Investigation of biological clogging in stormwater filters

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ABSTRACT
Biological clogging of infiltration systems has been acknowledged as a significant problem in the case of wastewater treatment systems. However, limited research has been conducted on biological clogging in stormwater treatment systems. This article, using a laboratory-based approach, aims to investigate the effect of biological clogging on the infiltration performance of high flow rate filters that treat stormwater. Different filter configurations were dosed with stormwater and their performances compared. It was found that all configurations perform differently in comparison to the basic configuration, which represents the most likely set of operational conditions in the field. For instance, the chlorinated configuration treated about 30% more stormwater compared with the basic configuration, whereas the nutrient loading configuration removed 7% less sediment. Columns dosed with sterilized sediment treated almost the same volume of stormwater but removed a greater quantity of sediment with higher treatment efficiency. These results indicate that there is some biological activity within filter bed normally and also contributes to the overall clogging of these systems. Further experiments are needed to understand the composition and nature of clogged material in the filter beds and the effect of drying and wetting on bio-clogging.

KEYWORDS
Biological clogging, clogging, filter media, hydraulic conductivity/ permeability, stormwater, treatment

1.0 INTRODUCTION
Clogging is the process of reduction in the permeability of a given system and the consequent decrease in its infiltration rate (Bouwer 2002). The clogging of a system can be due to physical, biological and chemical processes (Bouwer 2002). It has been established that in the case of wastewater treatment systems, biological clogging is often a significant operational issue (Chang *et al.* 1974; De Vries 1972; Rice, R. C.1974). Chang *et al.* (1974) concluded that although the initial reduction of porosity was caused by the capture of sediment, it was the growth of microbes around the trapped sediment that ultimately sealed the pores in the sample. Cunningham et al (1991) also found that bio-films start to form in porous media when microbial cells that exist in suspension adsorb to solid surfaces comprising the effective pore space. Seki and Miyazaki (2001) confirm this theory, by stating that bacteria attach to solid particles first reversibly and then irreversibly with exopolysaccharide polymers.

To date, limited research has been conducted on biological clogging in stormwater treatment systems. Stormwater flows are intermittent in nature, with high sediment load and low organic matter and nutrient content in comparison to other water types (Table 1). Therefore, following hypotheses have been made in context of high flow rate stormwater treatment:

- Physical clogging is more pronounced than chemical or biological clogging;
- The abundance and nature of microbes in stormwater imply that biological clogging should not be neglected altogether;

- Intermittent loading (i.e. the wetting/drying) regime can potentially affect biological clogging in the stormwater filters; and
- Adsorption, being the dominant removal mechanism in granular filter media, is very effective in removal of microbes.

This article focuses primarily on the second hypothesis and uses a laboratory based approach to investigate the effect of biological clogging on the infiltration performance and longevity of high flow rate filters treating stormwater.

Table 1. The characteristics of different water sources (Adapted from Mitchell et al 2002)

Quality parameter (mg/L)	Stormwater	Untreated grey water	Untreated wastewater	Treated wastewater
BOD5	3–73	90–290	100–500	8–80
Suspended Solids	13–1622	45–330	100–500	11–250
Total dissolved solids	44–208	284–1700	250–850	520–4940
Total phosphorus	0.049–2.14	0.6–27.3	4–30	
Total nitrogen	0.50–12.6	2.1–31.5	20–85	6.1–44.2

2.0 METHODS

2.1 Experimental setup

To investigate the above hypotheses in the context of stormwater filtration, zeolite media was combined with porous/permeable pavement based systems in a testing column. Zeolite has been selected as the filter media for these experiments because of its treatment potential (based on industry experience) and local availability. Experimental columns were constructed according to the design shown in Figure 1, wherein zeolite (2mm particle size) is located underneath a porous pavement to create an effective treatment train and treated stormwater is then collected from the outlet of column.

Different sets of experimental configurations (5 replicates each) were constructed using zeolite, as listed in Table 2. The different configurations were chosen to indirectly investigate the role of biological clogging in filtration media; the basic configuration is the control, while the others either promote biological activity (i.e. high nutrient loading) or discourage it (i.e. sterilising or disinfecting). The Basic configuration (1) is the 'control' and represents the likely set of operational conditions in the field; the Nutrient loaded (2) is promoting biological activity; while Chlorinated (3), Sterilized sediment (4) and Sterilized columns (5) inhibit biological activity.

