 4 different layers: (1) a porous paver top to remove gross pollutants and coarse sediment, (2) a sediment trap (layered filtration media) to protect subsequent layers from excessive clogging, (3) a sand-based filter media to remove finer sediment and dissolved pollutants, and (4) a drainage layer to prevent filter media migration and outlet clogging.

These filters were tested in a laboratory configuration using 100mm diameter PVC columns (Figure 1). Prior to testing, the inside of the columns was thoroughly washed and the sediment traps were flushed rigorously to ensure that the filter media would not be clogged/polluted by other sources than the incoming stormwater.

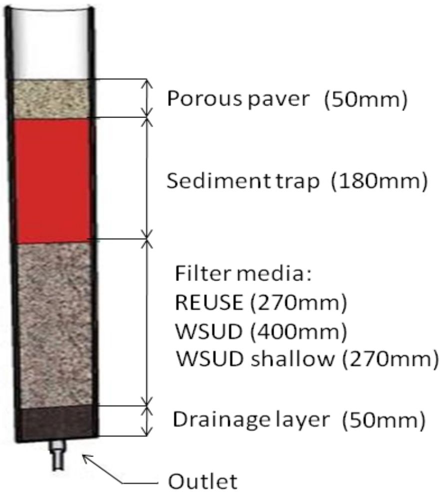


Figure 1. General filter column design (schematic drawing).

Primarily, the filter columns were developed to test the two main enviss™ systems over a year of operation in a Melbourne climate: REUSE filters and WSUD filters. The REUSE filter had 270mm of filter media, and specially designed slow-release chlorine blocks in the sediment trap to provide disinfection. The WSUD system had 400mm of filter media and did not include any disinfection. However, for comparison purposes, an additional configuration (WSUD shallow), which had 270mm of filter media but no chlorine, was also used to test the influence of filter depth and disinfectant. Five replicates of each configuration were used to allow for basic statistical comparisons.

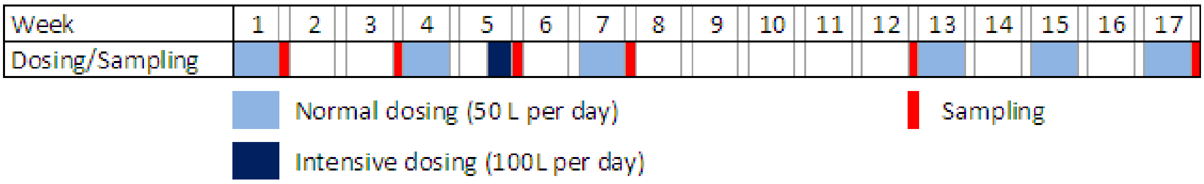
Experimental procedure

‘Semi-natural’ stormwater. The use of ‘semi-natural’ stormwater allowed us to perform controlled laboratory investigations while maintaining realistic stormwater composition: sediment was collected from a stormwater inlet pond, sieved through a 1000 μm sieve and mixed with dechlorinated tap water to achieve the target TSS concentration. Any deficit in other pollutants such as nutrients, metals and hydrocarbons was made up by adding appropriate chemicals. Target concentrations for the stormwater used to dose the filters were matched to ‘typical’ worldwide and Melbourne urban stormwater quality characteristics (Duncan, 1999; Taylor *et al.*, 2005). For further information about the method of producing this ‘semi-natural’ stormwater please refer to Hatt *et al.* (2007).

In order to assess the filters’ ability to remove potentially harmful microorganisms, the ‘semi-natural’ stormwater was spiked with indicator organisms on sampling days (as per Table 1). Due to OH&S constraints, only the following non-pathogenic indicator organisms were used: *Escherichia coli* (*E. coli*) for bacteria, *Clostridium perfringens* (*C. perfringens*) and F-RNA coliphages (F-RNA phages). These were thought the best indicators to represent the range of microorganisms known to be in urban stormwater (i.e. bacteria, protozoa and viruses).

Dosing/Sampling regime. A specific dosing and sampling regime was implemented in order to test the influence of dry and wet weather periods (Table 1). Due to time and cost constraints, the volume corresponding to a full year of Melbourne rainfall (1050 L) was applied to the filters in just four months by using a compressed time scale. For each dosing, and in order to achieve consistent input concentrations, the target volume (50 L per dosing event) was delivered via ten ‘passes’ of 5 L. The water was applied to the filters using smaller dosing cups, so that the head could be kept constant at all times.

Table 1. Dosing/sampling regime.



Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Dosing/Sampling	🟦🟥		🟥	🟦	■🟥		🟦🟥					🟥	🟦		🟦		🟦🟥

🟦 Normal dosing (50 L per day)

🟥 Sampling

■ Intensive dosing (100L per day)

On sampling days (Table 1), composite samples were taken from the inflow and outflow of each filter, and all samples were analysed in a NATA (National Association of Testing Authorities, Australia) accredited laboratory for pollutants: sediment, nutrients (nitrogen and phosphorous for both particulate and dissolved forms), heavy metals (20 elements), hydrocarbons (Total Polycyclic Aromatic Hydrocarbons TPAH and Total Recoverable Hydrocarbons TRH), microorganisms (*E. coli*, *C. perfringens* and F-RNA phages) and disinfection by-products (TriHalomethanes - THMs, chloral hydrate, chloroacetics, dichloromethane, etc.). Chlorine concentrations were determined immediately after sampling using a colorimetric testing kit.

Measurement of hydraulic conductivity. Using a simplified method to assess the saturated hydraulic conductivity of the filters, we recorded the time it took for a known volume to flow through the column when a constant head was kept above the filter media. These measurements were undertaken regularly at every dosing event. When the median hydraulic conductivity for a group of filters of a particular configuration dropped below half of its design value, the sediment trap was replaced. It is also noted that during replacement, the top 20mm of filter media was scraped off and replaced with clean/washed media, due to the high degree of sediment accumulation.

Data analysis

Results for the water quality data are expressed both in outflow concentrations (independent from the inflow) and in removal efficiencies (which depend on the inflow concentrations). However, for microorganisms we used log removal data instead of percentages ($\log(c_{in})-\log(c_{out})$).

RESULTS AND DISCUSSION

General pollutant treatment performance

Table 2 summarises the treatment performances for REUSE and WSUD filters over the experimental testing period.

Sediment and nutrients. Outflow concentrations were always below 7mg/L for TSS, which corresponds to over 93% removal efficiency. Whilst the overall performance for TP was good, the results show that the removal of particulate phosphorus was higher than for dissolved phosphorus, indicating that one of the main removal mechanisms could be filtration. TN concentrations varied greatly between sampling runs (between 0.6mg/L and 1.5mg/L / 25-75% removal for REUSE). Nutrient treatment was generally lower in REUSE filters, due to both the reduced filter media depth (i.e. shorter detention time) and the presence of chlorine (see below, Figure 2).

Heavy metals. The outflow concentrations and removal rates varied between heavy metals but, in general, the removal was higher than 50% for REUSE and 70% for WSUD.

Microorganisms. All REUSE samples in the first 4 sampling runs were under detection limit for *E. coli*. Whilst there were a couple of samples with detectable *E. coli* in sampling runs 5 and 6, the calculated log removals were still around 2, i.e. 99% removal. The treatment for *C. perfringens* was not as good, with organisms detected in almost every outflow, and values of up to 2,500 org/100mL in sampling run 2 (log removals ranged from 1.3 to 2.5). However, this might be attributable to the extremely high inflow concentrations for *C. perfringens* (mean 37,900 org/100mL) which well exceeded the target value of 2,500 org/100mL. All samples were under detection limit for F-RNA phages, which again might be partly related to the mismatch between target and actual inflow concentrations (inflow too low).

Chlorine and by-products. Chlorine outflow concentrations were between 0.2 and 1.4 mg/L. Whilst the concentrations in chlorine derivatives were relatively low (even often under detection limit), the presence of a dry period seemed to negatively influence, for example, THM removal (see below).

Hydrocarbons. Whilst all outflow PAH concentrations were under detection, some samples contained a detectable TRH concentration (in particular for REUSE filters). Dry weather seems to have an influence on hydrocarbon removal, indeed only detectable TRH samples for WSUD filters were taken after a dry weather period.

Table 2. Summary of results – Performance of REUSE and WSUD filters. Median values are shown together with the 2.5th and 97.5th percentiles (DL – Detection Limit).