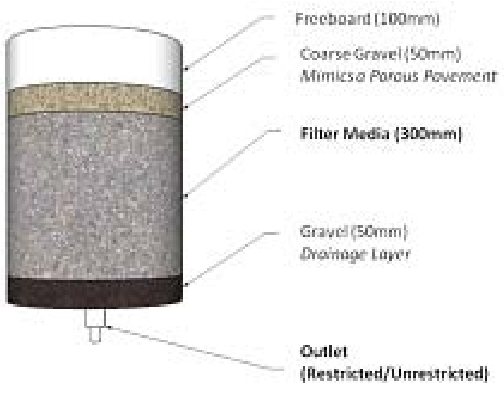

Figure 1. Basic configuration of experimental columns

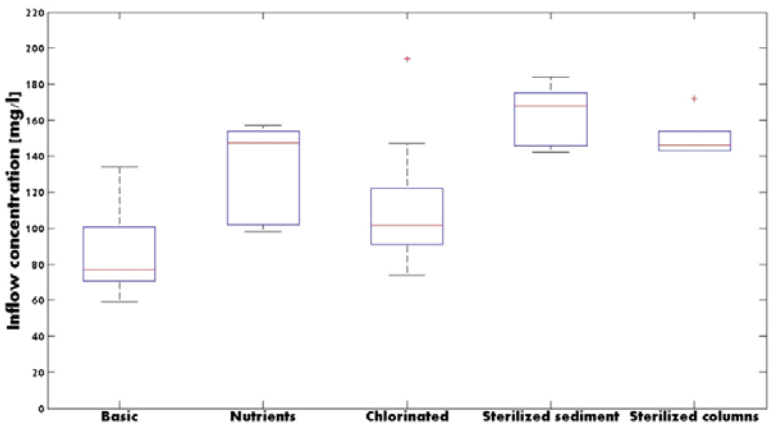

Figure 2. Range of TSS in inflows of different configurations

Table 2. Details of different configurations

Experiment details	Configuration type	Details of filter bed	Details of influent	Nature of biological activity
Natural conditions	1. Basic design	Zeolite	Normal stormwater	Natural conditions
Enhancing biological activity	2. Nutrient loaded	Zeolite	Stormwater with nutrient load	Higher nutrient dosing enhances normal biological activity
Inhibting biological activity	3. Chlorinated design	Zeolite with Chlorine tablets on the top of Porous pavement	Normal stormwater	Disinfects any biological activity in the filter bed
	4. Sterlized sediment	Zeolite	Sterlized sediment	Sterlizing the sediment curbs natural biological activity within the stormwater
	5. Sterlized columns	Autoclaved Zeolite, porous pavements and drainage layer	Sterlized stormwater	Any biological activity within the filter bed material is additionally curbed

Three different sterilization approaches were used to impede biological clogging because it was unclear if these approaches could have any side effects that influence the studied processes. For the chlorinated design, chlorine tablets were left on top of the porous pavements. For configurations requiring sterilised stormwater, the sediment was autoclaved at a steam pressure of 1 bar at 121°C for 20 minutes, prior to adding it to the stormwater mixture. For those configurations requiring sterilised media, the entire constituents of filter bed (porous pavement stones, filter media and gravel used in the drainage layer) were sterilized using hot air sterilisation technique in oven at 160°C for 2 hours (Salle A J 1967).

2.2 Experimental procedures

The columns were dosed with semi-synthetic stormwater. This was chosen instead of natural stormwater because of logistics; the high volume required for the tests and the timing of rainfall meant that using actual stormwater was not possible. This method also ensured a fairly consistent composition of inflow for the experiments. This stormwater was prepared in a 1000L tank using tap water and sediment harvested from a stormwater pond, sieved to select particles less than 1000µm in diameter. This size range was selected to represent real practice, as particles coarser than this size range are likely to settle down in the catchment before the stormwater reaches the filtration system, even with limited or no pre-treatment. This approach has been used in earlier studies to investigate the clogging and treatment phenomena (e.g. Siriwardene et al 2007, and Siriwardene et al 2008).

The sediment concentration was targeted at 150mg/l based on typical stormwater concentrations from a review of international data (Duncan, 1999) and was maintained at a relatively constant concentration for each experiment by a mixer in the stormwater tank. For dosing the Nutrient loading configurations, Total Nitrogen and Total Phosphorous concentrations were targeted at 5mg/l and 1.5mg/l respectively (as against the normal stormwater concentration of 0.31mg/l and 0.09mg/l respectively). Within experiments, the level of inflow TSS varied between 59-215mg/l and accordingly the number of dosing events varied between configurations. Inflow TSS was most consistent for the sterilized sediment and sterilized column configurations, ranging between 142-184mg/l, therefore reducing the number of dosing events (Figure 2). Residual chlorine in the chlorinated configuration ranged between 1-3mg/l.