Pollutant	**Inflow conc [mg/L]**	**REUSE filters**		**WSUD filters**	
		Outflow conc [mg/L]	**Removal [%]**	**Outflow conc [mg/L]**	**Removal [%]**
TSS	85 (47;133)	4.05 (2.09;6.03)	96% (93%;98%)	3.10 (1.55;6.53)	96% (93%;98%)
TP	0.31 (0.27;0.37)	0.16 (0.15;0.18)	51% (43%;63%)	0.13 (0.10;0.14)	64% (54%;70%)
TN	2.2 (1.9;2.7)	1.20 (0.70;1.50)	52% (29%;71%)	0.75 (0.40;1.33)	70% (37%;84%)
NH_3	0.34 (0.31;0.39)	0.004 (0.002;0.017)	99% (95%;99%)	0.008 (0.002;0.018)	98% (95%;99%)
FRP	0.13 (0.09;0.16)	0.11 (0.08;0.14)	17% (-1%;26%)	0.08 (0.06;0.11)	41% (11%;46%)
NO_x	1.20 (0.99;1.40)	0.72 (0.39;0.98)	42% (4%;68%)	0.47 (0.18;1.10)	62% (-10%;85%)
Al	0.85 (0.65;1.40)	0.38 (0.32;0.61)	64% (10%;75%)	0.29 (0.16;0.46)	77% (33%;79%)
Cd	3.9 (2.6;8.5) x 10^{-3}	1.5 (0.03;3.1) x 10^{-3}	77% (3%;96%)	0.6 (0. 3;0. 8) x 10^{-3}	86% (75%;96%)
Cr	1.2 (0.7;0.3) x 10^{-2}	5.0 (2.7;7.0) x 10^{-3}	75% (9%;86%)	2.5 (2.0;4.3) x 10^{-3}	80% (74%;90%)
Cu	4.5 (2.2;9.4) x 10^{-2}	1.5 (0.9;1.9) x 10^{-2}	80% (19%;86%)	0.9 (0.7;1.1) x 10^{-2}	85% (70%;90%)
Fe	1.30 (0.87;2.30)	0.33 (0.26;0.46)	73% (59%;87%)	0.25 (0.21;0.40)	80% (63%;89%)
Pb	0.12 (0.05;0.23)	0.05 (0.01;0.10)	72% (49%;80%)	0.03 (0.01;0.06)	81% (70%;91%)
Mn	0.19 (0.16;0.46)	0.11 (0.03;0.22)	70% (-29%;92%)	0.06 (0.02;0.12)	78% (48%;96%)
Ni	2.4 (1.9;5.0) x 10^{-2}	1.4 (0.5;2.5) x 10^{-2}	63% (-22%;89%)	1.0 (0.2;1.5) x 10^{-2}	76% (45%;96%)
Zn	0.23 (0.18;0.39)	0.10 (0.03;0.19)	67% (8%;92%)	0.05 (0.01;0.08)	85% (61%;97%)
***E. coli* *** [a]	22.5 (6.1;65.1) x 10^{3}	<1 (<1;392) [a]	100% (99%;100%) [a]	N/A	
C. perfringens*	37.5 (9.1;64.9) x 10^{3}	300 (134;1940)	99% (96%;100%)	N/A	
F-RNA phages*	800 (90;1770)	All samples under DL (<1 org/100mL)		N/A	
Chlorine	< DL (0.2mg/L)	0.60 (0.20;1.36)	N/A	Outflows < DL (0.2mg/L)	
THM [b]	2.2 (2.1;2.3) x 10^{-2}	1.4 (0. 6;2.4) x 10^{-2}	10% (0%;14%) [b]	N/A	
TRH [c]	2.34 (1.33;5.08)	0.37 (0.27;0.52)	85% (56%;89%)	0.14 (0.14;0.29) [c]	92% (86%;95%) [c]
PAH	6.5 (2.4;16.6) x 10^{-3}	All samples under DL (<0.001mg/L)			

*Concentrations are in org/100mL for *E. coli, C. perfringens* and F-RNA Phages

[a] REUSE - Only 3 samples were above detection limit (2 of which after an extended dry period)

[b] REUSE - Using 5 samples only (we only analysed THMs in the inflow for sampling run 1)

[c] WSUD - Only 7 samples above detection limit for TRHs – all of which were after a dry period

Influence of the presence of disinfection (chlorination)

Whilst previous results (Schang *et al.*, 2010) showed that the presence of chlorine as a disinfection method was very efficient at improving microorganism removal, it was unknown whether it would also affect the treatment capacity of other pollutants. This section therefore compares the results between REUSE filters and WSUD shallow filters (which are the same except they do not contain chlorine).