The experiments have been 'compressed in time', where months of operational life of the systems are compressed to several weeks due to time constraints. Such compressed time scale experiments have been successfully implemented previously (Hatt et al., 2007; Bratieres et al., 2008, Siriwardene et al 2007). To compress the time scale, an analysis of Melbourne's historical rainfall data (last 10 years) was conducted. It was determined that the average amount of rainfall during each event was calculated to be 5.9mm (for an annual rainfall of 512mm; total rainfall contributing to runoff - 422mm/yr and; number of events contributing to runoff- 72/yr). As such, during each dosing event, each column was dosed with 15l of stormwater, which equates to a sizing of this system of 0.3% of the catchment's impervious area and all the columns were dosed every alternate day.

The experimental columns were dosed with 50 litres of potable water (equivalent to 45-50 pore volumes of the media) to ensure the filter bed was clean of any intrinsic dust before stormwater was dosed. To ensure that the infiltration rate could be monitored accurately (using Darcy's Law), the columns were dosed to ensure a constant head was maintained. Estimation of infiltration rates were made for each dosing event and these estimates were normalised for temperature. Composite water quality samples were taken, for each dosing event, from the inflows and column outflows and were analysed for suspended sediment concentrations to determine the total load of sediment applied to and retained by each configuration. Dosing ceased on columns when clogging occurred, such that the infiltration rate was less than about 50 mm/hr.

2.3 Data analysis

The data were analysed for trends to investigate the impact of the key variables related to the hypotheses made. Simple statistical analysis, such as calculation of median, range of observations, inter-comparison of replicates, linear regression and statistical significance assessments, have been performed.

For all the results presented, the variables - Infiltration rate (IR), Total volume of stormwater passed and Overall treatment efficiency ([Total TSS applied – Total TSS in outflow)/ Total TSS applied] * 100) have been reported as median values and 95% confidence intervals (using percentile) of all the replicate columns of a given configuration. Statistical analysis, to test the statistical difference between the different groups of results, has been carried out using ANOVA tests, at $p=0.05$.

The total volume of stormwater passed before clogging has been expressed as (the passed mass and was normalised by dividing it by the target concentration of 150 mg/l to express all results in meters of treated water):

Equivalent metres of stormwater $= \sum [(V_i * TSS_i / A) / 150]$

where, V_i = litres of stormwater passed during the dosing event, TSS_i = TSS during the dosing event, A = Area of experimental column, and 150 represents the target TSS in stormwater (mg/l).

3.0 RESULTS

3.1 Initial infiltration rate

The initial infiltration rate (IR) of the different configurations was found to vary within replicates (Figure 3). The observed variation within replicates can be attributed to the natural variability in the media; the variation in their packing arrangement and the re-arrangement of filter particles in the filter bed as influent passes through (potable water in this case) and; the uncertainty associated with hydraulic conductivity measurement techniques (Le Coustumer et al 2007).

Statistical analysis of the comparative *Initial infiltration rate* (using one-way ANOVA with significance level 0.05) suggests that initial hydraulic performance does not vary amongst the different configurations ($F_{test} < F_{critical}$; P-value > 0.05). It may appear that the Basic Configuration has a slightly lower initial infiltration rate (Figure 3), but variation amongst its replicates is very large, which means that statistically it is not different from the other configurations. This also meant that all the results on development of clogging could be viewed in the light that all configurations start from almost similar initial infiltration rates.

3.2 Clogging and treatment performance

The infiltration rates for all configurations decrease steadily over time as more stormwater is passed through the filter bed. For instance, IR for the *Basic configuration* decreased from an initial median value of 25 m/hr respectively to a completely clogged state on passage of the equivalent 10 m of stormwater (with concentration of 150mg/L). It was observed that the treatment efficiency was lower at the start for all the filter configurations, but improved consistently as the filters became clogged; e.g. treatment efficiency for the different replicated of the *Basic configuration* improved consistently from an initial value of 40% to 90% when the filter was completely clogged, with an overall treatment efficiency of 58% (as shown in Figure 4). Similar trends in clogging and evolution of treatment performance were observed for the other configurations (Figure 5).

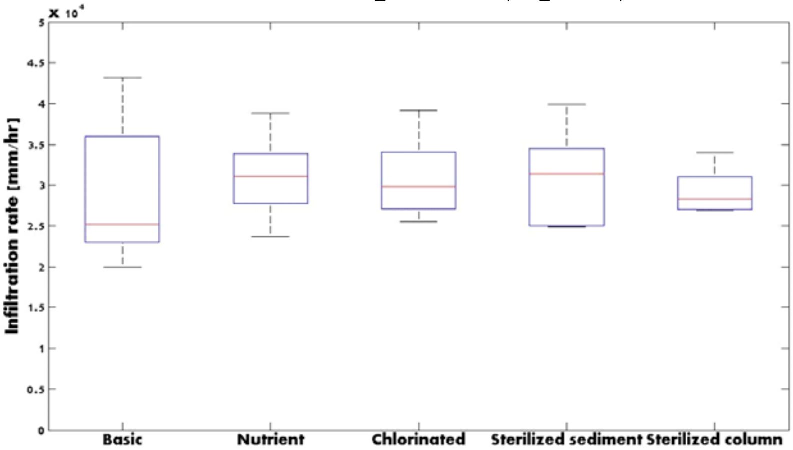

Figure 3. Initial infiltration rate of all configurations

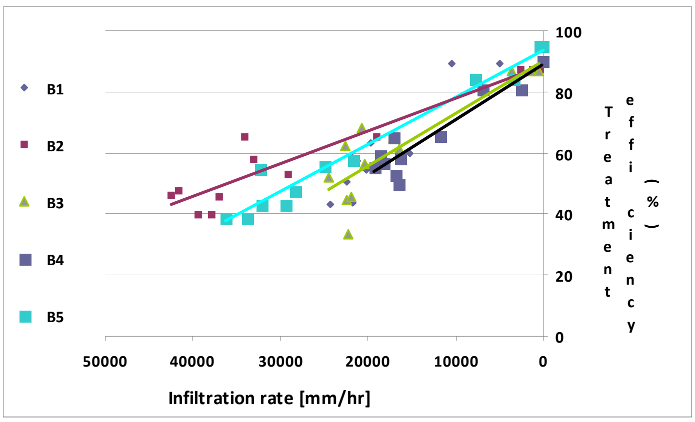

Figure 4. Evolution of Treatment efficiency in *Basic configuration* columns

It is evident that even though initial infiltration rates are not significantly different, their pattern of decline and longevity varies. Figure 6 provides a box plot for the total volume of stormwater treated by the configuration prior to it's clogging (expressed as metres of stormwater applied), while Figure 7 presents the overall sediment load removed. It is evident that the Chlorinated configuration passed the maximum volume of stormwater before clogging (statistically significant). *Chlorinated configurations* and *Sterilised sediment configurations* removed maximum sediment load before getting clogged. As shown in Figure 2, the *Sterilised sediment configurations* were dosed with higher sediment concentrations as compared with the *Basic* and *Chlorinated configuration.* The treatment performance of all configurations (measured as overall treatment efficiency) was also better as compared to the *Basic configuration*, with the *Sterilized sediment configuration* having a high overall treatment efficiency of 79%.

Statistical analysis of the performance of different configurations (using one-way ANOVA with significance level 0.05) confirms performance differences between different configurations. Post hoc F-tests for total sediment load removed before clogging suggest that there is insignificant difference in the performance of *Chlorinated configuration* and

Sterilized sediment configurations. Similarly, statistically the performances of the *Basic configuration* are similar to the *Nutrient configuration* and *Sterilized column configuration* for total sediment load retained.