Apart from the expected effect on *E. coli* removal, there was a significant influence on nutrient treatment performance, in particular for phosphorus. Indeed, Figure 2 clearly shows that the presence of chlorine reduces the treatment performance for the removal of TP. This might be related to the fact that adsorption sites are being taken up by chlorine instead of phosphorus in the REUSE systems, while this is not occurring in the WSUD shallow systems. However, given the suggested end-uses for REUSE filters, this side-effect was of no great concern. There was only a slight influence of the presence of chlorine for the treatment of metals: for Al, Cd, Cu and Fe, REUSE filters had slightly higher concentrations (i.e. lower removal rates) than their non-chlorinated counterparts, in particular after dry weather periods.

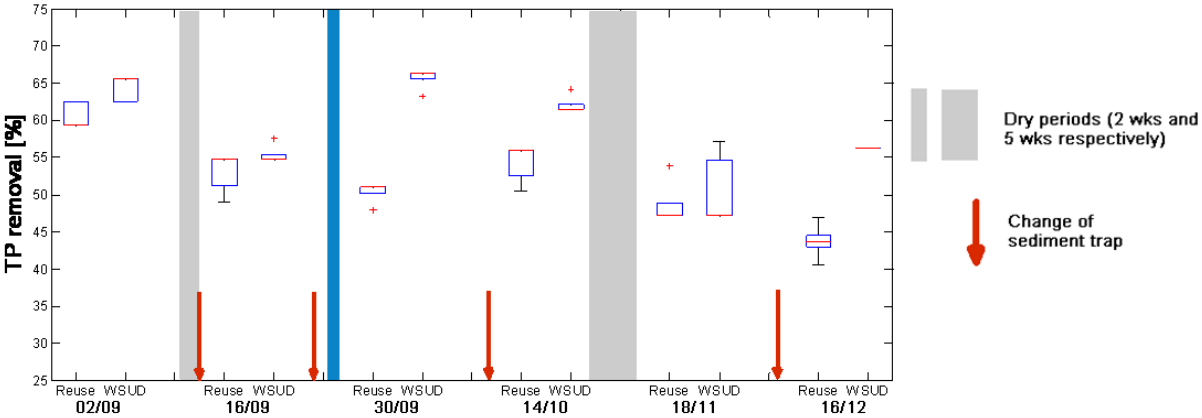


Figure 2. TP removal performances for REUSE and WSUD shallow filters.

Influence of filter media depth

As expected, the increased filter media depth (i.e. increased detention time) had a beneficial effect on TN and TP treatment performance, especially in the first part of the experiment (before the effect of time became preponderant, Figure 3). Unsurprisingly, the treatment performances for most metals was unaffected by the depth of the filter media. Indeed, metals are mostly in particulate form/attached to sediment, and are therefore mostly removed by filtration in the top section of the filter media. For some metals however, which are found mainly in dissolved form in urban stormwater (e.g. Cu, Ni and Zn), deeper filters were shown to have an increased treatment capacity.

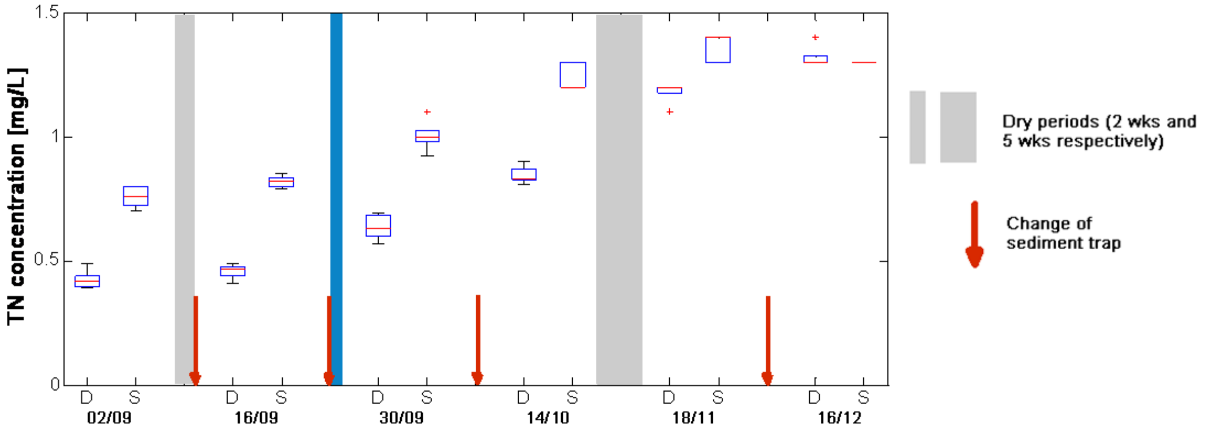


Figure 3. TN outflow concentrations WSUD (D) and WSUD shallow (S) filters.