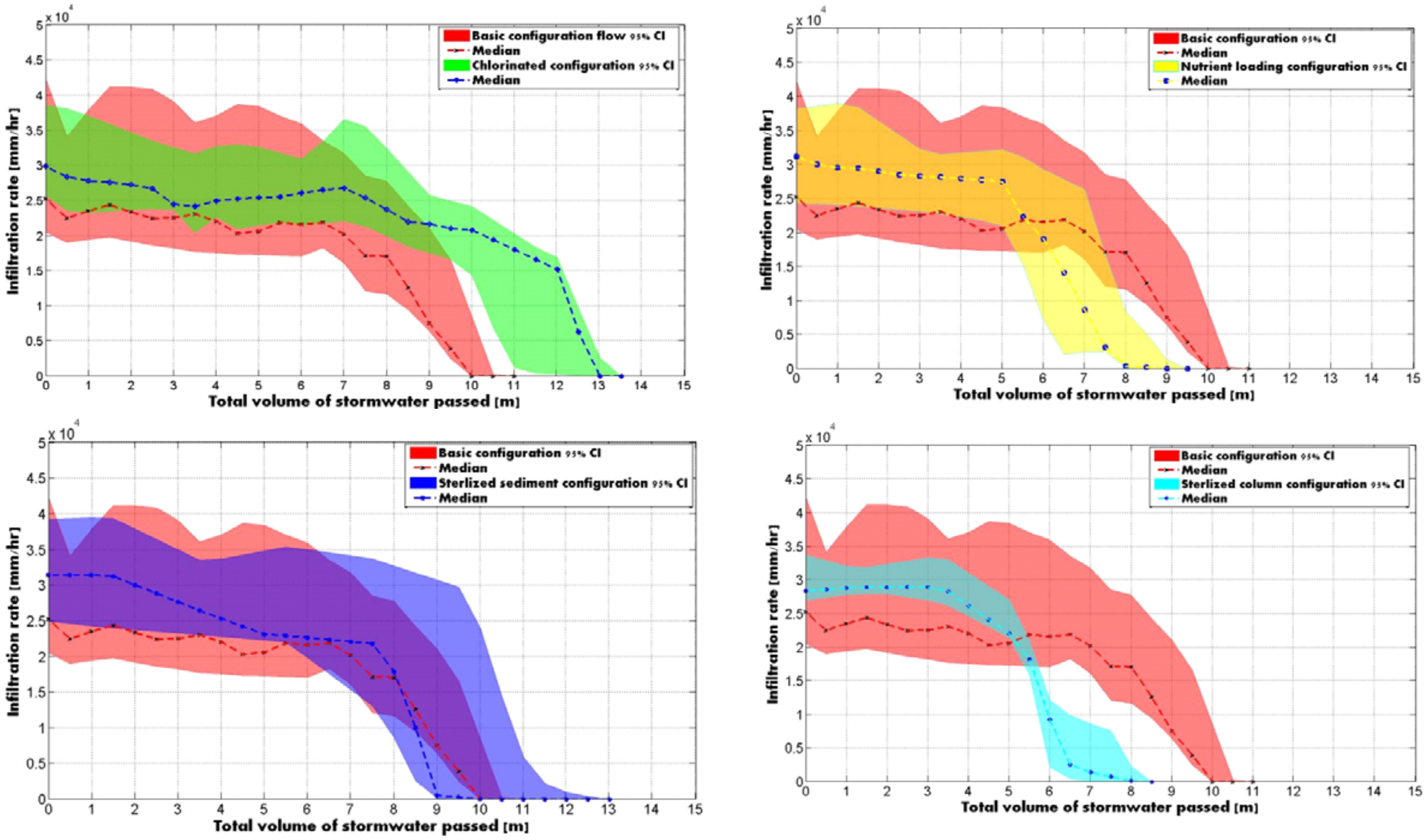

Figure 5. Evolution of Infiltration rate in different configurations
(can be read in comparison with the Basic configuration)