Influence of time

Due to the compressed time scale, the reduced number of sampling runs (six), and the complex dosing/sampling regime (mainly focussing on the effect of other parameters), it was hard to recognise a consistent pattern for the effect of time on the pollutant removal performance of the REUSE and WSUD filters. Whilst TP concentrations seemed to increase slightly over time, the major (and most problematic) trend was found for the treatment of nitrogen: For WSUD filters for example, the outflow concentrations almost tripled within one year (from 0.4mg/L in sampling run 1 to 1.3mg/L in the last sampling run), reducing the initial treatment performance from over 80% to only just under 40% removal (Figure 4). Whilst this loss of performance is of no concern for REUSE filters, it is more problematic for WSUD filters, which are releasing their outflows into downstream systems. This issue has been addressed in subsequent work by the authors (Schang *et al.*, 2011).

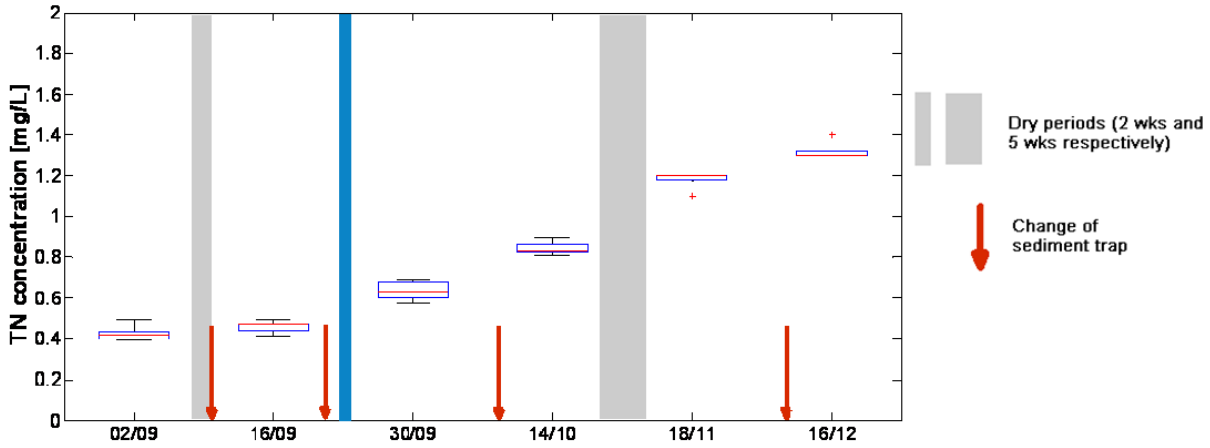


Figure 4. TN outflow concentrations for the 6 sampling runs for WSUD filters.

Influence of dry weather periods

Several of the results reveal that prolonged dry periods had an influence on pollutant removal performance. Indeed, during a period of drought, the filter media dries out, and cracks and macropores can develop in the soil matrix, reducing the filtering capacity and enabling the formation of preferential flow paths through the filter. This also leads to higher sediment outflow concentrations (fine sediments are not filtered out anymore), which in turn means that particulate associated pollutants will have increased outflow concentrations. Also, the development of preferential flow paths induces a decrease in detention time, in turn reducing direct opportunities for adsorption processes. Other processes can occur during dry weather periods, like decomposition of material, which can also explain some of the observations.

- As expected, dry weather had an influence on TSS removal performances, with higher outflow concentrations in sampling runs 2 and 5. Whilst the same could be said for phosphorus, the fact that the treatment of nitrogen was mostly dependent on time (Figure 4) makes it hard to quantify the relative significance of both factors.
- Chlorine concentrations were lower after a prolonged dry weather period, possibly because the chlorine block dries out, meaning that less is eluted during the subsequent dosing event. The opposite was true for chlorine by-products, where the first dosing after a dry spell produced elevated THM concentrations (e.g. sampling run 5). It is hypothesized that, during dry weather periods, the chlorine remaining in the filter media reacts with available organic matter forming a build-up of THMs. These are then washed out during the first dosing event.
- *E. coli* was only detected in the outflow samples after the prolonged dry weather period (sampling runs 5 and 6), establishing the effect of dry weather spells on bacteria treatment performance. Furthermore, the reduced chlorine concentrations could have resulted in decreased levels of disinfection, partly explaining the presence of *E. coli* in the outflow after the dry spells.
- The removal capacity for most metals was lower after the prolonged dry weather periods, with a more pronounced effect after the longer 5 week drought. Whilst most metals had recovered to their ‘pre-drought’ treatment performance by sampling run 6, some cases still showed increased outflow concentrations at the last sampling run (e.g. Al, Cd, Cu).