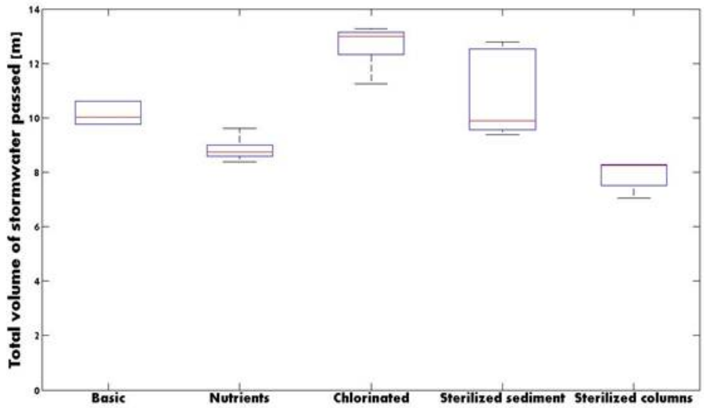

Figure 6. Total volume of stormwater passed before clogging

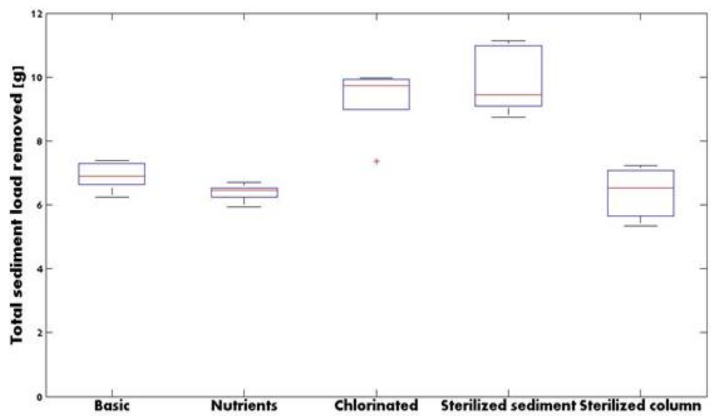

Figure 7. Total sediment load removed before clogging

4.0 DISCUSSIONS

Nutrient configurations, where biological activity was enhanced by dosing stormwater containing high nutrient load, clogged after application of about 90% of the stormwater volume passed through by the *Basic configuration* before clogging. This suggests that increased nutrient loading in stormwater enhanced microbial activity within the filter bed, even in a limited way. This eventually enhanced formation of clogging layer, thereby improving the system's treatment efficiency and hence it's sediment removal performance.

Comparison of the total volume of stormwater passing through the *Chlorinated configuration* before it clogged suggests that regular disinfection increased the volume of stormwater treated by 30% as compared with the *Basic configuration* (Figures 5, 6). The fact that *Chlorinated configuration* is less prone to clogging is also evident by the fact that the amount of sediment removed and overall treatment efficiency was better (40% and 9% respectively as shown in Figure 7). These differences in performance imply that the disinfection process was effective in inhibiting biological activity within the filter bed and eventually limiting the formation of bio-clogging layer. However, since the column still clogged, the clogging was due to the other more dominant process i.e. physical clogging.

The *Sterilized sediment configuration* treated almost the same volume of stormwater as the *Basic configuration*, but removed a greater quantity of sediment with higher treatment efficiency (Figure 5, 6, 7). The fact that these set of columns were dosed by double sediment concentrations than *Basic configuration* is very likely the main reason for the results on treated volume. This suggests that the sediment sterilisation subdued biological activity within the stormwater. The increase in treatment efficiency of this configuration may result from changes in sediment's characteristics during the autoclaving process (such as its particle size distribution etc) or because of the higher range of TSS in the inflow. From this comparison it is evident that biological clogging is present but that impact of physical clogging may be dominant. These interesting results suggest that we need further research to quantify the impact of biological clogging in comparison to physical clogging in stormwater filters.

The *Sterilized column configurations* had inferior performance as compared to the Basic configuration (Figure 5,6,7), which may be the result of changes in Zeolite and porous pavement stones during the sterilization process at a high temperature of 160ºC for 2 hours. It could be concluded that this configuration is just not suitable for testing our hypothesis on biological clogging, because of the change in the properties of the studied media.

5.0 CONCLUSIONS

The presence of biological clogging in high-flow-rate stormwater filters has been examined in this study. Different filter configurations that could be grouped into broad groups: Biological activity is present at 'typical' or 'enhanced' level and; the biological activity is suppressed. The biological activity is suppressed (using chemicals or sterilisation). All configurations had similar infiltration rate before stormwater was dosed.

Through the comparison of results on rates of clogging and sediment treatment it was clear that biological clogging is present in stormwater filters and should not be ignored. The level of its importance was however not estimated due to the fact that experiments have not been done in real time frame of the system activity but rather on compressed time frame.

More studies are needed to understand the impact and nature of biological clogging, such as to examine the:

- composition and nature of clogged material in the filter beds for which direct examination of clogged material needs to be carried out and

- effect of drying and wetting on biological clogging for which real time experiments need to be undertaken;
- effect of sterilization and sterilization methods on stormwater sediment and filter material;
- effect of changes in inflow sediment concentration and hydraulic loading on the clogging phenomenon

Further experiments will be conducted to analyse and understand the above. These results will further our understanding of the clogging phenomenon, including biological clogging of high flow granular filters in context of stormwater treatment, and its effect on treatment performance. This will further help develop a model that predicts the hydraulic and treatment performance of filters, along their lifespan. One of the main applications of such a tool would be in an improved design of granular water treatment systems, particularly for stormwater filtration aimed at ecosystem protection or the re-use of treated stormwater.

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