Hydraulic conductivity measurements

Whilst the drainage rate seemed to recover slightly after certain events (e.g. dry period, replacement of sediment traps), the median hydraulic conductivity was nevertheless decreasing over time (Figure 5). This proves that, in spite of the presence of a dedicated sediment trap, some of the finer sediment must be entering the system and clogging the deeper layers of the filter media. However, our experience shows that the compressed time scale used during this experiment has a tendency to overestimate maintenance requirements and it is likely that in field conditions this maintenance requirement could decrease to once a year, and even up to once every two years, but this heavily depends on climatic and specific site conditions. This is exactly what was seen at two demonstration sites (unpublished results), where infiltration rates were being maintained for over a year without sediment trap replacement.

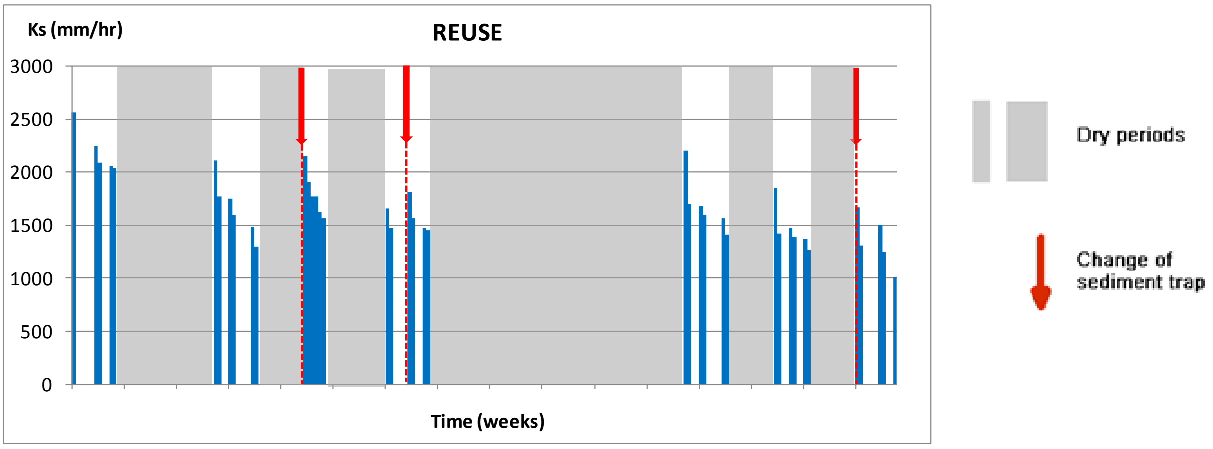


Figure 5. Median hydraulic conductivity for REUSE filters.

CONCLUSIONS

- The presence of chlorine as a disinfection agent proved to be very efficient for the removal of microorganisms in REUSE enviss™ filters, even though it had the side effect of slightly reducing the nutrient treatment performance. However, given the suggested end-uses for REUSE enviss™ filters, this reduced nutrient treatment was of no great concern (since the end-use is often toilet flushing or garden irrigation).
- WSUD enviss™ filters had the benefit of providing an elevated nutrient treatment performance compared to REUSE enviss™ filters, due to both the lack of chlorine and the extended depth of filter media. However, the beneficial influence of filter media depth decreased and almost disappeared with the effect of time (in particular for nitrogen): the TN outflow concentrations tripled within one year (from 0.4mg/L to 1.3mg/L), reducing the initial treatment performance from about 85% to only just under 40% removal. Whilst this loss of performance is of no concern for REUSE enviss™ filters, it is more problematic for WSUD enviss™ filters, which are releasing their outflows into downstream systems. The authors have worked to resolve this issue (see Schang *et al.*, 2011, which shows that nutrient removal is maintained above 60%-70% load reduction for five years of operation).
- Dry weather periods were found to have a negative effect on the treatment performance of almost all pollutants (nutrients, *E. coli* and heavy metals).
- Although hydraulic conductivity results indicated 2 or 3 sediment trap replacements per year is required to maintain filtration rates for both filters, it is expected that the experimental design overestimated this maintenance frequency. In fact, results from two demonstration sites (unpublished) show that *in-situ*, sediment traps can last longer than laboratory setups, depending on site characteristics.

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